UTILIZATION OF RECYCLED POLYETHYLENE TEREPHTHALATE AND RECYCLED POLYPROPYLENE PLASTICS IN SUSTAINABLE ASPHALT CONCRETE PAVEMENT

KONGSAK AKKHARAWONGWHATTHANA

A Thesis Submitted in Partial Fulfillment of the Requirements for the
Degree of Doctor of Philosophy in Civil Engineering
and Construction Management
Suranaree University of Technology
Academic Year 2024

การประยุกต์ใช้พลาสติกรีไซเคิลประเภทโพลิเอทิลีนเทเรฟทาเลตและโพลิโพรไพลีนในงานผิวทางแอสฟัลต์คอนกรีตอย่างยั่งยืน

นายคงศักดิ์ อัครวงศ์วัฒนา

วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรปริญญาปรัชญาดุษฎีบัณฑิต
สาขาวิชาวิศวกรรมโยธาและการบริหารงานก่อสร้าง
มหาวิทยาลัยเทคโนโลยีสุรนารี
ปีการศึกษา 2567

UTILIZATION OF RECYCLED POLYETHYLENE TEREPHTHALATE AND RECYCLED POLYPROPYLENE PLASTICS IN SUSTAINABLE ASPHALT CONCRETE PAVEMENT

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

Thesis Examining Committee

....

(Prof. Dr. Panich Voottipruex)

Chairperson

....

(Prof. Dr. Suksun Horpibulsuk)

Member (Thesis Advisor)

....

(Dr. Apichat Suddeepong)

Member (Thesis Co-Advisor)

....

(Prof. Dr. Avirut Chinkulkijniwat)

Member

....

(Assoc. Prof. Dr. Menglim Hoy)

Member

....

(Dr. Teerasak Yoawarat)

Member

....

(Dr. Apinun Buritatum)

Member

....

(Assoc. Prof. Dr. Yupaporn Ruksakulpiwat)

Vice Rector for Academic Affairs and Quality Assurance

....

(Assoc. Prof. Dr. Pornsiri Jongkol)

Dean of Institute of Engineering

คงศักดิ์ อัครวงศ์วัฒนา : การประยุกต์ใช้พลาสติกรีไซเคิลประเภทโพลิเอทิลีนเทเรฟทาเลต และโพลิโพรไพลีนในงานผิวทางแอสฟัลต์คอนกรีตอย่างยั่งยืน (UTILIZATION OF RECYCLED POLYETHYLENE TEREPHTHALATE AND RECYCLED POLYPROPYLENE PLASTICS IN SUSTAINABLE ASPHALT CONCRETE PAVEMENT)
อาจารย์ที่ปรึกษา : ศาสตราจารย์ ดร.สุขสันติ์ หอพิบูลสุข, 140 หน้า

คำสำคัญ: เศษผิวทางแอสฟัลต์คอนกรีตรีไซเคิล/เศษคอนกรีตรีไซเคิล/พลาสติกประเภทพอลิเอทิลีนเทเรฟทาเลต/พลาสติกประเภทโพลีโพพีลิน

หลายประเทศทั่วโลกรวมทั้งประเทศไทยมีการนำวัสดุเหลือทิ้งรีไซเคิลประเภทต่าง ๆ เช่น เศษผิวทางแอสฟัลต์คอนกรีตรีไซเคิล (Reclaimed asphalt concrete pavement, RAP) เศษคอนกรีตรีไซเคิล (Recycled concrete aggregate, RCA) และเศษพลาสติกมาใช้เป็นส่วนผสมของผิวทางแอสฟัลต์คอนกรีต ช่วยลดการใช้ทรัพยากรธรรมชาติและลดต้นทุนการก่อสร้างถนน อย่างไรก็ตาม การใช้งานวัสดุเหล่านี้ในส่วนผสมของแอสฟัลต์คอนกรีตยังถูกจำกัดให้ใช้ได้ในปริมาณที่ต่ำเนื่องจากเป็นวัสดุที่มีสมบัติทางวิศวกรรมด้อยกว่าวัสดุจากธรรมชาติ งานวิจัยนี้มีวัตถุประสงค์ที่จะศึกษาความเป็นไปได้ในการใช้ RAP และ RCA เป็นมวลรวมในส่วนผสมแอสฟัลต์คอนกรีตทั้งหมดโดยไม่ใช้มวลรวมธรรมชาติ ร่วมกับการปรับปรุงสมรรถนะของแอสฟัลต์คอนกรีตด้วยเศษขวดพลาสติกประเภทโพลิเอทิลีนเทเรฟทาเลต (Polyethylene terephthalate, PET) และศึกษาความเป็นไปได้ในการนำขยะพลาสติกประเภทโพลิโพรพิลีน (Polypropylene, PP) ที่ถูกหลอมขึ้นรูปเป็นเม็ดมาปรับปรุงแอสฟัลต์ซีเมนต์ประเภท AC60/70 เพื่อใช้เป็นส่วนผสมพอรัสแอสฟัลต์คอนกรีต สมรรถนะเชิงกลของแอสฟัลต์คอนกรีตทั้งแบบสถิตและพลวัตถูกประเมินผ่านการทดสอบเสถียรภาพ ดัชนีความแข็งแรง กำลังดึงทางอ้อม โมดูลัสคืนตัวเนื่องจากแรงดึงทางอ้อม การล้าเนื่องจากแรงดึงทางอ้อม และความต้านทานการเกิดร่องล้อ งานวิจัยนี้แบ่งการดำเนินงานออกเป็น 3 ส่วน ได้แก่ ส่วนที่ 1 การศึกษาการใช้เศษขวด PET ปรับปรุงแอสฟัลต์คอนกรีตที่ใช้ RAP เป็นมวลรวมทั้งหมด ส่วนที่ 2 ศึกษาการใช้ RAP และ RCA เป็นมวลรวม และปรับปรุงด้วยเศษขวด PET และส่วนที่ 3 ศึกษาการใช้ PP ปรับปรุงแอสฟัลต์ซีเมนต์ AC60/70 เพื่อใช้เป็นส่วนผสมพอรัสแอสฟัลต์คอนกรีต

ส่วนที่ 1 ศึกษาสมรรถนะเชิงกลของแอสฟัลต์คอนกรีตที่ใช้ RAP เป็นมวลรวมถูกประเมินในพจน์ของปริมาณเศษขวด PET ร้อยละ 0.0 0.2 0.4 0.6 0.8 และ 1.0 โดยน้ำหนักมวลรวม แอสฟัลต์คอนกรีตที่ใช้ RAP เป็นมวลรวมมีค่าดัชนีความแข็งแรงไม่ผ่านตามมาตรฐานกรมทางหลวง การเติมเศษขวด PET ลงในส่วนผสมแอสฟัลต์คอนกรีตช่วยให้แอสฟัลต์คอนกรีตที่ใช้ RAP เป็นมวลรวมมีสมบัติผ่านตามมาตรฐานและยังช่วยให้สมรรถนะเชิงกลมีค่าสูงขึ้น ปริมาณเศษขวด PET ที่เหมาะสมร้อยละ 0.6 ช่วยให้สมรรถนะเชิงกลของแอสฟัลต์คอนกรีตที่ใช้ RAP เป็นมวลรวมเพิ่มขึ้นสูงที่สุด โดย

ค่าเสถียรภาพเพิ่มขึ้นร้อยละ 25 ดัชนีความแข็งแรงเพิ่มขึ้นร้อยละ 19 กำลังดึงทางอ้อมเพิ่มขึ้นร้อยละ 69 โมดูลัสคืนตัวเนื่องจากแรงดึงทางอ้อมเพิ่มขึ้นร้อยละ 11 อายุการล้าเพิ่มขึ้นร้อยละ 270 และความต้านทานการเกิดร่องล้อเพิ่มขึ้นร้อยละ 80 เมื่อเปรียบเทียบกับแอสฟัลต์คอนกรีตที่ใช้ RAP เป็นมวลรวมที่ไม่ถูกปรับปรุงด้วย PET

ส่วนที่ 2 ศึกษาสมรรถนะเชิงกลของแอสฟัลต์คอนกรีตถูกประเมินในพจน์ของอัตราส่วน RAP/RCA เท่ากับ 100/0 90/10 80/20 และ 60/40 และในพจน์ของปริมาณเศษขวด PET ร้อยละ 0.0 0.2 0.4 0.6 0.8 และ 1.0 โดยน้ำหนักมวลรวม การแทนที่มวลรวมหยาบของ RAP ด้วย RCA ส่งผลให้สมบัติของแอสฟัลต์คอนกรีตผ่านตามมาตรฐานกรมทางหลวงและยังช่วยเพิ่มสมรรถนะเชิงกลของแอสฟัลต์คอนกรีต ที่ปริมาณเศษขวด PET ค่าเดียวกันแอสฟัลต์คอนกรีตที่ใช้อัตราส่วน RAP/RCA เท่ากับ 80/20 มีสมรรถนะเชิงกลสูงที่สุด นอกจากนี้ การใช้เศษขวด PET ปรับปรุงแอสฟัลต์คอนกรีตที่ใช้ RAP และ RCA เป็นมวลรวมส่งผลให้สมรรถนะเชิงกลเพิ่มขึ้นในทุกอัตราส่วน RAP/RCA โดยเศษขวด PET ปริมาณร้อยละ 0.6 ทำให้แอสฟัลต์คอนกรีตใช้ RAP และ RCA เป็นมวลรวมมีสมรรถนะเชิงกลสูงที่สุด

ส่วนที่ 3 แอสฟัลต์ซีเมนต์ AC60/70 ถูกปรับปรุงด้วย PP ร้อยละ 0 2 4 และ 6 โดยน้ำหนักของแอสฟัลต์ซีเมนต์ และแอสฟัลต์ซีเมนต์ที่ถูกปรับปรุงด้วย PP ถูกประเมินผ่านการทดสอบสมรรถนะเชิงกลของพอรัสแอสฟัลต์คอนกรีต แอสฟัลต์ซีเมนต์ AC60/70 ปรับปรุงด้วย PP ร้อยละ 2 มีสมบัติเป็นไปตามข้อกำหนดของมาตรฐานแอสฟัลต์ซีเมนต์ AC40/50 ที่กำหนดโดยมาตรฐานผลิตภัณฑ์อุตสาหกรรม โดยพอรัสแอสฟัลต์คอนกรีตที่ใช้แอสฟัลต์ซีเมนต์ AC60/70 ปรับปรุงด้วย PP ร้อยละ 2 มีสมรรถนะเชิงกลสูงที่สุด อย่างไรก็ตาม เมื่อเปรียบเทียบกับพอรัสแอสฟัลต์คอนกรีตที่ใช้แอสฟัลต์ซีเมนต์ PMA พอรัสแอสฟัลต์คอนกรีตที่ใช้แอสฟัลต์ซีเมนต์ปรับปรุงด้วย PP ร้อยละ 2 มีสมรรถนะเชิลกลต่ำกว่า งานวิจัยนี้จะช่วยปูทางสำหรับการพัฒนาวัสดุทางเลือกสำหรับใช้เป็นส่วนผสมของผิวทางแอสฟัลต์คอนกรีต ได้แก่ RAP RCA เศษขวด PET และ PP ที่มีความยั่งยืน เป็นมิตรต่อสิ่งแวดล้อม และสร้างแรงบันดาลใจในการพัฒนาโครงสร้างพื้นฐานที่เป็นมิตรกับสิ่งแวดล้อมมากยิ่งขึ้นในอนาคต

สาขาวิชา วิศวกรรมโยธาและการบริหารงานก่อสร้าง
ปีการศึกษา 2567

ลายมือชื่อนักศึกษา ....
ลายมือชื่ออาจารย์ที่ปรึกษา ....
ลายมือชื่ออาจารย์ที่ปรึกษาร่วม ....

