LABORATORY AND FIELD PERFORMANCE EVALUATION OF FIBER-REINFORCED ASPHALT CONCRETE FOR SUSTAINABLE PAVEMENT APPLICATION

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การประเมินสมรรถนะของผิวทางแอสฟัลต์คอนกรีตเสริมกำลังด้วยเส้นใยในห้องปฏิบัติการและในสนามเพื่อประยุกต์ใช้ในงานผิวทางอย่างยั่งยืน

นายถาวร ตะไก่แก้ว

วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรปริญญาวิศวกรรมศาสตรดุษฎีบัณฑิต
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Suranaree University of Technology has approved this thesis submitted in partial fulfillment of the requirements for the Degree of Doctor of Philosophy.

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ถาวร ตะไก่แก้ว : การประเมินสมรรถนะของผิวทางแอสฟัลต์คอนกรีตเสริมกำลังด้วยเส้นใยในห้องปฏิบัติการและในสนามเพื่อประยุกต์ใช้ในงานผิวทางอย่างยั่งยืน (LABORATORY AND FIELD PERFORMANCE EVALUATION OF FIBER-REINFORCED ASPHALT CONCRETE FOR SUSTAINABLE PAVEMENT APPLICATION) อาจารย์ที่ปรึกษา : ศาสตราจารย์ ดร.สุขสันติ์ หอพิบูลสุข, 138 หน้า.

วิทยานิพนธ์นี้ศึกษาความเป็นไปได้ของการประยุกต์ใช้เส้นใยเพื่อเสริมกำลังแอสฟัลต์คอนกรีตและใช้เป็นแนวทางการปรับปรุงคุณสมบัติของแอสฟัลต์คอนกรีตแบบดั้งเดิมที่ใช้แอสฟัลต์ซีเมนต์ที่มีในประเทศไทย ซึ่งการศึกษานี้แบ่งออกเป็น 2 ส่วนหลัก ดังนี้ คือ

ส่วนที่ 1 จะศึกษาและนำเสนอเกี่ยวกับการประเมินคุณภาพและสมรรถนะของแอสฟัลต์คอนกรีตที่เสริมกำลังด้วยเส้นใย โดยการประยุกต์ใช้กับแอสฟัลต์ซีเมนต์ที่มีใช้ในประเทศไทย ซึ่งในปัจจุบันแอสฟัลต์ซีเมนต์ที่มีใช้ในประเทศ ประกอบไปด้วย แอสฟัลต์ซีเมนต์ เพนิเตรชั่นเกรด 60/70 (Penetration grade AC60/70) แอสฟัลต์ซีเมนต์ปรับปรุงคุณภาพด้วยยางธรรมชาติ (Natural Rubber–Modified Asphalt : NRMA) และแอสฟัลต์ซีเมนต์ปรับปรุงคุณภาพด้วยโพลิเมอร์ (Polymer-Modified Asphalt : PMA) การประเมินผลที่ได้จากการเสริมกำลังแอสฟัลต์คอนกรีตด้วยเส้นใย ดำเนินการโดยการนำส่วนผสมแอสฟัลต์คอนกรีตที่เสริมกำลังด้วยเส้นใย เตรียมตัวอย่างและทดสอบคุณสมบัติทางวิศวกรรมในห้องปฏิบัติการ ประกอบด้วย การทดสอบค่าความเสถียรภาพด้วยวิธีมาร์แชล (Marshall stability) การทดสอบความต้านทานการรับแรงดึงทางอ้อม (Indirect Tensile Strength Test : ITS) การทดสอบค่าโมดูลัสยืดหยุ่น (Resilient Modulus Test : MR) การทดสอบค่าสติฟเนสโมดูลัสโดยใช้แรงดึงทางอ้อม (Indirect Tensile Stiffness Modulus : ITSM) การทดสอบค่าความคืบทางไดนามิกส์ (Dynamic Creep) การทดสอบค่าความต้านทานการแตกร้าวเนื่องจากความล้า (Diametrical Indirect Tensile Fatigue Test) และการทดสอบความต้านทานการเกิดร่องล้อ (Rutting Resistance Tests) การประเมินคุณสมบัติทางด้านวิศวกรรมของส่วนผมแอสฟัลต์คอนกรีตที่เสริมกำลังด้วยเส้นใย จะเปรียบเทียบระหว่างแอสฟัลต์ซีเมนต์ชนิด AC60/70 NRMA และ PMA ที่เสริมกำลังด้วยเส้นใยกับแอสฟัลต์ซีเมนต์แบบดั้งเดิม (ไม่มีเส้นใย) การเติมเส้นใยในส่วนผสมแอสฟัลต์คอนกรีต จะเติมเส้นใยในอัตราร้อยละ 0.05 โดยน้ำหนักของส่วนผสมแอสฟัลต์คอนกรีต จากผลการทดสอบ พบว่า การเติมเส้นใยในส่วนผสมแอสฟัลต์คอนกรีตเพื่อปรับปรุงคุณสมบัติ สามารถเพิ่มกำลังและคุณสมบัติทางวิศวกรรมของแอสฟัลต์คอนกรีตได้เป็นอย่างดี โดยแอสฟัลต์คอนกรีตที่เสริมกำลังด้วยเส้นใยจะสามารถเพิ่มความต้านทานการเกิดร่องล้อ ช่วยเพิ่มคุณสมบัติความต้านทานความแตกร้าวเนื่องจากความล้า เพิ่มค่าโมดูลัส

ยึดหยุ่น ในทุกชนิดของแอสฟัลต์ซีเมนต์ ผลจากการศึกษานี้แสดงให้เห็นว่าการเสริมกำลังแอสฟัลต์คอนกรีตด้วยเส้นใย สามารถเพิ่มความสามารถการรับน้ำหนักและคุณสมบัติทางด้านวิศวกรรม ในผิวทางแอสฟัลต์คอนกรีตที่เสริมกำลังด้วยเส้นใย สามารถเพิ่มอายุการใช้งานของถนน และลดค่าใช้จ่ายในการบำรุงรักษาผิวทางแอสฟัลต์คอนกรีตอีกด้วย

ส่วนที่ 2 แสดงผลการศึกษาการเปรียบเทียบผลจากการทดสอบการเสริมกำลังแอสฟัลต์คอนกรีตด้วยเส้นใยในห้องปฏิบัติการและการทดสอบในสนาม โดยการใช้แอสฟัลต์ซีเมนต์ชนิด AC60/70 และ PMA การผสมและเตรียมตัวอย่างจะดำเนินการโดยการเตรียมตัวอย่างแอสฟัลต์คอนกรีตที่เติมและไม่เติมเส้นใย ในห้องปฏิบัติการและการผสมส่วนผสมแอสฟัลต์คอนกรีตที่ได้จากโรงงานผสมแอสฟัลต์คอนกรีต ดำเนินการทดสอบคุณสมบัติทางวิศวกรรม ดังนี้ การทดสอบความต้านทานการรับแรงดึงทางอ้อม (Indirect Tensile Strength Test : ITS) การทดสอบค่าโมดูลัสยืดหยุ่นด้วยแรงดึงทางอ้อม (Indirect Tensile Resilient Modulus Test : MR) การทดสอบค่าความคืบทางไดนามิกส์ (Dynamic Creep Test) การทดสอบค่าความต้านทานการแตกร้าวเนื่องจากความล้า (Indirect Tensile Fatigue Test) และการทดสอบความต้านทานการเกิดร่องล้อ (Rutting Resistance Tests) ส่วนการทดสอบในสนาม ประกอบด้วย การทดสอบหาค่าดัชนีความเรียบ (International Roughness Index : IRI) ค่า texture depth และวัดค่าการเกิดร่องล้อบนผิวถนนแอสฟัลต์คอนกรีต (Rutting) ผลการทดสอบ พบว่า การเสริมกำลังแอสฟัลต์คอนกรีตด้วยเส้นใยที่ใช้แอสฟัลต์ซีเมนต์ชนิด PMA มีคุณสมบัติด้านวิศวกรรมดีที่สุด การเสริมกำลังด้วยเส้นใยสามารถเพิ่มประสิทธิภาพด้านความต้านทานการแตกร้าวเนื่องจากความล้า และช่วยต้านทานการเกิดร่องล้อได้เป็นอย่างดี ผลที่ได้จากงานวิจัยนี้สามารถใช้เป็นแนวทางในการพัฒนาการเสริมกำลังด้วยเส้นใยในผิวทางแอสฟัลต์คอนกรีตของกรมทางหลวง ประเทศไทย และประเทศอื่น ๆ ที่มีลักษณะการใช้งานที่ใกล้เคียงกัน

สาขาวิชาวิศวกรรมโยธา
ปีการศึกษา 2562

ลายมือชื่อนักศึกษา
ลายมือชื่ออาจารย์ที่ปรึกษา

THAWORN TAKAIKAEW : LABORATORY AND FIELD
PERFORMANCE EVALUATION OF FIBER-REINFORCED ASPHALT
CONCRETE FOR SUSTAINABLE PAVEMENT APPLICATION.
THESIS ADVISOR : PROF. SUKSUN HORPIBULSUK, Ph.D., 138 PP.

FIBERS/FIBER-REINFORCED ASPHALT CONCRETE/PERFORMANCE TEST/NATURAL RUBBER AND POLYMER MODIFIED ASPHALT BINDERS/RUTTING AND FATIGUE

This thesis studies the feasibility of using fiber-reinforced asphalt as an alternative for enhancing the quality of conventional asphalt binder used in Thailand . The investigation consists of two main parts.

First part presents performance of fiber-reinforced asphalt concrete with various asphalt binders in Thailand. Three commercially available asphalt binders were used :asphalt cement penetration grade AC60/70, natural rubber–modified asphalt NRMA (and polymer-modified asphalt) PMA. (The effect of fiber reinforcement in those asphalt mixtures was evaluated by a detailed laboratory experimental program, which included Marshall stability, indirect tensile strength) ITS (resilient modulus) MR (indirect tensile stiffness modulus) ITSM (dynamic creep, diametrical indirect tensile fatigue, and rutting resistance tests. The performance evaluation was performed by comparing the results between asphalt mixtures with and without fiber reinforcement for the AC60/70, NRMA, and PMA. The laboratory results indicate that without fiber reinforcement, the PMA exhibited better performance than NRMA and AC60/70, respectively. The addition of fibers 0.05 %by mass of the total mixture to asphalt concrete mixtures notably improved the rutting resistance, fatigue life, and resilient modulus, regardless of asphalt binder type .This research confirms that fiber reinforced asphalt pavements exhibit superior performance to traditional asphalt concrete pavement, hence resulting in longer service life.

Second part reported on both laboratory and field performance and cost analysis of FR-AC pavement using AC60/70 and polymer modified asphalt (PMA) as binders. The mixing quality of FR-AC from laboratory and plant was also investigated. The performance test included indirect tensile resilient modulus, indirect tensile strength modulus, and indirect tensile fatigue life and dynamic creep and wheel-tracking. The field trials of AC60/70 and PMA mixtures with and without fibers were constructed and the International Roughness Index, texture depth, and rutting were measured over time. The PMA + Fiber mixture exhibited the best performance and the performance of AC60/70 + Fiber mixture were comparable to PMA mixture. For AC60/70, the fiber reinforcement improved both fatigue cracking and rutting almost equally while it is more effective to improve fatigue cracking than rutting for PMA. The outcome of this research will be a guidance for establishing the specification of fiber-reinforced asphalt pavement for Department of Highways in Thailand and other countries using similar mix design.

School of Civil Engineering

Academic Year 2019

Student's Signature_______________

Advisor's Signature_______________

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Thaworn Takaikaew

TABLE OF CONTENTS

Page

CHAPTER

I INTRODUCTION

II LITERATURE REVIEW

TABLE OF CONTENTS (Continued)

Page

III PERFORMANCE OF FIBER-REINFORCED ASPHALT CONCRETES WITH VARIOUS ASPHALT BINDERS IN THAILAND

TABLE OF CONTENTS (Continued)

Page

IV **PERFORMANCE IMPROVEMENT OF ASPHALT CONCRETES USING FIBER REINFORCEMENT: LABORATORY AND FIELD STUDIES**

TABLE OF CONTENTS (Continued)

Page

V CONCLUSIONS AND RECOMMENDATIONS

TABLE OF CONTENTS (Continued)

Page

APPENDIX

LIST OF FIGURES

LIST OF FIGURES (Continued)

Figure **Page**

LIST OF TABLES

SYMBOLS AND ABBREVIATIONS

AC = asphalt concrete

ALF = accelerated loading facility

ASTM = American Society for Testing and Materials

BBR = bending beam rheometer

BS-EN = British Standards Institute European Norms

BSI = British Standards Institute

C_aO = calcium oxide

CR = crumb rubber

DH-S = Department of Highways specifications

DOH = Department of Highways

DOT = Department of Transportation

DSR = dynamic shear rheometer

Eq = equation

EVA = ethylene vinyl acetate

FHWA = Federal Highway Administration

FR-AC = fiber reinforced asphalt concrete

FRP = fiber reinforced polymer system

G_{mb} = bulk specific gravity

G_{mm} = theoretical maximum specific gravity

GPa = Gigapascals

SYMBOLS AND ABBREVIATIONS (Continued)

HMA = hot mix asphalt

H_z = hertz

IDT = indirect tensile

in = inch

INDOT = Indiana Department of Transportation

IRI = International Roughness Index

ITFT = indirect tensile fatigue test

ITS = indirect tensile strength

ITSM = indirect tensile stiffness modulus

JMF = job mix formula

kg = kilogram

kN = kilonewton

kPa = kilo Pascal

lb/ton = pound per ton

LVDT = linear variable differential transformer

MEPDG = Mechanistic-Empirical Pavement Design Guide

M_gO = magnesium oxide

min = minimum

mm = millimeter

M_R = resilient modulus

ms = millisecond

NRMA = natural rubber modified asphalt

SYMBOLS AND ABBREVIATIONS (Continued)

OAC = Optimum Asphalt Content

^{o}C = degree Celsius

PAC = polymerized asphalt cement

PennDOT = Pennsylvania Department of Transportation

PG = performance grade

pH = potential of Hydrogen ion

PMA = polymer modified asphalt

RAP = recycled asphalt pavement

RLAT = repeated-load axial test

RV = Rotation Viscometer

SAMI = stress-absorbing membrane interlayer

SB = styrene butadiene

SBR = styrene butadiene rubber

SBS = styrene butadiene styrene

SC-1C = slow-curing cationic

SMA = stone matrix asphalt

SSD = saturated surface dry

SST = superpave shear tester

TMD = theoretical maximum density

U.S. = the United States

UC = uniaxial creep

UTM = universal testing machine

SYMBOLS AND ABBREVIATIONS (Continued)

VFA = voids filled with asphalt

VMA = voids in mineral aggregate

VTM = voids in the total mix or air voids

WMA = warm mix asphalt

XRD = X-ray diffraction

XRF = X-ray fluorescence

γ_w = Specific gravity of water

CHAPTER I

INTRODUCTION

1.1 Statement of problem

Nowadays, the amount of traffic loading has been sharply increasing on various main roads, resulting in excessive repeated loads which damage and shorten the service life the pavement. The main causes of the pavement damage include crack and rutting which hinder the transportation and endanger drivers and road users (Olumide, 2016). Pavement crack is caused by the fact that the asphalt concrete pavement is subjected to repeated loads for a long time until fatigue and non-recoverable strain occur to the extent that the pavement cannot resist the loads (Garba, 2002). Rutting is another type of pavement damage which is caused by the collapse and permanent deformation due to the repeated loads of vehicle wheels which may occur within the structural layers or asphalt concrete layers. This leads to the study of improvement of asphalt concrete properties by fiber reinforcement. This study aims at investigating effectiveness of fiber reinforced asphalt concrete by using asphalt binders and local aggregate to increase fatigue cracking and rutting resistance and durability of the pavement via laboratory and field studies.

Fibers have been used to reinforce paving materials for many decades in various parts of the world. Their use in stone matrix asphalt and porous or open-graded mixtures to prevent draindown of the binder from the aggregate particles is very common. Less common is the use of fibers in dense-graded mixtures to increase stability (reduce rutting) and improve cracking resistance. Cracking of asphalt pavements appears to be an increasing concern in many states, so identification of a potential tool to reduce cracking could be very beneficial (NCHRP, 2015).

Fiber reinforcement is a powerful option for improving the quality of asphalt concrete using AC60-70 asphalt cement, Natural Rubber Modified Asphalt Cement (NRMA) and Polymer Modified Asphalt Cement. The common synthetic fibers are the compound between polyolefin fibers and aramid fibers (Waleed and Shane, 2014).

Fiber-reinforced asphalt concrete is a process of asphalt concrete quality improvement (Nelson and Xinjun, 2014). It is effective in extending the service life and reducing maintenance costs (Takaikaew et al., 2018). Fiber-reinforced asphalt concrete enhances tensile strength, modulus of elasticity and reduces fatigue cracking and rutting, as well as improving stability and flow (Kaloush et al., 2008). Kaloush et al. (2010) evaluated the material properties of a conventional (control) and fiber-reinforced asphalt mixtures using advanced performance tests including triaxial shear strength, dynamic modulus, repeated load permanent deformation, fatigue, crack propagation, and indirect tensile strength tests. It was concluded that the synthetic fibers can improve the performance against major pavement distresses including permanent deformation, fatigue cracking and thermal cracking (Kaloush et al., 2012).

To conclude, enhancement of asphalt concrete properties by fiber reinforcement is a promising option to develop and improve the quality of asphalt concrete pavement. In addition, the fiber-reinforced asphalt concrete can be used as pavement surface for high traffic volume road alternative to conventional asphalt concrete. The outcome of this project can be used as a guideline for development of code of practice on design and construction of fiber reinforced asphalt concrete in Thailand.

1.2 Objective of the study

The main aim of this study was to investigate the performance of asphalt concrete modified with Fibers and compared with conventional asphalt concrete, through comprehensive laboratory testing and field tests. To achieve the main aim, the specific objectives were:

1. To investigate the feasibility of using fiber-reinforced asphalt as an alternative for improving the performance of conventional asphalt binder (AC60/70, PMA, and NRMA)
2. To perform a series of performance tests on asphalt concrete mixtures with and without fiber reinforcement. The performance tests consist of the Marshall stability (ASTM D1559) test, the Indirect tensile strength test (ASTM D6931), the Resilient Modulus test (ASTM D4123-82), Dynamic creep test (BS-EN DD226:1996), Indirect tensile fatigue test (BS-EN12697-24: 2004), and the Wheel tracking test (BS-EN12697-22).

1.3 Structure of dissertation

This thesis consists of five chapters and divides according to the following outlines:

Chapter I is the introduction part that presents the objective and scope of the study.

Chapter II presents the summary of the literature review on the use of fibers in asphalt mixtures. Those studies focus on the use of fibers in asphalt mixtures. The results were grouped and focused on many aspects of fiber use included: fiber materials, fiber types and properties and the Fiber-reinforced asphalt concrete paving construction method and the costs analysis of fiber-reinforced asphalt concrete mixtures.

Chapter III presents a laboratory investigation into the effects of polyolefin and aramid fibers as a reinforcement material in hot-mix asphalt (HMA) mixtures, with different asphalt binders. Three commercially available asphalt binders were used: asphalt cement penetration grade AC60/70, natural rubber–modified asphalt (NRMA), and polymer-modified asphalt (PMA). The effect of fiber reinforcement in those asphalt mixtures was evaluated by a detailed laboratory experimental program, which included Marshall stability, indirect tensile strength (ITS), resilient modulus (MR), indirect tensile stiffness modulus (ITSM), dynamic creep, diametrical indirect tensile fatigue, and rutting resistance tests. The performance evaluation was performed by comparing the results between asphalt mixtures with and without fiber reinforcement for the AC60/70, NRMA, and PMA are analyzed and presented.

Chapter IV presents a study reports on the laboratory performance, field performance and cost analysis of fiber-reinforced asphalt concrete (FR-AC) pavement using AC60/70 and polymer modified asphalt (PMA) as binders. The mixing quality of FR-AC from laboratory and field plant was also investigated. The performance testing included indirect tensile resilient modulus, indirect tensile strength modulus, and indirect tensile fatigue life and dynamic creep and wheel-tracking. Field trials of

AC60/70 and PMA mixtures with and without fibers were undertaken and the International Roughness Index, texture depth, and rutting were measured over time.

Chapter V concludes the research work and provides the suggestion as well as recommendation for further research.

1.4 References

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CHAPTER II

LITERATURE REVIEW

2.1 Introduction

The chapter showed the result of various science reexamination on the fiber used for mixing in asphalt. Those studies focus on the use of fibers in asphalt mixtures. The results were grouped and focused on many aspects of fiber use included: fiber materials, fiber types and properties; experiment methods and the significance of those criteria; design, manufacturing, building with fiber-strengthen mixtures; workplace and completion of fiber-strengthen mixtures (dense grad), fiber in stone matrix asphalt (gap-graded) and the cost-saving of fibers application.

2.2 Fibers reinforced in asphalt concrete mixtures

There was completely understood the asphalt is robust for compression performance but exhausted in tensity (Busching et al., 1970). If fiber is added with full tensile, it will enhance the mixture of tensile strength. Theoretically, the stress can be departing to the compact fibers but that will weaken the asphalt mixture. It means the good bonding between fiber and asphalt will sustain the virtue of the stress transferring. The wider surface range of fibers can promote the bonding between them. The fiber required to be uniformly scattered in the compound to hinder the occurrence of the stress concentration (Busching et al., 1970). The principal purpose to increase fibers is to lower its binder drain-down. therefore, the high strength of asphalt mixtures is not required. The question is which fibers required to usefulness in the applications. How fiber properties shall improve their performance and how to make the measurement.

2.2.1 Fiber types

There are certain types of fiber that are commonly used as asphalt concrete mixtures included cellulose, mineral, and polymer fibers. Table 2.1 showed the common fibers use, benefits, and disadvantages.

(A) **Cellulose**: Cellulose fibers are extracted from plants included wood. But some made from the recycled newspaper. The fibers have high absorption properties. The cellulose fibers have high asphalt cement capacity in mixtures. Cellulose fibers can be found in loose pulverize as powder form or pelletize as pallet form.

(B) **Mineral**: Mineral fibers that sometimes can be name as mine wool or support woolen. It is manufacture by liquefaction minerals then spinning or extruding until the forming as fibers. There are some kinds of minerals application to manufacture fibers: contain slag or a compound of slag and rock (USEPA, 1995 and Brown et al., 1996), basalt (Morova, 2013), brucite (Guan et al.,2014), steel (Garcia et al., 2009, 2012 a and b, 2013 a and b and Serin et al., 2012), and carbon (Clevin, 2000; Liu and Shaopeng, 2011; Khattak et al., 2012, 2013 and Yao et al., 2013). In much study, Steel fibers have been commonly application for study. The steel fibers were wearing away as quickly as exposure to water therefore they were not competent in the extensive term (Freeman et al., 1989 and Putnam, 2011). While Carbon fibers and steel fibers have been used for the composition of the electrically conducting asphalt.

Asbestos fibers were used in hot mixed asphalt during the 1920's (Serfass and Samanos, 1996) until the 1960's. The reason to stop using of Asbestos fibers due to environmental and health issues (Busching et al., 1970).

(C) **Synthetic polymer fibers**: There are some example of Synthetic polymer fibers commonly application include aramid, polypropylene, polyester and other combinations of polymers. While poly para-phenyleneterephthalamide, nylon and the others are less generally used. The liquefaction point of each polymer is required to be careful for the adding of hot mix asphalt. Aramid fibers can be wrinkled at high temperatures therefore it has a high benefit to withstand pavement deformation (Kaloush et al., 2010). The synthetic of fibers can be exhibit as yarn but it does not generally use in the mix together asphalt concrete. (Busching et al., 1970).

(D) **Other plant-based fibers**: There are some other kinds of plant-based fiber included jute, flax, straw, and hemp which derived from woody fibers.

(E) **Glass fibers**: The glass fibers have unique and needed properties such as high tensile modulus, low elongation, high elastic recovery, and high softening point. But it needs to be used carefully due to it is brittle. (Abtahi et al., 2013).

(F) **Recycled fibers**: The sustainability in fabrication industrial led to increased interest in recycled materials. The devastated fibers from distinct origin such as reusing stripped carpet fibers or a tire fiber from the industrial of automobile manufacturing which has a benefit in terms of increased compound toughness, lasting transformation, and moisture resistance (Putnam and Amirkhanian, 2004). The studied application of recycled fibers from tires industrial and found it accomplish well, in reducing drain-down (Chowdhury et al., 2005).

(G) **Natural fibers**: The natural fibers are useful in many conditions included low price, competent strength, and mechanical properties, and sustainability. While also it has a drawback in moisture absorbing then can reason the swell of structure shown in Table 2.1. Moreover, this property will weaken the bounding of hydrophobic asphalt cement with the moisture-laden fibers. But, some fibers of natural, such as sisal or jute, can be application to replace synthetic fibers in asphalt concrete mixtures. (Abiola et al., 2014).

Different surface coatings are applied to each application for any purpose. The stain resistant of coatings used for carpet fibers might be not suitable with asphalt concrete mixture due to excess static is difficult for handling and mixing fibers.

In a study by Putnam (2011) aims to find the relationship between the binder and the fiber coating. One binder has been used with different kinds of fiber coating and another part used one fiber source but with different types of asphalt cements and many sources. The result showed different type of asphalt cements had compatibilities with fiber reinforced in various forms. The result also showed different finishes affected to tensile properties of binder sources. But the numbers of finish applied to a fiber did not cause any differences in asphalt cement properties (Putnam, 2011).

Table 2.1 The advantages and disadvantages of ordinary fiber types

Type of fiber	Advantages of fiber-reinforced	Disadvantages of fiber-reinforced
Cellulose Fibers	• sustain to stabilizes asphalt cement for open and gap-graded of stone matrix asphalt (SMA) mixtures. • Absorbs binder well and permit high binder content to extend the lastingness of mixture. • Quite cheap. • Widely usable to used. • Can be founded from recycled-materials.	• High binder absorption extends binder price. • Not solid in tensile form.
Mineral Fibers	• Stabilizes asphalt cement in open- and gap-graded (SMA) mixtures. • Not absorptive as much as cellulose. • Electrically conducting fibers can be application for inferential heating in condition of deicing aim or to recover of cracking.	• Some may impair or degrade because of humidity circumstances. • May produce harsh mixes that are difficult to dense and may be incursive, causing tire damage if used in surfaces.
Polyester Fibers	• Resistance of fracture, rutting, and potholes of asphalt concrete pavement. • can enhance the strength and steadiness of mixture. • Have higher liquefaction point than polypropylene. • Have highest tensile strength.	• Higher specifying gravity indicate fewer fibers per unit load added. • Cost-efficiency not proved or alternate.

2.2.2 Method of test fibers and fiber reinforced asphalt concrete mixtures

There are several methods of fiber testing which came from the textile industry. The common methods used for the interest properties needed to be tested as followed:

The physical dimensions: It is important due to it affect the performance of the fibers to dispersed and interact with the other components of mixes. The long fiber is related to the aggregate size in the mixture but the Long fibers are difficult for yielding the uniform mixture in the lab or plant. (Tapkin et al., 2009, 2010 and Do Vale et al., 2014).

A Sieve analysis is appropriated to measure the fiber size. It can be used for measuring wire-mesh screens or devices called an Alpine Air Jet Sieve. This analysis can identify the denier of fiber (a measure of its fineness). The denier is related to the fiber surface area therefore it related to asphalt demand and holding strength in a mixture.

The ash content commonly shows the organic content in natural fiber, especially plant-based fibers. The remaining ash after the fiber is heated to burn off organic contents. ASTM D128 is a procedure to determine the ash content.

The shot content specified for mineral fibers (shot is small globules of mineral material after the mineral fibers are produced). ASTM C1335 is one method used to measure the shot content.

There are some fiber properties included pH, oil absorption, and moisture content that can determine the compatibility and bonding of organic fibers with asphalt binder. The said properties also found in organic fibers but less specified for synthetic fibers. The measurement of pH is made by used soaking fiber in distilled water then using pH meter. A compatibility of the fiber with asphalt is measured by the oil absorption. The method is made by used suspending a measured fiber in the mineral for about five minutes. Later, shaking the excess mineral spirits off from the surface and measure the remaining fiber mass by counting and monitoring: how many times of the mass fiber is absorbed.

Gap-graded mixtures for SMA is tested to find the percentage binder drain-down. Stuart and Malmquist (1994) showed the differences between the three methods to determine the Gap-and open-graded mix.

- The German drain-down test is made by heating mixture of one kg in oven at 60-degree temperature for ± 1 min. Later, found the difference in the mixture mass loss before and after drain-down. The maximum allowable drain-down loss using this method is 0.3%.
- The FHWA drain-down test is made by the heating mixture of one kg in the oven at 60-degree temperature for ± 1 min. While the one kg mixture place in 2.36-mm sieved set on top of bowl. Later, found a difference in a mixture mass loss before and after drain-down.
- A third test is made by spreading one kg mixture on the Pyrex pied plate then putting them it in the oven with a certain temperature. After the mixture is cooled down. Later, check how much asphalt cement or mastic asphalt which have accumulated on a bottom of plate.

Figure 2.1 Images example for demonstrated asphalt contents from drain-down test

The Austroads drain-down test method is made by the heating mixture of one kg in the oven at 60-degree temperature for ± 1 min before the beaker turned upside down. But the oven temperature is varied by the mix type (gap-graded or SMA). The temperature is ranged from 160 °C for an unmodified OGFC to 185 °C for a modified SMA. Sometimes, the polymer-modified binders can be added into the mixture if the remaining amount of mixture is higher than 0.3% of the original mass of the mix. The solvent is used to wash off the remaining mixture from the beaker through a tared 0.600 mm sieve. This process helps to find the number of fine aggregate particles might be trapped in the modified binder (Austroads, 2006).