KONGSAK AKKHARAWONGWHATTHANA : UTILIZATION OF RECYCLED POLYETHYLENE TEREPHTHALATE AND RECYCLED POLYPROPYLENE PLASTICS IN SUSTAINABLE ASPHALT CONCRETE PAVEMENT.
THESIS ADVISOR : PROF. SUKSUN HORPIBULSUK, Ph.D., 140 PP.

Keywords: Reclaimed Asphalt Pavement/ Recycled Concrete Aggregate/ Polyethylene Terephthalate/ Polypropylene

Many countries worldwide, including Thailand, have used various recycled waste materials, such as reclaimed asphalt concrete pavement (RAP), recycled concrete aggregate (RCA), and plastic waste, in asphalt concrete pavement mixtures. This approach helps reduce the use of natural resources and lowers construction costs. However, using these materials in asphalt concrete mixtures is usually limited to low percentages due to their inferior engineering properties compared to natural materials. This research aims to explore the feasibility of using RAP and RCA as aggregates in asphalt concrete mixtures without natural aggregates and to enhance the performance of asphalt concrete with recycled polyethylene terephthalate (PET) crushed bottle fragments. This research also investigates the feasibility of using recycled polypropylene (PP) pellets to modify asphalt cement penetration grade 60 to 70 (AC60/70) for use in porous asphalt concrete. The static and dynamic performances of asphalt concrete were accessed via the Marshall stability, the strength index (SI), the indirect tensile strength (ITS), the indirect tensile fatigue (ITF), the indirect tensile resilient modulus (IT_{MR}), and the resistance to rutting tests.

The research is divided into three parts. The first part examines the use of PET to improve the mechanical performances of asphalt concrete made with 100% RAP aggregate. The mechanical performances of RAP asphalt concrete were evaluated in terms of PET content at 0.0, 0.2, 0.4, 0.6, 0.8, and 1.0% by weight of the total aggregate. Without PET, the strength index value of RAP asphalt concrete did not meet the Department of Highways standard. Adding PET to the mixture improved the properties to meet the Department of Highways standards and enhanced mechanical performance. The optimum PET content of 0.6% provided the best mechanical performance across all experimental testing, resulting in a 25% improvement in

Marshall stability, 19% in SI, 69% in ITS, 11% in IT_{MR}, 270% in ITF, and 80% in rutting resistance compared to 0% PET content.

The second part studied the mechanical performances of asphalt concrete using RAP and RCA as aggregates, which were improved with PET. Coarse RAP was replaced with RCA in terms of RAP/RCA ratios of 100/0, 90/10, 80/20, and 60/40. The mechanical performances were evaluated based on PET content at 0.0, 0.2, 0.4, 0.6, 0.8, and 1.0% by total aggregate weight. Replacing coarse RAP with RCA enhanced the properties to meet the Department of Highways standards and improved mechanical performance. Asphalt concrete with the 80/20 RAP/RCA ratio yielded the highest mechanical performances at a particular PET content. Adding PET can enhance the mechanical performance of RAP-RCA asphalt concrete of RAP/RCA mixtures across all ratios. With 0.6% PET content, RAP-RCA asphalt concrete was enhanced with the highest mechanical performance.

The third part investigated the use of PP to modify AC60/70 for use as asphalt cement in porous asphalt concrete (PAC). The study revealed that 2% of PP-modified AC60/70 (AC60/70-2%PP) met the AC40/50 standard specified by the Thai Industrial Standards Institute. The mechanical performances of PAC using AC60/70-2%PP were the highest. However, compared to PMA-PAC, the mechanical performance of AC60/70-2%PP-PAC was lower. This research paves the way for the development of alternative materials for use in asphalt concrete mixtures, including RAP, RCA, PET, and PP, which are sustainable and environmentally friendly, inspiring a future of greener infrastructure.

School of Civil Engineering and Construction Management | Student's Signature ....

Academic Year 2024 | Advisor's Signature..............

Co-Advisor's Signature ....

ACKNOWLEDGMENT

I would like to express my sincere gratitude to my thesis advisor Professor Dr. Suksun Horpibulsuk, and thesis co-advisor, Dr. Apichat Suddeepong, who has always supported me while I was doing my Ph.D. studies. They taught me new things about education and research. They taught me patience, motivation, enthusiasm, and knowledge I had never experienced before. Moreover, they have also been role models in my personal development of excellent academic skills. Without their guidance and diligence, this dissertation would not have been possible until now. It gives me great confidence that studying for a PhD in civil engineering and construction management at Suranaree University of Technology was one of the best decisions I have made in my life.

In addition, I would like to thank the examination committee that played an essential role in my thesis, including Professor Dr. Panich Wuttipruk, chairman of the thesis examination committee; Professor Dr. Avirut Chinkulkijniwat, and Assist Prof Dr. Menglim Hoy.

I am grateful for the scholarship support throughout my Ph.D. program in Civil Engineering and Construction Management from Suranaree University of Technology. I also extend my heartfelt thanks to the officials and individuals who assisted me with this thesis, particularly Dr. Apinun Buritatum, Dr. Teerasak Yaowarat, and Nantipat Pongsri.

Finally, I would like to thank my beloved family for their constant spiritual support, even when I was tired, discouraged, and drowning in sadness. My family pushed me to overcome many problems and obstacles throughout my Ph.D. studies, making me the strong person I am today.

Kongsak Akkharawongwhatthana

TABLE OF CONTENTS

Page

TABLE OF CONTENTS (Continued)

Page

TABLE OF CONTENTS (Continued)

Page

TABLE OF CONTENTS (Continued)

Page

LIST OF TABLES

Table | Page

LIST OF TABLES (Continued)

LIST OF FIGURES

LIST OF FIGURES (Continued)

LIST OF FIGURES (Continued)

Figure **Page**

SYMBOLS AND ABBREVIATIONS

a	=	Fatigue parameter
AASHTO	=	American Association of Highway and Transportation Officials
AC	=	Asphalt cement
AC40/50	=	Asphalt cement penetration grade 40/50
AC60/70	=	Asphalt cement penetration grade 60/70
AI	=	Asphalt Institute
ASTM	=	American Society for Testing and Materials
b	=	Fatigue parameter
BS	=	British standard
BS EN	=	British standard implementations of English language versions of European standards
BSI	=	British Standards Institution
°C	=	Degree Celsius
C&D	=	Construction and demolition
cm	=	Centimeter
cm^3	=	Cubic centimeter
D	=	Sample diameter
DH-S	=	Department of Highway standards
DH-SP	=	Department of Highway specifications
DOH	=	Department of Highways
DRR	=	Department of Rural Roads
DSR	=	Dynamic shear rheometer
EN	=	European standards
g	=	Gram
G*	=	Complex modulus
HMA	=	Hot mix asphalt concrete
H_r	=	Recoverable horizontal deformation

SYMBOLS AND ABBREVIATIONS (Continued)

Hz	=	Hertz or cycle per second
ITF	=	Indirect tensile fatigue
ITFL	=	Indirect tensile fatigue life
IT_{MR}	=	Indirect tensile resilient modulus
ITS	=	Indirect tensile strength
kN	=	Kilonewton
kPa	=	kilopascal
M_f	=	Weight of sample after test
M_i	=	Weight of sample before test
min	=	Minute
mm	=	Millimeter
MS	=	Marshall stability
N	=	Newton
NA	=	Natural aggregate
N_f	=	Fatigue life
OGFC	=	Open-graded friction courses
P	=	Maximum load
PAC	=	Porous asphalt concrete
PE	=	Polyethylene
PET	=	Polyethylene terephthalate
PMA	=	Polymer modified asphalt cement
PP	=	Polypropylene
RA	=	Recycled aggregate
RAP	=	Reclaimed asphalt pavement
RCA	=	Recycled concrete aggregate
rpm	=	Rotations per minute
SBS	=	Styrene butadiene styrene
sec	=	Second
SI	=	Strength index

SYMBOLS AND ABBREVIATIONS (Continued)

SMA	=	Stone matrix asphalt
t	=	Sample thickness
TIS	=	Thai Industrial Standards
TISI	=	Thai Industrial Standards Institute
VFA	=	Void filled by asphalt cement
VMA	=	Void in mineral aggregate
W_{fc}	=	Final weight of container
W_{ic}	=	Initial weight of container
W_{is}	=	Initial weight of the mixture sample
d	=	Phase angle
$m\varepsilon_t$	=	Micro-initial tensile strain
ν	=	Poisson's ratio
ε_t	=	Initial tensile strain
σ	=	Applied stress
%	=	Percentage

CHAPTER I
INTRODUCTION

1.1 Statement of the problem

The construction sector is the leading industrial activity contributing to the environmental impact, particularly in the form of substantial natural resource consumption and enormous solid waste generation. Construction and demolition (C&D) wastes resulting from construction activities, such as demolished asphalt concrete pavement, demolished concrete structures, and crushed brick, increase annually due to the rapid expansion of urban areas because of economic development. For instance, according to the United States Environmental Protection Agency report, the quantity of C&D wastes in the United States remained at over 600 million tons annually (EPA, 2018). The substantial amount of C&D wastes generated impacts conventional waste disposal management systems, mainly through stockpiling and landfill methods, by exceeding landfill capacity. Moreover, several research publications indicated that unsustainable waste disposal is the major contributor to the hazardous effect on the ecosystem (Al-Qadi et al., 2007; Gautam et al., 2018; Zaumanis et al., 2014; Zhang & Muhunthan, 2017). Consequently, the government and private agencies in several countries worldwide have attempted to develop a sustainable solution for C&D wastes management rather than relying solely on conventional waste disposal methods (Ghaffar et al., 2020; Mercante et al., 2012).

The demolition of asphalt concrete pavements and concrete structures is recognized as the largest contributor to C&D waste worldwide. According to the European Asphalt Pavement Association, the estimated amount of demolished asphalt concrete pavement was 50 million tons in 2020 (Hesham & Aditia, 2023). Moreover, the Federal Highway Administration reported that approximately 140 million tons of wasted concrete pavement are generated annually (Cavalline, 2016). Several studies have suggested using asphalt concrete and concrete wastes as sustainable recycled aggregates (RA) with natural aggregate (NA) for road construction

(Arulrajah et al., 2013; Jayakody et al., 2021; Naser et al., 2022). According to these studies, reclaimed asphalt concrete pavement (RAP) and recycled concrete aggregate (RCA) exhibit mechanical properties comparable to NA, especially for low-traffic roads. However, RAP contains aged asphalt cement that can become brittle over time, reducing flexibility, and increasing susceptibility to cracking. Additionally, RCA is more porous than NA, resulting in higher water absorption and increasing the risk of moisture-induced damage such as stripping, where the asphalt cement separates from the aggregate. To ensure that RAP-RCA asphalt concrete pavement meets expected performance, and durability, it is necessary to add supplemental additives such as rejuvenators, polymers, and fibers. (Hagos et al., 2012).

Using polymer as an additives in asphalt concrete, such as styrene butadiene styrene (SBS), polyethylene (PE), polypropylene (PP), and polyethylene terephthalate (PET) have been widely studied by many researcher (Ahmadinia et al., 2011; Angelone et al., 2016; Badejo et al., 2017; Costa et al., 2013; El-Naga & Ragab, 2019). The presence of polymers enhances the elastic properties of asphalt concrete, thus improving the bond strength between the materials and increasing the service life of the pavement.

Plastic materials are massively present in everyday life and are virtually used in every branch of industry (Datta & Kopczyńska, 2016; Dwivedi et al., 2019). They are utilized as raw materials for a wide range of products, such as plastic drink cups, bottles, housewares, plastic storage containers, and pipes. However, these products ultimately become waste, resulting in serious environmental issues (Behnood & Gharehveran, 2019). Plastic pollution is a major global issue due to the growing volume of plastic waste in need of disposal and the accumulation of floating plastic debris in the ocean (Angelone et al., 2016; Cózar et al., 2014). The cumulative amount of plastic waste available to enter the marine environment from waste generated on land is predicted to increase over the following years due to population growth, high levels of plastic resin production, and inefficient waste management infrastructure. In 2010, nearly 275 million metric tons of plastic waste were generated in 192 coastal countries, wherein 4.8–12.8 million metric tons may have entered the ocean (Jambeck et al., 2015). The increasing amount of plastic waste in oceans and landfills has interest in recycling and reusing plastic (Hamad et al., 2013). Using wasted plastics to develop polymer-modified asphalt concrete mixtures is a promising field of application. This application is an interesting alternative from both an environmental and technical standpoint. It reduces the amount of plastic waste sent to landfills while improving the mechanical properties of asphalt cement (Garcia-Morales et al., 2004). As a result, asphalt concrete performs better in major performances (Duarte & Faxina, 2021). PET, a thermoplastic polyester used to manufacture plastic bottles, can also be used as an additive in an asphalt concrete mixture (Shukla & Harad, 2006). However, due to its high melting point (approximately 250°C), achieving homogeneity when mixing PET with asphalt cement using the wet method can be an issue. Therefore, the dry method is commonly utilized in many studies to add PET to the asphalt concrete mixture. PP is often used for containers, bottles (such as ketchup or syrup bottles), yogurt containers, and caps. It has a lower melting point (approximately 160°C), which is nearly the pre-heat temperature of asphalt cement (approximately 160-168°C). Hence, the wet method is suitable for incorporating PP with asphalt cement (Giustozzi & Boom, 2021).

Waste materials, such as recycled aggregate and recycled plastic, have been studied for use in asphalt concrete mixtures. Reusing recycled aggregate from waste provides a sustainable alternative to natural aggregates. While previous research has discussed the effects of adding recycled plastic to asphalt concrete mixtures, there remains a need to understand further the impact that combining recycled aggregates and recycled plastic has on the properties and performance of asphalt concrete.

This study explores using recycled PET and recycled PP plastics to improve the mechanistic performance of two types of asphalt concrete including dense-graded asphalt concrete and open-graded asphalt concrete. The study can be separated into three parts. The first part examines the use of recycled PET as an additive to improve the mechanistic performance of RAP asphalt concrete. The second part involves using recycled PET to enhance the mechanistic performance of RAP-RCA asphalt concrete. This part also studies the effect of the RAP/RCA ratio on the Marshall properties and mechanical performance. In both the first and second parts, the effectiveness of PET is evaluated using the dry method and is incorporated into dense-graded asphalt concrete mixtures. The third part evaluates the use of PP through the wet method, where the properties of asphalt cement are assessed. PP-modified asphalt cement is then evaluated for use in open-graded asphalt concrete mixtures, also called porous asphalt concrete. The results of this study will provide valuable insights into the potential use of waste materials in asphalt concrete pavement to improve waste management and enhance the sustainability of pavement infrastructure.

1.2 Objective of study

This research has been undertaken with the following objectives:

1) To investigate the effect of PET content on the optimum asphalt cement, the Marshall properties, and the mechanistic performances of RAP asphalt concrete.

2) To investigate the effect of PET content on the optimum asphalt cement, the Marshall properties, and the mechanistic performances of RAP-RCA asphalt concrete.

3) To investigate the effect of PP content on the asphalt cement properties and the effect of PP-modified asphalt cement on the optimum asphalt cement, the Marshall properties, and the mechanistic performances of porous asphalt concrete.

1.3 Structure of dissertation

This thesis consist of six chapters and outlines of each chapter are presented as follows:

Chapter 1 presents the introduction part consisting of statement of problem, the objectives of study, and the structure of dissertation.

Chapter 2 presents the literature review related to the asphalt concrete mixtures such as aggregate, and asphalt cement, the Marshall properties of asphalt concrete, the mechanistic performance of asphalt concrete, application of recycled materials for asphalt concrete, influence of using recycled PET and recycled PP plastics on Marshall properties and mechanistic performances of asphalt concrete, and development of fatigue distress model.

Chapter 3 presents the study result of the properties and mechanical performances of 100% RAP asphalt concrete modified with PET.

Chapter 4 presents the study result of the influence of RCA replacing in coarse RAP aggregate and modified with PET on properties and mechanical performances of asphalt concrete.

Chapter 5 presents the use of PP to modify asphalt cement. It evaluates the impact of PP on asphalt cement properties, the influence of PP-modified asphalt cement on Marshall properties, and the mechanistic performance of porous asphalt concrete.

Chapter 6 presents the conclusion of each chapter, the overall conclusion, and the suggestion for further study.

1.4 References

Al-Qadi, I. L., Elseifi, M., & Carpenter, S. H. (2007). Reclaimed asphalt pavement-a literature review. FHWA-ICT-07-001.

Angelone, S., Cauhapé Casaux, M., Borghi, M., & Martinez, F. O. (2016). Green pavements: reuse of plastic waste in asphalt mixtures. Materials and Structures, 49, 1655-1665.

Arulrajah, A., Piratheepan, J., Disfani, M. M., & Bo, M. W. (2013). Geotechnical and geoenvironmental properties of recycled construction and demolition materials in pavement subbase applications. Journal of Materials in Civil Engineering, 25(8), 1077-1088.

Behnood, A., & Gharehveran, M. M. (2019). Morphology, rheology, and physical properties of polymer-modified asphalt binders. European Polymer Journal, 112, 766-791.

Cavalline, T. (2016). Quantifying the Sustainability Benefits of Concrete Pavement Recycling. Tech Brief: Concrete Pavement Recycling Series (2).

Cózar, A., Echevarría, F., González-Gordillo, J. I., Irigoien, X., Úbeda, B., Hernández-León, S., Palma, Á. T., Navarro, S., García-de-Lomas, J., & Ruiz, A. (2014). Plastic debris in the open ocean. Proceedings of the National Academy of Sciences, 111(28), 10239-10244.

Datta, J., & Kopczyńska, P. (2016). From polymer waste to potential main industrial products: Actual state of recycling and recovering. Critical reviews in environmental science and technology, 46(10), 905-946.

Dwivedi, P., Mishra, P., Mondal, M. K., & Srivastava, N. (2019). Non-biodegradable polymeric waste pyrolysis for energy recovery. Heliyon, 5(8).

EPA. (2018). Construction and Demolition Debris Generation in The United States 2015. U.S. Environmental Protection Agency.

Fernandes, S. R., Costa, L., Silva, H. M. R. D. d., & Oliveira, J. (2015). Utilization of waste materials to improve asphalt mixtures performance.

Garcia-Morales, M., Partal, P., Navarro, F., Martinez-Boza, F., & Gallegos, C. (2004). Linear viscoelasticity of recycled EVA-modified bitumens. Energy & Fuels, 18(2), 357-364.

Gautam, P. K., Kalla, P., Jethoo, A. S., Agrawal, R., & Singh, H. (2018). Sustainable use of waste in flexible pavement: A review. Construction and Building Materials, 180, 239-253.

Ghaffar, S. H., Burman, M., & Braimah, N. (2020). Pathways to circular construction: An integrated management of construction and demolition waste for resource recovery. Journal of cleaner Production, 244, 118710.

Hagos, E., van de Ven, M., & Merine, G. (2012). Investigation into tensile properties of polymer modified Bitumen (PMB) and mixture performance. 7th RILEM International Conference on Cracking in Pavements,

Hamad, K., Kaseem, M., & Deri, F. (2013). Recycling of waste from polymer materials: An overview of the recent works. Polymer degradation and stability, 98(12), 2801-2812.

Hesham, A., & Aditia, R. (2023). Recycling Asphalt Pavements: The State of Practice. In Recycling Strategy, Challenges Associated with Waste Management Towards Sustaining the World. IntechOpen.

Jambeck, J. R., Geyer, R., Wilcox, C., Siegler, T. R., Perryman, M., Andrady, A., Narayan, R., & Law, K. L. (2015). Plastic waste inputs from land into the ocean. Science, 347(6223), 768-771.

Jayakody, S., Gallage, C., & Ramanujam, J. (2021). Assessment of RCA with RAP materials for pavement applications. IOP Conference Series: Materials Science and Engineering,

Leng, Z., Sreeram, A., Padhan, R. K., & Tan, Z. (2018). Value-added application of waste PET based additives in bituminous mixtures containing high percentage of reclaimed asphalt pavement (RAP). Journal of cleaner Production, 196, 615-625.

Mercante, I. T., Bovea, M. D., Ibáñez-Forés, V., & Arena, A. P. (2012). Life cycle assessment of construction and demolition waste management systems: a Spanish case study. The International Journal of Life Cycle Assessment, 17, 232-241.

Mogawer, W. S., Austerman, A. J., Bonaquist, R., & Roussel, M. (2011). Performance characteristics of thin-lift overlay mixtures: High reclaimed asphalt pavement content, recycled asphalt shingles, and warm-mix asphalt technology. Transportation research record, 2208(1), 17-25.

Naser, M., tasim Abdel-Jaber, M., Al-shamayleh, R., Louzi, N., & Ibrahim, R. (2022). Evaluating the effects of using reclaimed asphalt pavement and recycled concrete aggregate on the behavior of hot mix asphalts. Transportation Engineering, 10, 100140.

Zaumanis, M., Mallick, R. B., & Frank, R. (2014). 100% recycled hot mix asphalt: A review and analysis. Resources, Conservation and Recycling, 92, 230-245.

Zhang, K., & Muhunthan, B. (2017). Effects of production stages on blending and mechanical properties of asphalt mixtures with reclaimed asphalt pavement. Construction and Building Materials, 149, 679-689.

CHAPTER II

LITERATURE REVIEW

2.1 Introduction

The growth in urbanization and infrastructure development worldwide has amplified the demand for construction materials, including aggregates and binders for road construction. This escalating demand, with environmental concerns and the decreasing availability of natural resources, has driven researchers and engineers to seek sustainable and eco-friendly alternative materials in road construction. Two alternative materials that have gained prominence in recent decades are reclaimed asphalt concrete pavement (RAP) and recycled concrete aggregate (RCA) as substitutes for natural aggregates (NA) in asphalt concrete mixtures. Concurrently, the global surge in plastic waste, such as polyethylene terephthalate (PET) and polypropylene (PP), has prompted investigations into its potential use as an additive in asphalt mixtures, capitalizing on its inherent properties to enhance pavement performance. This chapter finds the extensive literature surrounding the meaning of asphalt concrete mixture, using RAP, RCA, PET, and PP for asphalt concrete applications. It explores their benefits, challenges, and implications for sustainable road construction.

2.2 Aggregate

As a significant component of pavement, the aggregates affect the performances of asphalt mixture due to the mutual interactions, especially for the morphological features of aggregates, such as the bond strength between aggregate and asphalt cement, the skeleton structure, and the mechanical performance of asphalt concrete mixture (Kuang et al., 2017; Rajan & Singh, 2017). Morphological characterizations of aggregate could be identified as three independent components: form (shape), angularity, and texture (Sun, 2015) as shown in Figure 2.1. These components are related to the construction and service performances of asphalt concrete mixture: the shape features of aggregate influence the structural performance, friction properties, and skid resistance (Gong et al., 2021).