The Cantabro test is commonly used by compacting mixture in Los Angeles abrasion test drum. The determining of the changed in the mass before and after testing is showed the mixture durability. The study of Lyons and Putnam found the adding of fibers improved durability in some cases. (Lyons and Putnam, 2013).

Many methods mentioned above raised the question that is there any test to measured the uniformity of the distribution of fibers. (Austroads, 2007). Figure 2.2 showed the visibility of fibers. But the comparison between the mass is not significantly different and cannot detect the presence of fibers. There are some methods to determine the presence of fibers include a solvent extraction and sieve analysis. But the method is not suitable for small amount of fibers per ton. The method cannot determine the uniformity of fiber distribution.

Figure 2.2 Fibers showed in asphalt concrete mixtures

From the study of Huang and White to assessed a fiber content in Indiana asphalt concrete mixtures with the polypropylene fiber. They found three techniques as followed: The first, they used trichloroethylene to washed the asphalt cement and the fibers from a mixture of asphalt concrete and then filtered a solvent for fiber separation. Later, the ashes were removed from the fiber. The measurement of fiber content before and after founding the ash. The second technique, they try to used the water to float a fiber and some fines from extracted procedure of ASTM D2172. Later, they remove the fibers with ashing and weight the fibers. The third technique, they used sieve analysis (ASTM C136-84a) for fiber removal. The ashing were used to separated a fiber and the fine aggregates. Huang and White concluded that the first technique was easy to determine fiber content only. The second technique was made for the determinate of asphalt content. While, the third technique was useful to needed for gradation of aggregate. (Huang and White, 1996).

2.3 Asphalt concrete mix design with fibers

Mix design proceeds have always been mentioned with the drain-down test. The use of appropriate fibers content in the asphalt concrete mixture has become almost standard for definite fiber types. For example, used of 0.3% by weight of mixture is a very common addition rate for cellulose fibers in SMA mixture. Some research showed the use of too much of fiber content can cause compaction more difficult and higher air void contents in the laboratory or field-compacted mixtures. (Serin et al., 2012 and Crispino et al., 2013 and Morova, 2013).

2.3.1 Objectives of asphalt concrete paving mix design

The design of asphalt concrete paving mixes, as with other engineering materials designs, is largely a matter of selecting and proportioning materials to obtain the desired qualities and properties in the finished construction. The overall objective for the design of asphalt concrete paving mixes is to determine an economical blend and gradation of aggregates (within the limits of the project specifications) and asphalt that yields a mix having:

(1) Sufficient asphalt to ensure a durable pavement.

(2) Sufficient mix stability to satisfy the demands of traffic without distortion or displacement.

(3) Sufficient voids in the total compacted mix to allow for a slight amount of additional compaction under traffic loading without flushing, bleeding, and loss of stability, yet low enough to keep out harmful air and moisture.

(4) Sufficient workability to permit efficient placement of the mix.

2.3.2 Sample preparation by Marshall method

Hot mix asphalt mixtures have traditionally been designed in the laboratory. The test specimens were prepared based on the JMFs for the asphalt concrete. In this study used the Marshall method for prepared specimens and then tested and evaluated based on the performance of asphalt concrete. Loose mixes from asphalt concrete plant were used for prepared specimens compared with specimens prepared from mixing bowl in laboratory. Significant equipment and material differences exist between scale operation of the mixing bowl and an asphalt mixing facility. (Takaikaew et al., 2018)

Mix from laboratory: The test specimens were prepared for two groups: a control mix of AC60-70 and PMA with no fibers added and a mixture that contained the fiber content (40% aramid fiber and 60% polyolefin fiber) was fixed at 0.05% of the total mass of mixture for mixture design, as recommended by the manufacturers (Waleed and Shane 2014)

Mix from asphalt concrete plant : The test specimens were prepared for two groups: a control mix of AC60-70 and PMA with no fibers added and a mixture that contained 1-lb of fibers per ton of asphalt mixture.

Aggregates were heated in an oven between 170 and 190 ºC, which is about 20 ºC higher than the mixing temperature (150 ºC for AC6-70 and 170 ºC for PMA) to facilitate mixing temperature and then add the fiber to the aggregate by 1-lb of fibers per ton of asphalt mixture then mixed with aggregates under dry conditions for a duration of 10 s and mixed with aggregate thoroughly. Consequently, the melted asphalt binder at 160 ºC was added into fiber-aggregate mixes and mixed thoroughly till a well coated and evenly distributed mixture was obtained. Subsequently, the hot mixtures were placed in a steel mold (101.6 mm in diameter and 63,5 mm in height) and compacted under 75 blows on each side at 150 ºC for AC60-70 and 170 ºC for PMA to attain a Marshall specimen according to the Department of Highways Thailand (DOH) specification. (Takaikaew et al., 2018)

In order to examine the performance of asphalt mixes using fiber reinforced, the following tests were performed on samples from the two mixes: Marshall stability/loss of Marshall stability; indirect tensile strength; resilient modulus; indirect tensile fatigue and indirect tensile stiffness modulus. For consistency reasons, Marshall compactor was used to compact the test samples at 4% air voids.

2.4 The Fiber-reinforced asphalt concrete paving construction method

The Fiber-Reinforced asphalt mixture shall be constructed according to the conventional asphalt pavement construction methods.

The production of Fiber-reinforced mixture was prepared based on the job mix formula (JMF) for the asphalt concrete and the appropriate constituents of the asphalt concrete mixtures, based on the Marshall mix design method and in accordance with DOH: Thailand specifications [DH-S 408/2532 (DOH 1989)].

Aggregates were heated at 180–190°C to facilitate the mixing temperature, and add the fibers that contained 1-lb of fibers per ton of asphalt mixture were then mixed with aggregates under dry conditions for a duration of 10 second. Asphalt binders heated to 160°C were then added into the fiber–aggregate mixtures and mixed thoroughly to obtain well coated and evenly distributed mixtures. Subsequently, the hot mixtures were placed to the site that already to improve the adhesion between the Fiber-reinforced asphalt mixture layer and the base course layer by asphalt emulsion prime coat shall be sprayed generally by 0.4 to 0.6 ℓ/m^2 in order to improve the adhesion between the Fiber-reinforced asphalt mixture layer and the base course layer.

The Marshall test shall be carried out for the mixture produced at the asphalt mixing plant. And, some test results on the mixture would be evaluated, and the asphalt content and the gradation of the mixture shall be confirmed by the printed records or the extraction test. The Fiber-reinforced asphalt mixture shall be produced under the suitable temperature control and the suitable quality control.

The Fiber-reinforced asphalt mixture shall be transported by using clean cars so as not to change the quality. The attentions to be paid, like keeping temperature during transport and not to make the quality changed. Then, the Fiber-reinforced asphalt mixture were laying by the paving machine. There are various types of the machines to be used for the Fiber-reinforced asphalt pavement, on the function, capability and type. The paving machines shall be selected so as to match the purpose and paving conditions. Road roller and/or tire roller are used for compacting the mixture. The vibration roller may be used in static conditions instead of the roller. As the assistant machines, the walk behind type vibrating roller or the vibrating compactor may be used. The standard of the machines used are shown in Table 2.2.

Table 2.2 Example of the standard machine organization

Purpose		Name of machine
Lifting or Laying		Asphalt Paving machine
Rolling, Compaction	Breakdown, second rolling	Road roller (10-12t) or Vibrating roller (6-10t)
	Final rolling	Tandem roller (6-10t) or Tire roller (8-15t)

Laying the Fiber-reinforced asphalt mixture shall be carried out by an asphalt paving machine in principle to be the thickness required. The laying of the Fiber-reinforced asphalt mixture shall be carried out as same as the conventional asphalt mixture. Final step, the Fiber-reinforced asphalt mixture shall be compacted after laying so that the degree of compaction desired can be secured. Regarding the compaction of the Fiber-reinforced asphalt mixture, it is preferable that the degree of the compaction desired shall be secured through the breakdown rolling and the second rolling using the road roller. The points to be paid attention on the rolling works are as follows;

(a) Breakdown rolling and second rolling

- The road roller with the weight of 10 to 12 tons shall be used for the breakdown rolling. For the second rolling, the roller which was being used for the breakdown rolling is used or used the vibrating roller with the weight of 6 to 10 tons.
- For the prevention from attaching of asphalt mixture to the roller, a small amount of water or the antifouling agent can be sprayed by the spraying device attached to the roller.

(b) Final rolling

- The final rolling is carried out to remove the roller marks, in general, the tandem roller or the tire roller with the weight of 6 to 10 tons shall be used, and the number of rolling is about two passes (one lap).
- For the compaction by the tire roller, the mixture is easy to attach to the tire and the concern that air void may be squashed occurs if the temperature is high. Therefore, the compaction by the tire roller must be carried out after the surface temperature would fall to the temperature at which the mixture does not attach, like about 70 °C.

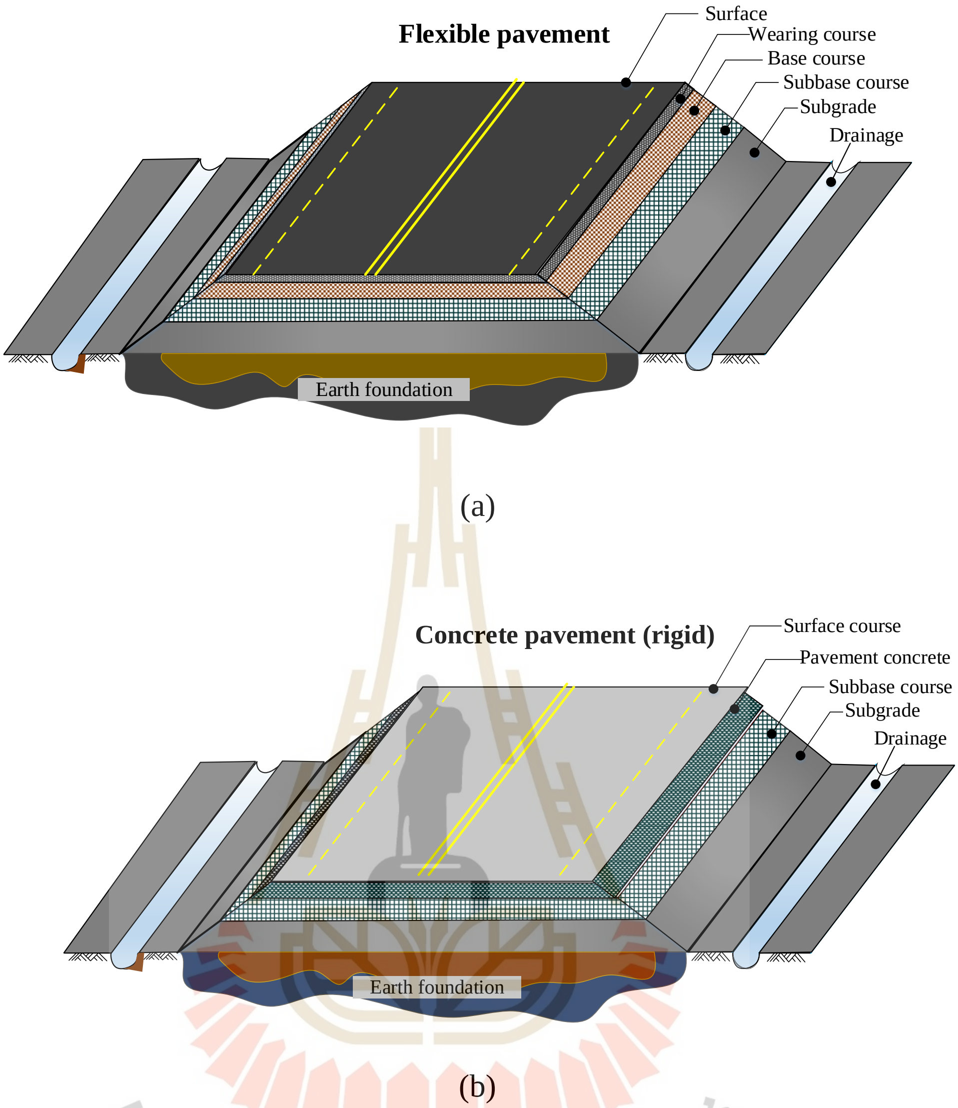
The temperature in being opened to the general traffic affects the initial rutting and the air void squash. Therefore, the impact on the pavement would be well controlled by lowering the surface temperature at the opening to the general traffic by like 50 °C or less.

2.4.1 Specification for pavement construction

Collins et al., (1993) recently conducted a survey of specifications in use for aggregates and shown that the specification of pavement structure in most of the countries did not differ significantly in fundamental principles. All countries use similar (but not identical) tests to determine suitability and adopt a layer technique for road construction as shown in Figure 2.3.

In general, difference country has completely independent highway authority under the Department of Highway or Department of Rural Road. Thailand, however national road authorities' specification has adopted from the great influence of international standards, namely the American Association of State Highway and Transportation Officials (AASHTO) and the American Society of Testing Materials (ASTM). Both international standards have issued specifications for subbase and base materials.

The specification covers the quality and grading of the following materials for use in the construction of subbase, base, and surface courses: sand-clay mixtures, gravel, stone or slag screenings, sand, crusher-run coarse aggregate consisting of gravel, crushed stone, or slag combined with soil mortar, or any combination of these materials.



(a)

(b)

Figure 2.3 Typical pavement construction layers (a) flexible pavement, and (b) concrete pavement (rigid) (not to scale) (Sherwood, 2001).

2.4.2 Construction of fiber reinforcement asphalt concrete mixtures

Fiber mixed can be manufactured in various methods. Wet-mixing is the method to produce fibers by adding fibers into the liquid binder. Dry-mixing is the method to produce fibers by adding fibers into the aggregate (Abiola et al., 2014). Figure 2.4 showed the mixing plant for the fiber-reinforced asphalt concrete. Figure

2.5 showed fibers were added to the plant in bags. The other fiber productions were adding fibers to plug mill and then mixed with aggregate then added with the binder for batch plants. (Shoenberger, 1996 and Watson et al., 1998). The addition rate of fiber-reinforced must be coordinated with the plant production rate to ensure that a consistent mix is produced (Schmiedlin, 1998).

Figure 2.4 The mixing plant of fiber reinforced asphalt concrete

Figure 2.5 The process of fibers added into the plant

Figures 2.6 show sample of fiber reinforced asphalt concrete mixtures by scanning electron microscopy (SEM) analysis

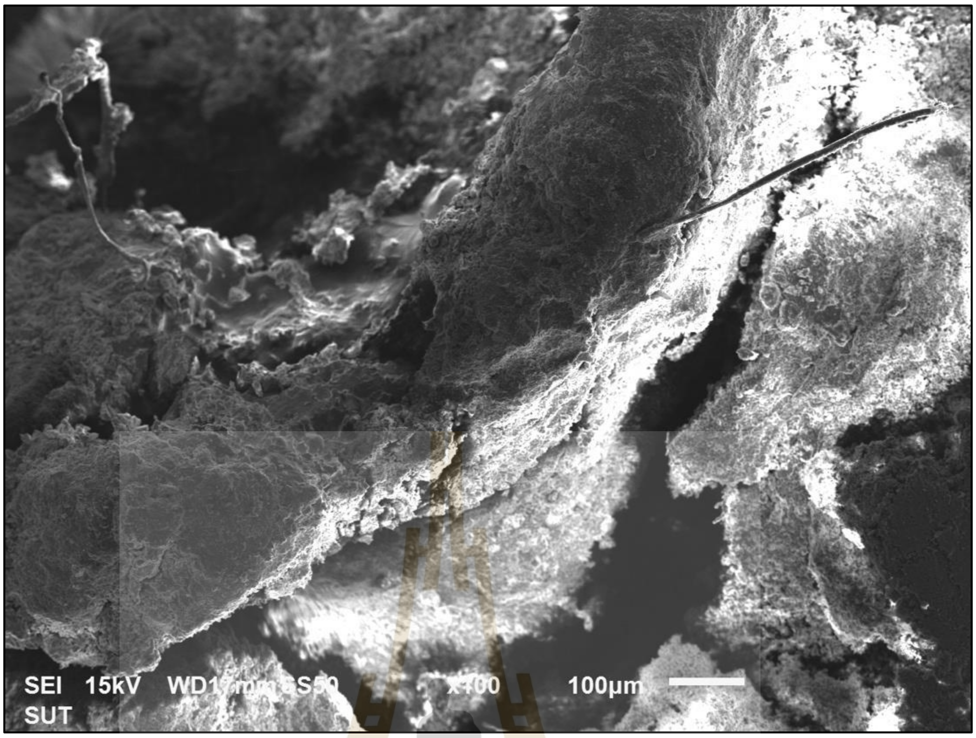


Figure 2.6 Scanning electron microscopy (SEM) analysis (Takaikaew et al., 2018)

2.5 Performance of asphalt concrete mixtures reinforced by fiber

2.5.1 Asphalt concrete properties

There are three fundamental properties of asphalt concrete which are of concern to the engineer:

(1) The properties of stiffness modulus.

(2) The resistance to permanent deformation.

(3) The fatigue cracking resistance characteristics.

These parameters need to be measured and it would be desirable to have simple practical methods for doing this on a routine basis. To this end a suite of tests has been developed at the University of Nottingham using the Nottingham

Asphalt Tester (NAT), a simple closed-loop computer controlled pneumatic testing system, allowing an assessment of each of the above properties. (John, 1996)

2.5.1.1 Stiffness

The elastic stiffness in a pavement is a materials ability to spread the traffic loading over an area. The higher the elastic stiffness of the pavement and hence, the individual layers the wider the area which reduces the level of stain experienced lower down in the pavement structure, dependent upon the temperature and speed of loading.

2.5.1.2 Permanent deformation

Permanent deformation or rutting is the accumulation of tiny irrecoverable strains in a material under repeated loading which eventually cause a measurable rut to be developed. These small strains are due to the visco-elastic response of bituminous materials to dynamic loading showed in Figure 2.7 and they accumulate over millions of applications of traffic loading to form a large deformation.

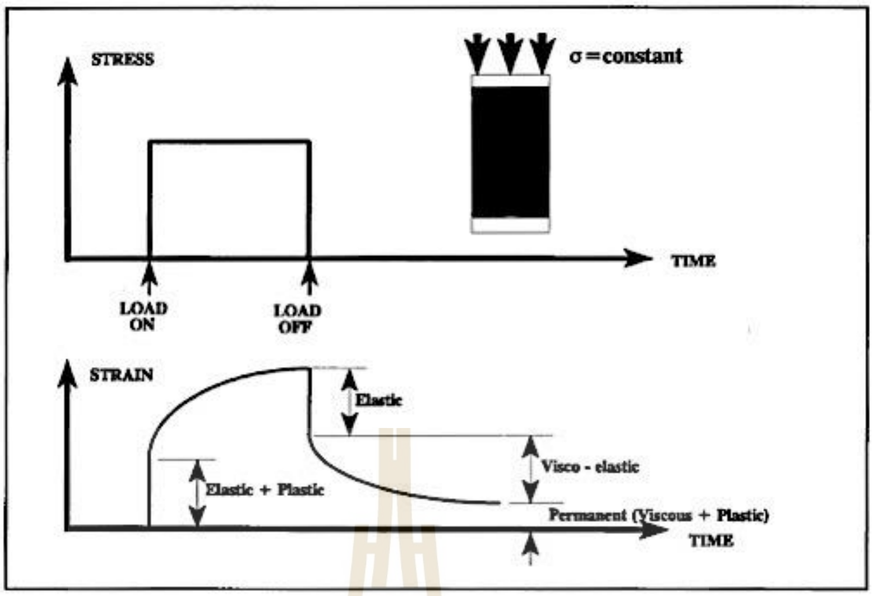


Figure 2.7 Strain response to an applied stress pulse (Perl et al., 1983)

2.5.1.3 Fatigue cracking

Fatigue cracking consists of two phases crack initiation and crack propagation. Crack initiation is generally described as the coalescence of micro-crack under the repeated application of tensile strains. Crack propagation is the growth of the macro crack though the material under further application of tensile strains. There are many complicated tests which can measure the life to crack initiation but no test which can, at present, reliably measure crack propagation and as described earlier analytical methods which are the way forward require this information.

It must be stated at this point that the fatigue properties of a bituminous mixture cannot be taken in isolation and that the stiffness must also be considered as it is this which determines the magnitude of the tensile strain experienced by the material. This then determines the life to crack initiation of the material.

2.5.2 The Falling Weight Deflectometer Technology

Fatigue During the last fifteen years, falling weight deflectometer measurements have gained their own place in pavement management. A technology originally developed for scientific research has now become a fully developed tool utilized for general pavement evaluation, and, subsequently, used in pavement management systems. Falling Weight Deflectometers (FWD) are now used to test the bearing capacity as part of the routine evaluation of the road network in many countries.

Bearing capacity evaluation by FWD is an analytically based method. The advantages compared with more empirical methods are that FWD analyses may be used on any type of material and structure, and under all climatic conditions, whereas the empirical method should only be used under those conditions for which the empirical relationship was developed.

A falling mass induces, via a buffer system, a load on a circular loading plate placed on the road surface. The falling mass, the drop height, and the buffer system, are selected to simulate the stresses produced in a pavement structure similar to that of a heavy truck passing at 60 km/h. The peak impact force and deflections in the centre and at eight distances from the impact centre are recorded. These measurements, combined with information on material types, layer thicknesses, and test temperatures, enables a computer calculation of the stresses and strains in the pavement that would be induced in the layers from a standard axle load of for example, 80 kN (8.2 tonne) at the specified design conditions.

The analytical method of calculating strengthening design is based on the concept that a pavement is a composition of several, more-or-less linear-elastic layers. The stress and strain distribution under a wheel load in an infinite half-space of isotropic materials is given by the Boussinesq equations. The software program, ELMOD, calculates the stresses and strains in each layer and relates them to the critical stress and strain values that are specific for the pavement materials. Based on a specified design period and the estimated traffic volume for the design period, the program will calculate the residual structural lifetime, and if required, the necessary overlay thickness at each measurement point. (DOH: Thailand, 2001)

2.6 Costs analysis of fiber-reinforced asphalt concrete mixtures

Fiber-Reinforced asphalt pavement generally require a larger initial investment than conventional asphalt concrete. However, benefits in long-term performance reduce the overall cost of the project when examined over its entire life cycle. Updated costs for the applied rehabilitation activities were obtained according to Department of Highways (DOH) Thailand. A Life Cycle Cost Analysis (LCCA) method was apply by using The Falling weight deflectometer (FWD) testing has been used to evaluate structural condition of pavements to predict the layer moduli using back calculation process. Preliminary the Falling weight deflectometer (FWD) simulations were conducted on a conventional pavement section so that the pavement would yield a balanced performance with respect to rutting and fatigue cracking. This section was designed to be as close as possible to the failure criteria of rutting or alligator cracking after 7 years from the initial construction. The total rutting failure criteria was 0.75 inch and the alligator failure criteria were 20% of the pavement area.

The LCCA is conducted considering only one lane/km for both conventional and fiber-reinforced pavements. The patching area was calculated by taking 33% of the cracked area and assuming one third of the alligator cracking area has severe cracks. The crack sealing length was estimated assuming there is one main fatigue crack under each wheel path. Costs are assessed using both the Net Present Worth (NPW), Equation (1), and the Equivalent uniform Annualized Cost (EAC), Equation (2), methods. The net present worth converts all costs during the life cycle to current year dollars whereas the equivalent uniform annualized method distributes the costs over the life time (accounting for the time-value of money). Discount rates of 4% were used, which represent the conventionally suggested rates for LCCA. Results from all of the analysis cases are summarized in Table 2.3 and Table 2.4, as the difference in the PWC or EAC between the conventional and fiber mixes. In all cases the benefits of fiber-reinforced are clear.

$$NPW = InitialCost + \sum_{j=1}^{N} Rj \left[\frac{1}{(1+i')n}\right] - SalvageValue\left[\frac{1}{(1+i')n}\right] \qquad (2.1)$$

$$EAC = PWC\left[\frac{i'(1+i')n}{(1+i')n-1}\right] \qquad (2.2)$$

Where,

i’ = discount rate

n = year of expenditure

Rj = rehabilitation expenditure (single cost expenditure)

Table 2.3 Summary of cost analysis for Conventional Pavement (lane/km)

Activity	**Time, year**	**Unit**	**Unit Cost, $**	**Quantity**	**Total Cost, $**	**Present Worth, $**
Initial Construction	0	m^2	6.84	3,500	23,940.00	23,940.00
Crack Sealing_1	2	m	0.4	580	232.00	214.50
Patching_1	3	m^2	6.02	1,670	10,053.40	8,937.44
Crack Sealing_2	4	m	0.4	580	232.00	198.31
Patching_2	5	m^2	6.02	1,670	10,053.40	8,263.16
Milling (cause by rutting)	7	m^2	1.5	3,500	5,250.00	3,989.57
Net Present Worth, $						45,542.98
EAC, $						7,587.90

Table 2.4 Summary of cost analysis for Fiber-Reinforced Pavement (lane/km)

Activity	**Time, year**	**Unit**	**Unit Cost, $**	**Quantity**	**Total Cost, $**	**Present Worth, $**
Initial Construction	0	m^2	7.50	3,500	26,250.00	26,250.00
Crack Sealing_1	4	m	0.4	580	232.00	198.31
Patching_1	7	m^2	7.58	1,670	12,658.60	9,619.50
Milling (cause by rutting)	9	m^2	1.5	3,500	5,250.00	3,688.58
Net Present Worth, $						39,756.39
EAC, $						5,346.96

Table 2.3 and 2.4 demonstrates the results of A Life Cycle Cost Analysis (LCCA) based on the design life of asphalt concrete pavement and condition survey with FWD according to Department of Highways (DOH) Thailand at a discount rate of 4% shows the addition of the Fiber-Reinforced at 1 lb/ton dosage and following the same initial design reduces the net present worth cost by $5,786.59 per lane/km (a reduction of 12.71%) and the Equivalent uniform Annualized Cost (EAC) savings of 29.53% with the Fiber-Reinforced depending on how it is used and the analysis period considered (before milling cause by rutting). The savings in the net present worth due to the fiber usage is anticipated to increase if the user cost is considered due to the lower rehabilitation activities rate of the fiber-reinforced pavement compared to the control pavement. That means the user delays in case of the fiber-reinforced pavement is much less compared to the conventional pavement.

However, the predicted pavement layer moduli sometimes may not be accurate even if computed and measured deflection basin has fulfilled the standard and is in concurrence with certain tolerable limits. The characteristics of pavement structure, including pavement layer thickness condition and temperature variation, affect the predicted pavement structural capacity and back calculated layer modulus. Therefore, for the analysis and prediction life cycle and decisions maintenance of asphalt concrete pavement should be evaluated with visual assessments or condition survey to the preparation of a maintenance plan.

Some of the summon studies prove the accomplishments of using fibers and also support to:

- To reduce drain-down in gap-graded asphalt concrete mixtures
- To increase resist able to rutting and fracture,

- To improve lastingness, and
- To increase toughness and long-term stability.

But the benefit of cost ratios or cost-effectiveness studies are not affected detail and found in many literatures. Only Stempihar (2012) designate the cost estimation. The price for the fiber mix in that study was approximately 11% higher than the price for the control mixture. The increased price could be justified by an lengthen in the service life of 0.9 to 1.1 years. (Stempihar et al., 2012).

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CHAPTER III

PERFORMANCE OF FIBER-REINFORCED ASPHALT CONCRETES WITH VARIOUS ASPHALT BINDERS IN THAILAND

3.1 Introduction

The rapid growth of cities has resulted in higher requirements for performance and service life for transportation infrastructure. Pavements are now subjected to significant increases in traffic volume and truck loads, causing traditional pavements to fail before reaching the end of their design life. The two principal modes of failure in pavements are fatigue cracking and permanent deformation (Olumide 2016). Pavement engineers seek to maintain failures within acceptable limits during the design life span of the pavement.

Permanent deformation is caused by a gradual buildup of irrecoverable strains under repeated loading, which develops into a measurable rut. These strains are due to the viscous-elastic/plastic response of bituminous materials to dynamic loading. In a pavement structure, there are two major contributors to permanent deformation: poor quality of the asphalt concrete layer and the presence of weak base/subbase courses. Rutting resulting from the accumulation of permanent deformation in the asphalt layer is considered to be the principal failure component of flexible pavement (Garba 2002).

The problems of fatigue cracking and permanent deformation have been addressed using different approaches. There are many options used to mitigate deterioration of asphalt concrete (AC) pavements. The options for hot-mix asphalt (HMA) pavements include use of stiffer bitumen, inclusion of modifiers such as polymer-modified asphalt (PMA) or natural rubber–modified asphalt (NRMA), use of synthetic/crumb rubber or fiber-reinforced asphalt, and use of the preeminent pavement design methods or Superpave or AC Duopave, which are commonly used for high-volume roads (Waleed and Shane 2014).

The asphalt concrete used for Thailand's road pavement surfaces mostly consists of a conventional mix using asphalt cement penetration grade 60-70 (AC60/70) and aggregates (Sawasdisan 2011). No special additives or up-to-date technology are currently used to improve the performance of pavements in Thailand. This is a concern because, given the severe traffic and changing environmental conditions in Thailand, the road network's condition is not being adequately maintained. Consequently, the AC60/70 pavement surface often provides only a short service life. Improvement in the quality of asphalt for pavement applications is of prime importance to prolong the lifecycle serviceability design of road construction projects in Thailand. Different types of asphalt binders have different performance characteristics in terms of surface durability. Although PMA and NRMA have been used previously to enhance the mechanical properties of asphalt binders, the high cost of these pavement methods are an obstacle for adoption of these binders in road construction projects. Therefore, the focus of this research is to explore the performance of alternative binders for enhancing the quality of asphalt pavement from the aspects of sustainability and economic benefit.

Typically, when a manufactured asphalt does not meet the climate, traffic, and pavement structure requirements, modifications are used to improve the asphalt properties (Kim 2008). Generally, polymers and fibers have been successfully used as alternative modifications (Rahnama 2009; Wu et al. 2008). Although the most popular bitumen modification technique is polymer modification, it has also been reported that fibers have also been used successfully as modifiers for asphalt (Airey 2004; Yildirim 2007). A literature review study demonstrated that various fibers have been used to improve the performance of asphalt pavements (Gibson and Li 2014). One of the earliest applications of fibers in asphalt mixtures was reported by Puzinauskas (1969) with natural asbestos fibers, which were found to demonstrate effectiveness in improving the low-temperature cracking properties of an asphalt mixture. A study conducted by the Federal Highway Administration (FHWA) investigated a synthetic fiber-reinforced asphalt mixture in the laboratory using full-scale accelerated pavement testing (Gibson et al. 2012). A polyester fiber–reinforced mix was placed in 1 of 12 test lanes in the FHWA’s accelerated loading facility (ALF) trial study. Results showed that the fatigue cracking of the fiber-reinforced section was measurably better than that of the polymer-modified sections, even though unmodified asphalt binder was used in the mix.

Blends of polypropylene/aramid fibers have been used to improve the performance of asphalt mixtures. The asphalt mixtures had a nominal maximum aggregate size of 19 mm and used a Superpave performance grade (PG 70-10) asphalt binder for resistance against permanent deformation and fatigue cracking (Kaloush 2008). de S. Bueno et al. (2003) studied the addition of randomly distributed synthetic fibers containing both fibrillated fibers and slit-film fibers on the mechanical response of a cold-mixed, densely graded slow-curing cationic (SC-1C) type of emulsified asphalt mixture using the Marshall test, as well as static and cyclic triaxial tests. The results showed that the addition of fibers caused small variations in the mixture's triaxial shear strength parameters. Lee et al. (2005) evaluated the influence of recycled carpet fibers on the fatigue cracking resistance of asphalt concrete using fracture energy and reported that the increase in fracture energy represents potential for improving the fatigue life of asphalt.

Kaloush et al. (2010) undertook a study evaluating the material properties of conventional and fiber-reinforced asphalt mixtures using advanced material characterization tests, which included triaxial shear strength, dynamic modulus, repeated load permanent deformation, fatigue, crack propagation, and indirect tensile strength tests. Synthetic fibers were reported to improve performance in several ways against anticipated major pavement distresses, including permanent deformation, fatigue cracking, and thermal cracking, compared with a conventional mixture.

Fiber-reinforced asphalt concretes have been previously researched by several authors who reported its potential for improving the performance of asphalt concrete in terms of reducing permanent deformation and fatigue cracking (Alhozaimy et al. 1996; Choi and Yuan 2005; Kaloush and Zeiada 2012; Song et al. 2005; Xu et al. 2010; Yao et al. 2003). However, limited knowledge of this asphalt technology when using fiber reinforcement remains a primary barrier to its translation into practice for pavement construction projects in Thailand. In Thailand, the asphalt binders commonly used are AC60-70, NRMA, and PMA, and the preparation of asphalt concrete mixtures is based on the Marshall method due to insufficient information being available on the laboratory and/or field evaluation of the fiber reinforcement.

The objective of this research is to investigate the possibility of using fiber-reinforced asphalt as an alternative binder for enhancing the quality of conventional asphalt binder AC60/70 from sustainability and economical perspectives. A complete suite of pavement laboratory tests was conducted in this research to ascertain the viability of the fiber-reinforcement application for pavement construction. This research involves conducting a detailed laboratory investigation into the effects of fiber reinforcement (combination of polyolefin and aramid fibers) to improve the performance of asphalt concrete with different common asphalt binders. Three types of asphalt binders were studied: AC60/70, NRMA, and PMA. This research is significant because new knowledge is required for sustainable pavement design and practice in Thailand and other countries that use similar types of asphalt binders and aggregates. The results are fundamental for future research for the Superpave and Mechanical-Empirical Design methods, which are also used in other countries. The outcome from this research will significantly enable the development of construction guidelines for researchers, pavement engineers, and designers alike in assessing a suitable method of fiber-reinforced asphalt concrete in road construction.

3.2 Materials and methods

3.2.1 Aggregate and Asphalt Binders

The aggregates and asphalt binders, including AC60/70, NRMA, and PMA, for asphalt concrete mixtures used in this study were characterized in accordance with the standards of the Department of Highways [DH-S204/2000 (DOH 2000)], Thailand. The physical properties of binders are summarized in Table 3.1. The laboratory tests performed to evaluate the properties of coarse aggregates for the wearing course are presented in Table 3.2 (a), (b) and (c). Fig. 3.1 presents the grading curves of the aggregate as well as the upper and lower limits of the DOH specifications. The aggregate was a basalt-type rock obtained from Nakhon Ratchasima Province, Thailand. The mineral components and chemical compositions of the aggregates were examined by X-ray diffraction (XRD) and X-ray fluorescence (XRF) analyses. XRD and XRF results indicated that the main mineral components of aggregate were dolomite and calcite, and the dominant chemical components were CaO (85.6%) and MgO (13.50%). This finding is consistent with the result reported previously by Siriphun et al. (2016). Aggregates form the major structural framework of asphalt mixtures that absorb and control different stresses on the pavement (Golalipour et al. 2012).

Table 3.1 Basic physical characteristics of binders.

Characteristic	AC60/70	NRMA	PMA
Penetration (25°C)	69	52	55
Flash point (°C)	292	274	315
Elastic recovery (%)	25	52.5	92.5
Softening point (°C)	47.8	57.6	76.3
Ductility (5 cm/min)	105	116	128
Specific gravity (g/cm^3)	1.03	1.00	1.02

3.2.2 Fiber Properties

The fibers used in this study were a blend of synthetic fibers designed for use in HMA applications. The proprietary blend consisted of polyolefin and aramid fibers. Fig. 3.2 shows a photograph of fibers and the microstructural characteristics of fiber-reinforced asphalt captured by scanning electron microscopy (SEM) analysis. Fig. 3.2 (a) shows the aramid and polyolefin fibers. Aramid fibers with a high decomposition temperature are a class of heat-resistant and strong synthetic fibers that exhibit good resistance to abrasion and organic solvents. Aramids share a high degree of orientation and good fabric integrity with polyolefin fibers. Use of the aramids and polyolefin fibers is also economically beneficial due to the low cost of polyolefin fibers. The fibers were designed to reinforce the HMA in three-dimensional orientations. Table 3.3 provides the main physical properties of both fibers. The decomposition temperature or melting point of polyolefin and aramid fibers is 130 and 450°C, respectively. The mixture of aramid and polyolefin fiber has a high degree of orientation and good fabric integrity, as shown in Fig. 3.2(a). Figs. 3.2(b and c) show that the aramid fiber in the asphalt mixture did not melt during the mixing process of HMA, which confirm that the fiber-reinforcement has a high heat resistance.

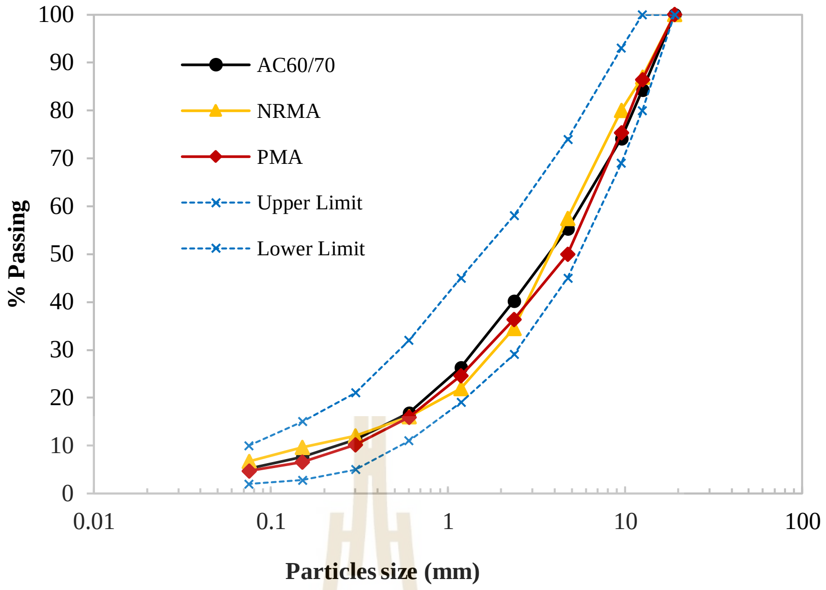


Figure 3.1 Grain-size distributions of aggregates used in asphalt mixtures.

3.2.3 Mixture Design and Sample Preparation

The experimental work in this study started with a mix design to establish the job mix formula (JMF) and the appropriate constituents of the asphalt concrete mixtures, based on the Marshall mix design method and in accordance with DOH specifications [DH-S 408/2532 (DOH 1989)]. The JMF for this study is summarized in Table 3.2 (a), (b) and (c)

The test specimens were prepared based on the JMFs for the asphalt concrete. Aggregates were heated at 180–190°C to facilitate the mixing temperature, and fibers were then mixed with aggregates under dry conditions for a duration of 10 s. The polyolefin fiber melts during the mixing process, and its melting compound improves the chemical and physical properties of asphalt binder, which has been illustrated by Kaloush (2008). The fiber content (40% aramid fiber and 60% polyolefin fiber) was fixed at 0.05% of the total mass of mixture for mixture design, as recommended by the manufacturers (Waleed and Shane 2014). Asphalt binders heated to 160°C were then added into the fiber–aggregate mixtures and mixed thoroughly to obtain well-coated and evenly distributed mixtures. Subsequently, the hot mixtures were placed in a steel mold (101.6 mm in diameter and 63.5 mm in height) and compacted under 75 blows on each side at 150°C for AC60/70 and 170°C for NRMA and PMA to attain a Marshall specimen in accordance with the DOH specification.

Table 3.2 (a) Properties of the aggregate and JMF for AC60/70.

Property	**AC60/70**	
	Criterion	**Results**
Flakiness index (%)	35 maximum	33
Elongation index (%)	35 maximum	13
Asphalt absorption (%)	N/A	0.25
Los Angeles abrasion (%)	40 maximum	22.7
Soundness (%) coarse/fine	9 maximum	1.0/3.2
Sand equivalent (%)	50 minimum	64
Asphalt content (%)	5.0 ± 0.3	5.0
Marshall density (gm/cl)	2.40–2.42	2.418
Marshall air voids (%)	3.40–4.80	4.0
Strength index (%)	75 minimum	78.1
Aggregate crushing value (%)	-	-
Aggregate impact value (%)	-	-
Polished stone value (%)	-	-

Table 3.2 (b) Properties of the aggregate and JMF for NRMA.

Property	NRMA	
	Criterion	**Results**
Flakiness index (%)	35 maximum	27
Elongation index (%)	35 maximum	21
Asphalt absorption (%)	N/A	0.25
Los Angeles abrasion (%)	35 maximum	26.2
Soundness (%) coarse/fine	9 maximum	2.4/5.4
Sand equivalent (%)	60 minimum	64
Asphalt content (%)	5.1 ± 0.3	5.1
Marshall density (gm/cl)	2.38–2.40	2.393
Marshall air voids (%)	3.40–4.90	4.2
Strength index (%)	75 minimum	75.8
Aggregate crushing value (%)	25 minimum	21.9
Aggregate impact value (%)	25 minimum	18.1
Polished stone value (%)	-	-

Table 3.2 (c) Properties of the aggregate and JMF for PMA.

Property	**PMA**	
	Criterion	**Results**
Flakiness index (%)	35 maximum	32
Elongation index (%)	35 maximum	23
Asphalt absorption (%)	N/A	0.25
Los Angeles abrasion (%)	35 maximum	21.5
Soundness (%) coarse/fine	9 maximum	1.0/3.0
Sand equivalent (%)	60 minimum	66
Asphalt content (%)	5.0 ± 0.3	5.0
Marshall density (gm/cl)	2.36–2.38	2.369
Marshall air voids (%)	3.40–4.60	4.0
Strength index (%)	75 minimum	80.9
Aggregate crushing value (%)	25 minimum	20.2
Aggregate impact value (%)	25 minimum	17.8
Polished stone value (%)	47 minimum	51.1

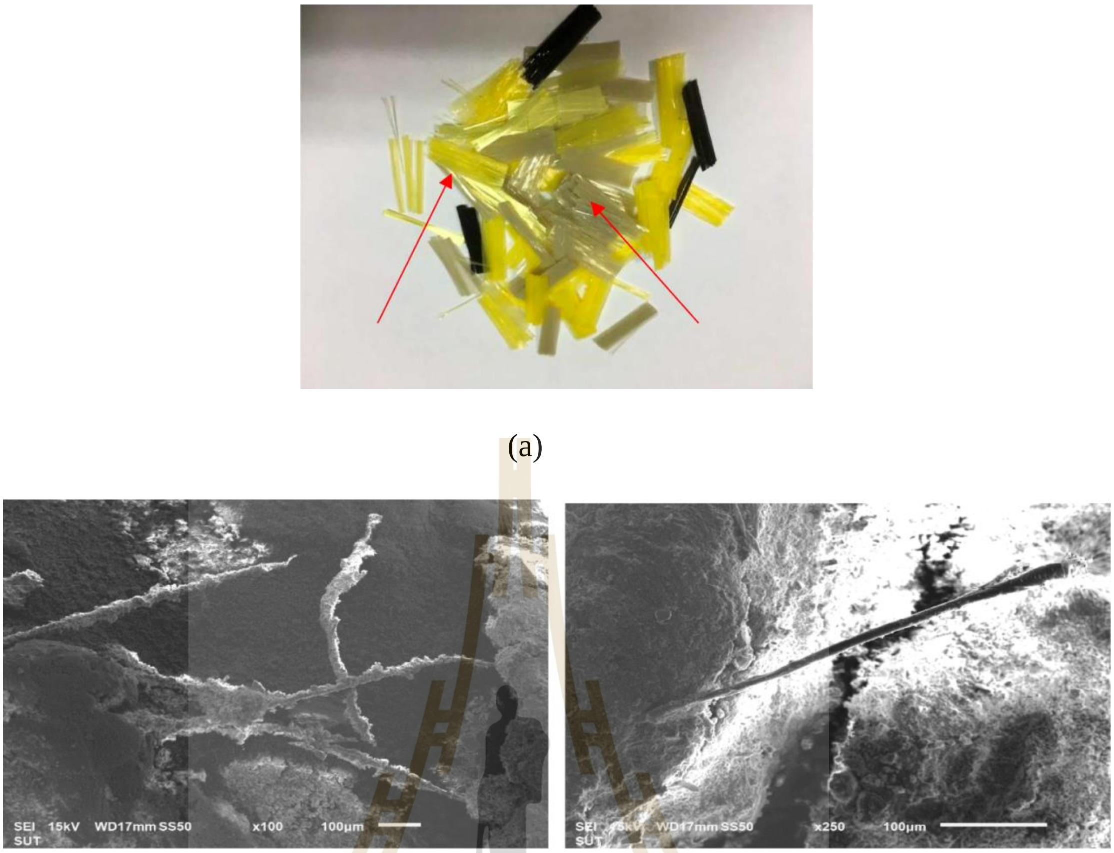
3.3 Performance Tests

3.3.1 Stability and Flow

The Marshall stability was measured using the Marshall apparatus in accordance with ASTM D1559-89 (ASTM 1989). This method covers the measurement of resistance to plastic flow of cylindrical specimens of asphalt concrete bituminous paving mixture loaded on the lateral surface by means of the Marshall apparatus. The cylindrical mold was 101.6 mm in diameter and 76.2 mm in height. The average values of Marshall stability and flow from each asphalt concrete mixture were obtained by testing triplicate samples to ensure data consistency. In the test, compressive loading was applied to the specimen at a rate of 50.8 mm/min until it was broken. The maximum loading at failure is the Marshall stability, and the associated plastic flow (deformation) of the specimen is the flow value.

Table 3.3 Physical characteristics of the fibers.

Characteristic	**Polyolefin**	**Aramid**
Specific gravity	0.91	1.45
Tensile strength (MPa)	> 483	> 2,750
Length (mm)	19.0	19.0
Color	Tan	Yellow
Acid/Alkali resistance	Inert	Good
Decomposition temperature (melting point) (ºC)	130	> 450



(a)

(b) (c)

Figure 3.2 (a) Fibers used; and SEM images at (b) 100 times; and (c) 250 times of a loose asphalt mixture with fiber reinforcement.

3.3.2 Indirect Tensile Strength

The indirect tensile strength (ITS) test was carried out in accordance with ASTM D6931-17 (ASTM 2017). The ITS value of the asphalt mixture was determined by loading a cylindrical specimen across its vertical diametrical plane at a 50.8 mm/min rate of deformation at 20°C. The peak load at failure was recorded and used to calculate the ITS of the specimens as shown in Eq. (1)

$$ITS = \frac{2P}{\pi DT} \tag{3.1}$$

where P = peak value of the applied vertical load (kN); T = mean thickness of the test specimen (m), and D = specimen diameter (m). The values of T and D were 63.5 and 101.6 mm, respectively. The ITS results were used to evaluate the relative quality of asphalt mixtures as well as estimating the potential for rutting or cracking.

3.3.3 Resilient Modulus

Resilient modulus (M_R) is a relative measurement of the mixture stiffness and load distribution ability; higher M_R values lead to stiffer mixtures with higher load-distribution ability. The M_R was determined on cylindrical specimens (101.6 mm in diameter and 63.5 mm in height) for each mixture at designed asphalt contents in the indirect tension mode, which was conducted at 35°C. The test was carried out using a universal testing machine (UTM) in accordance with ASTM D4123-82 (ASTM 1995) and AASHTO TP31-94 (AASHTO 1994), and the M_R in MPa was calculated using the following equation:

$$M_R = \frac{P(0.27+\nu)}{(\Delta H)D} \tag{3.2}$$

where P = peak value of the applied vertical load (N); H = mean amplitude of the horizontal deformation obtained from last five applications of the load pulse (mm); D = mean thickness of the specimen (mm); and υ = Poisson's ratio.

M_R represents the cyclic pavement response in terms of dynamic stresses and their relation to recoverable strains. Indirect tensile strength from the previous test was used as reference load for this test. The M_R test used 15% of ITS for target peak pulse load. There were two perpendicular alignment loads applied on each sample. M_R was then measured by averaging the last five values when the test reached the first 150 cycles (Baburamani 1992). Four samples from each mix were placed in two positions for the diametrical M_R.

3.3.4 Indirect Tensile Stiffness Modulus

Stiffness modulus of asphalt concrete is a fundamental parameter used in pavement design models to evaluate pavement mixtures and in performance-based contracts related to pavement layers. The indirect tensile stiffness modulus (ITSM) test, defined in BS-EN-DD-213 (BSI 1993), is the most commonly used test method for determining the stiffness modulus of a specimen by using indirect tensile force. The target horizontal deformation was 0.005% of the specimen diameter, and the target load pulse rise time (time from start of load application to peak load) was 124 ms (equivalent to a frequency of 1.33 Hz). Poisson's ratio was assumed to be 0.40 at 35°C. The applied forces on the specimen as well as its conditioning pulses were then recorded automatically using software. These conditioning pulses were used to make the minor adjustments to the magnitude of the force, which were needed to generate the specified horizontal deformation and to seat the loading strips correctly on the specimen. Once the conditioning pulses were completed, the system applied five load pulses, which generated an indirect movement on the horizontal diameter. The stress and strain values as well as stiffness modulus of the specimen were then calculated.

3.3.5 Dynamic Creep Test

The dynamic creep test has been used to evaluate the deformation resistance (rutting susceptibility) of asphalt mixtures. The most popular dynamic creep test is the unconfined dynamic creep test, known as the repeated-load axial test (RLAT). The term creep test is used to indicate tests for assessing the permanent deformation resistance of asphalt mixtures. The development of plastic strains in the skeleton of an aggregate contributes significantly to permanent deformation. The effect of this form of loading in inducing plastic strains had already been recognized by Goetz et al. (1957).

The RLAT is increasingly used in preference to the uniaxial creep (UC) test because the pulsed load is a more accurate simulation of traffic loading. The specimen was subjected to repeated load pulses of 1-s duration separated by 1-s rest periods (up to 10,000 pulses). An optional pretest conditioning period (ranging from 0 to 60 min) is available.

The cumulative permanent deformation as a function of load applications (pulses) was recorded and correlated to the rutting potential of asphalt mixtures. Tests can be run at different temperatures and varying loads. A dynamic creep test was conducted by applying a dynamic load to a HMA specimen and then measuring the specimen's permanent deformation by LVDTs after unloading. A high value of permanent deformation may correlate to higher rutting potential. The loading conditions were selected in order to evaluate the relative performance of different asphalt concrete mixtures in accordance with BS-DD-226 (BSI 1996) for determining the resistance of bituminous mixtures to permanent deformation. Standard test conditions and requirements for the dynamic creep test were

- conditioning stress: 10 kPa,
- conditioning period: 30 s,
- test stress: 120 kPa,
- test duration: 10,000 pulses,
- test cycle: square wave, and
- test temperature: 40°C.

3.3.6 Indirect Tensile Fatigue Test

In order to fully characterize the studied asphalt mixtures, the determination of fatigue properties is also required to identity the long-term performance of the asphalt concrete. The indirect tensile fatigue test (ITFT) was performed in accordance with BS-EN-12697-24 (BSI 2004a) by using a repeated controlled stress pulse to damage the specimen, and the accumulation of vertical deformation against a number of load pulses was plotted. The load was applied through a 12.5-mm-wide stainless-steel curved loading strip.

A have sine loading pulse with a frequency of 10 Hz, approximately equivalent to a vehicle speed of 80 km/h, was used. The loading period of the pulse, 0.1 s, was followed by a rest period of 0.9 s. The Poisson's ratio was assumed to be 0.35 at 25°C. The tests were performed in an environmental chamber at 25°C. The results were an average of four samples. Standard test conditions and requirements for the ITFT test were

- target test stress: 300 kPa,
- target rise time: 125 ms,
- failure criteria: 9-mm vertical deformation, and
- test temperature: 25°C.

In order to determine the strength of HMA against fatigue cracks induced by repeated loads, samples from the six mixtures were tested diametrally under repeated pulsed uniaxial loading to determine the number of loading cycles required to fail the samples.

3.3.7 Wheel-Tracking Test (Rutting Resistance)

The permanent deformation (rutting) of asphalt pavements has an important impact on the performance of the pavements during their lifetimes. When a load is applied to the surface of an asphalt pavement, it deforms, and a variable amount of irreversible deformation remains in the asphalt mixtures, resulting in a very small permanent residual strain. Hence, accumulations of millions of these strains due to repeated axle loadings result in surface rutting (Alataş et al. 2012; Moghaddam et al. 2014). Rutting develops gradually as the number of load applications increase and appears as longitudinal depressions in the wheel paths and small upheavals to the sides (Brovelli et al. 2015).

The wheel-tracking test was carried out using a moving wheel in the laboratory to reproduce the field condition and to represent the passage of vehicles along the surface of the pavement asphalt. The rutting tests were performed in accordance with British and European standard BS-EN-12697-22 (BSI 2004) at 60°C in order to determine the resistance of the asphalt mixtures to permanent deformation, namely rutting resistance of the asphalt mixtures. The test slab specimens were prepared in the laboratory using a roller compactor in accordance with British and European standard BS-EN-12697-33 (BSI 2004b). The rut depth after a specified number of wheel passes, namely 1,000, 3,000, and 10,000 loading cycles, was measured, and the average of at least 15 values was the representative rut depth of the bituminous mixtures tested.

3.4 Results and Discussion

Fig. 3.3 shows the Marshall stability results of asphalt mixtures with different asphalt binders. The modified asphalt mixtures (NRMA and PMA) exhibit better resistance to plastic flow than the conventional AC60/70. The Marshall stability values of NRMA and PMA were 15.6 and 34.6% higher than that of AC60/70, respectively. It is interesting that the Marshall stability of the conventional AC60/70 can be improved significantly by fiber reinforcement. The Marshall stability value of AC60/70 + Fiber was increased by 13.7% compared with the conventional AC60/70, and this value is comparable to the NRMA binder (without fiber).

The Marshall stability of NRMA and PMA can also be improved by fiber reinforcement. The Marshall stability values of NRMA + Fiber and PMA + Fiber were increased by 18.4 and 17.9%, respectively, compared with the mixtures without fiber reinforcement. The Marshall stability value of NRMA + Fiber was slightly higher than that of PMA (without fiber), whereas PMA + Fiber exhibited the highest Marshall stability value. This finding is similar to previous research showing that the use of polypropylene fibers could notably increase the Marshall stability of HMA (Tapkın 2008).

Fig. 3.4 shows the ITS results of studied asphalt mixtures with and without fiber reinforcement. NRMA and PMA had greater tensile resistance than the conventional AC60/70. Similar to the Marshall stability results, the PMA exhibited the highest ITS value, followed by NRMA and AC60/70, respectively. The ITS values of NRMA and PMA were 9.4 and 22.8% higher than that of AC60/70. ITS values of all mixtures were improved significantly by fiber reinforcement, i.e., all mixtures with fiber reinforcement produced consistently higher ITS values compared with mixtures without fibers. The ITS values of AC60/70 + Fiber, NRMA + Fiber, and PMA + Fiber were increased by 10.6, 11.3, and 10.2%, respectively, compared with those without fiber reinforcement. As evident in Fig. 3.4, the ITS value of AC60/70 + Fiber was slightly higher than that of NRMA without fiber reinforcement, and the ITS value of NRMA + Fiber was as high as PMA (without fiber). This can be attributed to the strong mechanical bonding between the fibers and mastic of the asphalt binder to increase the tensile strength of the HMA mixture (Bonica et al. 2016).

The resilient modulus (M_R) values of all studied mixtures are summarized in Fig. 3.5. Both NRMA and PMA exhibited greater M_R than the AC60/70. The M_R values of NRMA and PMA were 29.8 and 38.4% higher than M_R value of AC60/70, respectively. The noticeable effect of improvement by fiber reinforcement on the M_R of the studied mixtures was observed in that the M_R values of AC60/70 + Fiber, NRMA + Fiber, and PMA + Fiber were 35.6, 27.8, and 28.4% higher than those of AC60/70, NRMA, and PMA without fiber, respectively. The M_R value of AC60/70 + Fiber was comparable to both NRMA and PMA. Lavasani et al. (2015) reported that the fibers could increase the adherence of aggregate and asphalt, and hence produce the higher deformation resistance and M_R of asphalt concrete.

Fig. 3.6 shows the indirect tensile stiffness modulus (ITSM) of all studied mixtures. Similarly, the ITSM results indicated that the NRMA and PMA had higher ITSM than the AC60/70. The ITSM values of NRMA and PMA were 30.0 and 54.9%, higher than the value of AC60/70, respectively. Improvement of ITSM of AC60/70, NRMA, and PMA was obviously observed with use of the fiber reinforcement in that the ITSM values of AC60/70 + Fiber, NRMA + Fiber, and PMA + Fiber were increased by 32.4, 32.1, and 33.5%, respectively, compared with the mixtures without fiber reinforcement. It is evident that the ITSM of AC60/70 + Fiber was comparable with that of NRMA (without fiber).

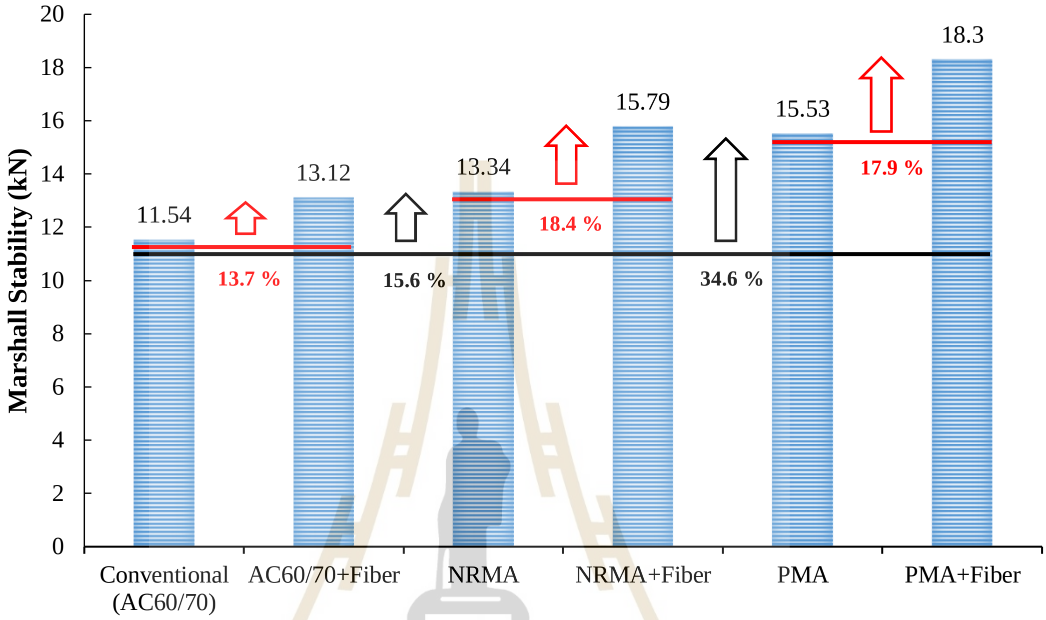


Figure 3.3 Marshall stability test results.