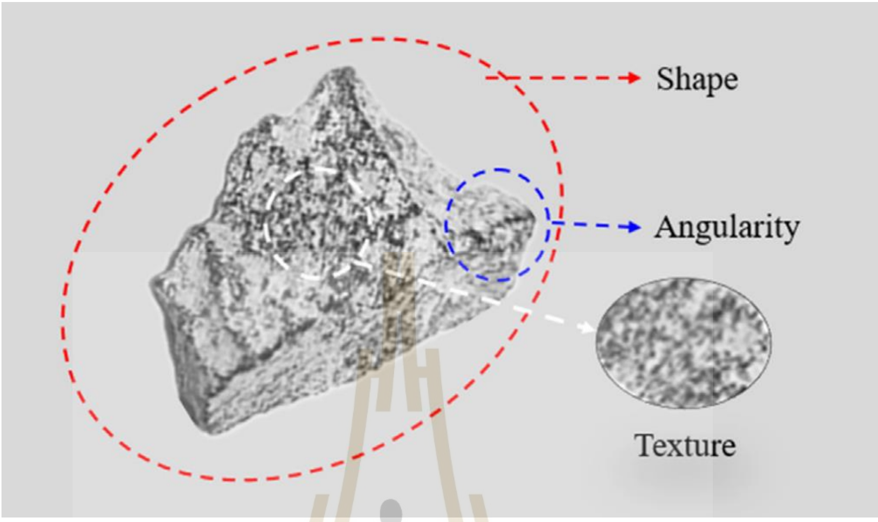

Figure 2.1 Morphological characterizations of an aggregate (Gong et al., 2021).

The morphological characteristics affect the compacting properties of asphalt mixtures (Wang et al., 2019); the interfacial strength of asphalt aggregate is verified to be subject to the angularity and roundness of coarse aggregate through the Marshall test, dynamic stability, split strength ratio, and low-temperature flexural tensile strength (Kuang et al., 2019). Many testing methods are used to measure the morphological characterizations of aggregates, and several image-based techniques have also been developed or under research in recent years. Some conventional testing methods are conducted to measure the morphological characterizations of aggregates as shown in Table 2.1 (China, 2005; Gudimettla et al., 2006; Lugo et al., 2008; Pan, 2006). In addition, some non-natural aggregate particles have also been utilized in road engineering, and more descriptors have been generated to characterize them, such as coral aggregates, recycled aggregates, and ceramists (Gholizadeh-Vayghan et al., 2020).

Table 2.1 Conventional testing methods for aggregate in specifications (China, 2005; Gudimettla et al., 2006; Lugo et al., 2008; Pan, 2006).

No.	Test method	Specification	Size
1	Specific gravity	ASTM C127	Coarse aggregate
2	Los Angeles abrasion	ASTM C131	Coarse aggregate
3	Sand equivalent value	ASTM D2419	Fine aggregate
4	Elongated particles and Flakiness particles	ASTM D4791	Coarse aggregate

2.2.1 Properties of aggregate for asphalt concrete mixtures

The properties of aggregates significantly influence the behavior and performance of asphalt concrete mixtures. Table 2.2 explained the important properties of aggregates for asphalt concrete mixtures.

Table 2.2 Important properties of aggregates for asphalt concrete mixtures (China, 2005; Fang et al., 2019; Fletcher et al., 2002; Gholizadeh-Vayghan et al., 2020; Gudimettla et al., 2006).

Properties	Descriptions
Particle size and gradation	• Refers to the distribution of particle sizes in the aggregate material. • Influences workability, stability, voids in the mix, and the amount of asphalt cement required.
Particle shape and texture	• Aggregate particles can be angular, rounded, flaky, or elongated. • Angular and rough-textured aggregates provide better interlock and asphalt cement adhesion, which is preferred for asphalt concrete mixtures.

Table 2.2 Important properties of aggregates for asphalt concrete mixtures (China, 2005; Fang et al., 2019; Fletcher et al., 2002; Gholizadeh-Vayghan et al., 2020; Gudimettla et al., 2006). (Continued)

Properties	Descriptions
Specific gravity and absorption	• Specific gravity indicates the relative density of the aggregate material. • Absorption capacity shows the aggregate's tendency to absorb asphalt cement, influencing the amount of asphalt cement required.
Durability and soundness	• Measures the aggregate's resistance to weathering and disintegration when subjected to repeated freeze-thaw cycles. • Tested usually by subjecting aggregates to a solution of sodium or magnesium sulfate.
Strength and toughness	• Aggregate should resist crushing under traffic loads. • Common tests include the Los Angeles abrasion Test.
Cleanliness and deleterious Materials	• Aggregates should be free from materials that can affect the bonding with the asphalt cement or decrease the durability of the asphalt concrete mixture. • Materials such as clay, shale, wood, mica, etc., should be limited.
Affinity for asphalt cement	• Aggregates should have an affinity for asphalt cement to ensure a proper bond. • Aggregates with high water absorption or that are prone to stripping (loss of asphalt cement due to water presence) might require treatments or additives to improve their affinity for asphalt cement.

Table 2.2 Important properties of aggregates for asphalt concrete mixtures (China, 2005; Fang et al., 2019; Fletcher et al., 2002; Gholizadeh-Vayghan et al., 2020; Gudimettla et al., 2006). (Continued)

Properties	Descriptions
Flakiness and elongation Index	• Measures the shape of the aggregate particles. • Flaky or elongated aggregates can compromise the mixture's stability.

2.3 Asphalt cement (AC)

AC is a product derived from the refining of crude oil. It is a solid and versatile binding material with weather and chemical-resistant characteristics that can be used ideally for road, bridge, highway, and runway construction and maintenance. Since the AC is the primary bonding material for the road, its properties are crucial to the service performance and service life of the pavement, that is, the quality of the pavement in service life depends largely on the quality of the AC (Howson et al., 2012; Sun et al., 2016). So far, many scholars have studied the technical performance of AC (Huang et al., 2009; Liu et al., 2017), including aging resistance, adhesion property, self-healing behavior, fatigue-resistance performance, and modified improvement (Leng et al., 2014; Liu et al., 2017; Roque et al., 2005; Wei et al., 2013). Most of these investigations are based on the experiments including the penetration test, ductility test, softening point test, and dynamic shear rheometer test (DSR) (Qu et al., 2018).

2.3.1 The composition and structure of asphalt cement

AC is a chemical compound that is composed of various molecules with stable structures (Masson, 2008). These molecules interact with each other, which is crucial to the properties of AC materials. There are four main chemical compositions of AC, namely asphaltenes, resins, oil aromatics, and oil saturates. Changes in these compositions can significantly alter the structure and properties of AC, such as its physical, mechanical, and rheological properties. Several studies have highlighted the importance of understanding the interaction between these different molecular groups to develop better AC materials (Hunter et al., 2015; Michalica et al., 2008). Their characteristic parameters are listed in Table 2.3 and the structure of AC is illustrated in Figure 2.2.

Table 2.3 Characteristic parameters of four main asphalt cement fraction (Zhang et al., 2020)

Group	Oil		Resins	Asphaltenes
	Saturates	Aromatics		
Descriptions	Colorless or lightly colored liquid	Yellow to dark red liquid 	Dark brown to black solid or semi-solid 	Dark brown to black powder 
Weight percent range (%)	5-20	30-65	30-45	5-20

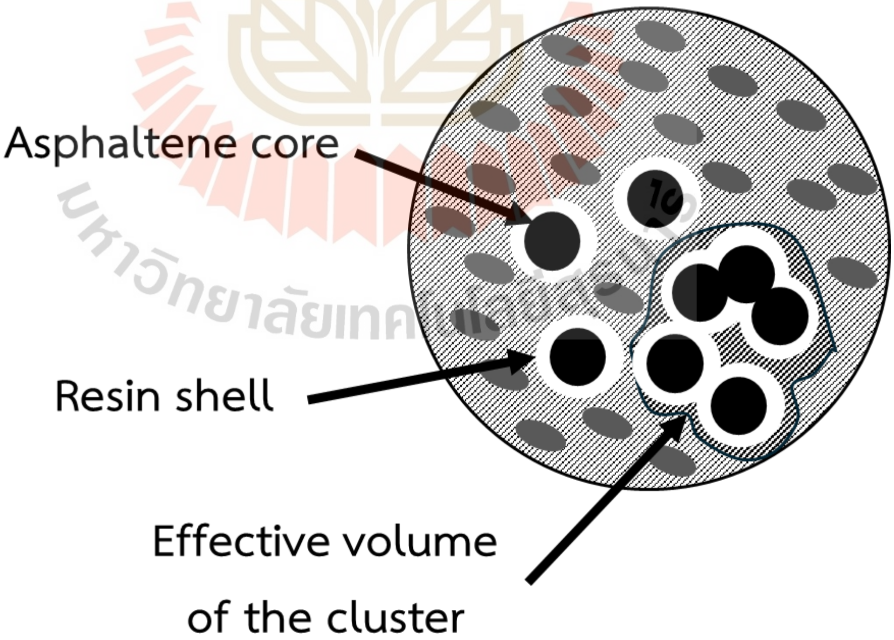

Figure 2.2 Structure of asphalt cement (Zhang et al., 2020)

Oil saturates are generally considered the most stable fraction of AC and have good aging properties. However, they do not contribute significantly to adhesion or rheological properties of the AC. Oil aromatics have intermediate polarity and are less susceptible to oxidation compared to resins and asphaltenes. They significantly influence the physical properties of the AC, especially its rheological characteristics. Resins are susceptible to oxidation, which can cause hardening of the AC over time. They enhance the ductility and elasticity of the AC and help in preventing phase separation between asphaltenes and the rest of the matrix. Asphaltenes are responsible for the black color of asphalt. They provide the body and stiffness to the AC but can also lead to brittleness if present in excessive amounts. An increase in the asphaltene content can also increase the susceptibility of the AC to thermal cracking. The relative proportions and the characteristics of these four components significantly influence the physical and rheological properties of AC. For example, an increase in the asphaltene content may lead to a stiffer AC, while a higher proportion of oil saturates and oil aromatics can lead to a softer AC (Hussein et al., 2020; Zhang & Muhunthan, 2017; Zhang et al., 2020).

In the aging process, the content of saturates might not change significantly during the aging process. The oil saturates fraction remains relatively stable. Aging can cause a reduction in the aromatics fraction. This happens due to the oxidation process which transforms some of the aromatic compounds into more polar compounds, shifting them to the resins and asphaltenes fractions. Initially, the resins fraction can increase due to aging, as oxidation transforms some of the aromatics and saturates into compounds that fit the resins category. However, with prolonged aging, even resins can further oxidize and transform into asphaltenes. A higher concentration of asphaltenes makes the aged AC stiffer and more brittle, which can impact the performance of asphalt concrete mixtures.

2.3.2 Properties of asphalt cement for asphalt concrete mixtures

AC, often referred to simply as asphalt or binder, is a key component of asphalt concrete mixtures. Its properties are crucial for determining the behavior and performance of the asphalt concrete mixture. Table 2.4 listed the properties of AC and the corresponding tests that evaluate them.

Table 2.4 Properties of asphalt cement for asphalt concrete mixtures.

Properties	Test method	Descriptions
Penetration	AASHTO T 49	Measures the depth to which a standard needle will penetrate a sample of AC under specified conditions of temperature and load. This test gives an indication of the hardness or softness of the AC.
Viscosity	ASTM D 4402	Determines the flow characteristics of the AC. It is vital to understand how the AC will behave during mixing and compaction, and under traffic loads.
Softening Point	ASTM D 36	Indicates the temperature at which the AC starts to soften. It gives an idea about the temperature susceptibility of the AC and its ability to resist rutting under high temperatures.
Ductility	AASHTO T 51	Measures the distance of a sample of AC will stretch before breaking. It gives an indication of the AC's elasticity and ability to deform without breaking.
Aging Characteristics	AASHTO T 179	Evaluates the short-term aging effects due to heat and air, simulating the aging that occurs during mixing and compaction.
Flash and Fire Point	ASTM D 92	Indicates the temperatures at which the AC can ignite. It ensures safe handling and application temperatures.
Performance Grading	AASHTO T 315	These tests are part of the Superpave system which grades AC based on their performance at specific temperatures. They give an indication of the AC's rutting, fatigue, and low-temperature cracking resistances.
Toughness and Tenacity	ASTM D 6084	Provides an indication of the AC's ability to recover after being stretched, indicating its elasticity.