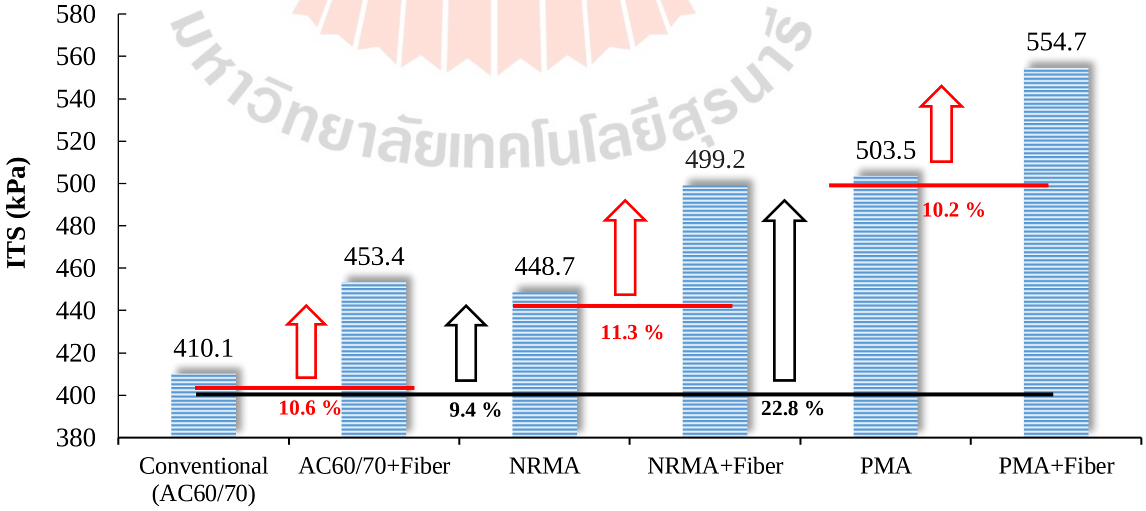


Figure 3.4 Indirect tensile strength test results.

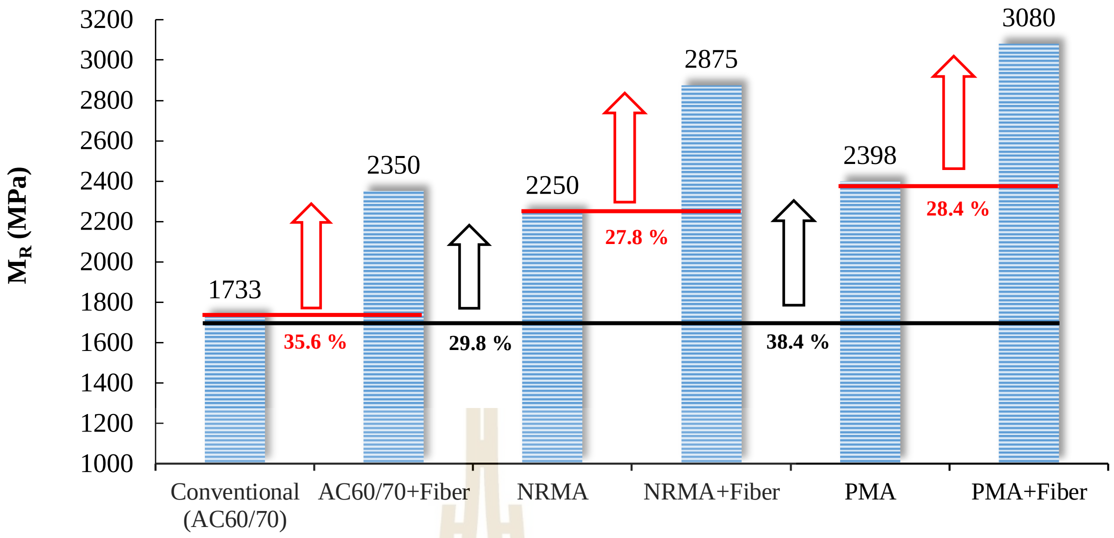


Figure 3.5 Resilient modulus test results.

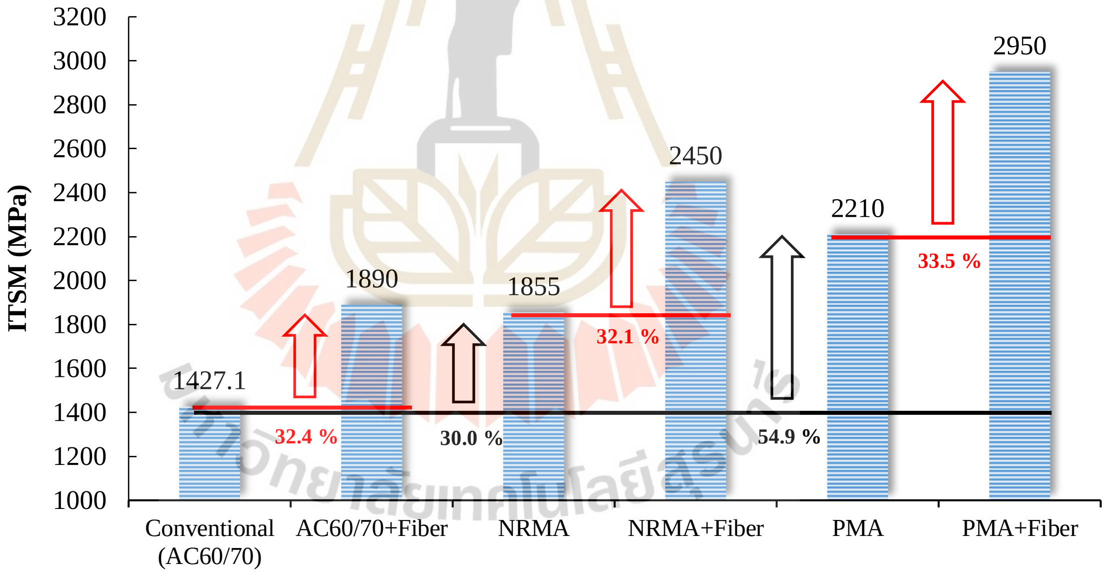
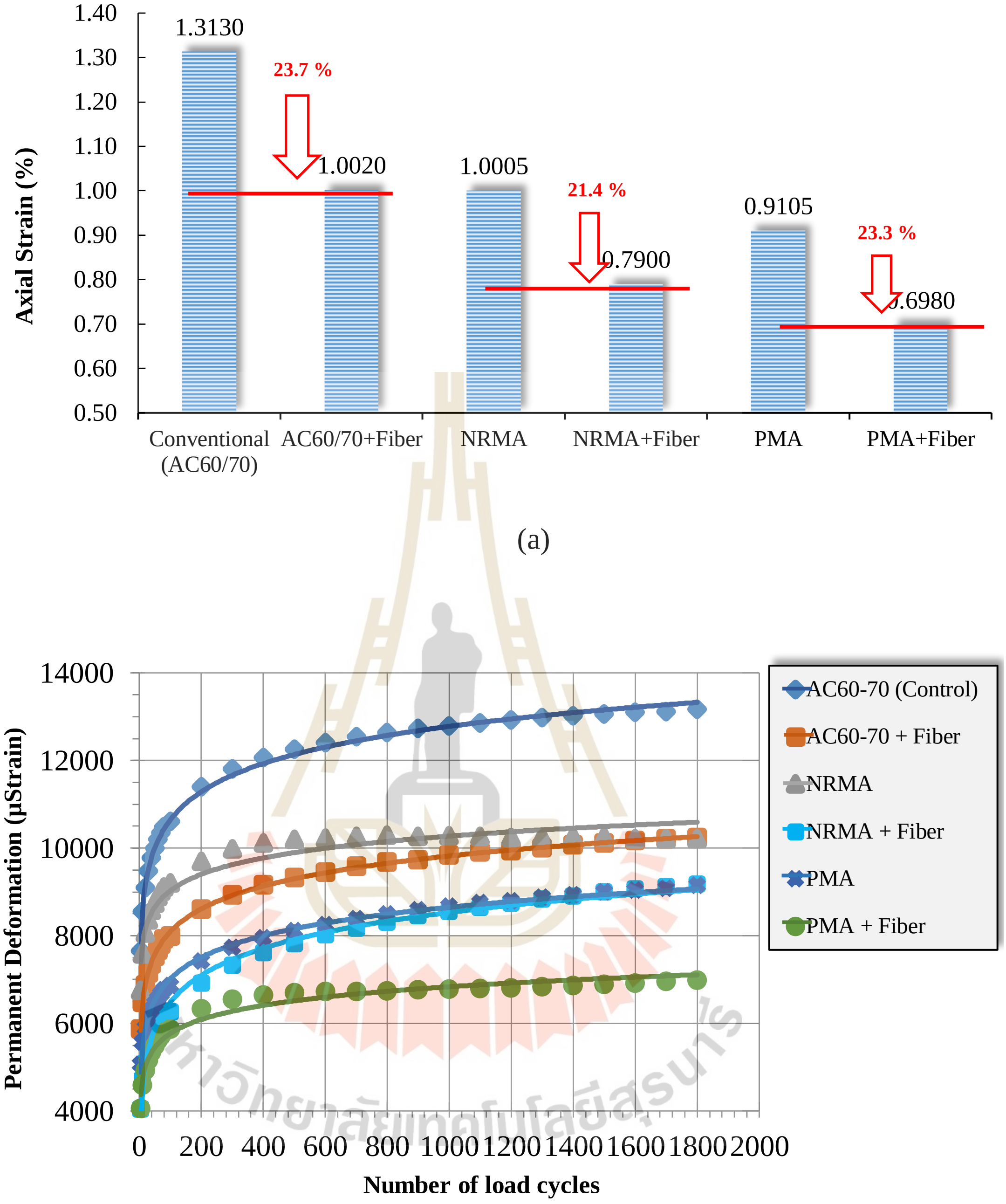


Figure 3.6 Indirect tensile stiffness modulus test results.



(a)

(b)

Figure 3.7 Dynamic creep test results: (a) axial strain (strain rate); and (b) permanent deformation (μ strain).

Dynamic creep testing is known as a highly reliable test to predict permanent deformation susceptibility of asphalt mixtures, and its results are displayed in Fig. 3.7. Fig. 3.7(a) shows the axial strains of all studied mixtures. The NRMA and PMA had lower axial strain than the conventional AC60/70. The axial strain of AC60/70 + Fiber, NRMA + Fiber, and PMA + Fiber was decreased by 23.7, 21.4, and 23.3% when compared with the mixtures without fiber reinforcement, respectively. Fig. 3.7(b) shows the relationship between accumulated permanent deformation (μ strain) versus the number of load cycles for the mixtures. The NRMA and PMA had higher resistance to permanent deformation than AC60/70 for the same number of load cycles. Furthermore, the accumulation of permanent strain of the studies mixtures was decreased when the fibers were added.

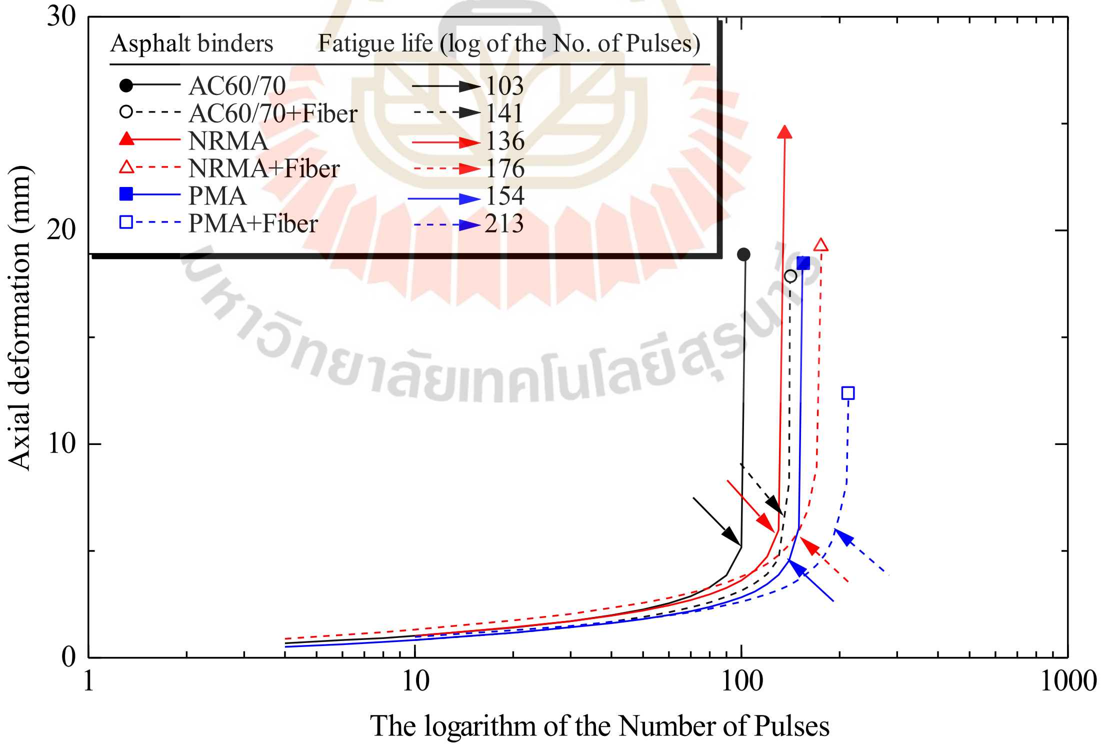


Figure 3.8 Fatigue life of the six asphalt mixtures.

Fig. 3.8 shows a relationship between axial deformation versus the logarithm of number of applied load repetitions until failure under the indirect tensile fatigue test. Fatigue life is defined as the intersection of small axial deformation portion and large axial strain deformation portion. The fatigue life for each mixture is also presented in Fig. 3.8. The results imply that mixtures containing fibers had longer fatigue life than that mixtures without fibers. Based on the test results, the fatigue life of fiber-reinforced asphalt mixtures increased by 36.9, 29.4, and 38.3% for the AC60/70, NRMA, and PMA mixtures, respectively. The highest fatigue life was found for PMA+Fiber.

The rut depth after a specified number of wheel passes, namely 1,000, 3,000, and 10,000 loading cycles from a wheel-tracker test, was measured and is summarized in Fig. 3.9. The test slab specimens containing fibers exhibited smaller rutting depth (RD) compared with specimens without fibers. This rutting depth is directly related to the permanent deformation. The rutting resistance increased by 34.4, 31.0, and 35.4% at 10,000 loading cycles for AC60/70, NRMA, and PMA mixtures with fibers compared with those without fibers.

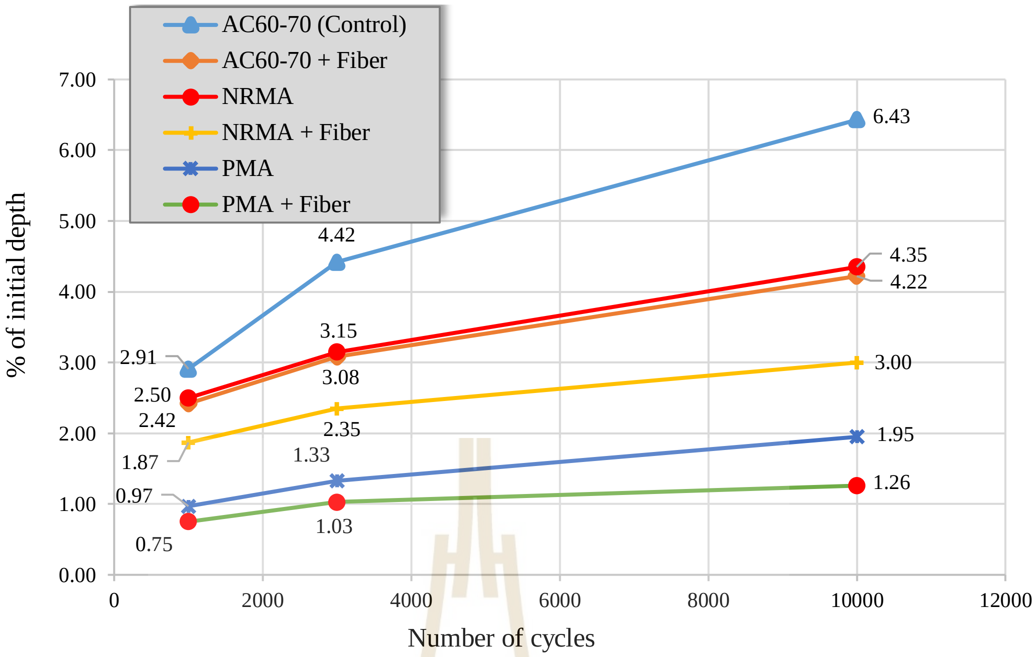


Figure 3.9 Pavement rutting test results.

To evaluate the effect of fibers on the properties of asphalt concrete with different binders, a complete suite of laboratory tests was conducted and its results compared with those of virgin unreinforced asphalt. The laboratory performance test results confirmed that an addition of fibers (0.05% by total mass of mixture) to the three asphalt concrete mixtures typically used in Thailand had positive impacts on performance, including Marshall stability, indirect tensile strength, resilient modulus, stiffness modulus, permanent deformation, fatigue life, and pavement rutting resistance. It is interesting that fiber reinforcement can enhance the Marshall stability, ITS, MR, and ITSM values of all fiber-reinforced mixtures, and the percentage increases were almost similar for the different fiber-reinforced mixtures. The Marshall stability, ITS, MR, and ITSM of all mixtures with fiber reinforcement increased by average values of approximately 17, 11, 31, and 33%, respectively. As such, the Marshall stability, ITS, MR, and ITSM of reinforced AC60/70, NRMA, and PMA can be predicted once the values of unreinforced AC60/70, NRMA, and PMA are determined.

This finding has important practical implications for the design of high-performance asphalt pavements, and this technique can also be applied to other types of asphalts manufactured by the hot-mix asphalt method, in which a combination of approximately 95% heated coarse and fine aggregates are bound together by heated asphalt binders with fiber reinforcement. The improved performance of the fiber-reinforced asphalt indicated enhancement of its stiffness and provided good resistance against permanent deformation and fatigue cracking at high traffic volumes. This results in the possibility of extending the service life of asphalt concretes. This research broadens the applications of fiber-reinforced asphalt as an alternative pavement asphalt concrete, which can provide the economical and sustainable advantages for highway construction work. The use of fiber-reinforced asphalt concrete with the incorporation of other recycled and/or waste aggregates will furthermore result in alleviating environmental issues associated with the current practice of landfilling all wastes (Mohajerani et al. 2017; Paranavithana and Mohajerani 2006).

3.5 Conclusion

The performance of fiber-reinforced asphalt concrete was evaluated with different asphalt binders. The fibers used in this research were a mixture of polyolefin and aramid fibers. The performance of the fiber-reinforced mixtures was compared with that of mixtures without fiber (control mix). Based on the performance tests, the results indicated that the fibers improved the performance of the mixtures in several unique ways:

- Addition of fibers (0.05% by mass of total mixture) to asphalt concrete mixtures considerably improved the Marshall stability, indirect tensile strength, resilient modulus, stiffness modulus, permanent deformation, fatigue life, and pavement rutting resistance.
- Modified asphalt mixtures (NRMA and PMA) exhibited better resistance to plastic flow than the conventional mixture (AC60/ 70). It is very interesting that the Marshall stability of the conventional AC60/70, NRMA, and PMA can be improved significantly by the fiber reinforcement.
- Fiber-reinforced asphalt concrete mixtures showed higher tensile strength compared with the control mix. All mixtures with fibers exhibited consistently higher ITS compared with the mixtures without fibers. The ITS values of AC60/70 + Fiber, NRMA + Fiber, and PMA + Fiber were increased notably compared with those without fibers.
- A noticeable positive effect of fiber reinforcement on the resilient modulus (M_R) of the studied mixtures was observed, which indicated that the M_R value of all mixtures without fiber can be improved significantly by fiber reinforcement in that the M_R value of AC60/70 + fiber, NRMA + Fiber, and PMA + Fiber was demonstrably much higher than that of HMA without fiber.
- Improvement in stiffness modulus of AC60/70, NRMA, and PMA was observed with use of the fiber reinforcement, by which the stiffness modulus values of AC60/70 + Fiber, NRMA + Fiber, and PMA + Fiber were increased dramatically compared with the mixtures without fiber reinforcement.

- Fiber-reinforced mixtures had higher recoverable deformation than the control mix. This indicates that fiber-reinforced mixtures have better potential to resist permanent deformation than the control mix. In other words, the addition of fibers had a greater influence on deformation values and improved resistance to fatigue cracking.

It can be concluded that although the mechanical property values of all mixtures (without fiber) were different, i.e., PMA exhibited the highest values, followed by NRMA and AC60/70, respectively, fiber reinforcement can improve the performance of these three asphalt mixtures. The Marshall stability, ITS, M_R, and ITSM of all HMA+Fiber mixes increased by approximately average values of 17, 11, 31, and 33%, respectively. Interestingly, the performance of conventional AC60/70 mixtures with fiber is comparable with that of PMA mixtures typically used for heavy traffic load. In other words, the AC60/70 mixture with fiber can be used instead of a PMA mixture from a performance perspective. The outcomes from this research will result in positive impacts for the use of fiber reinforcement in asphalt concrete and can be used as a guideline for the application of fiber-reinforced asphalt in future road construction projects. Further investigation of fiber-reinforced asphalt with recycled aggregate is recommended for future work, which can result in further development of asphalt concrete as green construction material.

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CHAPTER IV

PERFORMANCE IMPROVEMENT OF ASPHALT CONCRETES USING FIBER REINFORCEMENT: LABORATORY AND FIELD STUDIES

4.1 Introduction

Over the past few decades, it has been evident that Thailand’s road network has suffered considerable deterioration in the form of excessive permanent deformation and fatigue cracking. The repeated traffic loading induces tensile and shear stresses in the Asphalt Concrete (AC), which cause a loss of the structural integrity of the AC pavement. These poor road conditions have instigated the search by Thailand road authorities and practitioners for solutions in the form of alternative and superior pavement materials.

The improvement of Hot Mix Asphalt (HMA) pavements to mitigate the premature deterioration of AC pavements includes the use of higher asphalt contents, and the inclusion of modifiers such as polymers, synthetic/crumb rubber, and fibers, etc. (Waleed and Shane, 2014). Various fibers have been used to improve the performance of AC pavements (Nelson and Xinjun, 2014). The earliest application of fibers in asphalt mixtures was reported by Puzinauskas (1969) using natural asbestos fibers. It was demonstrated that the fibers improved the low temperature cracking properties. Button and Hunter (1984) showed that the additional fibers improved flexible behavior and thus increased the resistance to cracking as manifested by greater elongation at failure without a significant decrease in tensile strength. This corresponds to an increase in the energy required to fail the material. Maurer and Malasheskie (1988) indicated that a fiber reinforced AC exhibited lower reflective cracking than a conventional AC (without fiber).

A 10-year field study on the comparison of performance of AC stabilized with various materials including ground tire rubber and chemical antistrip agents, ethylene vinyl acetate modified binder, hydrated lime, and polyester and polypropylene fibers have been conducted by Oregon Department of Transportation (Edgar, 1998). The fiber reinforced trial sections had better performance than other trial sections in term of resistance to transverse and block cracking. However, both the control section (without stabilization) and the fiber reinforced section were subjected to rutting, fatigue cracking, and raveling. McDaniel and Shah (2003) reported on an Indiana Department of Transportation's field study on seven different polymer modifiers and polyester fiber reinforcement at the base, intermediate and surface of AC mixes placed on an interstate concrete pavement. The fiber modified section was well-performed in their resistance to longitudinal and transverse cracking after 11 years of service.

Interstate Highway's field study conducted by Prowell (2000) for the Virginia Department of Transportation during the transition from Marshall mix design to Superpave mix design was motivated to address rutting performance rather than cracking issues. The trial section reinforced with polypropylene and polyester fibers exhibited a better performance than the trial section with styrene-butadiene-styrene and air blown binder. Higher asphalt content was required for the fiber reinforced sections, which resulted in lower voids in mineral aggregate (VMA). Moreover, no rutting or cracking was reported in any section after 45 months of monitoring.

Fibers have been used to improve the performance of AC mixtures against permanent deformation and fatigue cracking (Kaloush et al., 2008). Kaloush et al. (2010) evaluated the material properties of a conventional (control) and fiber-reinforced asphalt mixtures using advanced performance tests including triaxial shear strength, dynamic modulus, repeated load permanent deformation, fatigue, crack propagation, and indirect tensile strength tests. It was concluded that the synthetic fibers can improve the performance against major pavement distresses including permanent deformation, fatigue cracking and thermal cracking.

Bueno et al. (2003) studied the effect of randomly distributed synthetic fibers on the mechanical response of a cold-mixed and densely graded AC mixture via the Marshall test, as well as static and cyclic triaxial tests. The results showed that the addition of fibers caused small variations in the triaxial shear strength parameters. Lee et al. (2005) evaluated the influence of recycled carpet fibers on the fatigue cracking resistance and fracture energy. The recycled carpet fibers were found to improve fracture energy and fatigue life of AC.

Although many researchers have confirmed the physical and mechanical advantages of fiber reinforced AC (FR-AC) over the traditional AC, it is still at the laboratory stage in Thailand and Asian countries (Takaikaew et al., 2018). Therefore, this study would report on both laboratory and field performance and cost analysis of FR-AC pavement using AC60/70 and polymer modified asphalt (PMA) as binders. Four types tested AC included conventional AC60/70 asphalt concrete as control mixture, PMA concrete, fiber reinforced AC60/70 asphalt concrete and fiber reinforced PMA concrete. These four tested ACs were mixed in laboratory and plant and the performance tests of laboratory mixed FR-AC specimens and plant mixed FR-AC specimens were conducted to compare the mixing quality between laboratory and plant. The performance tests included those related to the fatigue cracking failure, which are indirect tensile resilient modulus (M_R), indirect tensile strength modulus (ITSM), indirect tensile fatigue life and those related to the rutting failure, which are dynamic creep and wheel-tracking. Two field trials were conducted to investigate field performance of FR-AC, which is International Roughness Index (IRI), texture depth and rutting. Finally, the cost analysis of FR-AC was performed based on the comparison of performance and construction cost of AC with and without fiber reinforcement. The outcome of this research will promote the usage of fiber-reinforced AC as an economic and durable pavement surface for high traffic volume road. The research output can be served as a guideline for the development of code of practice and pavement standards in Thailand and other countries using similar mix design method.

4.2 Materials and specimen preparation

4.2.1 Aggregate and Asphalt Binders

Aggregate is the major structural framework of asphalt mixture to absorb and control different stresses on the AC pavement (Amir et al., 2012). Crushed limestone samples, complying with the specifications of Department of Highways (DOH), Thailand, were obtained from Khon Kaen Province, Thailand and used as the aggregate in this study. The aggregate was prepared by dividing into 4 bins with different sizes including bin 1 (<4.75 mm), bin 2 (<9.50 mm), bin 3 (<12.50 mm), and bin 4 (<19.00 mm). **Figure 4.1** shows the gradation curve of aggregate, which was comprised of 42% of maximum aggregate size 4.75 mm (Bin 1), 25% of maximum aggregate size 9.5 mm (Bin 2), 15% of maximum aggregate size 12.5 mm (Bin 3) and 18% of maximum aggregate size 19.0 mm (Bin 4). Its gradation distribution is within a gradation limit specified by DOH of Thailand. The basic properties of aggregates compared with the DOH’s requirements are presented in **Table 4.1**.

Table 4.1 Basic properties of aggregate for job mix formula of asphalt concrete.

Property	**AC 60/70**		**PMA**	
	Criterion	**Results**	**Criterion**	**Results**
Flakiness index (%)	35 maximum	33	35 maximum	32
Elongation index (%)	35 maximum	13	35 maximum	23
Asphalt absorption (%)	N/A	0.25	N/A	0.25
Los Angeles abrasion (%)	40 maximum	22.7	35 maximum	21.5
Soundness (%) coarse/fine	9 maximum	1.0/3.2	9 maximum	1.0/3.0
Sand equivalent (%)	50 minimum	64	60 minimum	66
Asphalt content (%)	5.0 ± 0.3	5.0	5.0 ± 0.3	5.0
Marshall density (g/cL)	2.40 - 2.42	2.418	2.36 - 2.38	2.369
Marshall air voids (%)	3.40 - 4.80	4.0	3.40 - 4.60	4.0
Strength index (%)	75 minimum	78.1	75 minimum	80.9
Aggregate crushing value (%)	-	-	25 maximum	20.2
Aggregate impact value (%)	-	-	25 maximum	17.8
Polished stone value (%)	-	-	47 minimum	51.1

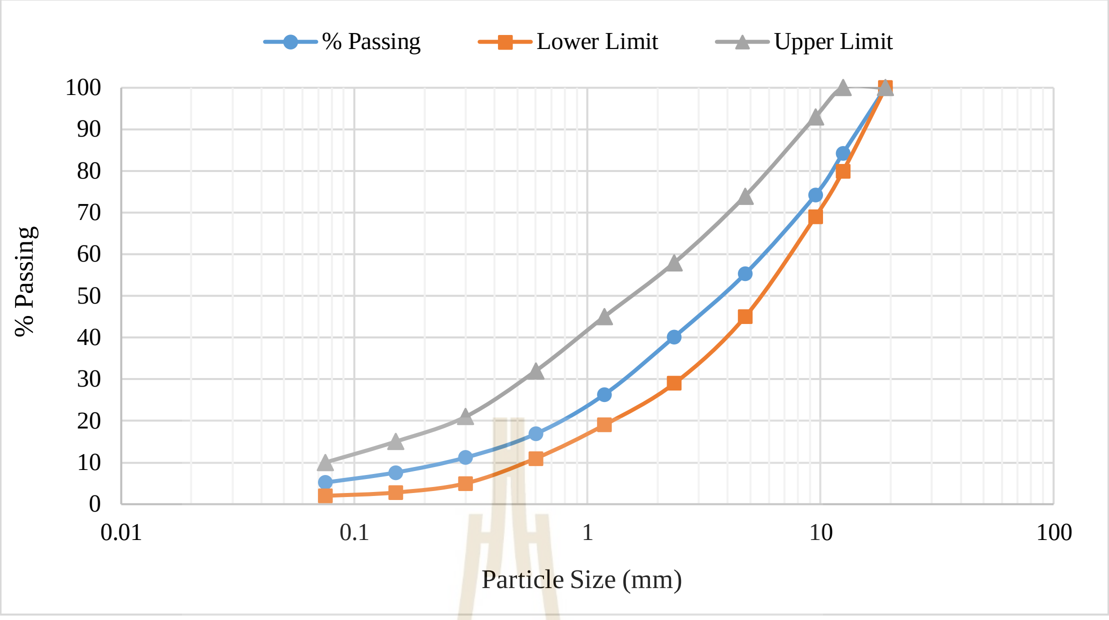


Figure 4.1 Upper and lower limit, and gradation curve for aggregates.

Two studied types of asphalt binders: asphalt cement penetration grade 60/70 (AC60/70) and polymer modified asphalt (PMA), were obtained from an asphalt refinery plant in Bangkok, Thailand. Both were tested to determine their properties for compliance with DOH specifications. The traditional rheological tests were performed to evaluate the asphalt properties including the Penetration at 25ºC, Ring and Ball (R&B) Softening Point, Specific Gravity, Viscosity at 135ºC and 165ºC using Brookfield Rotation Viscometer (RV), Flash Point, Elastic Recovery and Ductility tests. The rutting resistance parameter or dynamic shear ($G^*/\sin\delta$) of PMA binder was measured at 76ºC and 10 rad/s, in control stress mode using Dynamic Shear Rheometer (DSR). The physical properties of PMA and AC60/70 compared with the standards were summarized and are presented in **Table 4.2** and **Table 4.3,** respectively.

4.2.2 Fiber Reinforced Asphalt Concrete

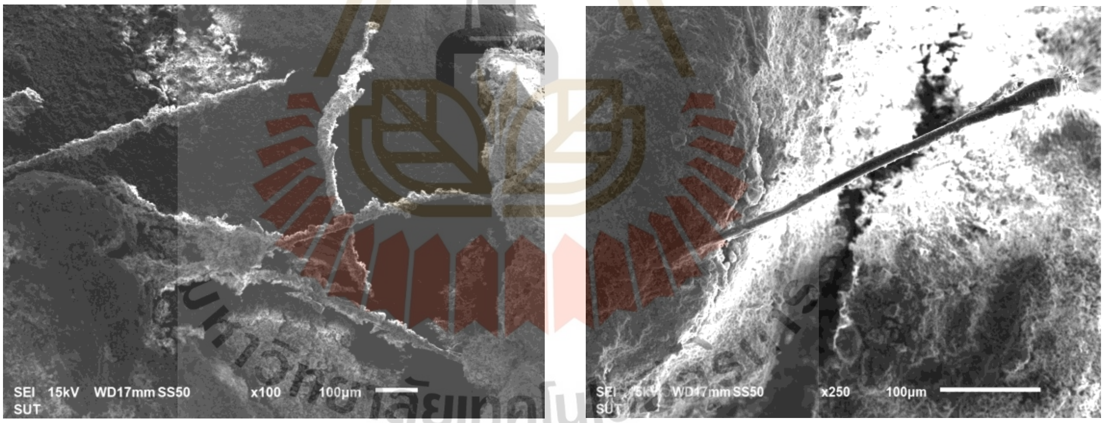
The studied fiber was a blend of synthetic polyolefin (tan-colored) and aramid (yellow-colored) fibers designed for HMA applications. Polyolefin fibers are widely used as reinforcing agents in concrete and asphalt concrete. **Figure 4.2** shows the microstructural characteristics of a fiber reinforced asphalt mixture, by scanning electron microscope (SEM) analysis. **Table 4.4** shows physical properties of polyolefin and aramid fibers.

Table 4.2 Fundamental Properties and Standards used for Polymer Modified Asphalt.

Parameter measured	Test method	Results	Specification
Penetration at 25°C, 100g, 5 sec.,0.1 mm	TIS 1201-93	55	55-70
Softening Point, Ring and Ball, °C	TIS 1216-94	76.3	70 Min.
Ductility at 13°C, 5 cm/min., cm	TIS 1202-93	128	55 Min.
Elastic Recovery at 25°C, 10 cm, %	ASTM D6084-06	92.5	70 Min.
Toughness, kg.cm	ASTM D5801-95	374	170 Min.
Tenacity, kg.cm	ASTM D5801-95	291	100 Min.
Brookfield Viscosity, shear rate 18.6 s-1,			
Spindle no.21	ASTM D4402-06	1355	3000 Max.
At 135 °C, m Pa.s		465	1000 Max.
At 165 °C, m Pa.s			
Storage Stability at 163 °C, 24 hrs.	ASTM D5892-00	1.4	2 Max.
Different in Softening Point, °C	TIS 1216-94		
Density at 25 °C, g/cc	ASTM D70-09e1	1.02	1.00-1.05
Flash Point, Cleveland Open Cup, °C	TIS 1182 Part 2-94	315	220 Min.
Solubility in Toluene, % wt.	ASTM D5546-09	99.90	99.0 Min.
Dynamic Shear, G*/sin δ at 76 °C, 10 rad/s, kPa.	AASHTO TP5-98	2.3	1.0 Min.
Weight Loss, % wt.	ASTM D2872-12	0.126	0.5 Max.

Table 4.3 Fundamental Properties and Standards used for Asphalt Cement AC60-70.

Parameter measured	Test method	Results	Specification
Penetration at 25ºC, 100g, 5 sec.,0.1 mm	DH-T 403/1975	69	60-70
Flash Point (Cleveland Open Cup), ºC	DH-T 406/1976	292	232 Min.
Softening Point, Ring and Ball, ºC	TIS 1216-94	47.8	45-55
Ductility at 13ºC, 5 cm/min., cm	DH-T 405/1976	Over 100	100 Min.
Solubility in Trichloroethylene, % wt.	DH-T 409/1977	99.85	99.0 Min.
Thin Film Oven Test, 3.2 mm, 163ºC, 5 hrs.	AASHTO T179	0.05	0.8 Max.
Loss on Heating, % wt.		71.5	54 Min.
Penetration of Residue, % of Original		Over 50	50 Min.
Ductility of Residue at 25ºC, 5 cm/min., cm			



(a) (b)

Figure 4.2 (a) and (b) Representative SEM images of a loose asphalt mixture with fiber-reinforcement.

Table 4.4 Physical Characteristics of the studied fiber.

Materials	**Polypropylene**	**Aramid**
Form	Twisted Fibrillated Fiber	Monofilament Fiber
Specific Gravity	0.91	1.45
Tensile Strength (MPa)	483	3000
Length (mm)	19.05	19.05
Color	Tan	Yellow
Acid/Alkali Resistance	inert	inert
Decomposition Temperature (ºC)	157	>450

4.2.3 Specimen Preparation

The experimental work started with a HMA mix design to establish the Job Mix Formula and the appropriate constituents of the AC mixtures, based on DOH specifications, which is equivalent to the Marshall mix design process.

The aggregate was heated in an oven between 170 and 190 ºC, which are about 20 ºC higher than the mixing temperature (150 ºC for AC6/70 and 170 ºC for PMA) and then fibers were added and mixed with aggregate thoroughly. The melted asphalt binder at 150 ºC for AC60/70 and 170 ºC for PMA was added into the fiber-aggregate mixture and mixed thoroughly till a well coated and evenly distributed mixture was obtained. The recommended 0.05% fiber content (by mass of total mixture) for mixture design was used in this study (Waleed et al., 2014). The hot mixtures from both laboratory mixing and plant mixing were placed in a steel mold (101.6 mm in diameter and 63,5 mm in height) and compacted under 75 blows on each side at 150 ºC for AC60/70 and 170 ºC for PMA to attain a Marshall specimen. To investigate the influence of fiber on performance of asphalt mixtures, 4 types of mixtures namely AC60/70, AC60/70 + Fiber, PMA, and PMA + Fiber were studied.

In the Marshall method, each compacted test specimen was subject to the following tests: (a) Bulk Specific Gravity Determination, (b) Stability and Flow Test, and (c) Density and Voids Analysis. The asphalt content at the maximum density, 4% air void, and maximum Marshall stability was determined, and the average value was used as the Optimum Asphalt Content (OAC) (Asphalt institute, 1997). For each mixture, three specimens were prepared at 4.5%, 5.0%. 5.5%, 6.0% and 6.5% asphalt content to determine OAC and five specimens were prepared to determine the theoretical maximum density (TMD). The obtained values were compared with the criteria indicated by DOH specification.

Since the lateral side of the specimens was not porous (Muniandy et al., 2014), the bulk specific gravity (G_{mb}) test was performed as soon as freshly compacted specimens have cooled down to room temperature in accordance with ASTM D2726. The G_{mb} was calculated using the following equation:

$$G_{mb} = \frac{A}{C-B} \tag{4.1}$$

where *A* is the weight of specimen in air (g), *B* is the weight of specimen submerged in water (g), and *C* is the saturated surface dry (SSD) weight of the specimen (g).

The theoretical maximum specific gravity (G_{mm}) was determined by AASHTO T209/ASTM D2041 in which vacuuming was used to extract all the air from the mixtures. This represents 100% density (assumed to be no air voids) for a particular asphalt mixture. This value is used in conjunction with the bulk specific gravity to determine the density of the compacted mixture. The G_{mm} was calculated using the following equation:

$$G_{mm} = \frac{W_c - W_a}{(W_c - W_a) - (W_d - W_b)} \tag{4.2}$$

where,

W_a: weight of container in air, g.

W_b: weight of container in water, g.

W_c: weight of container and sample in air, g.

W_d: weight of container and sample in water, g.

TMD = Theoretical maximum density of the mix = $G_{mm}\,\gamma_w$, g/cm^3

γ_w = Specific gravity of water (1 g/cm^3)

The following equations were employed to determine the volumetric properties, voids in the total mix or air voids (VTM), voids in mineral aggregate (VMA), and voids filled with asphalt (VFA), respectively.

$$VTM = 100\left(1 - \frac{Gmb}{Gmm}\right) \tag{4.3}$$

$$VMA = 100\left(1 - \frac{Gmb(1-Pb)}{Gsb}\right) \tag{4.4}$$

$$VFA = 100\left(\frac{VMA-VTM}{VMA}\right) \tag{4.5}$$

4.3 Performance Tests on Laboratory and Plant Mixed Specimens

This research aims to evaluate the performance of the FR-AC compared with conventional AC (without fiber-reinforcement) with different binders (AC60/70 and PMA) via laboratory and field studies. The mixing quality of FR-AC in both laboratory and plant was also investigated to understand the scale effect on the mechanical properties and performance of AC.

HMA mixtures are traditionally designed with their properties being validated in laboratory, but the designed mixtures were produced and constructed in the field using an asphalt mixing plant. The mechanical properties of the plant mixtures in a large batch might be different from the laboratory mixtures. The performance comparison of specimens mixed in laboratory and plant was then carried out to ensure that the laboratory mix design is applicable to the real construction.

The performance testing program included traditional (Marshall stability and flow, and indirect tensile strength) and performance tests. The performance tests included those simulating rutting (dynamic creep and wheel-tracking) due to excessive bearing stress on the AC pavement surface and fatigue cracking (indirect tensile resilient modulus, indirect tensile stiffness modulus, and indirect tensile fatigue) due to excessive tensile stress at the bottom of AC pavement.

4.3.1 Laboratory Experimental Program

4.3.1.1 Marshall stability and flow test

The Marshall stability and the flow tests were carried out on the compacted specimens at various asphalt cement contents (4.5 – 6.5%) based on ASTM D1559 using a compression loading with a strain rate of 50.8 mm/min. The test cylinder mold was 101.6 mm (4 in.) in diameter and 63.5 mm (2 ½ in.) in height.

The maximum loading at material failure is called Marshall stability, and the associated plastic flow (deformation) of the specimen is called flow value. The average Marshall stability and flow values were reported from triplicate samples of each asphalt content, to ensure testing consistency.

4.3.1.2 Indirect tensile strength (ITS)

The indirect tensile test was performed for the determination of the strength of bituminous mixtures according to ASTM D6931 using a deformation rate of 50.8 mm/min at the temperature of 25ºC. The reported results are an average from three specimens. Equation (6) was used to calculate the tensile strength of asphalt concrete,

$$ITS = \frac{2P}{\pi DT} \tag{4.6}$$

where ITS is the indirect tensile strength; P is the peak value of the applied vertical load; T is the mean thickness of the test specimen; and D is the specimen diameter.

4.3.1.3 Indirect tensile resilient modulus

Indirect tensile resilient modulus (M_R) is a relative measure of mixture stiffness and load distribution ability. Higher M_R values indicate stiffer mixtures with higher load distribution ability. M_R was determined from the tests on cylindrical specimens for each mixture at designed asphalt contents in the indirect tension mode. The test was carried out using Universal Testing Machine in accordance with ASTM D4123-82 and AASHTO TP31-94 at temperature of 35 ºC. M_R in MPa is calculated by the following equation:

$$M_R = \frac{P(0.27+\nu)}{(\Delta H)D} \tag{4.7}$$

where P is the peak value of the applied vertical load (N), □H is the mean amplitude of the horizontal deformation obtained from the last 5 applications of the load pulse (mm), D is the mean thickness of the specimen (mm), and ν is the Poison's ratio.

Test stress	15% of ITS
Test duration	150 cycles
Test cycle	square wave pulse 1 sec on, 1 sec off
Test temperature	35 ºC

4.3.1.4 Indirect tensile stiffness modulus (ITSM)

The indirect tensile stiffness modulus (ITSM) test, defined in BS-EN DD 213 (1993), is the widely used test method for the determination of the stiffness modulus of a specimen. The test is simple and can be completed quickly. The operations are selecting the target horizontal deformation and a target load pulse rise time (time from start of load application to peak load). The force applied to the specimen was then automatically calculated by the computer and a number of conditioning pulses were applied to the specimen. These conditioning pulses are used to make any minor adjustment to the magnitude of the force needed to generate the specified horizontal deformation and to seat the loading strips correctly on the specimen. Once the conditioning pulses have been completed, the system applied five load pulses. This generated an indirect movement on the horizontal diameter and the strain was calculated based on the known diameter of the specimen. As the cross-sectional area of the specimen was also known and the force applied was measured, the applied stress could be calculated. Thus, ITSM can be calculated based on these stress and strain values. Standard test conditions and requirements for the ITSM test are:

Horizontal strain	0.005% of the specimen diameter
Rise time	124 ms – equivalent to a frequency of 1.33 Hz
Specimen diameter	102 mm
Specimen thickness	64 mm
Test temperature	35 ºC
Poisson’s ratio	0.40 for 35 ºC

4.3.1.5 Indirect tensile fatigue test (ITFT)

The indirect tensile fatigue test (ITFT) used a repeated controlled stress pulse to damage the specimen and the accumulation of vertical deformation against a number of load pulses was plotted (John maddison read, 1996). The test was performed according to BS-EN12697-24: 2004. The load was applied through a 12.5 mm wide stainless-steel curved loading strip.

A haversine loading pulse with a frequency of 10 Hz was used, which is approximately equivalent to a vehicle speed of 50 mph (80 km/h). The loading period of the pulse of 0.1 seconds was followed by a rest period of 0.9 seconds. Poisson’s ratio was assumed to be 0.35 at 25 ºC. The tests were performed in an environmental chamber at 25 ºC. The report results were an average of three specimens. Standard test conditions and requirements for ITST were:

Target test stress	300 kPa
Target rise time	125 ms
Failure criteria	9 mm vertical deformation
Test temperature	25 ºC

4.3.1.6 Dynamic creep test

The dynamic creep (confined/unconfined) test has been widely performed to evaluate the deformation resistance (rutting susceptibility) of the asphalt mixture. The most popular dynamic creep test is the unconfined dynamic creep test (also known as repeated load axial test). The development of plastic strains in the skeleton of an aggregate contributes significantly to permanent deformation. The effect of this form of loading in inducing plastic strains had already been recognized by Goetz et al. (1957)

The specimen was subjected to repeated load pulses of 1-second duration separated by 1-second duration rest periods. An optional pre-test conditioning period (selectable 0 to 60 minutes) was available. During the test, the relationship between axial strain and number of load pulses was plotted on the computer screen. The accumulative permanent deformation as a function of load applications (pulses) was recorded and correlated to the rutting potential of asphalt mixtures.

For this study, the loading conditions were selected following the specification in BS DD226: 1996 for determining the resistance of bituminous mixtures to permanent deformation. Standard test conditions and requirements for the dynamic creep test were:

Conditioning stress	10 kPa
Conditioning period	30 s
Test Stress	120 kPa
Test Duration	1800 Pulses
Test cycle	square wave pulse 1 sec on, 1 sec off
Test temperature	40 ºC

4.3.1.7 Wheel-track test

Life cycle assessment of the in-service asphalt pavements can be predicted by the permanent deformation (rutting) using wheel-track test. Rutting is defined as permanent residual strain, which is irreversible and caused by the applied load to the surface of AC. The tremendous accumulations of permanent strains due to repeated axle loadings result in pavement surface rutting (Alataşet al. 2012; Moghaddam et al. 2014).

The rutting test was performed using a moving wheel-tracking in the laboratory to simulate the passage of vehicles along the surface of the pavement asphalt. The wheel-tracking test was carried out in accordance with British and European standard BS-EN-12697-22 (BSI 2004) at temperature of 60°C. The slab specimen with 500 mm length, 180 mm wide, and 100 mm in height was prepared in the laboratory using a roller compactor followed British and European standard BS-EN-12697-33 (BSI 2004a). The average of at least 15 values after a specified number of wheel passes: 1,000, 3,000 and 10,000 loading cycles was the representative of rut depth of the tested asphalt mixtures.

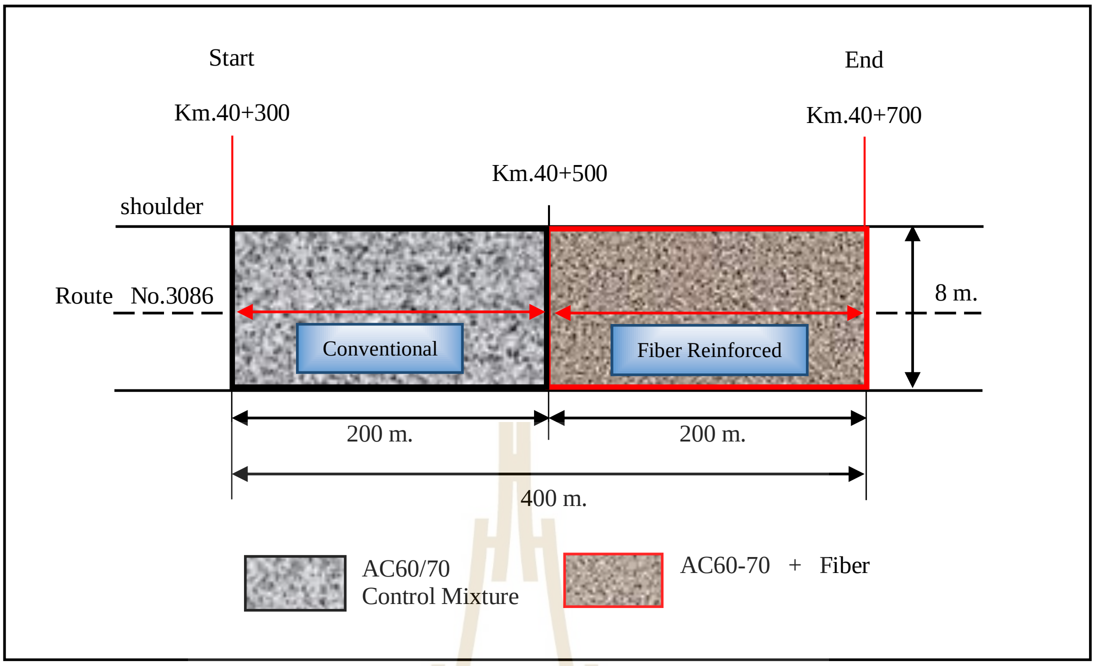
4.4 Field Trial Tests

The field trial tests were carried out to assure that the quality of the construction and materials conforming with the specification requirements. The performance of pavement trials after years of traffic loading was measured on both control AC pavement and FR-AC pavement. The performance tests included International Roughness Index (IRI), rutting, and texture depth tests. The transverse permanent deformation of the trial sections was determined using a profilometer to determine rutting. IRI is the roughness index obtained from measured longitudinal road profiles. It was calculated using a quarter-car vehicle math model, whose response was accumulated to yield a roughness index with units of slope (m/km). IRI has been used worldwide for evaluating and managing road systems. IRI is also used to evaluate new pavement construction, to determine penalties or bonus payments based on smoothness (Sayers et al., 1998). The texture depth test was carried out by following the standard sand patch testing procedure in accordance with ASTM E965-96, 2011 and BSI 812-110, 1990.

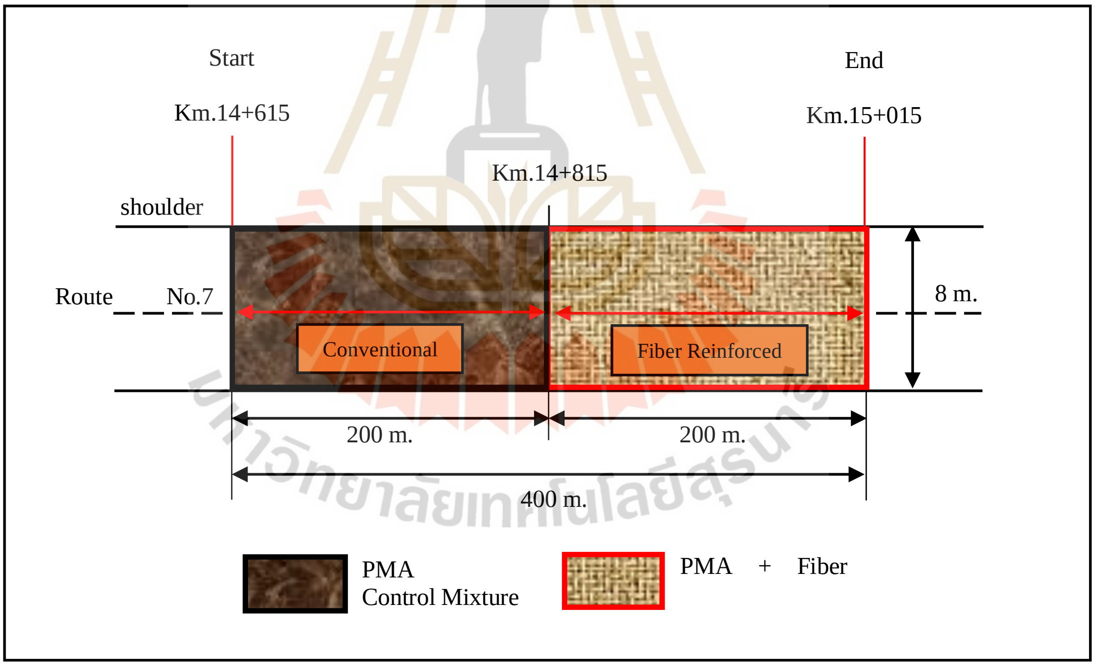
Two road trials were constructed in collaboration with Bureau of Highways 10 (Suphunburi Province, DOH Thailand) and FORTA Corporation: Trial 1 Route No.3086 in Kanchanaburi Province and Trial 2 Route No. 7 in Chonburi Province, Thailand. Both trials were constructed based on the Marshall mix design procedure in accordance with the specifications of DOH, Thailand. The aggregate was crushed limestone sourced from Khon Kaen Province, Thailand. The optimum of 5% asphalt content at 4% air void of the total mix by mass were used in this study.

Trial 1 was composed of conventional AC60/70 section (without fiber) and a FR-AC60/70 (AC60/70 + Fiber) section (**Figure 4.3a**). Trial 2 was composed of a conventional PMA mixture (without fiber) section and an FPR-PMA (PMA + Fiber) section (**Figure 4.3b**). The traffic volume for Trial 1 and 2 was approximately 3 million vehicles and 106 million vehicles per year, respectively. The mix production at asphalt plant and construction process are shown in **Figure 4.4**.

The AC60/70, AC60/70 + Fiber, PMA, and PMA + Fiber sections were constructed based on the asphalt pavement construction methods and guideline of DOH, Thailand (DH-S408/2532, 1989). The job mix formula used to mix the aggregates and asphalt binders was based on the Marshall mix design method. Similar to the laboratory mix processes, the aggregates were heated at 170 and 190 ºC and then 0.05% fiber content by mass of the total mixture were added and mixed with aggregate thoroughly under dry conditions for a duration of 10 s. The asphalt binders: AC60/70 and PMA were respectively heated at 150 and 170 ºC and added into fiber-aggregate mixes and mixed thoroughly to obtain well coated AC60/70 + Fiber mixture and PMA + Fiber mixture. The HMA mixtures were placed to the desired trial sections by the asphalt paving machines. The asphalt emulsion prime coat was sprayed (about 0.4 to 0.6 l/m^2) prior to HMA placement in order to improve the adhesion between the FR-AC layer and base course layer. Subsequently, the HMA mixtures were first compacted by road rollers (10 – 12 tons) and followed by second compaction using vibrating rollers (6 – 10 tons). The road pavements were finished by the final rolling using tandem rollers (6 – 10 tons) with two passes (one lap) at the surface temperature of about 50 ºC to lessen the impact of initial rutting and the air void squash due to traffic effects.



(a) Route No. 3086



(b) Route No. 7

Figure 4.3 Schematic diagram showing the road section for field verification tests.

(a) (b)

Figure 4.4 (a) mix production at asphalt plant. (b) test section construction.

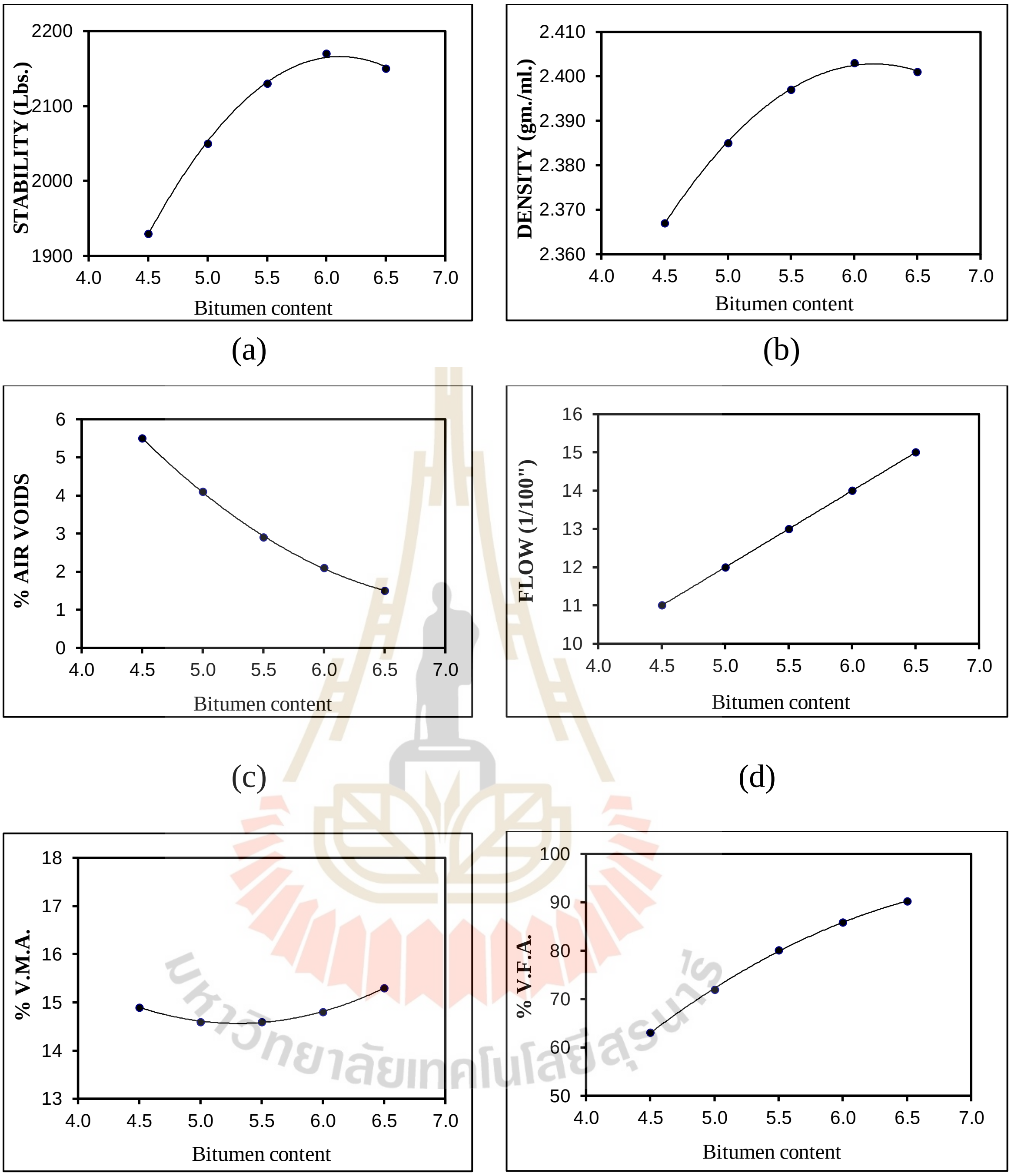
4.5 Results and Discussion

4.5.1 Laboratory Performance Test Results

Figure 4.5 shows the Marshall mix design results. The optimum asphalt content was obtained from the result of several trial mixes, providing targeted air void of 4%. The optimum asphalt content was found to be 5.0% of total mix by mass. The results of the Marshall stability of all mixtures prepared in the laboratory and in the plant are presented in **Figure 4.6**. The stability values of all mixtures were higher than the minimum stability requirement (> 8.2 kN) specified by the DOH, Thailand. The stability values of laboratory and plant mixed PMA specimens were 15.5 kN and 15.1 kN, respectively, which were remarkably higher than laboratory and plant AC60/70 mixtures (11.5 kN and 11.8 kN). For both laboratory and plant mixed specimens, the AC60/70+Fiber specimens and PMA + Fiber specimens had higher stability values than the AC60/70 specimens and PMA specimens, respectively. This implied the role of fiber reinforcement on the enhancement of Marshall stability.