2.4 Asphalt concrete

Asphalt concrete pavement consists of fine aggregates, coarse aggregate, and AC which are important in carrying traffic load which depends on the selection of bonding materials (Brovelli et al., 2015; Movilla-Quesada et al., 2015). It is a multi-phase dispersed system with a spatial network structure formed by an aggregate and AC. Essentially, asphalt concrete mixture is a type of loose structure even bonded by AC. The mechanistic performance of an asphalt concrete mixture depends on the cohesion and internal friction resistance (Chen & Liao, 2002; Mamlouk & Zaniewski, 2014). Asphalt concrete mixtures are formulated to meet specific needs and conditions. The type of mixture selected often depends on the intended use, climate, traffic loads, and other factors. The gradation of aggregates in asphalt concrete mixtures significantly impacts the performance, workability, and durability of the finished pavement.

After bearing the traffic load for a period, the asphalt concrete becomes damaged as evidenced by cracks, distortion or deformation, surface defects and various distress (DOH, 2007). Figure 2.3 shown the two main damage characteristics in asphalt concrete pavement that are caused by the traffic load are permanent deformation (also known as rutting) and fatigue cracking (Kasikitwiwat & Jantarachot, 2021) as shown in Figure 2.3(a) and 2.3(b), respectively. Fatigue cracking is characterized by the formation of cracks resulting from the accumulation of damage after a significant number of repetitive reversible loading cycles at intermediate temperatures (Al-Khateeb & Shenoy, 2004). Permanent deformation is identified by depressions in the wheel path due to the repetitive passage of heavy traffic loading, which occurs mainly during the summer season when the high service temperatures cause a reduction in the AC viscosity (Tangella et al., 1990). Such damage affects the road surface and may be noticeable as cracks (Perng, 1989) and overall, the damage results in a shorter pavement lifespan (Sadeq et al., 2016).

(a) (b)

Figure 2.3 The two main damage characteristics in asphalt concrete pavement (Wang et al., 2021).

2.4.1 Type of asphalt concrete mixture

Based on aggregate gradation, asphalt concrete mixtures can be broadly categorized into 3 types namely dense-graded, gap-graded, and open-graded. The characteristics of dense-graded mixtures have a good distribution of all aggregate sizes, from coarse to fine, ensuring closely packed aggregates with minimum void spaces. It is most used for road surfaces, including highways, arterial roads, and city streets. This mixture offers excellent durability, resistance to skidding, and water impermeability. It can be further categorized into fine-graded (more fine aggregates) and coarse-graded (more coarse aggregates) (Fang et al., 2019; Hasita et al., 2021). Gap-graded mixtures intentionally leave out specific aggregate sizes, which creates gaps in the gradation curve. Gap-graded mixture is usually done for stone matrix asphalt (SMA) and specific texture needs. These mixtures can increase stability and resistance to rutting, particularly when used in SMA. However, they may segregate during placement. Since specific sizes are omitted, designing and laying these mixtures can be challenging, but they can offer superior resistance to rutting (Fang et al., 2019; Gallo & Valentin, 2019). Open-graded mixtures contain lower fine aggregates, resulting in increased air voids and better water drainage. They are specifically designed for open-graded friction courses (OGFC) and porous asphalt concrete (PAC) pavements. These mixtures are applied as thin overlays on existing pavements. PAC helps improve safety by reducing splash and spray during rain, decreasing hydroplaning risk, and enhancing nighttime visibility. Additionally, they are used to create noise-reducing surfaces (Fang et al., 2019; Suddeepong et al., 2023). Figure 2.4 shows the asphalt concrete mixture schematic.

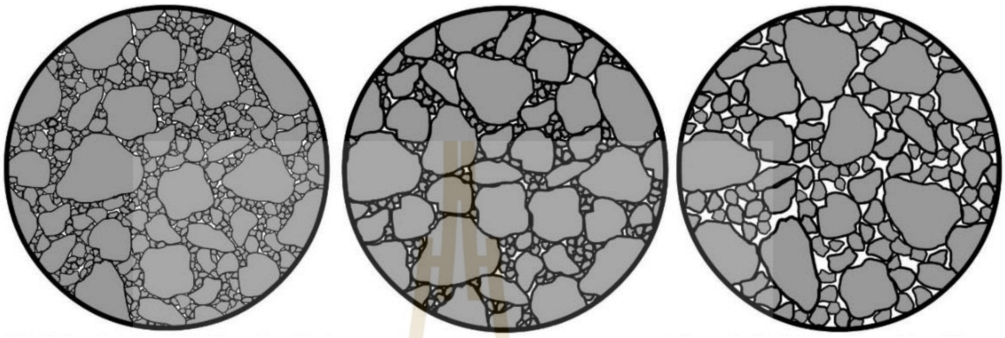

Figure 2.4 Asphalt concrete mixture schematic (a) Dense-graded mixture, (b) Gap-graded mixture, and (c) Open-graded mixture (Facts, 2007).

2.4.2 Volumetric properties and mechanical properties of asphalt concrete

The formation of asphalt concrete starts from aggregate selection, and the essential requirement of its bearing capacity comes from traffic and environmental loads. Different aggregate properties produce different road performances of asphalt concrete pavement. Meanwhile, the strength of asphalt concrete is mainly formed by aggregates, AC, and their spatial distribution status in the mixture (Fang et al., 2019). This leads to the volumetric and mechanical properties being extremely important. Due to the difficulty in using voids of each aggregate to design asphalt concrete mixture directly, the related mass and density are easier to gain by appropriate tests.

The volumetric properties of asphalt concrete mixture consist of the density, void in mineral aggregate (VMA), air voids, and void filled by AC (VFA) have significant effects on the physical properties of asphalt concrete mixture (Marshall stability and Marshall flow) (Hossain et al., 2016). The volume fractions are shown in Figure 2.5. VMA is the air void among the aggregates. In designing the asphalt concrete mixture, VMA is used to ensure that the AC film thickness is sufficient to protect the asphalt concrete mixture from the abrasive action of tires and water (Moghaddam et al., 2015). The air void is considered as one of the most important parameters in designing asphalt concrete. The air void generated from insufficient AC coating creates cracking in the asphalt concrete mixture. However, rutting and AC bleeding are generated due to low air voids in the asphalt concrete mixture. Air voids are used to determine the optimum AC content for a given aggregate (Aghayan & Khafajeh, 2019). VFA is the percentage portion of void space between the aggregate particles that are filled by the effective AC (Hossain et al., 2016).

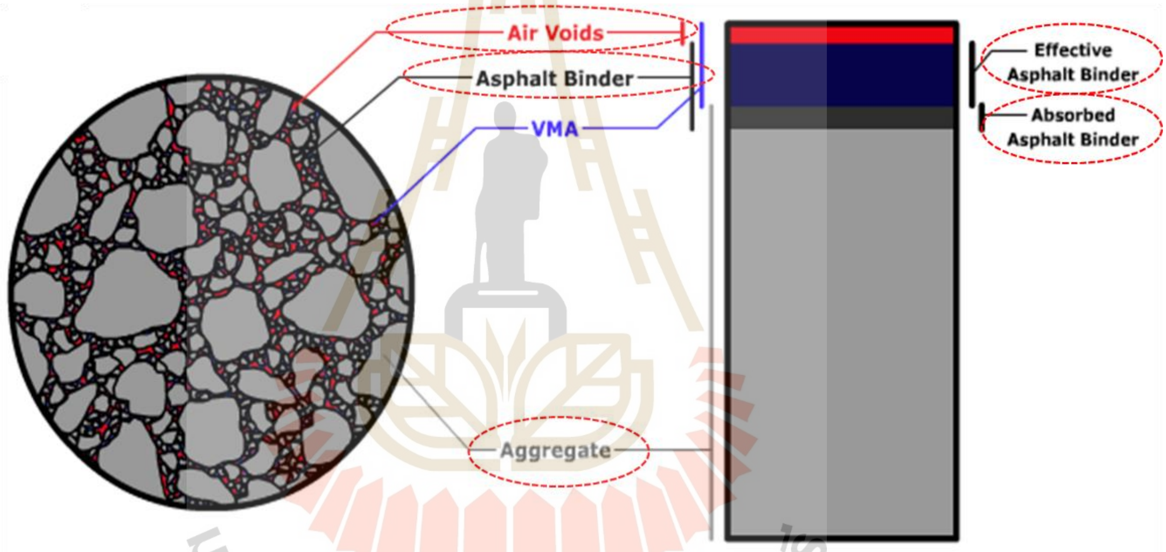

Figure 2.5 The volume fractions of asphalt concrete mixture (Kumar et al., 2021)

Marshall stability is the potential and strength of asphalt concrete against rutting. Flow is the ability of the asphalt concrete mixture to adjust to slow deformation and movements with no cracking. As the flow value increases, the applicability of the mixture increases while the deformation resistance decreases. However, as the flow value is decreased, the stiffness of the mixture is increased (Aghayan & Khafajeh, 2019).

2.4.3 Asphalt concrete mixture design

Various asphalt concrete mix design methods are practiced worldwide, such as Asphalt Institute triaxial, Marshall, Hubbard field, Superpave, and Hveem mix design methods. Out of these three are the most widely practiced: Marshall, Superpave, and Hveem mix design methods (Bahia, 1993). The Marshall mix design procedure is currently practiced in Thailand for the design of asphalt concrete. This method was developed by Bruce Marshall for the Mississippi Highway Department in 1939 (McRae, 1962). It is still widely used in many countries because the equipment is relatively inexpensive and portable. The Marshall method criteria allows the engineer to choose an optimum AC content to be added to specific aggregate blend to a mix where the desired properties of density, stability and flow are met.

The Marshall method uses standard hot mix asphalt (HMA) samples that are 101.6 mm in diameter and 63.5 mm high. The preparation procedure is carefully specified, and involves heating, mixing, and compacting AC/aggregate mixtures. Test specimens are compacted by applying 75 blows per side with the Marshall compaction hammer. The number of blows is determined by the expected traffic level of the pavement section (Brown et al., 2009). Once the Marshall samples have been prepared, they are used to determine the average asphalt mix properties for each AC content. A density-voids analysis is used to determine density, air voids, VMA, and VFA. The Marshal test machine is used to measure the stability and flow of the specimens.

The optimum AC content is determined based on the combined results of Marshall stability and flow and volumetric analysis. Plots of AC content versus measured values of Marshall stability, Marshall flow, density, air voids, VFA, and VMA are generated. Optimum AC content is commonly selected to correspond to 4% and 20% air voids for dense-graded HMA and open-graded HMA, respectively. Then, the percentage of AC is checked to ensure that it is within the limiting criteria for Marshall flow, Marshall stability, VMA, and VFA (Association & Association, 2000).

Furthermore, the Department of Highway, Thailand, specified the strength index (SI) property for HMA design. The durability and moisture susceptibility of HMA is evaluated through the SI value. To conduct the test, the laboratory must adhere to the AASHTO T283 standard (AASHTO, 2007). The SI sample was prepared by compression under a constant pressure of 20.7 MPa for 2 minutes using a double plunger compactor. The compacted sample has a 63.5-mm height and a 101.6-mm diameter. Two sample groups were made: unsoaked samples, designated as a control sample, and soaked samples, which were vacuum-saturated with the sodium chloride solution for 60 minutes and then soaked at 60°C for one day. The ratio between Marshall's stability of soaked and unsoaked samples is the SI value. The Marshall's stability test was run at 25°C using a compression speed of 50 mm/min. The Department of Highways, Thailand (DOH, 1999) specified that the SI value of asphalt concrete should be above 75%.