Although the similar trend was observed between the specimens mixed in laboratory and plant, the plant mixed AC60/70+Fiber specimen (stability = 13.9 kN) had higher stability value than the laboratory mixed specimen (stability = 12.0 kN). While the laboratory mixed PMA + Fiber specimen (stability = 15.5 kN) had similar stability value to the plant mixed PMA + Fiber specimen (stability = 15.0 kN).

Figure 4.7 presents ITS results of the laboratory and plant mixed specimens. ITS of the laboratory mixed specimens was slightly different from that of the plant mixed specimens, except the AC60/70+Fiber specimens whereby the plant mixed specimens exhibited relatively higher ITS value (ITS = 489.3 kPa) than the laboratory mixed specimens (ITS = 435.3 kPa). For a particular asphalt binder, the specimens with fiber-reinforcement exhibited higher ITS values than the specimens without fiber-reinforcement (i.e., ITS of the laboratory mixed AC60/70 + Fiber specimen and AC6070 specimen was 435.3 kPa and 409.3 kPa, respectively and ITS of the laboratory mixed PMA + Fiber specimen and PMA specimen was 485.9 kPa and 471.2 kPa, respectively). This evidence proved that the fiber-reinforcement improved ITS of the conventional asphalt concrete. Bonica et al. (2016) indicated that the mechanical bonding between fiber and asphalt binder played an important role in increasing the tensile strength of HMA mixtures. Furthermore, the higher tensile strength of FR-AC mixtures attributes to the high resistance to crack propagation of the AC pavement.

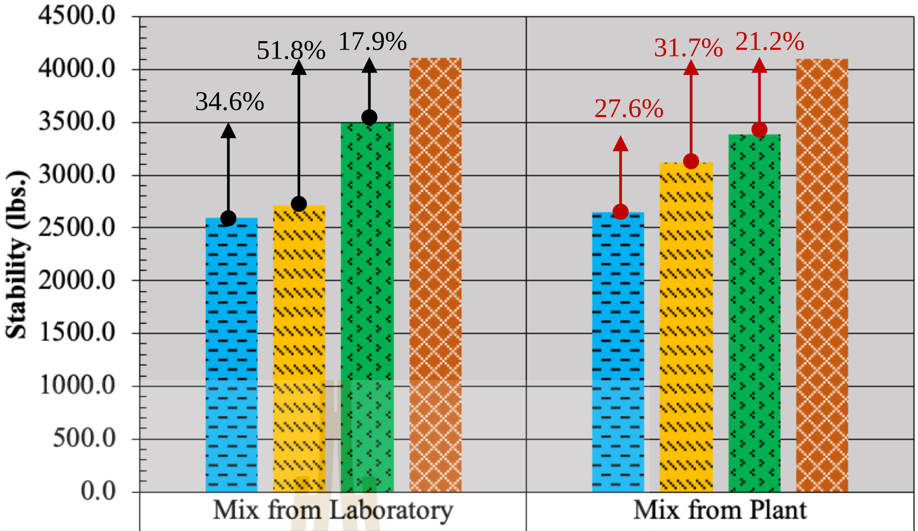


(a) (b)

(c) (d)

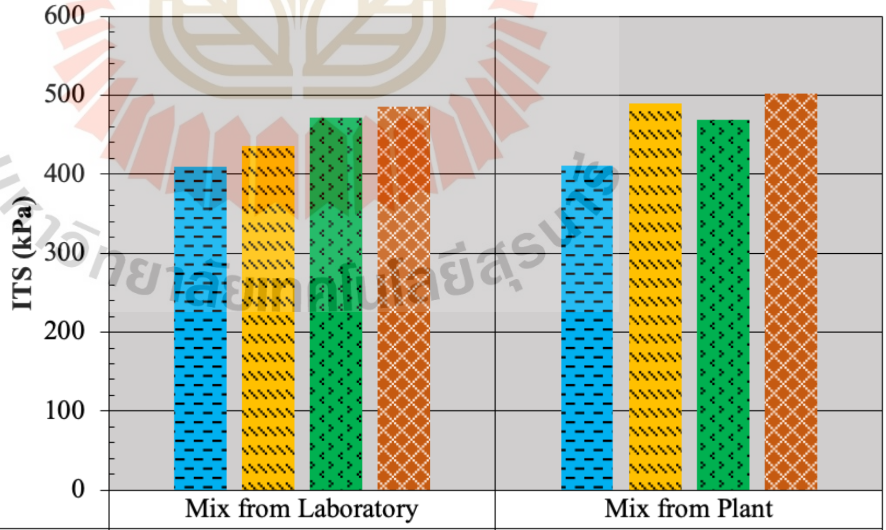
(e) (f)

Figure 4.5 Results obtained from the Marshall mix design: (a) Stability, (b) Density, (c) Voids in total mix or air voids, (d) Flow, (e) Voids filled with asphalt, and (f) Voids in mineral aggregate.



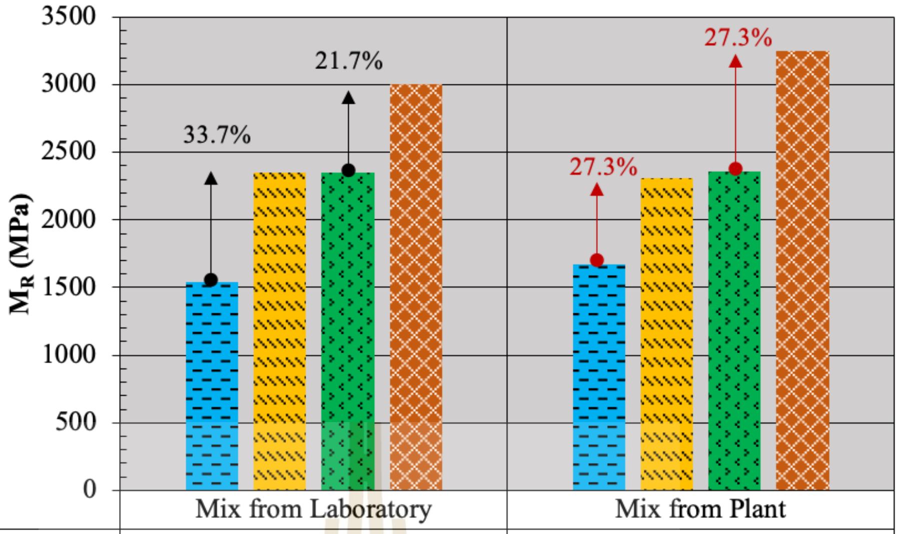
	Mix from Laboratory	Mix from Plant
🟦 AC 60/70	2593.8	2652.1
🟨 AC 60/70 + Fiber	2710.2	3115.5
🟩 PMA	3491.0	3385.0
🟧 PMA + Fiber	4115.0	4102.0

Figure 4.6 Marshall stability test results.



	Mix from Laboratory	Mix from Plant
🟦 AC 60/70	409.3	411.2
🟨 AC 60/70 + Fiber	435.3	489.3
🟩 PMA	471.2	469.0
🟧 PMA + Fiber	485.9	502.2

Figure 4.7 Indirect tensile strength test results.

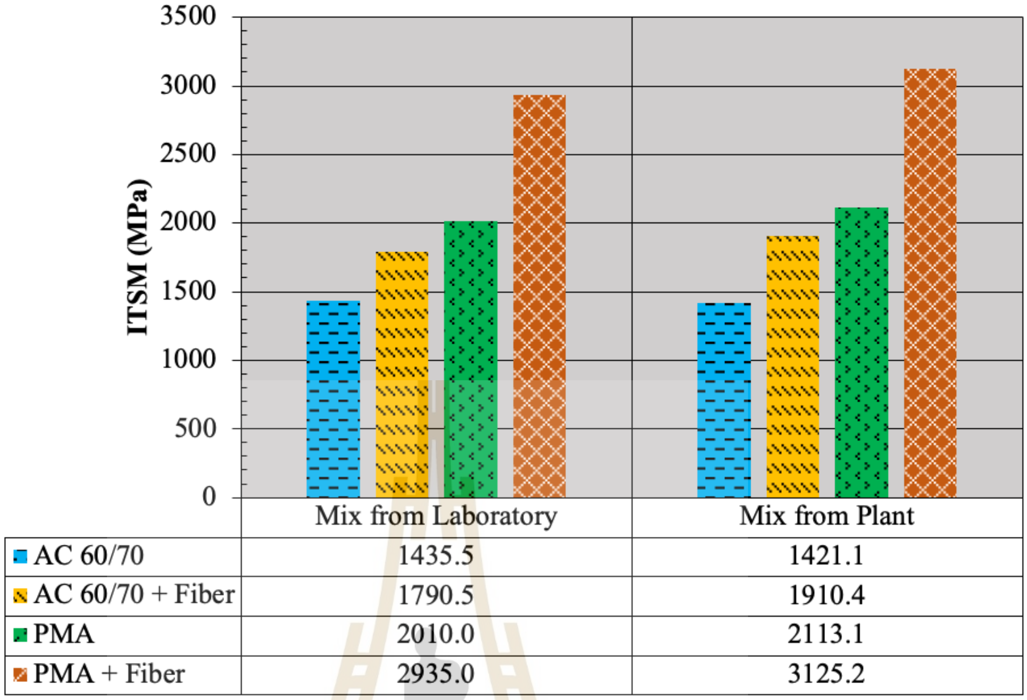


	Mix from Laboratory	Mix from Plant
🟦 AC 60/70	1542.2	1675.2
🟨 AC 60/70 + Fiber	2352.0	2305.5
🟩 PMA	2352.0	2361.0
🟧 PMA + Fiber	3005.0	3245.6

Figure 4.8 Resilient modulus test results.

Figure 4.8 shows the test results of M_R of both laboratory and plant mixed specimens. It illustrated that the plant mixed PMA + Fiber specimens had relatively higher M_R value (M_R = 3245.6 MPa) than the laboratory mixed specimens (M_R = 3005.0 MPa), while the M_R values of other laboratory and plant mixed specimens were similar. It is worth mentioning that the M_R value of the AC60/70+Fiber specimens (2352.0 MPa and 2305.5 MPa) was comparable to that of the PMA specimens (2352.0 MPa and 2361.0 MPa) and was remarkably higher than the control AC60/70 specimens (1542.2 MPa and 1675.2 MPa), mixed from laboratory and plant, respectively. In addition, the fiber-reinforcement can significantly enhance M_R of the PMA mixture. It can be seen that the M_R value of the plant and laboratory mixed PMA + Fiber specimens were respectively 3245.6 MPa and 3005.0 MPa, which were notably higher than the PMA specimens (without fiber) (2361.0 MPa and 2352.0 MPa).

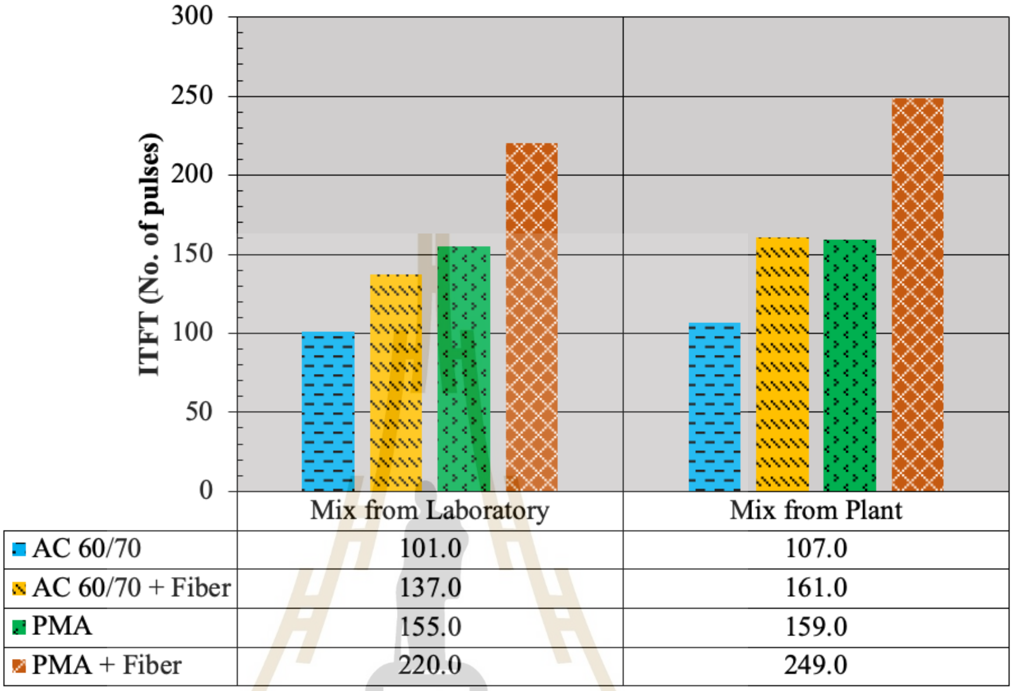
The ITSM results of the laboratory and plant mixed specimens are presented in **Figure 4.9**. For both binders with and without fiber reinforcement, the ITSM values of the plant mixed specimens were slightly higher than those of the laboratory mixed specimens. The PMA + Fiber specimens indicated the highest ITSM values (i.e., 3125.2 MPa and 2935.0 MPa for plant and laboratory mixed specimens) and significantly higher than the control AC60/70 specimens (i.e., 1421.1 MPa and 1435.5 MPa for plant and laboratory mixed specimens). The ITSM value of the plant mixed AC60/70 + Fiber specimen was 1910.4 MPa and slightly higher than that of the laboratory mixed specimen of 1790.5 MPa. While the ITSM values of plant and laboratory mixed PMA specimens were 2113.1 MPa and 2010.0 MPa, respectively, which were about 10.6% and 12.3% higher than those of plant and laboratory mixed AC60/70 + Fiber specimens, respectively.



	Mix from Laboratory	Mix from Plant
🟦 AC 60/70	1435.5	1421.1
🟨 AC 60/70 + Fiber	1790.5	1910.4
🟩 PMA	2010.0	2113.1
🟧 PMA + Fiber	2935.0	3125.2

Figure 4.9 Indirect tensile stiffness modulus test results.

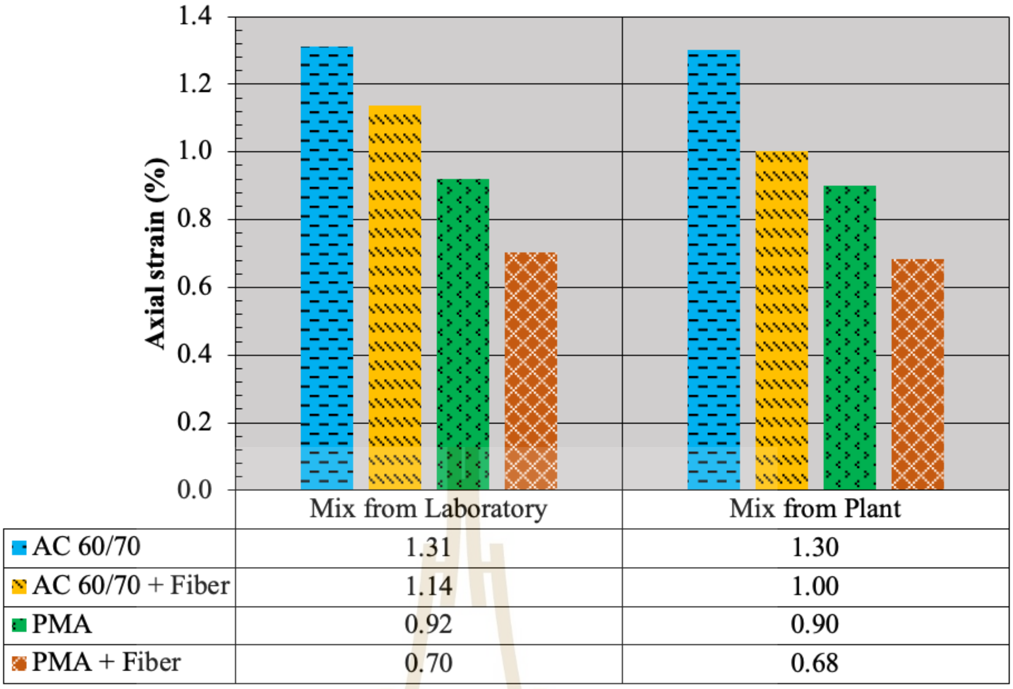
The indirect tensile fatigue test results of the laboratory and plant mixed specimens are shown in **Figure 4.10**. Fatigue life of AC is presented by the number of pules at failure; the higher number of pules indicates the longer service life of AC. **Figure 4.10** indicates that the plant mixed specimens exhibited high fatigue life than the laboratory mixed specimens. For instance, the fatigue life values of plant mixed AC60/70, AC60/70 + Fiber, and PMA + Fiber specimens were 107, 161, and 249, respectively, while the fatigue life values of laboratory mixed AC60/70, AC60/70 + Fiber, and PMA + Fiber specimens were 101, 137, and 220, respectively. However, the fatigue life values of the plant and laboratory mixed PMA specimens were more or less the same. Similar to the ITS results, the fatigue life of AC60/70 + Fiber mixtures was comparable to that of PMA mixtures, while the highest fatigue life was found for PMA + Fiber specimens.



	Mix from Laboratory	Mix from Plant
■ AC 60/70	101.0	107.0
▧ AC 60/70 + Fiber	137.0	161.0
▦ PMA	155.0	159.0
▩ PMA + Fiber	220.0	249.0

Figure 4.10 Indirect tensile fatigue test results.

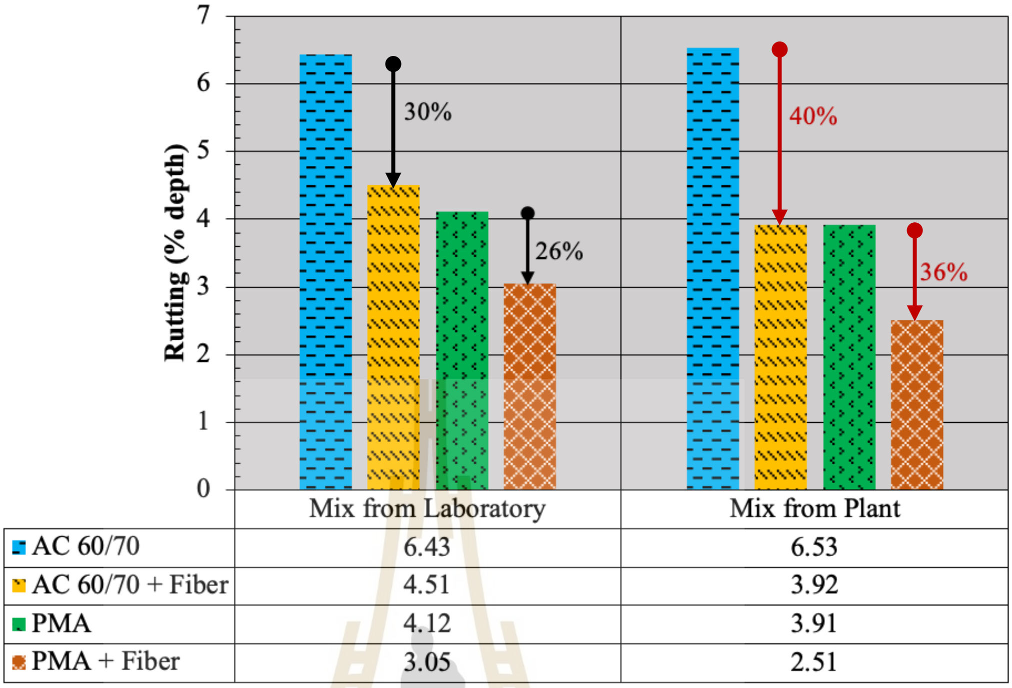
The permanent deformation from the dynamic creep test, which represented by the axial strain of all mixtures are shown in **Figure 4.11**. AC60/70 + Fiber, PMA, and PMA + Fiber specimens had respectively lower axial strain than the conventional AC60/70 specimen. The permanent deformation of plant mixed and laboratory mixed specimens were more or less the same for all ingredients. The accumulation of permanent strain for the FR-AC was low, which clearly indicated a superior resistance to permanent deformation when the number of cycles was high. In other words, the FR-AC had higher recoverable deformation than the unreinforced AC.



	Mix from Laboratory	Mix from Plant
AC 60/70	1.31	1.30
AC 60/70 + Fiber	1.14	1.00
PMA	0.92	0.90
PMA + Fiber	0.70	0.68

Figure 4.11 Dynamic creep (axial strain) test results.

Figure 4.12 shows the rutting depths of the laboratory and plant mixed specimens at 10000 cycles. The rutting depth of the plant mixed specimens was slightly lower than the laboratory mixed specimens. For the plant mixed specimens, the rutting for AC60/70, AC60/70 + Fiber, PMA, and PMA + Fiber specimens were 6.53, 3.92, 3.91 and 2.51%, respectively. It was evident that the rutting of AC60/70 and PMA specimens was improved by approximately 40% and 36% with fiber-reinforcement, respectively. The rutting depths of the AC60/70+Fiber specimens were comparable to the PMA specimens. This implied the potential use of fiber to improve permanent deformation and rutting under high traffic load.



	Mix from Laboratory	Mix from Plant
🟦 AC 60/70	6.43	6.53
🟨 AC 60/70 + Fiber	4.51	3.92
🟩 PMA	4.12	3.91
🟧 PMA + Fiber	3.05	2.51

Figure 4.12 Pavement rutting test results.

Overall, the performance in both fatigue cracking and rutting criteria of laboratory and plant mixed specimens is essentially the same. This implied that the mixing quality from both plant and laboratory is practically the same and the laboratory performance test results of the designed HMA can be directly used to interpret the field performance of the HMA pavement.

Brown et al. (1990) and Fitzgerald (2000) reported that fiber imparted the physical changes of asphalt mixture and improve its cohesive and tensile strength. Also, the fibers form a three-dimensional reinforcement network in asphalt binder and enables a better transfer of the mechanical loads from the mineral structure to the fiber-reinforced mastic (Putman and Amirkhanian (2004) and Tam and Bhatnagar, 2016). The FR-AC was thus capable to store more energy than conventional AC and hence the improvement of M_R, fatigue life, ITRM, and rutting. It was observed that the performance of AC60/70 mixture is comparable with that of PMA mixture, having higher cost.

4.5.2 Field trail results

Trial 1 (AC60/70 and AC60/70 + Fiber) and Trial 2 (PMA and PMA + Fiber) were constructed in April 2013 and March 2015, respectively. The field trail measurement included International Roughness Index (IRI), texture depth and rutting. The field measurement on Trial 1 was carried out at 12 months (in April 2014), 15 months (in July 2014), and 18 months (in October 2014) after it was opened to traffic. While the field measurement on Trial 2 was carried out at three months (in June 2015), one year (in March 2016), and two years (in February 2017) after it was opened to traffic.

Table 4.5 demonstrates the results of IRI, texture depth and rutting of Trial 1 on AC60/70 and AC60/70 + Fiber sections. IRI values of both sections exhibited the good performance of lower than 2.5, which is specified by DOH of Thailand. It was evident that AC60/70 + Fiber section had lower IRI than AC60/70 section. The field measured rutting was consistent with the laboratory measured one; the rutting of AC60/70 + Fiber section was lower than that of AC60/70 section (without fiber). These results clearly demonstrated that the fiber-reinforcement can enhance the resistance to permanent deformation of AC60/70 pavement due to real repeated traffic loading (3 million vehicles per year).

Table 4.5 The results of IRI, texture depth and rutting of AC60/70 mixtures and AC60/70+Fiber mixtures.

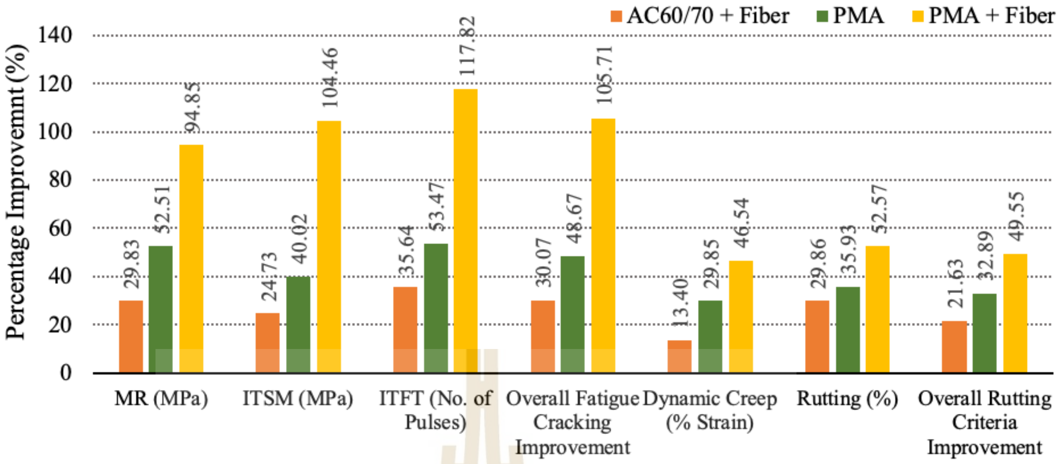
Test Date	**Station**	**Surface Type**	**IRI** (m/km)	**Texture Depth** (mm)	**Rutting** (mm)
April 27, 2014	40+325 – 40+475	AC60/70	2.21	0.59	1.16
	40+525 – 40+675	AC60/70 + Fiber	1.95	0.60	1.02
July 31, 2014	40+325 – 40+475	AC60/70	1.78	0.62	1.90
	40+525 – 40+675	AC60/70 + Fiber	1.79	0.58	1.21
October 10, 2014	40+325 – 40+475	AC60/70	1.82	0.55	1.92
	40+525 – 40+675	AC60/70 + Fiber	1.78	0.57	1.43

Similarly, the results of IRI of Trial 2 on PMA and PMA + Fiber sections are presented in **Table 4.6**. The IRI values of the PMA + Fiber section were lower than that PMA section under the same high traffic volume. Furthermore, the rutting of PMA + Fiber section was lower than PMA section (without fiber). The rutting in Trial 2 (PMA mixtures) was lower than that in Trial 1 (AC60/70 mixtures) even though the traffic volume (106 million of vehicles per year) of Trial 2 was significantly higher than that of Trial 1 (3 million of vehicles per year) and the service time of Trail 2 was longer than that of Trial 1. For example, the rutting of AC60/70 section and AC60/70 + Fiber section were 1.92 mm and 1.43 mm, respectively after 18 months opened to traffic, while the rutting of PMA section and PMA + Fiber section were 1.42 mm and 1.32 mm after 24 months opened to traffic. This indicated that PMA mixtures had higher resistance to permanent deformation than AC60/70 mixture although the cost of PMA mixture was higher.

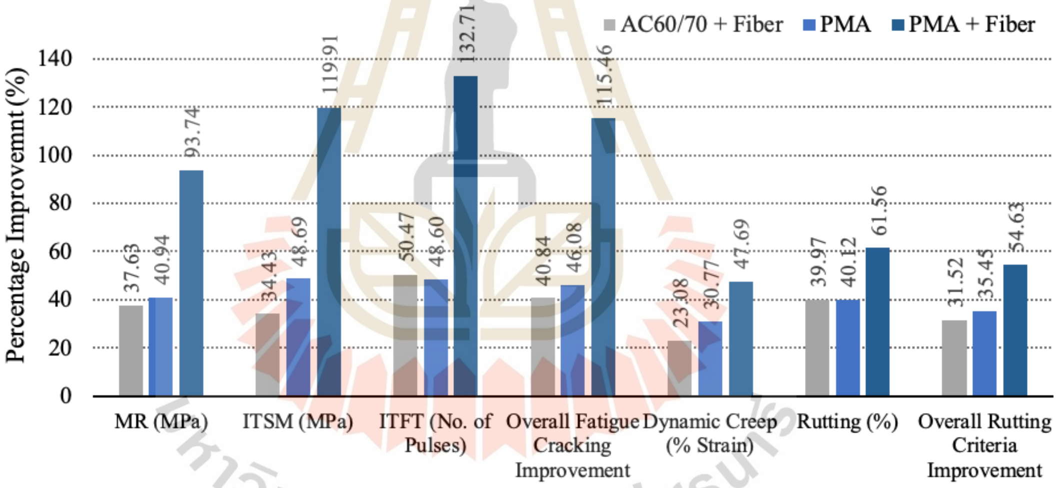
Table 4.6 The results of IRI, texture depth and rutting of PMA mixtures and PMA + Fiber mixtures.

Date	**Station**	**Surface Type**	**IRI** (m/km)	**Texture Depth** (mm)	**Rutting** (mm)
June 27, 2015	14+625 –14+815	PMA	1.56	0.70	0.68
	14+815 –15+015	PMA + Fiber	1.37	0.73	0.56
March 3, 2016	14+625 –14+815	PMA	1.82	0.66	1.19
	14+815 –15+015	PMA + Fiber	1.39	0.67	1.15
February 21, 2017	14+625 –14+815	PMA	1.89	0.33	1.42
	14+815 –15+015	PMA + Fiber	1.85	0.33	1.32

On the other hand, the texture depths of both AC60/70 section and AC60.70 + Fiber section in Trial 1 were more or less the same at each time of field measurement. Similar texture depths were also recorded for the PMA section and PMA + Fiber section in trial 2. The texture depth is directly related to skid resistance of AC pavement, which represents the road safety condition (Siriphun et al., 2016 and 2019). This implied that the fiber-reinforcement insignificantly improved the skid resistance of AC pavement.



(a) mixed from laboratory



(b) mixed from plant

Figure 4.13 Overall improvement of fatigue cracking and rutting criteria of various types of asphalt mixtures compared with control AC60/70 mixtures: (a) mixed from laboratory and (b) mixed from plant.

The percent of performance improvement (fatigue cracking and rutting criteria) of AC60/70 + Fiber, PMA and PMA + Fiber specimens compared with control AC60/70 specimen is shown in **Figure 4.13**. The overall fatigue cracking improvement was defined as the average value of percent improvement of M_R, ITSM, and ITFT, while the overall rutting improvement was defined as the average value of percent improvement of dynamic creep (performance deformation) and rutting. It clearly indicated that the overall fatigue cracking improvement of PMA + Fiber specimens was the highest (about 106% to 116% for laboratory and plant mixed specimens), while its overall rutting improvement were about 50% and 55% for laboratory and plant mixed specimens, respectively (*see* **Figure 4.13a-b**). In other words, for PMA, the fiber-reinforcement had higher potential in improving the fatigue cracking resistance than the rutting resistance. The same is not true for AC60/70 mixtures, similar improvement in fatigue cracking and rutting was found for AC60/70 + Fiber specimens, i.e., 30% for fatigue cracking and 21% for rutting and 41% for fatigue cracking and 32% for rutting, for the laboratory and plant mixed specimens, respectively. In other words, the fiber-reinforcement almost equally contributed to the fatigue cracking and rutting improvement for the AC60/70 mixtures.

The economic study was carried out by comparing both overall fatigue cracking and rutting improvement of AC pavement with its percent increase in construction cost (USD/m^2) (see **Table 7**). According to Comptroller General's Department, Thailand, the construction cost (USD/m^2) of AC60/70 mixture for 50 mm thickness (typical in Thailand) in 2020, AC60/70 + Fiber mixture, PMA mixture, and PMA + Fiber mixture were 7.56, 8.29, 11.55, and 12.70, respectively. The percent increase of construction cost of AC60/70 + Fiber mixture, PMA mixture, and PMA + Fiber pavement were respectively 9.65%, 52.67%, and 67.94% when compared with the construction cost of control AC60/70 pavement. It is apparent that although the overall performance improvement of PMA mixture and PMA + Fiber mixture were high, its percent increase of construction cost was also high. The 53% increase in construction cost of PMA pavement can have its overall fatigue cracking and rutting improvement of 38% and 35% (data from plant mixing), while only 10% increase of construction cost of AC60/70 + Fiber pavement can have the overall improvement cracking and rutting improvement of 35% and 32% (data from plant mixing). This indicated better economic benefit of AC60/70 + Fiber pavement over PMA pavement. In other words, by using the performance and construction cost of AC60/70 mixtures, the ratio of overall fatigue cracking improvement to 1% of construction cost increase of AC60/70 + Fiber mixture, PMA mixture, and PMA + Fiber mixture were 2.50% and 3.67%, 0.76% and 0.72%, and 1.23% and 1.36% for the laboratory and plant mixed specimens, respectively. Similarly, the ratio of overall rutting improvement to 1% of construction cost increase of AC60/70 + Fiber mixture, PMA mixture, and PMA + Fiber mixture were 2.24% and 3.27%, 0.62% and 0.67%, and 0.73% and 0.80%, for the laboratory and plant mixed specimens, respectively.

Table 4.7 Cost analysis of asphalt mixtures based on control AC60/70 mixture.

Type of Asphalt Mixture	Construction Cost (USD/m^2)	Cost Increase (%)	Overall Fatigue Cracking Improvement				Overall Rutting Improvement			
			Mixed from Laboratory		Mixed from Plant		Mixed from Laboratory		Mixed from Plant	
			Increase (%)	Per 1% of cost increase	Increase (%)	Per 1% of cost increase	Increase (%)	Per 1% of cost increase	Increase (%)	Per 1% of cost increase
AC60/70 (control mixture)	7.56	–	–	–	–	–	–	–	–	–
AC60/70+ Fiber	8.29	9.65	24.14	2.50%	35.38	3.67%	21.63	2.24%	31.52	3.27%
PMA	11.55	52.67	40.28	0.76%	38.07	0.72%	32.89	0.62%	35.45	0.67%
PMA+Fiber	12.70	67.94	83.96	1.23%	92.12	1.36%	49.55	0.73%	54.63	0.80%

4.6 Conclusions

The laboratory and field tests were carried out to investigate the performance of fiber-reinforced conventional AC60/70 mixture and PMA mixture. Four asphalt mixtures: AC60/70 mixture, AC60/70 + Fiber mixture, PMA mixture, and PMA + Fiber mixture were prepared based on the Marshall mix design in accordance with the specification of DOH, Thailand. The mixing quality of FR-AC in both laboratory and plant was also investigated to understand the scale effect on the mechanical properties and performance of AC.

Two field trials were constructed: Trial 1 for AC60/70 mixture and AC60/70 + Fiber mixture and Trial 2 for PMA mixture and PMA + Fiber mixture to investigate the effect of fiber reinforcement on field performance improvement. The field measurement included International Roughness Index (IRI), texture depth, and rutting. Finally, the economic analysis was performed based on the two criteria: overall fatigue cracking improvement and overall rutting improvement when compared with the performance of AC60/70 mixture. The overall fatigue cracking improvement was calculated from the average performance improvement of indirect tensile strength modulus, indirect resilient modulus, and indirect tensile fatigue life. The overall rutting improvement was calculated from the average performance improvement of permanent deformation and rutting depth.

The main conclusion that can be drawn from this research is that the overall performance in both fatigue cracking and rutting criteria of laboratory and plant mixed specimens is principally the same. This indicated that the mixing quality from both laboratory and plant is practically the same, hence the laboratory performance test results of the designed HMA can be directly used to interpret the field performance of the HMA pavement. The laboratory and field test results evidently proved that the fiber-reinforcement can enhance both overall fatigue cracking and rutting criteria improvement of conventional AC60/70 mixtures and PMA mixtures. The field trial tests were performed after years of opening to traffic and the field measurement indicated that all studied AC sections exhibited very good performance as their IRI values were lower than 2.5, which is specified by DOH, Thailand. The fiber-reinforced sections exhibited lower IRI and rutting than the unreinforced sections. This implied that fiber-reinforcement can improve the resistance of the permanent deformation of conventional AC mixtures and PMA mixtures. However, the texture depth measurement, an indicator of skid-resistance of AC pavement, indicated insignificant difference between AC60/70 mixture and AC60/70 + Fiber mixture as well as PMA mixture and PMA + Fiber mixture. This implied that the fiber-reinforcement insignificantly improved the skid-resistance of AC pavement.

The additional of 0.05% of fiber in AC mixes by total mass can notably enhance the overall performance of AC60/70 mixture and PMA mixture. This is due to the formation of a three-dimensional reinforcement network in asphalt binder, which enables a better transfer of the mechanical loads from the mineral structure to the fiber-reinforced mastic. The overall fatigue cracking improvement of plant mixed AC60/70 + Fiber, PMA, and PMA + Fiber mixtures was approximately 35%, 38%, and 92%, respectively when compared with the plant AC60/70 mixture. While, the overall rutting improvement of plant mixed AC60/70 + Fiber, PMA, and PMA + Fiber mixtures was approximately 32%, 35%, and 55%, respectively when compared with the plant AC60/70 mixture.

It is worth mentioning that the AC60/70 + Fiber mixture and PMA mixture had practically the same overall improvement in both fatigue cracking and rutting criteria. Whereas, the overall fatigue cracking improvement of PMA + Fiber mixture of 92% was significantly higher than the overall rutting improvement of 50%. This implied that fiber-reinforcement in PMA mixture had higher potential in improving fatigue cracking resistance than rutting resistance. Based on the economic analysis of AC pavement using the construction cost of AC60/70 pavement as a reference, the increase in construction cost of AC60/70 + Fiber, PMA, and PMA + Fiber pavement was about 10%, 53%, and 68%. The cost effectiveness of AC60/70 + Fiber pavement was clearly evident once the overall fatigue cracking and rutting improvement was analyzed taking the construction cost into account. The ratios of overall fatigue cracking improvement to one percent of cost increase of AC60/70 + Fiber, PMA, and PMA + Fiber pavements were approximately 3%, 0.75%, and 1.3%, respectively. While, the ratios of overall rutting improvement to one percent of cost increase of AC60/70 + Fiber, PMA, and PMA + Fiber pavements were approximately 2.7%, 0.67%, and 0.76%, respectively.

The present laboratory and field trial studies confirmed the potential and efficient utility of fiber-reinforcement to improve the mechanical properties and performance of traditional asphalt concrete pavement in Thailand. The research output can be used to develop a code of practice and guideline and/or specification for improving the service life of AC pavement using fiber-reinforcement in Thailand and other countries using a similar mix design method.

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CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

5.1 Summary

The primary objective of this study was to investigate the performance of asphalt concrete modified with fibers and compared with conventional asphalt concrete, through comprehensive laboratory testing and compare with field tests. A detailed discussion on the problem statement was provided in Chapter 1. Chapter 2 provided a literature review on the use of fibers in asphalt mixtures. Chapter 3 presented the performance of fiber-reinforced asphalt concretes with various asphalt binders in Thailand. Chapter 4 presented the laboratory performance, field performance and cost analysis of fiber-reinforced asphalt concrete (FR-AC) pavement using AC60/70 and polymer modified asphalt (PMA) as binders. The mixing quality of FR-AC from laboratory and field plant was also investigated. The following conclusions can be drawn from this study:

5.1.1 Performance of fiber-reinforced asphalt concretes with various asphalt binders in Thailand

The mixture of asphalt concretes with various asphalt binder consists of asphalt cement penetration grade AC60/70, natural rubber–modified asphalt (NRMA), and polymer-modified asphalt (PMA). It can be concluded that although the mechanical property values of all mixtures (without fiber) were different, i.e., PMA exhibited the highest values, followed by NRMA and AC60/70, respectively, fiber reinforcement can improve the performance of these three asphalt mixtures. The Marshall stability, ITS, M_R, and ITSM of all HMA+Fiber mixes increased by approximately average values of 17, 11, 31, and 33%, respectively. Interestingly, the performance of conventional AC60/70 mixtures with fiber is comparable with that of PMA mixtures typically used for heavy traffic load. In other words, the AC60/70 mixture with fiber can be used instead of a PMA mixture from a performance perspective. This research confirms that fiber-reinforced asphalt pavements exhibit superior performance to traditional asphalt concrete pavement, hence resulting in longer service life. The outcomes from this research will result in positive impacts for the use of fiber reinforcement in asphalt concrete and can be used as a guideline for the application of fiber-reinforced asphalt in future road construction projects.

5.1.2 Performance improvement of asphalt concretes using fiber reinforcement: laboratory and field studies

The laboratory and field test results evidently proved that the fiber-reinforcement can enhance both overall fatigue cracking and rutting criteria improvement of conventional AC60/70 mixtures and PMA mixtures. The PMA + Fiber mixture exhibited the best performance among the materials tested and the performance of AC60/70 + Fiber mixture were found to be comparable to PMA mixture. For AC60/70, the fiber reinforcement improved both fatigue cracking and rutting almost equally while it was found to be more effective to improve fatigue cracking than rutting for PMA. Since the performance of FR-AC was found to be similar for both laboratory and plant mixed specimens, the laboratory mix design results can be used to interpret the field performance. The field trial tests were performed after years of opening to traffic and the field measurement indicated that all studied AC sections exhibited very good performance as their IRI values were lower than 2.5, which is specified by DOH, Thailand. The fiber-reinforced sections exhibited lower IRI and rutting than the unreinforced sections. This implied that fiber-reinforcement can improve the resistance of the permanent deformation of conventional AC mixtures and PMA mixtures. However, the texture depth measurement, an indicator of skid-resistance of AC pavement, indicated insignificant difference between AC60/70 mixture and AC60/70 + Fiber mixture as well as PMA mixture and PMA + Fiber mixture. This implied that the fiber-reinforcement insignificantly improved the skid-resistance of AC pavement. The economic analysis indicated that the fiber reinforcement in AC60/70 mixture was the most economical, having the highest ratio of overall performance improvement to cost increase to the control AC60/70 mixture. The outcome of this research will be a guidance for establishing the specification of fiber-reinforced asphalt pavement for Department of Highways in Thailand and other countries using similar mix design.

5.2 Recommendation for future work

In summary, the uses of fibers in asphalt mixtures are well established and successful. Opportunities exist to use fibers in pavement applications to extend its service life and improve the level of service, but more research is needed to ensure that those potential benefits are consistently realized.

Some plausible avenues of future work that could extend the work in this thesis are stated as follows:

1. Further investigation of fiber-reinforced asphalt with recycled aggregate or reclaimed asphalt pavement (RAP) is recommended for future work, which can result in further development of asphalt concrete as green construction material.

2. Use of waste or recycled fibers is recommended for future work. The increasing importance of sustainability in construction has led to increased interest in reusing the recycled materials that would otherwise be disposed of, including waste fibers from a variety of sources. For example, the possibility of reusing waste carpet fibers and recycled tire fibers from the auto manufacturing industry.

APPENDIX A

PUBLICATIONS

List of Publications

INTERNATIONAL JOURNAL PAPER

Takaikaew, T., Horpibulsuk, S., Hoy, M., Kaloush, K., and Arulrajah, A. (2018). **Performance of Fiber-Reinforced Asphalt Concretes with Various Asphalt Binders in Thailand**. Journal of Materials in Civil Engineering. ASCE, Vol.30, No.8, Article No.04018193

INTERNATIONAL CONFERENCE PAPERS

Takaikaew, T., Horpibulsuk, S., Jitsangiam, P., and Dechasakulsom, M. (2014). **A Fibre-reinforced Polymer System in Asphalt Concrete for use in Thailand**. The RGJ.Ph.D international conference. Bangkok. Thailand.

Takaikaew, T., Horpibulsuk, S., Hoy, M., and Kaloush, K. (2017). **Effects of fibers on the performance of asphalt concrete with different asphalt binder in Thailand.** The International Convention on Civil Engineering – ICCE2017, The Greenery Resort Khao Yai, Nakhon Ratchasima, Thailand, July 20-21, 2017

Performance of Fiber-Reinforced Asphalt Concretes with Various Asphalt Binders in Thailand

Thaworn Takaikaew[1]; Promma Tepsriha[2]; Suksun Horpibulsuk, Ph.D.[3]; Menglim Hoy, Ph.D.[4]; Kamil E. Kaloush, Ph.D.[5]; and Arul Arulrajah, Ph.D.[6]

Abstract: This research presents a laboratory investigation into the effects of polyolefin and aramid fibers as a reinforcement material in hot-mix asphalt (HMA) mixtures, with different asphalt binders. Three commercially available asphalt binders were used: asphalt cement penetration grade AC60/70, natural rubber–modified asphalt (NRMA), and polymer-modified asphalt (PMA). The effect of fiber reinforcement in those asphalt mixtures was evaluated by a detailed laboratory experimental program, which included Marshall stability, indirect tensile strength (ITS), resilient modulus (M_R), indirect tensile stiffness modulus (ITSM), dynamic creep, diametrical indirect tensile fatigue, and rutting resistance tests. The performance evaluation was performed by comparing the results between asphalt mixtures with and without fiber reinforcement for the AC60/70, NRMA, and PMA. The laboratory results indicate that without fiber reinforcement, the PMA exhibited better performance than NRMA and AC60/70, respectively. The addition of fibers 0.05% by mass of the total mixture to asphalt concrete mixtures notably improved the rutting resistance, fatigue life, and resilient modulus, regardless of asphalt binder type. The average values of Marshall stability, M_R, ITS, and ITSM of all the fiber-reinforced mixtures was increased by approximately 17, 31, 11, and 33%, respectively, compared with the mixtures without fiber reinforcement. This research confirms that fiber-reinforced asphalt pavements exhibit superior performance to traditional asphalt concrete pavement, hence resulting in longer service life. **DOI: 10.1061/(ASCE)MT.1943-5533.0002433.** *© 2018 American Society of Civil Engineers.*

Author keywords: Fibers; Fiber-reinforced asphalt concrete; Performance test; Natural rubber and polymer modified asphalt binders; Rutting and fatigue.

Introduction

The rapid growth of cities has resulted in higher requirements for performance and service life for transportation infrastructure. Pavements are now subjected to significant increases in traffic volume and truck loads, causing traditional pavements to fail before reaching the end of their design life. The two principal modes of failure in pavements are fatigue cracking and permanent deformation (Olumide 2016). Pavement engineers seek to maintain failures within acceptable limits during the design life span of the pavement.

Permanent deformation is caused by a gradual buildup of irrecoverable strains under repeated loading, which develops into a measurable rut. These strains are due to the viscous-elastic/plastic response of bituminous materials to dynamic loading. In a pavement structure, there are two major contributors to permanent deformation: poor quality of the asphalt concrete layer and the presence of weak base/subbase courses. Rutting resulting from the accumulation of permanent deformation in the asphalt layer is considered to be the principal failure component of flexible pavement (Garba 2002).

The problems of fatigue cracking and permanent deformation have been addressed using different approaches. There are many options used to mitigate deterioration of asphalt concrete (AC) pavements. The options for hot-mix asphalt (HMA) pavements include use of stiffer bitumen, inclusion of modifiers such as polymer-modified asphalt (PMA) or natural rubber–modified asphalt (NRMA), use of synthetic/crumb rubber or fiber-reinforced asphalt, and use of the preeminent pavement design methods or Superpave or AC Duopave, which are commonly used for high-volume roads (Waleed and Shane 2014).

The asphalt concrete used for Thailand's road pavement surfaces mostly consists of a conventional mix using asphalt cement penetration grade 60-70 (AC60/70) and aggregates (Sawasdisan 2011). No special additives or up-to-date technology are currently used to improve the performance of pavements in Thailand. This is a concern because, given the severe traffic and changing environmental conditions in Thailand, the road network's condition is not being adequately maintained. Consequently, the AC60/70 pavement surface often provides only a short service life. Improvement in the quality of asphalt for pavement applications is of prime

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importance to prolong the lifecycle serviceability design of road construction projects in Thailand. Different types of asphalt binders have different performance characteristics in terms of surface durability. Although PMA and NRMA have been used previously to enhance the mechanical properties of asphalt binders, the high cost of these pavement methods are an obstacle for adoption of these binders in road construction projects. Therefore, the focus of this research is to explore the performance of alternative binders for enhancing the quality of asphalt pavement from the aspects of sustainability and economic benefit.

Typically, when a manufactured asphalt does not meet the climate, traffic, and pavement structure requirements, modifications are used to improve the asphalt properties (Kim 2008). Generally, polymers and fibers have been successfully used as alternative modifications (Rahnama 2009; Wu et al. 2008). Although the most popular bitumen modification technique is polymer modification, it has also been reported that fibers have also been used successfully as modifiers for asphalt (Airey 2004; Yildirim 2007). A literature review study demonstrated that various fibers have been used to improve the performance of asphalt pavements (Gibson and Li 2014). One of the earliest applications of fibers in asphalt mixtures was reported by Puzinauskas (1969) with natural asbestos fibers, which were found to demonstrate effectiveness in improving the low-temperature cracking properties of an asphalt mixture. A study conducted by the Federal Highway Administration (FHWA) investigated a synthetic fiber-reinforced asphalt mixture in the laboratory using full-scale accelerated pavement testing (Gibson et al. 2012). A polyester fiber–reinforced mix was placed in 1 of 12 test lanes in the FHWA's accelerated loading facility (ALF) trial study. Results showed that the fatigue cracking of the fiber-reinforced section was measurably better than that of the polymer-modified sections, even though unmodified asphalt binder was used in the mix.

Blends of polypropylene/aramid fibers have been used to improve the performance of asphalt mixtures. The asphalt mixtures had a nominal maximum aggregate size of 19 mm and used a Superpave performance grade (PG 70-10) asphalt binder for resistance against permanent deformation and fatigue cracking (Kaloush 2008). de S. Bueno et al. (2003) studied the addition of randomly distributed synthetic fibers containing both fibrillated fibers and slit-film fibers on the mechanical response of a cold-mixed, densely graded slow-curing cationic (SC-1C) type of emulsified asphalt mixture using the Marshall test, as well as static and cyclic triaxial tests. The results showed that the addition of fibers caused small variations in the mixture's triaxial shear strength parameters. Lee et al. (2005) evaluated the influence of recycled carpet fibers on the fatigue cracking resistance of asphalt concrete using fracture energy and reported that the increase in fracture energy represents potential for improving the fatigue life of asphalt.

Kaloush et al. (2010) undertook a study evaluating the material properties of conventional and fiber-reinforced asphalt mixtures using advanced material characterization tests, which included triaxial shear strength, dynamic modulus, repeated load permanent deformation, fatigue, crack propagation, and indirect tensile strength tests. Synthetic fibers were reported to improve performance in several ways against anticipated major pavement distresses, including permanent deformation, fatigue cracking, and thermal cracking, compared with a conventional mixture.

Fiber-reinforced asphalt concretes have been previously researched by several authors who reported its potential for improving the performance of asphalt concrete in terms of reducing permanent deformation and fatigue cracking (Alhozaimy et al. 1996; Choi and Yuan 2005; Kaloush and Zeiada 2012; Song et al. 2005; Xu et al. 2010; Yao et al. 2003). However, limited knowledge of this asphalt technology when using fiber reinforcement remains a primary barrier to its translation into practice for pavement construction projects in Thailand. In Thailand, the asphalt binders commonly used are AC60-70, NRMA, and PMA, and the preparation of asphalt concrete mixtures is based on the Marshall method due to insufficient information being available on the laboratory and/or field evaluation of the fiber reinforcement.

The objective of this research is to investigate the possibility of using fiber-reinforced asphalt as an alternative binder for enhancing the quality of conventional asphalt binder AC60/70 from sustainability and economical perspectives. A complete suite of pavement laboratory tests was conducted in this research to ascertain the viability of the fiber-reinforcement application for pavement construction. This research involves conducting a detailed laboratory investigation into the effects of fiber reinforcement (combination of polyolefin and aramid fibers) to improve the performance of asphalt concrete with different common asphalt binders. Three types of asphalt binders were studied: AC60/70, NRMA, and PMA. This research is significant because new knowledge is required for sustainable pavement design and practice in Thailand and other countries that use similar types of asphalt binders and aggregates. The results are fundamental for future research for the Superpave and Mechanical-Empirical Design methods, which are also used in other countries. The outcome from this research will significantly enable the development of construction guidelines for researchers, pavement engineers, and designers alike in assessing a suitable method of fiber-reinforced asphalt concrete in road construction.

Materials and Methods

Aggregate and Asphalt Binders

The aggregates and asphalt binders, including AC60/70, NRMA, and PMA, for asphalt concrete mixtures used in this study were characterized in accordance with the standards of the Department of Highways [DH-S204/2000 (DOH 2000)], Thailand. The physical properties of binders are summarized in Table 1. The laboratory tests performed to evaluate the properties of coarse aggregates for the wearing course are presented in Table 2. Fig. 1 presents the grading curves of the aggregate as well as the upper and lower limits of the DOH specifications. The aggregate was a basalt-type rock obtained from Nakhon Ratchasima Province, Thailand. The mineral components and chemical compositions of the aggregates were examined by X-ray diffraction (XRD) and X-ray fluorescence (XRF) analyses. XRD and XRF results indicated that the main mineral components of aggregate were dolomite and calcite, and the dominant chemical components were CaO (85.6%) and MgO (13.50%). This finding is consistent with the result reported previously by Siriphun et al. (2016). Aggregates form the major structural framework of asphalt mixtures that absorb and control different stresses on the pavement (Golalipour et al. 2012).

Table 1. Basic physical characteristics of binders

Characteristic	AC60/70	NRMA	PMA
Penetration (25°C)	69	52	55
Flash point (°C)	292	274	315
Elastic recovery (%)	25	52.5	92.5
Softening point (°C)	47.8	57.6	76.3
Ductility (5 cm/min)	105	116	128
Specific gravity (g/cm^3)	1.03	1.00	1.02

Table 2. Properties of the aggregate and JMF for AC60/70, NRMA, and PMA

	AC60/70		NRMA		PMA	
Property	Criterion	Results	Criterion	Results	Criterion	Results
Flakiness index (%)	35 maximum	33	35 maximum	27	35 maximum	32
Elongation index (%)	35 maximum	13	35 maximum	21	35 maximum	23
Asphalt absorption (%)	N/A	0.25	N/A	0.25	N/A	0.25
Los Angeles abrasion (%)	40 maximum	22.7	35 maximum	26.2	35 maximum	21.5
Soundness (%) coarse/fine	9 maximum	1.0/3.2	9 maximum	2.4/5.4	9 maximum	1.0/3.0
Sand equivalent (%)	50 minimum	64	60 minimum	64	60 minimum	66
Asphalt content (%)	5.0 ± 0.3	5.0	5.1 ± 0.3	5.1	5.0 ± 0.3	5.0
Marshall density (g/cL)	2.40–2.42	2.418	2.38–2.40	2.393	2.36–2.38	2.369
Marshall air voids (%)	3.40–4.80	4.0	3.40–4.90	4.2	3.4–4.6	4.0
Strength index (%)	75 minimum	78.1	75 minimum	75.8	75 minimum	80.9
Aggregate crushing value (%)	—	—	25 maximum	21.9	25 maximum	20.2
Aggregate impact value (%)	—	—	25 maximum	18.1	25 maximum	17.8
Polished stone value (%)	—	—	—	—	47 maximum	51.1

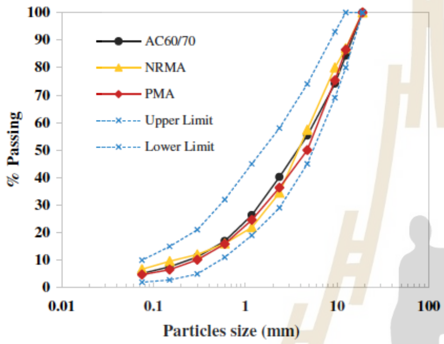


Fig. 1. Grain-size distributions of aggregates used in asphalt mixtures.

Fiber Properties

The fibers used in this study were a blend of synthetic fibers designed for use in HMA applications. The proprietary blend consisted of polyolefin and aramid fibers. Fig. 2 shows a photograph of fibers and the microstructural characteristics of fiber-reinforced asphalt captured by scanning electron microscopy (SEM) analysis. Fig. 2(a) shows the aramid and polyolefin fibers. Aramid fibers with a high decomposition temperature are a class of heat-resistant and strong synthetic fibers that exhibit good resistance to abrasion and organic solvents. Aramids share a high degree of orientation and good fabric integrity with polyolefin fibers. Use of the aramids and polyolefin fibers is also economically beneficial due to the low cost of polyolefin fibers. The fibers were designed to reinforce the HMA in three-dimensional orientations. Table 3 provides the main physical properties of both fibers. The decomposition temperature or melting point of polyolefin and aramid fibers is 130 and 450°C, respectively. The mixture of aramid and polyolefin fiber has a high degree of orientation and good fabric integrity, as shown in Fig. 2(a). Figs. 2(b and c) show that the aramid fiber in the asphalt mixture did not melt during the mixing process of HMA, which confirm that the fiber-reinforcement has a high heat resistance.

Mixture Design and Sample Preparation

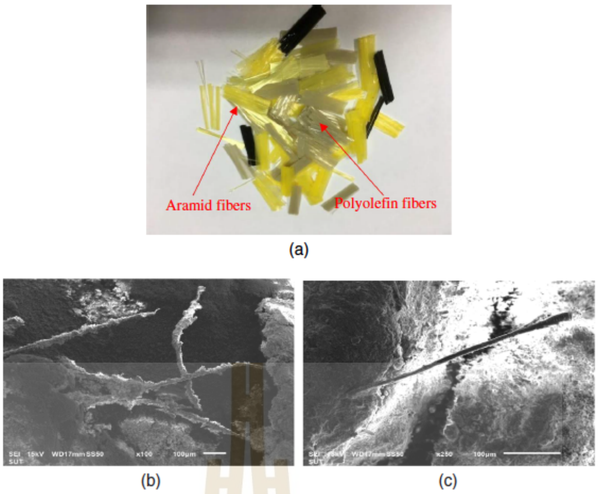
The experimental work in this study started with a mix design to establish the job mix formula (JMF) and the appropriate constituents of the asphalt concrete mixtures, based on the Marshall mix design method and in accordance with DOH specifications [DH-S 408/2532 (DOH 1989)]. The JMF for this study is summarized in Table 2.