Additionally, for open-graded HMA or PAC, crucial tests were required to evaluate the properties of PAC mixture, concluding drain down and Cantabro abrasion tests. The drain down test measured the potential for the AC to drain out of the mixture when subjected to elevated temperatures, which can indicate how well the PAC mixture retains its AC during handling, transport, and placement. According to AASHTO T305 (AASHTO, 2018), uncompacted PAC mixtures were evaluated for the drains down characteristics. First, the uncompacted PAC sample determined the initial weight. Second, the uncompacted PAC sample was moved into a wire basket and placed the basket into an oven at mixing temperature (approximately 150°C) with container plate. After 1 hr of heating, the weight of uncompacted PAV sample was measured. The loss percentage of PAC sample by weight was regarded as the drain down value. The Cantabro abrasion was conducted to evaluate the resistance to particle loss of PAC samples according to ASTM D7064 (ASTM, 2021). The PAC samples were prepared by Marshall method. PAC samples shall be tested in 7 days after de-mold in two conditions, concluding soaked and unsoaked. The soaked PAC sample was submerged in water bath at 25°C for 24 hours and then placed in Los Angeles abrasion machine for 300 rotations with speed of 30-33 rpm. The unsoaked PAC sample was placed directly into the Los Angeles abrasion machine. The test was conducted without steel sphere. After 300 rotations, the broken particle of PAC sample was discarded. The weight of PAC sample before and after test was measured.

The loss in PAC sample weight is expressed in percentage of ratio of weight of disintegrated to the initial weight of the specimen.

2.4.4 Performance of asphalt concrete

Performance testing for asphalt concrete aims to assess its potential behavior under operational conditions and predict its long-term performance under various environmental and traffic loading scenarios. This section explains commonly used performance tests for asphalt concrete.

1) Indirect tensile strength (ITS)

The ITS test is widely used to evaluate the cohesive strength of asphalt mixtures. Rather than applying a direct load to pull the sample apart (as in a direct tension test), the ITS test applies a compressive load along the vertical diameter of a cylindrical asphalt concrete sample, causing the sample to fail in horizontal tension. The point at which the sample fails provides a measure of its tensile strength. This method is particularly effective for asphalt concrete mixtures since they are weak in tension.

The ITS test is analyzed using the ASTM D 6931 standards (ASTM, 2017). The Marshall method is used to prepare the samples, and they are tested by loading them across their vertical diametrical plane at a 50 mm/min deformation rate at varying temperatures. The ITS value of the sample is determined using the observed maximum load and the following equation:

$$\mathrm{ITS} = \frac{2000\,\mathrm{P}}{\pi t D} \tag{2.1}$$

where ITS stands for indirect tensile strength (kPa), *P* represents maximum load (N), *t* denotes the sample thickness (mm), and *D* is the sample diameter (mm).

2) Indirect tensile resilient modulus (IT_{MR})

The IT_{MR} is a metric that indicates the ability of an asphalt concrete mixture to recover after repeated loading or its elastic response. This property is important to consider when designing pavements and assessing their performance under traffic loading. The IT_{MR} is not the same as ITS, which measures the strength of the material. In simpler terms, IT_{MR} gauges the material's resistance to deformation or its resilience.

The IT_{MR} is determined by ASTM D 4123-82 (ASTM, 1995) standard by subjecting a Marshall sample to dynamic loading under indirect tensile conditions. Each sample is subjected to a load equivalent to 15% of its ITS along its vertical diameter. The loading frequency is set to 1 Hz with a 0.1-second load and 0.9-second rest period. The test protocol involves 200 loading pulses, and the sample is tested at desired temperature. The IT_{MR} is calculated as the average elastic stiffness over the last five values after the first 150 cycles, as described in equation (2.2).

$$IT_{MR} = \frac{P(0.27+\nu)}{tH_r} \tag{2.2}$$

where IT_{MR} is indirect tensile resilient modulus (MPa), v is Poisson's ratio, t is the sample thickness, and H_r is recoverable horizontal deformation (mm).

3) Indirect tensile fatigue (ITF)

One major cause of pavement failure is fatigue cracking from repeated loads that accumulate damage. According to BS-EN-12697-24 (BSI, 2004), the stress control method is selected using varying target stress levels. A loading strip made of 12.5 mm wide curved stainless steel was used to apply the load. A haversine loading pulse is used to simulate repetitive traffic loading at 1 Hz with a 0.1-second load and 0.9-second rest period. The Marshall sample is subjected to repetitive loading until failure, and its vertical deformation is recorded relative to the number of loading pulses. There are three zones of vertical deformation. In the first zone, the deformation increment is relatively high due to a rapid decrease in air void caused by initial loading cycles. The second zone shows a linear increase in vertical deformation with the number of cycles. During this stage, plastic deformation accumulates, which leads to the formation of microcracks throughout the loading period. The third zone, the development of the microcracks from the first and second zones propagate the macrocrack, resulting in complete failure (Aragao et al., 2008). Indirect tensile fatigue life (ITFL) can be estimated from the second and third-zone slopes intersection points.

4) Rutting resistance

Based on AASHTO T324 (AASHTO, 2008), the rutting resistance of asphalt concrete samples is determined through wheel track testing using the Hamburg wheel tracker testing machine. The testing sample includes two adjacent cylindrical specimens measuring 150 mm in diameter and 60 mm in thickness for measuring rut depth. The testing sample is securely mounted using plastic molds to maintain stability during loading and minimize movement. The cylindrical specimens must be precisely trimmed to fit the plastic molds. A 47-mm wide steel wheel applied the 705-N load on the sample, operating at a rate of 26 cycles/min. The test will end automatically after 10,000 cycles or a rut depth of 20 mm, whichever comes first. The rutting resistance of the asphalt concrete sample is determined through the measurement of the rut depth.

These tests allow for a comprehensive assessment of the behavior of asphalt concrete under various conditions. The results help in mix design optimization, quality control, and the prediction of pavement service life.

2.5 Using recycled materials as aggregate in asphalt concrete mixture

Several studies have suggested using asphalt concrete and concrete wastes as sustainable recycled aggregates (RA) for road construction (Arulrajah et al., 2014; Jayakody et al., 2021; Naser et al., 2022). According to these studies, RAP and RCA exhibit mechanical properties comparable to natural aggregates (NA), especially for low-traffic roads. Moreover, RCA has been found to have superior mechanical properties compared to RAP. RAP and RCA as a substitute for NA in producing new asphalt concrete have exhibited favorable and equivalent mechanistic performance to conventional asphalt concrete (Shu et al., 2008; Sreeram et al., 2018). Shu et al. (2018) investigated the effect of different RAP replacement ratios (0, 10, 20, and 30% by weight of NA) on the mechanistic performance of asphalt concrete. Their findings show that increasing RAP replacement ratio increases ITS and IT_{MR} but decreases fatigue life of asphalt concrete. The improvement of ITS and IT_{MR} can be attributed to the higher stiffness of aged AC present in RAP aggregate compared to new AC, which enhances the overall stiffness of asphalt concretes. However, the stiff aged AC in RAP aggregate negatively affects the fatigue resistance of the asphalt concrete. Abdul-Mawjoud and Ismaeel (2015) also found a similar result in their study, where rutting resistance and ITS increased with increasing RAP replacement content. However, fatigue resistance decreased with increasing RAP replacement content. Nokkaew (2018) reported that asphalt concrete with 40% RAP content has the highest ITS and IT_{MR}, while asphalt concrete with 10% RAP content has the lowest permanent deformation. Thephsriha et al. (2018) conducted a study to investigate the effect of replacing NA with RAP at varying percentages of 0, 20, 40, and 60%. They found that 60% RAP content resulted in the highest ITS and ITFL. However, they recommended that the maximum RAP content should be less than 60% due to its mostly fine particle composition, which can affect the job mix formula. Table 2.5 shows the summary of reviewed research for use of RAP as aggregate in asphalt concrete.

Table 2.5 Summary of reviewed research for use of RAP as aggregate in asphalt concrete

RAP content (%weight by aggregate)	Conditions	Findings	References
0, 10, 20, 30	Replaces in NA	- ITS and IT_{MR} increase as RAP content increase. The highest improvement is found at 30% of RAP content.	Shu et al. (2008)
0, 20, 30, 50, 100	Replaces in NA	- ITS and rutting resistance increase as RAP content increase. The highest improvement is found at 100% RAP. - ITFL decrease as RAP content increases.	Abdul-Mawjoud & Ismaeel (2015)

Table 2.5 Summary of reviewed research for use of RAP as aggregate in asphalt concrete (Continued)

RAP content (%weight by aggregate)	Conditions	Findings	References
10, 20, 30, 40, 50, 60, 70	Replaces in NA	- ITS and IT_{MR} increase as RAP content increases. - Lowest permanent deformation is found at 10% RAP content.	Nokkaew (2018)
20, 40, 60	Replaces in NA	- ITS increases as RAP content increases. - The highest ITFL is found at 60% RAP content. - Lowest permanent deformation is found at 60% RAP content.	Thephsriha et al. (2018)

Radevic et al. (2017) investigated the substitution of coarse RCA (>4.75 mm) for NA in asphalt concrete. Their finding indicated that replacing 30% of NA with RCA resulted in the lowest rut depth, attributed to the interlocking and friction of RCA particles with rough surfaces and sharp edges. Exceeding the 30% replacement of NA with RCA led to an increase in rut depth due to the higher porosity and lower density of RCA compared to NA, which resulted in reduced stiffness and strength of the asphalt concrete. Motter et al. (2009) conducted a study investigating the effect of different percentages of RCA content on rutting resistance. The percentages tested were 0, 25, 50, 75, and 100%. The results showed that rut depth was lower than NA at 25, 50, and 75% RCA content. The lowest rut depth was observed at 75% RCA content. Nejad et al. (2013) conducted a study that used 0%, 35%, 70%, and 100% RCA replacement content. They found that using 70% of RCA replacement content resulted in the highest ITFL. Their results indicate that RCA can be used with RAP to improve the ITFL of asphalt concrete. However, Hou et al. (2018) reported that RCA replacement negatively impacted the IT_{MR}, fatigue resistance, and rutting resistance of asphalt concrete, attributable to RCA's high porosity and microcracks. Huang et al. (2021) investigated the elastic modulus of the interfacial transition zone between the AC and the surface of various aggregates, including RCA, crushed brick, aged granite, and natural limestone. The interfacial transition zone around the RCA particle is thicker than the other aggregates due to its higher porosity. The interfacial transition zone of RCA asphalt concrete also exhibited the lowest elastic modulus, resulting in adverse effects on the performance of asphalt concrete. The summary of reviewed research for use of RCA as aggregate in asphalt concrete are shown in Table 2.6.

Table 2.6 Summary of reviewed research for use of RCA as aggregate in asphalt concrete

RCA content (%weight by aggregate)	Conditions	Findings	References
0, 15, 30, 45	Replaces in NA	- The lowest rut depth is found at 30% RCA content.	Radevic et al. (2016)
0, 25, 50, 75, 100	Replaces in NA	- 25, 50, and 75% RCA content result in lower rut depth than NA. - The lowest rut depth is found at 75% RCA content.	Motter et al. (2009)
0, 35, 70, 100	Replaces in NA	- 70% of RCA content result in highest ITFL.	Nejad et al. (2013)

2.6 Improvement of asphalt concrete mixture

Under intensive environmental effects, road pavements can only sometimes meet the desirable quality requirements. For instance, the impact of temperature differences between summer and winter, load deformation, etc. This results in the fact that pavement service life is decreased (Syrmanova et al., 2017). Road pavements also have thermal susceptibilities and often experience thermal cracking in cold weather and creep and distortion in high-temperature regions (Maharaj & Maharaj, 2015). Moreover, traffic road volume rises and requires an increase in the load-bearing capacities of pavements and their service life span. Such factors illustrate the need for developing AC with enhanced characteristics compared to conventional AC (Fernandes et al., 2017).

The performance of asphalt concrete mixtures implemented in the wearing course of road pavements is likely to be enhanced with different additives to AC like crumb rubber, polymers, rubber latex, etc (Appiah et al., 2017). The most used modifiers or additives in the asphalt concrete mixtures industry are polymers, mostly virgin elastomers, and plasterers, but more recently, other polymers from plastic wastes have also been investigated. Plastic wastes can improve the properties of AC and, consequently, the performance and durability of asphalt concrete mixtures, and they present environmental and economic advantages. On this basis, waste plastics can partially replace AC (Fernandes et al., 2015).

Plastic waste can be either recycled, landfilled, or incinerated for energy recovery (Luijsterburg, 2015). Recycling can further be divided into chemical and mechanical recycling, wherein the latter is the most common method and applied at large scale worldwide (Stenmarck et al., 2017). Chemical recycling allows polymeric waste to be chemically degraded in its monomers or other basic chemicals that can later be reused as a raw material for the production of plastic and petrochemicals, or even as an alternative fuel (Al-Salem et al., 2009; Stenmarck et al., 2017). Mechanical recycling which is the main focus of this study stands out from the other alternatives since it generates pellets/granules that can later be transformed into new plastic products (Aznar et al., 2006) or be used for other purposes such as in the asphalt industry for road paving applications (Ling et al., 2019; White, 2019; White & Reid, 2018). Mechanical recycling is applied to recycle thermoplastic polymers through a mechanical process, which usually includes collection, sorting, shredding, separation, washing, drying, and granulating (Ragaert et al., 2017; Stenmarck et al., 2017). Figure 2.6 illustrates the typical stages of mechanical recycling.

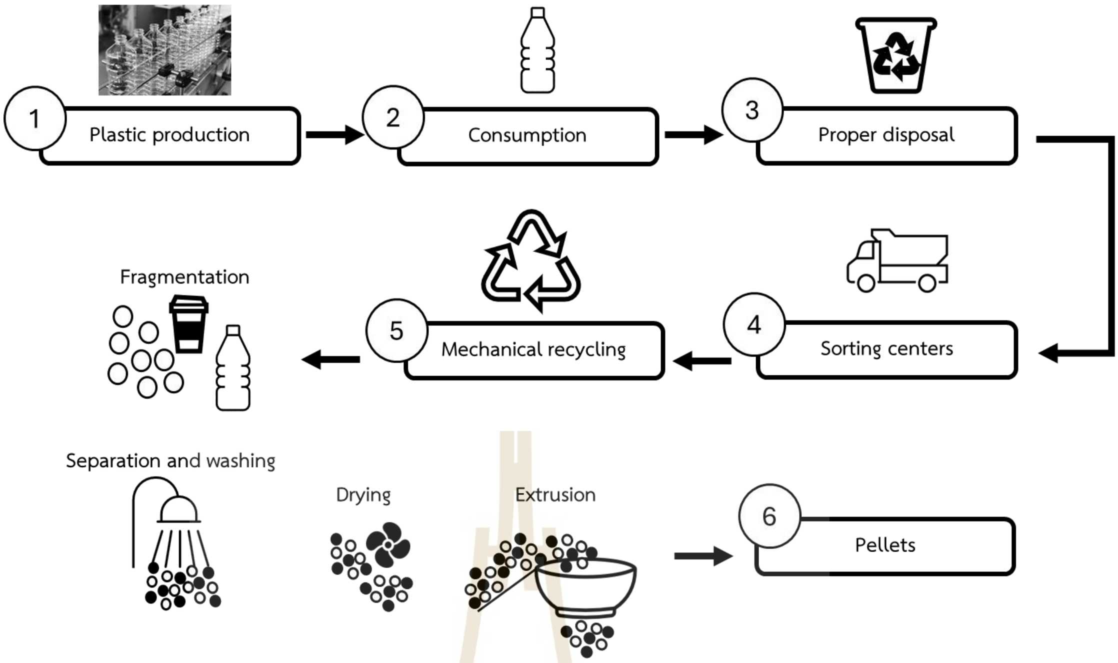

Figure 2.6 Schematic illustration of mechanical recycling of plastic materials (Duarte & Faxina, 2021).

Figure 2.7 illustrates the procedure to incorporate recycled polymers into asphalt concrete mixtures in a discontinuous asphalt plant. As previously stated, in the wet process, plastic is directly added to the hot AC before mixing with aggregates when point ‘b’ is opened, ‘a’ and ‘c’ are closed. In the dry process, plastic is added to the aggregates and mixed properly, then AC is added to this mixture when points ‘a’ and ‘c’ are opened, ‘b’ is closed (Brasileiro et al., 2019).

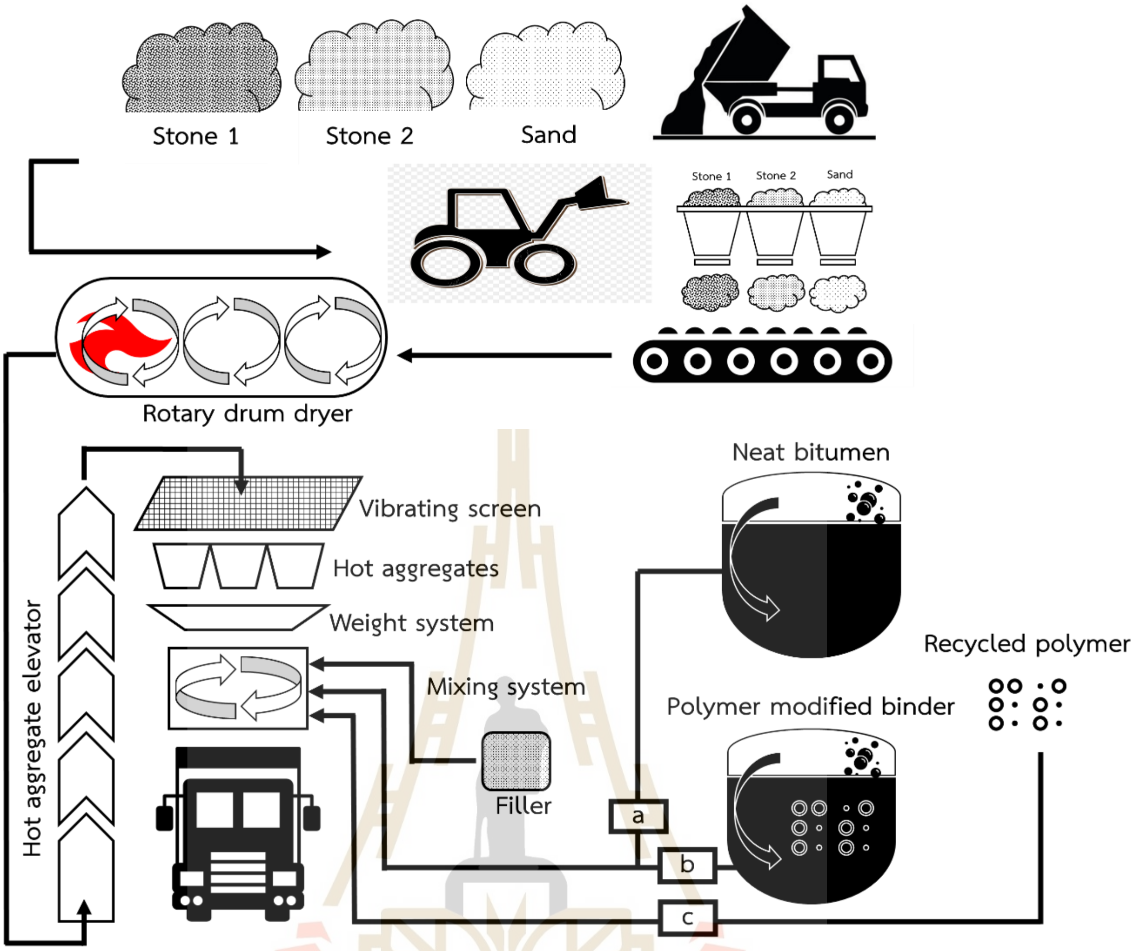

Figure 2.7 Schematic illustrates of the wet and dry processes in a discontinuous asphalt plant (Brasileiro et al., 2019).

The first use of waste plastics in the form of fiber was used in asphalt modification (Tapkın et al., 2009). Since then, the inclusion of all types of plastics has been investigated by researchers (Polacco et al., 2015). The most common forms are the polyethylene terephthalate (PET), polyethylene (PE), and polypropylene (PP) (Giustozzi & Boom, 2021).

The investigations have shown that asphalt performance parameters such as rutting resistance (El-Naga & Ragab, 2019), fatigue resistance (Yu et al., 2019), and stiffness (Nouali et al., 2020) can be improved when plastic waste is added to the asphalt concrete mixture. Nevertheless, some conflicting results were found in the literature. For example, experiments on the effects of HDPE and PP on rutting resistance are not aligned (Wu & Montalvo, 2021). There are various reasons for the inconsistencies, including sample variabilities, poor mixing conditions, lack of temperature controls, and experimental errors. Understanding how waste plastic is introduced into the mixture is also essential. Different mixing methods have different effects on the performance of the resultant mixture.

According to the studies, the wet process enhances some characteristics of virgin AC, such as rutting resistance, temperature susceptibility, and rheological properties (Akkouri et al., 2020; Ibrahim et al., 2020; Köfteci et al., 2020; Nizamuddin et al., 2020; Ponnada & Krishna, 2020). The waste plastic-modified AC is reported to have a higher softening point and lower penetration value than virgin AC (Padhan et al., 2020; Shahane & Bhosale, 2021). The wet process requires special blending equipment, a high-energy and time-consuming process. Moreover, the amount of plastic being recycled in this process is minimal because plastics substitute a small proportion of the AC, and the AC itself is only around 5% of the total weight of the asphalt concrete mixture (Gawande et al., 2012). Similar to the wet process, the dry process has its pros and cons. Compared with the wet process, it can consume more plastic with minor modifications (Cao, 2007; Yildirim, 2007). It is also easier and requires no special equipment (Rodríguez-Fernández et al., 2020). Much of the research on the dry process states that waste plastic modification improves the stiffness modulus, fatigue behavior, rutting resistance, moisture susceptibility, and temperature susceptibility of the mixture (Almeida et al., 2020). These improvements are because the plastics can coat the aggregate surface and enhance the aggregate and AC connection (Vasudevan, 2012; Zoorob & Suparma, 2000) or modify the AC later in the mixing process (Khurshid et al., 2019). However, only some of the research found the same results. The adverse effects of the dry process on the abovementioned properties have been reported (da Silva et al., 2018; Jeong et al., 2011; Moreno et al., 2012). It has been stated that plastics introduced in the dry process are poorly absorbed into the AC due to the short mixing time (Martin-Alfonso et al., 2019). This problem results in an insufficient interaction between the AC and plastics (Tahami et al., 2019).

2.6.1 PET-modified asphalt concrete mixture by dry method

In the dry process, crushed PET bottles are typically added as an aggregate to the asphalt concrete mixture to enhance the road pavement's resistance to permanent deformation and fatigue life (Ahmadinia et al., 2011; Moghaddam et al., 2014). Moghaddam et al. (2012) reported that modifying asphalt concrete with crushed PET bottles with a maximum size of 2.36 mm at various contents, from 0.2 to 1.0%, using the dry method, led to a significant improvement in fatigue life and rutting resistance (Moghaddam et al., 2012). PET's melting components enhance the bond between aggregate and AC, while solid components absorb or dissipate energy during loading cycles. The air void is a crucial factor in the design of asphalt concrete mixtures. Insufficient coating of AC due to increased air voids in the asphalt concrete mixture can lead to pavement cracking. According to multiple studies, increasing the amount of PET in asphalt concrete leads to more air voids (Ahmadinia et al., 2011; Badejo et al., 2017; Moghaddam et al., 2015; Taherkhani & Arshadi, 2019). Therefore, it is necessary to increase the amount of AC to maintain a consistent level of air voids, as noted by Buritatum et al. (2022). The summary of reviewed research for use of PET as an additive in asphalt concrete is shown in Table 2.7.