The test specimens were prepared based on the JMFs for the asphalt concrete. Aggregates were heated at 180–190°C to facilitate the mixing temperature, and fibers were then mixed with aggregates under dry conditions for a duration of 10 s. The polyolefin fiber melts during the mixing process, and its melting compound improves the chemical and physical properties of asphalt binder, which has been illustrated by Kaloush (2008). The fiber content (40% aramid fiber and 60% polyolefin fiber) was fixed at 0.05% of the total mass of mixture for mixture design, as recommended by the manufacturers (Waleed and Shane 2014). Asphalt binders heated to 160°C were then added into the fiber–aggregate mixtures and mixed thoroughly to obtain well-coated and evenly distributed mixtures. Subsequently, the hot mixtures were placed in a steel mold (101.6 mm in diameter and 63.5 mm in height) and compacted under 75 blows on each side at 150°C for AC60/70 and 170°C for NRMA and PMA to attain a Marshall specimen in accordance with the DOH specification.

Performance Tests

Stability and Flow

The Marshall stability was measured using the Marshall apparatus in accordance with ASTM D1559-89 (ASTM 1989). This method covers the measurement of resistance to plastic flow of cylindrical specimens of asphalt concrete bituminous paving mixture loaded on the lateral surface by means of the Marshall apparatus. The cylindrical mold was 101.6 mm in diameter and 76.2 mm in height. The average values of Marshall stability and flow from each asphalt concrete mixture were obtained by testing triplicate samples to ensure data consistency. In the test, compressive loading was applied to the specimen at a rate of 50.8 mm/min until it was broken. The maximum loading at failure is the Marshall stability, and the associated plastic flow (deformation) of the specimen is the flow value.



(a)

(b) (c)

Fig. 2. (a) Fibers used; and SEM images at (b) 100 times; and (c) 250 times of a loose asphalt mixture with fiber reinforcement.

Table 3. Physical characteristics of the fibers

Characteristic	Polyolefin	Aramid
Specific gravity	0.91	1.45
Tensile strength (MPa)	>483	>2,750
Length (mm)	19.0	19.0
Color	Tan	Yellow
Acid/alkali resistance	Inert	Good
Decomposition temperature (melting point) (°C)	130	>450

Indirect Tensile Strength

The indirect tensile strength (ITS) test was carried out in accordance with ASTM D6931-17 (ASTM 2017). The ITS value of the asphalt mixture was determined by loading a cylindrical specimen across its vertical diametrical plane at a 50.8 mm/min rate of deformation at 20°C. The peak load at failure was recorded and used to calculate the ITS of the specimens as shown in Eq. (1)

$$\mathrm{ITS} = \frac{2P}{\pi DT} \tag{1}$$

where P = peak value of the applied vertical load (kN); T = mean thickness of the test specimen (m), and D = specimen diameter (m). The values of T and D were 63.5 and 101.6 mm, respectively. The ITS results were used to evaluate the relative quality of asphalt mixtures as well as estimating the potential for rutting or cracking.

Resilient Modulus

Resilient modulus (M_R) is a relative measurement of the mixture stiffness and load distribution ability; higher M_R values lead to stiffer mixtures with higher load-distribution ability. The M_R was determined on cylindrical specimens (101.6 mm in diameter and 63.5 mm in height) for each mixture at designed asphalt contents in the indirect tension mode, which was conducted at 35°C. The test was carried out using a universal testing machine (UTM) in accordance with ASTM D4123-82 (ASTM 1995) and AASHTO TP31-94 (AASHTO 1994), and the M_R in MPa was calculated using the following equation:

$$M_R = \frac{P(0.27 + \nu)}{HD} \tag{2}$$

where P = peak value of the applied vertical load (N); H = mean amplitude of the horizontal deformation obtained from last five applications of the load pulse (mm); D = mean thickness of the specimen (mm); and υ = Poisson's ratio.

M_R represents the cyclic pavement response in terms of dynamic stresses and their relation to recoverable strains. Indirect tensile strength from the previous test was used as reference load for this test. The M_R test used 15% of ITS for target peak pulse load. There were two perpendicular alignment loads applied on each sample. M_R was then measured by averaging the last five values when the test reached the first 150 cycles (Baburamani 1992). Four samples from each mix were placed in two positions for the diametrical M_R.

Indirect Tensile Stiffness Modulus

Stiffness modulus of asphalt concrete is a fundamental parameter used in pavement design models to evaluate pavement mixtures and in performance-based contracts related to pavement layers. The indirect tensile stiffness modulus (ITSM) test, defined in BS-EN-DD-213 (BSI 1993), is the most commonly used test method for determining the stiffness modulus of a specimen by using indirect tensile force. The target horizontal deformation was 0.005% of the specimen diameter, and the target load pulse rise time (time from start of load application to peak load) was 124 ms (equivalent to a frequency of 1.33 Hz). Poisson's ratio was assumed to be 0.40 at 35°C. The applied forces on the specimen as well as its conditioning pulses were then recorded automatically using software. These conditioning pulses were used to make the minor adjustments to the magnitude of the force, which were needed to generate the specified horizontal deformation and to seat the loading strips correctly on the specimen. Once the conditioning pulses were completed, the system applied five load pulses, which generated an indirect movement on the horizontal diameter. The stress and strain values as well as stiffness modulus of the specimen were then calculated.

Dynamic Creep Test

The dynamic creep test has been used to evaluate the deformation resistance (rutting susceptibility) of asphalt mixtures. The most popular dynamic creep test is the unconfined dynamic creep test, known as the repeated-load axial test (RLAT). The term creep test is used to indicate tests for assessing the permanent deformation resistance of asphalt mixtures. The development of plastic strains in the skeleton of an aggregate contributes significantly to permanent deformation. The effect of this form of loading in inducing plastic strains had already been recognized by Goetz et al. (1957).

The RLAT is increasingly used in preference to the uniaxial creep (UC) test because the pulsed load is a more accurate simulation of traffic loading. The specimen was subjected to repeated load pulses of 1-s duration separated by 1-s rest periods (up to 10,000 pulses). An optional pretest conditioning period (ranging from 0 to 60 min) is available.

The cumulative permanent deformation as a function of load applications (pulses) was recorded and correlated to the rutting potential of asphalt mixtures. Tests can be run at different temperatures and varying loads. A dynamic creep test was conducted by applying a dynamic load to a HMA specimen and then measuring the specimen's permanent deformation by LVDTs after unloading. A high value of permanent deformation may correlate to higher rutting potential.

The loading conditions were selected in order to evaluate the relative performance of different asphalt concrete mixtures in accordance with BS-DD-226 (BSI 1996) for determining the resistance of bituminous mixtures to permanent deformation. Standard test conditions and requirements for the dynamic creep test were

- conditioning stress: 10 kPa,
- conditioning period: 30 s,
- test stress: 120 kPa,
- test duration: 10,000 pulses,
- test cycle: square wave, and
- test temperature: 40°C.

Indirect Tensile Fatigue Test

In order to fully characterize the studied asphalt mixtures, the determination of fatigue properties is also required to identity the long-term performance of the asphalt concrete. The indirect tensile fatigue test (ITFT) was performed in accordance with BS-EN-12697-24 (BSI 2004a) by using a repeated controlled stress pulse to damage the specimen, and the accumulation of vertical deformation against a number of load pulses was plotted. The load was applied through a 12.5-mm-wide stainless-steel curved loading strip.

A haversine loading pulse with a frequency of 10 Hz, approximately equivalent to a vehicle speed of 80 km/h, was used. The loading period of the pulse, 0.1 s, was followed by a rest period of 0.9 s. The Poisson's ratio was assumed to be 0.35 at 25°C. The tests were performed in an environmental chamber at 25°C. The results were an average of four samples. Standard test conditions and requirements for the ITFT test were

- target test stress: 300 kPa,
- target rise time: 125 ms,
- failure criteria: 9-mm vertical deformation, and
- test temperature: 25°C.

In order to determine the strength of HMA against fatigue cracks induced by repeated loads, samples from the six mixtures were tested diametrally under repeated pulsed uniaxial loading to determine the number of loading cycles required to fail the samples.

Wheel-Tracking Test (Rutting Resistance)

The permanent deformation (rutting) of asphalt pavements has an important impact on the performance of the pavements during their lifetimes. When a load is applied to the surface of an asphalt pavement, it deforms, and a variable amount of irreversible deformation remains in the asphalt mixtures, resulting in a very small permanent residual strain. Hence, accumulations of millions of these strains due to repeated axle loadings result in surface rutting (Alataş et al. 2012; Moghaddam et al. 2014). Rutting develops gradually as the number of load applications increase and appears as longitudinal depressions in the wheel paths and small upheavals to the sides (Brovelli et al. 2015).

The wheel-tracking test was carried out using a moving wheel in the laboratory to reproduce the field condition and to represent the passage of vehicles along the surface of the pavement asphalt. The rutting tests were performed in accordance with British and European standard BS-EN-12697-22 (BSI 2004) at 60°C in order to determine the resistance of the asphalt mixtures to permanent deformation, namely rutting resistance of the asphalt mixtures. The test slab specimens were prepared in the laboratory using a roller compactor in accordance with British and European standard BS-EN-12697-33 (BSI 2004b). The rut depth after a specified number of wheel passes, namely 1,000, 3,000, and 10,000 loading cycles, was measured, and the average of at least 15 values was the representative rut depth of the bituminous mixtures tested.

Results and Discussion

Fig. 3 shows the Marshall stability results of asphalt mixtures with different asphalt binders. The modified asphalt mixtures (NRMA and PMA) exhibit better resistance to plastic flow than the conventional AC60/70. The Marshall stability values of NRMA and PMA were 15.6 and 34.6% higher than that of AC60/70, respectively. It is interesting that the Marshall stability of the conventional AC60/70 can be improved significantly by fiber reinforcement. The Marshall stability value of AC60/70 + Fiber was increased by 13.7% compared with the conventional AC60/70, and this value is comparable to the NRMA binder (without fiber).

The Marshall stability of NRMA and PMA can also be improved by fiber reinforcement. The Marshall stability values of NRMA + Fiber and PMA + Fiber were increased by 18.4 and 17.9%, respectively, compared with the mixtures without fiber reinforcement. The Marshall stability value of NRMA + Fiber was slightly higher than that of PMA (without fiber), whereas PMA + Fiber exhibited the highest Marshall stability value. This finding is similar to previous research showing that the use of polypropylene fibers could notably increase the Marshall stability of HMA (Tapkın 2008).

Fig. 4 shows the ITS results of studied asphalt mixtures with and without fiber reinforcement. NRMA and PMA had greater tensile resistance than the conventional AC60/70. Similar to the Marshall stability results, the PMA exhibited the highest ITS value, followed by NRMA and AC60/70, respectively. The ITS values of NRMA and PMA were 9.4 and 22.8% higher than that of AC60/70.

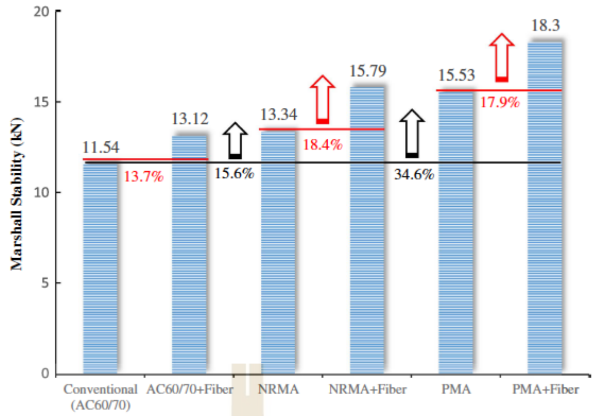


Fig. 3. Marshall stability test results.

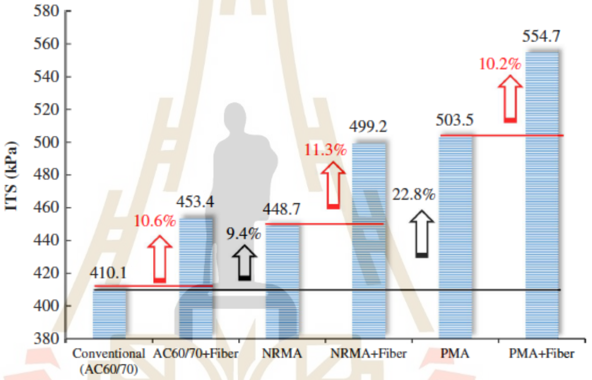


Fig. 4. Indirect tensile strength test results.

ITS values of all mixtures were improved significantly by fiber reinforcement, i.e., all mixtures with fiber reinforcement produced consistently higher ITS values compared with mixtures without fibers. The ITS values of AC60/70 + Fiber, NRMA + Fiber, and PMA + Fiber were increased by 10.6, 11.3, and 10.2%, respectively, compared with those without fiber reinforcement. As evident in Fig. 4, the ITS value of AC60/70 + Fiber was slightly higher than that of NRMA without fiber reinforcement, and the ITS value of NRMA + Fiber was as high as PMA (without fiber). This can be attributed to the strong mechanical bonding between the fibers and mastic of the asphalt binder to increase the tensile strength of the HMA mixture (Bonica et al. 2016).

The resilient modulus (M_R) values of all studied mixtures are summarized in Fig. 5. Both NRMA and PMA exhibited greater M_R than the AC60/70. The M_R values of NRMA and PMA were 29.8 and 38.4% higher than M_R value of AC60/70, respectively. The noticeable effect of improvement by fiber reinforcement on the M_R of the studied mixtures was observed in that the M_R values of AC60/70 + Fiber, NRMA + Fiber, and PMA + Fiber were 35.6, 27.8, and 28.4% higher than those of AC60/70, NRMA, and PMA without fiber, respectively. The M_R value of AC60/70 + Fiber was comparable to both NRMA and PMA. Lavasani et al. (2015) reported that the fibers could increase the adherence of aggregate and asphalt, and hence produce the higher deformation resistance and M_R of asphalt concrete.

Fig. 6 shows the indirect tensile stiffness modulus (ITSM) of all studied mixtures. Similarly, the ITSM results indicated that the NRMA and PMA had higher ITSM than the AC60/70. The ITSM values of NRMA and PMA were 30.0 and 54.9%, higher than the value of AC60/70, respectively. Improvement of ITSM of AC60/70, NRMA, and PMA was obviously observed with use of the fiber reinforcement in that the ITSM values of AC60/70 + Fiber,

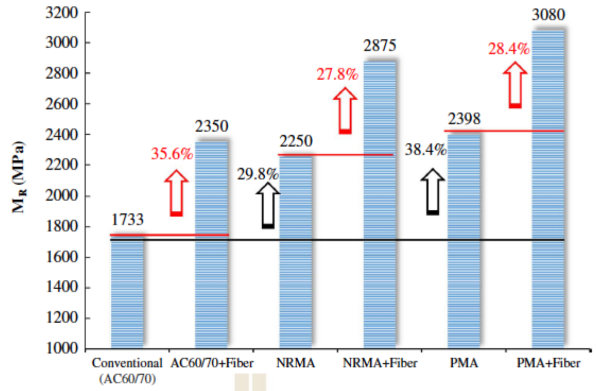


Fig. 5. Resilient modulus test results.

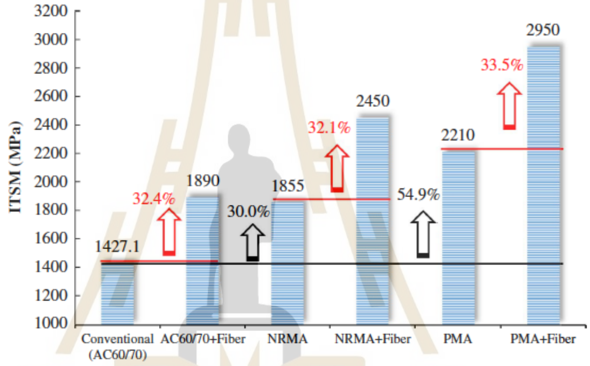


Fig. 6. Indirect tensile stiffness modulus test results.

NRMA + Fiber, and PMA + Fiber were increased by 32.4, 32.1, and 33.5%, respectively, compared with the mixtures without fiber reinforcement. It is evident that the ITSM of AC60/70 + Fiber was comparable with that of NRMA (without fiber).

Dynamic creep testing is known as a highly reliable test to predict permanent deformation susceptibility of asphalt mixtures, and its results are displayed in Fig. 7. Fig. 7(a) shows the axial strains of all studied mixtures. The NRMA and PMA had lower axial strain than the conventional AC60/70. The axial strain of AC60/70 + Fiber, NRMA + Fiber, and PMA + Fiber was decreased by 23.7, 21.4, and 23.3% when compared with the mixtures without fiber reinforcement, respectively. Fig. 7(b) shows the relationship between accumulated permanent deformation (μ strain) versus the number of load cycles for the mixtures. The NRMA and PMA had higher resistance to permanent deformation than AC60/70 for the same number of load cycles. Furthermore, the accumulation of permanent strain of the studies mixtures was decreased when the fibers were added.

Fig. 8 shows a relationship between axial deformation versus the logarithm of number of applied load repetitions until failure under the indirect tensile fatigue test. Fatigue life is defined as the intersection of small axial deformation portion and large axial strain deformation portion. The fatigue life for each mixture is also presented in Fig. 8. The results imply that mixtures containing fibers had longer fatigue life than that mixtures without fibers. Based on the test results, the fatigue life of fiber-reinforced asphalt mixtures increased by 36.9, 29.4, and 38.3% for the AC60/70, NRMA, and PMA mixtures, respectively. The highest fatigue life was found for PMA+Fiber.

The rut depth after a specified number of wheel passes, namely 1,000, 3,000, and 10,000 loading cycles from a wheel-tracker test, was measured and is summarized in Fig. 9. The test slab specimens containing fibers exhibited smaller rutting depth (RD) compared with specimens without fibers. This rutting depth is directly related to the permanent deformation. The rutting resistance increased by 34.4, 31.0, and 35.4% at 10,000 loading cycles for AC60/70,

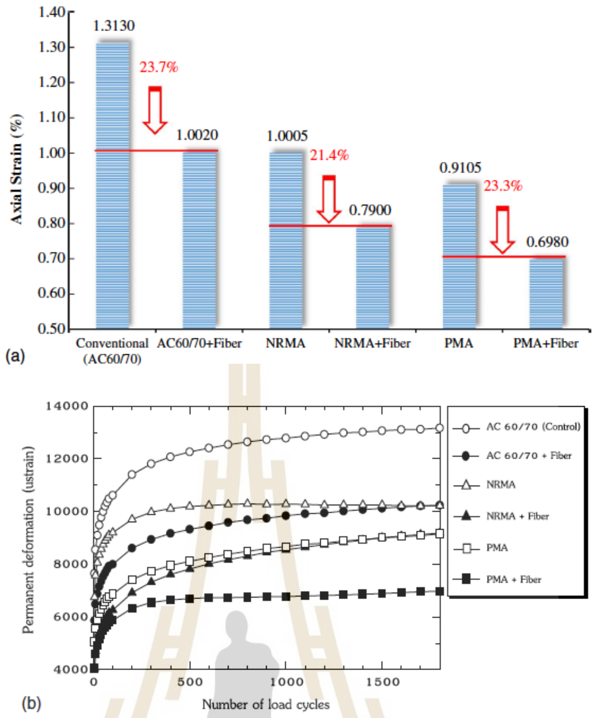


Fig. 7. Dynamic creep test results: (a) axial strain (strain rate); and (b) permanent deformation (μ strain).

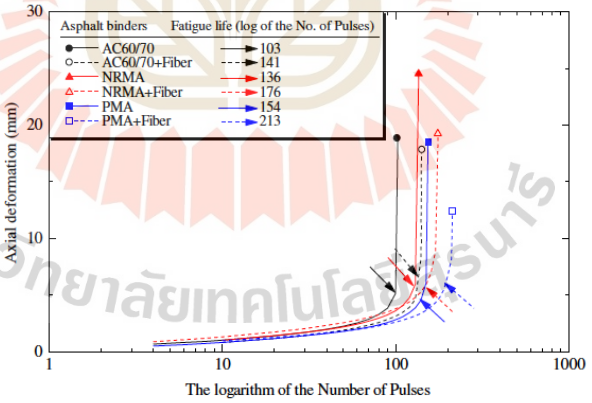


Fig. 8. Fatigue life of the six asphalt mixtures.

J. Mater. Civ. Eng., 2018, 30(8): 04018193

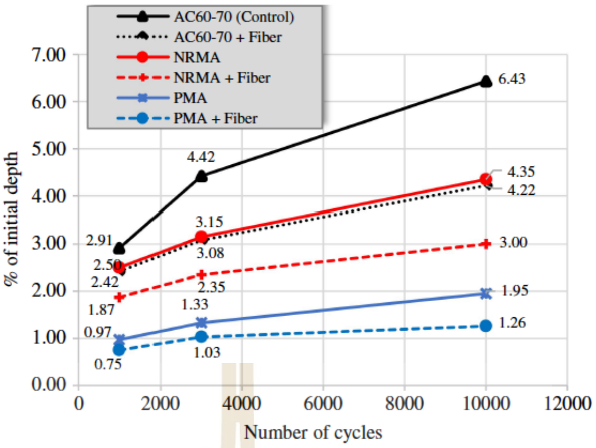


Fig. 9. Pavement rutting test results.

NRMA, and PMA mixtures with fibers compared with those without fibers.

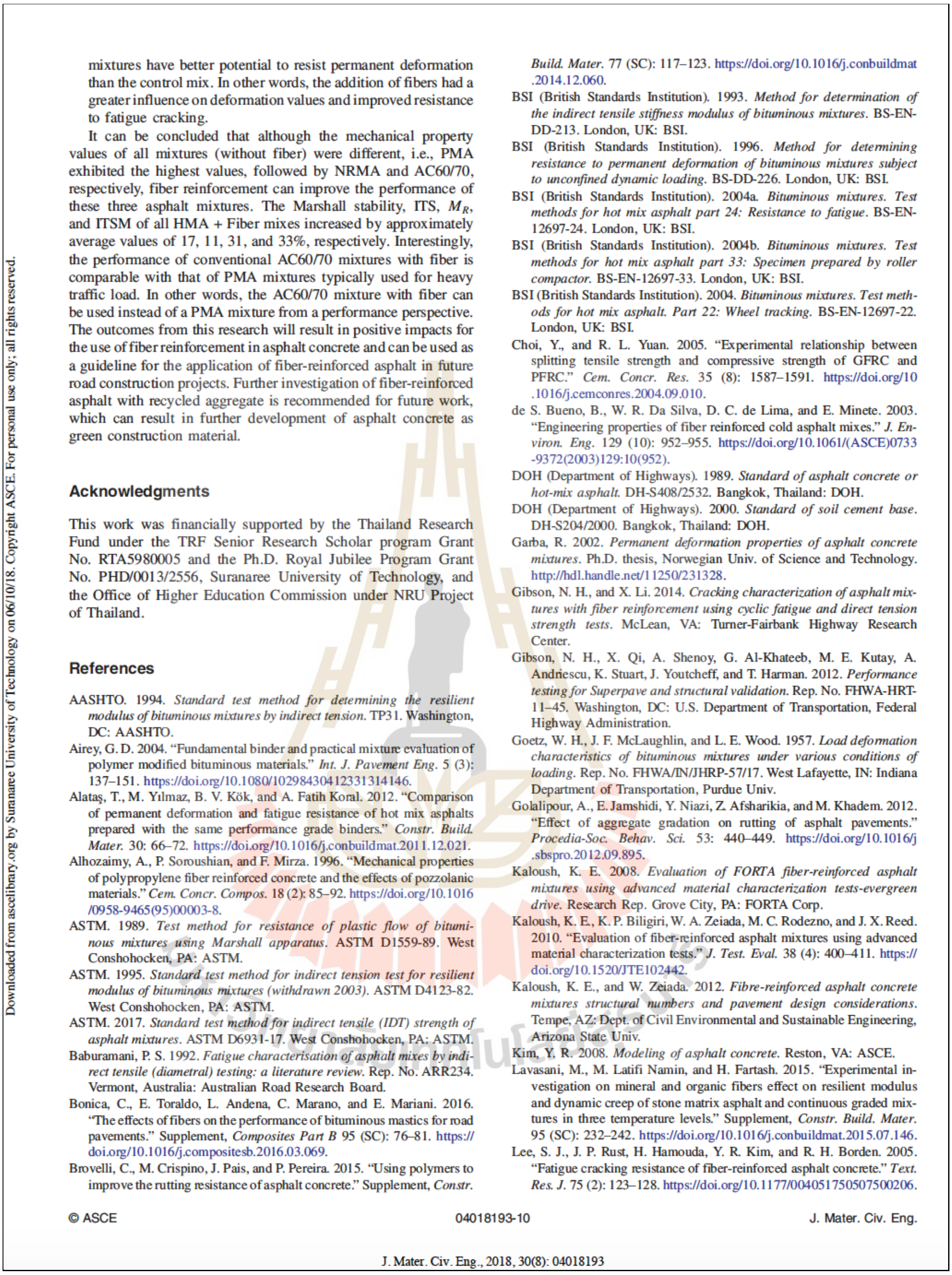
To evaluate the effect of fibers on the properties of asphalt concrete with different binders, a complete suite of laboratory tests was conducted and its results compared with those of virgin unreinforced asphalt. The laboratory performance test results confirmed that an addition of fibers (0.05% by total mass of mixture) to the three asphalt concrete mixtures typically used in Thailand had positive impacts on performance, including Marshall stability, indirect tensile strength, resilient modulus, stiffness modulus, permanent deformation, fatigue life, and pavement rutting resistance. It is interesting that fiber reinforcement can enhance the Marshall stability, ITS, M_R, and ITSM values of all fiber-reinforced mixtures, and the percentage increases were almost similar for the different fiber-reinforced mixtures. The Marshall stability, ITS, M_R, and ITSM of all mixtures with fiber reinforcement increased by average values of approximately 17, 11, 31, and 33%, respectively. As such, the Marshall stability, ITS, M_R, and ITSM of reinforced AC60/70, NRMA, and PMA can be predicted once the values of unreinforced AC60/70, NRMA, and PMA are determined.

This finding has important practical implications for the design of high-performance asphalt pavements, and this technique can also be applied to other types of asphalts manufactured by the hot-mix asphalt method, in which a combination of approximately 95% heated coarse and fine aggregates are bound together by heated asphalt binders with fiber reinforcement. The improved performance of the fiber-reinforced asphalt indicated enhancement of its stiffness and provided good resistance against permanent deformation and fatigue cracking at high traffic volumes. This results in the possibility of extending the service life of asphalt concretes. This research broadens the applications of fiber-reinforced asphalt as an alternative pavement asphalt concrete, which can provide the economical and sustainable advantages for highway construction work. The use of fiber-reinforced asphalt concrete with the incorporation of other recycled and/or waste aggregates will furthermore result in alleviating environmental issues associated with the current practice of landfilling all wastes (Mohajerani et al. 2017; Paranavithana and Mohajerani 2006).

Conclusions

The performance of fiber-reinforced asphalt concrete was evaluated with different asphalt binders. The fibers used in this research were a mixture of polyolefin and aramid fibers. The performance of the fiber-reinforced mixtures was compared with that of mixtures without fiber (control mix). Based on the performance tests, the results indicated that the fibers improved the performance of the mixtures in several unique ways:

- Additionof fibers (0.05% by mass of total mixture) to asphalt concrete mixtures considerably improved the Marshall stability, indirect tensile strength, resilient modulus, stiffness modulus, permanent deformation, fatigue life, and pavement rutting resistance.
- Modified asphalt mixtures (NRMA and PMA) exhibited better resistance to plastic flow than the conventional mixture (AC60/70). It is very interesting that the Marshall stability of the conventional AC60/70, NRMA, and PMA can be improved significantly by the fiber reinforcement.
- Fiber-reinforced asphalt concrete mixtures showed higher tensile strength compared with the control mix. All mixtures with fibers exhibited consistently higher ITS compared with the mixtures without fibers. The ITS values of AC60/70 + Fiber, NRMA + Fiber, and PMA + Fiber were increased notably compared with those without fibers.
- A noticeable positive effect of fiber reinforcement on the resilient modulus (M_R) of the studied mixtures was observed, which indicated that the M_R value of all mixtures without fiber can be improved significantly by fiber reinforcement in that the M_R value of AC60/70 + fiber, NRMA + Fiber, and PMA + Fiber was demonstrably much higher than that of HMA without fiber.
- Improvement in stiffness modulus of AC60/70, NRMA, and PMA was observed with use of the fiber reinforcement, by which the stiffness modulus values of AC60/70 + Fiber, NRMA + Fiber, and PMA + Fiber were increased dramatically compared with the mixtures without fiber reinforcement.
- Fiber-reinforced mixtures had higher recoverable deformation than the control mix. This indicates that fiber-reinforced



mixtures have better potential to resist permanent deformation than the control mix. In other words, the addition of fibers had a greater influence on deformation values and improved resistance to fatigue cracking.

It can be concluded that although the mechanical property values of all mixtures (without fiber) were different, i.e., PMA exhibited the highest values, followed by NRMA and AC60/70, respectively, fiber reinforcement can improve the performance of these three asphalt mixtures. The Marshall stability, ITS, M_R, and ITSM of all HMA + Fiber mixes increased by approximately average values of 17, 11, 31, and 33%, respectively. Interestingly, the performance of conventional AC60/70 mixtures with fiber is comparable with that of PMA mixtures typically used for heavy traffic load. In other words, the AC60/70 mixture with fiber can be used instead of a PMA mixture from a performance perspective. The outcomes from this research will result in positive impacts for the use of fiber reinforcement in asphalt concrete and can be used as a guideline for the application of fiber-reinforced asphalt in future road construction projects. Further investigation of fiber-reinforced asphalt with recycled aggregate is recommended for future work, which can result in further development of asphalt concrete as green construction material.

Acknowledgments

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BIOGRAPHY

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