Table 2.7 Summary of reviewed research for use of PET as an additive in asphalt concrete.

PET content (%)	Conditions	Findings	References
0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0	- Dry method - %weight of aggregate - size of PET less than 2.36 mm	- The highest IT_{MR} is found at 0.1% PET content. - Permanent deformation decrease as PET content increase.	Moghaddam et al., 2014
10, 11, 12, 13, 14, 15	- Dry method - %weight of AC - size of PET less than 2.36 mm	- Highest ITS is found at 12% PET content. - Lowest rut depth is found at 14% PET content.	El-Naga et al., 2019
5, 10, 15, 20, 25	- PET replaces in fine aggregate - %weight of mixture - size of PET in range 1.18 to 2.36 mm - 5% AC content is fixed	- IT_{MR} decreases as PET content increases. - Lowest permanent deformation is found at 20% PET content.	Rahman and Wahab., 2012

2.6.2 PP-modified AC by wet method

Polypropylene (PP) pellets can be added to asphalt concrete (AC) using the wet method to enhance its specific properties, such as stiffness, rutting resistance, and temperature susceptibility. The process involves integrating the polymer directly into the AC. First, an initial percentage of PP pellets must be decided

Table 2.8 Summary of reviewed research for use of PP as an additive in asphalt concrete (Continued)

PP content (%)	Conditions	Findings	Reference
0, 1, 3, 5	- Wet method - %weight of AC	- The PP-modified AC has a lower penetration value than virgin AC. - The softening point of PP-modified AC is higher than that of virgin AC. - The viscosity of PP-modified AC is higher than that of virgin AC. - The ductility of PP-modified AC is lower than that of virgin AC. - The highest improvement value is found at 5% PP content.	Fattah et al., 2021

2.7 Fatigue distress model

Fatigue cracking is a failure which directly affects the service life of asphalt pavement. Usually, the vertical loads applied by traffic create horizontal tensile stress on the bottom of asphalt concrete layers. Strain caused by this stress eventually leads to the occurrence of fatigue cracks in the bottom of asphalt layer as shown in Figure 2.8. Cracks which developed at the bottom of layer will propagate vertically due to increase of load repetitions (Sewell, 2017). These cracks not only decrease the load spreading capacity of asphalt layers, but also allow water to percolate to the base and subgrade, thereby accelerating the complete destruction of pavement, if timely maintenance is not taken up (Pandey, 2003). Fatigue cracks mostly occur at medium and low temperatures because reducing the temperature increases the AC stiffness and at these temperatures asphalt concrete mix tends to behave like a brittle material (ASTM, 1995). Most standards of fatigue testing propose to analyze the fatigue response of asphalt concrete mixtures at moderate temperatures (e.g., 25°C).

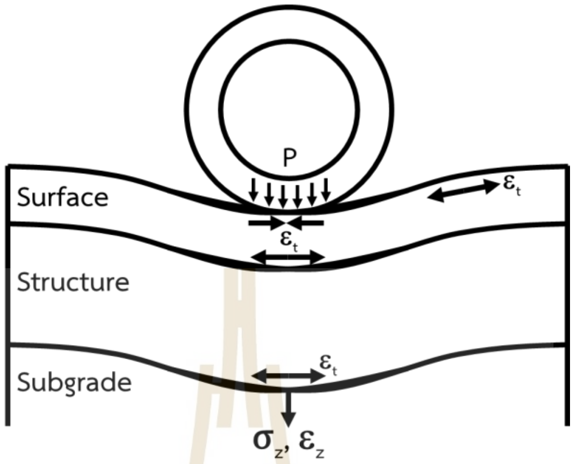

Figure 2.8 Tensile and compressive strain in pavement

Fatigue distress models are mathematical representations that describe the relationship between the number of load repetitions (cycles) and the damage progression in the pavement. These models are crucial for predicting the life of a pavement under given conditions and are instrumental in the design process. A fatigue distress model can be developed by utilizing fatigue law and analyzing data from dynamic testing.

The BS EN 12697-24 (BSI, 2004) standard identifies a linear relationship on a log scale between the fatigue life (N_f) and the initial tensile strain (ε_t), which is known as fatigue law. Based on this law, a fatigue distress model can be developed using the initial tensile strain as a determining factor as follows:

$$N_f = a\left[\frac{1}{\mu\varepsilon_t}\right]^b \qquad (2.3)$$

where *a* and *b* stand for the fatigue parameters based on the regression coefficients, depending upon the material characteristic.

It should be noted that the initial tensile strain can be derived from the applied stress level, Poisson’s ratio, and IT_{MR}, which is obtained through experimental measurements (Kennedy, 1979; Mohammad & Paul, 1993). The initial tensile strain can be calculated using the following equation:

$$\varepsilon_t = \frac{\sigma(1+3v)}{IT_{MR}} \tag{2.4}$$

where σ is applied stress level (kPa) obtained from ITF test, v stands for Poisson’s ratio which, is assumed to be 0.35 based on BS EN 12697-24.

2.8 Reference

AASHTO. (2008). Standard method of test for Hamburg wheel-track testing of compacted hot-mix asphalt (HMA). AASHTO T324. Washington, DC: American Association of State Highway and Transportation Officials.

Aghayan, I., & Khafajeh, R. (2019). Recycling of PET in asphalt concrete. In Use of Recycled Plastics in Eco-efficient Concrete (pp. 269-285). https://doi.org/10.1016/b978-0-08-102676-2.00012-8

Ahmadinia, E., Zargar, M., Karim, M. R., Abdelaziz, M., & Shafigh, P. (2011). Using waste plastic bottles as additive for stone mastic asphalt. Materials & Design, 32(10), 4844-4849.

Akkouri, N., Baba, K., Simou, S., ELfarissi, L., & Nounah, A. (2020). Recycled thermoplastics modified bitumen improved with thermoplastic elastomer. E3S Web of Conferences,

Al-Khateeb, G., & Shenoy, A. (2004). A distinctive fatigue failure criterion. Journal of the association of asphalt paving technologists, 73, 585-622.

Al-Salem, S., Lettieri, P., & Baeyens, J. (2009). Recycling and recovery routes of plastic solid waste (PSW): A review. Waste Management, 29(10), 2625-2643.

Almeida, A., Capitão, S., Bandeira, R., Fonseca, M., & Picado-Santos, L. (2020). Performance of AC mixtures containing flakes of LDPE plastic film collected from urban waste considering ageing. Construction and Building Materials, 232, 117253.

upon, typically between 1% to 5% of the weight of the AC. However, the optimal amount can vary based on the desired properties and specific applications (Giustozzi & Boom, 2021). The next step is to homogenize the mixture of AC and PP pellets using high shear to break down the pellets and achieve uniform polymer dispersion in the AC (Garside, 2020; Gawande et al., 2012; Heydari et al., 2021; Martin-Alfonso et al., 2019). Once the mixing is complete, samples of the PP-modified AC should be drawn and tested for their properties. Table 2.8 summarizes some reviewed research on using PP as an additive in asphalt concrete.

Table 2.8 Summary of reviewed research for use of PP as an additive in asphalt concrete.

PP content (%)	Conditions	Findings	Reference
0, 5, 7	- Wet method - %weight of AC	- The highest ITS and Marshall stiffness is found at 5% PP content.	Moubark et al., 2017
0, 3, 5	- Wet method - %weight of AC	- The PP-modified AC has higher shear dynamic value than virgin AC.	Yeh et al., 2005
0, 1, 2, 3	- Wet method - %weight of AC	- The PP-modified AC has higher viscosity than virgin AC. - The penetration of PP-modified AC is lower than that of virgin AC. - The softening point of PP-modified AC is higher than that of virgin AC. - The highest improvement value is found at 3% PP content.	Habib et al., 2011

Appiah, J. K., Berko-Boateng, V. N., & Tagbor, T. A. (2017). Use of waste plastic materials for road construction in Ghana. Case studies in construction materials, 6, 1-7.

Aragao, F. T. S., Kim, Y.-R., & Lee, J. (2008). Research on Fatigue of Asphalt Mixtures and Pavements in Nebraska.

Arulrajah, A., Piratheepan, J., & Disfani, M. M. (2014). Reclaimed asphalt pavement and recycled concrete aggregate blends in pavement subbases: Laboratory and field evaluation. Journal of Materials in Civil Engineering, 26(2), 349-357.

Association, N. A. P., & Association, A. P. W. (2000). Hot-Mix Asphalt Paving Handbook 2000: AC150/5370–14A Appendix 1 (0309071577).

ASTM. (1995). Standard test method for indirect tension test for resilient modulus of bituminous mixtures. ASTM D4123-82. West Conshohocken, PA: ASTM.

ASTM. (2017). Standard test method for indirect tensile (IDT) strength of asphalt mixtures. ASTM D6931. West Conshohocken, PA: ASTM.

Aznar, M. P., Caballero, M. A., Sancho, J. A., & Francés, E. (2006). Plastic waste elimination by co-gasification with coal and biomass in fluidized bed with air in pilot plant. Fuel processing technology, 87(5), 409-420.

Badejo, A. A., Adekunle, A. A., Adekoya, O. O., Ndambuki, J. M., Kupolati, K. W., Bada, B. S., & Omole, D. O. (2017). Plastic waste as strength modifiers in asphalt for a sustainable environment. African Journal of Science, Technology, Innovation and Development, 9(2), 173-177.

Bahia, H. U. (1993). Bibliographies for physical properties of asphalt cement.

Brasileiro, L., Moreno-Navarro, F., Tauste-Martínez, R., Matos, J., & Rubio-Gámez, M. d. C. (2019). Reclaimed polymers as asphalt binder modifiers for more sustainable roads: A review. Sustainability, 11(3), 646.

Brovelli, C., Crispino, M., Pais, J., & Pereira, P. (2015). Using polymers to improve the rutting resistance of asphalt concrete. Construction and Building Materials, 77, 117-123.

Brown, E. R., Kandhal, P. S., Roberts, F. L., Kim, Y. R., Lee, D.-Y., & Kennedy, T. W. (2009). Hot mix asphalt materials, mixture design, and construction. NAPA research and education foundation.

BSI. (2004). Bituminous mixtures. Test methods for hot mix asphalt part 24: Resistance to fatigue. BS-EN12697-24. .

Cao, W. (2007). Study on properties of recycled tire rubber modified asphalt mixtures using dry process. Construction and Building Materials, 21(5), 1011-1015.

Chen, J.-S., & Liao, M.-C. (2002). Evaluation of internal resistance in hot-mix asphalt (HMA) concrete. Construction and Building Materials, 16(6), 313-319.

China, D. (2005). Test methods of aggregate for highway engineering. JTG E42-2005. Beijing: China DOT.

da Silva, L., Benta, A., & Picado-Santos, L. (2018). Asphalt rubber concrete fabricated by the dry process: Laboratory assessment of resistance against reflection cracking. Construction and Building Materials, 160, 539-550.

DOH. (2007). Pavement Distress Identification Manual. Ministry of Transport, Bureau of Martials Analysis and Inspection, Bureau of Highway Maintenance Management, Department of Highway, Thailand.

Duarte, G. M., & Faxina, A. L. (2021). Asphalt concrete mixtures modified with polymeric waste by the wet and dry processes: A literature review. Construction and Building Materials, 312, 125408.

El-Naga, I. A., & Ragab, M. (2019). Benefits of utilization the recycle polyethylene terephthalate waste plastic materials as a modifier to asphalt mixtures. Construction and Building Materials, 219, 81-90.

Facts, L. (2007). National Asphalt Pavement Association (NAPA). Landham, MD, no date, in.

Fang, M., Park, D., Singuranayo, J. L., Chen, H., & Li, Y. (2019). Aggregate gradation theory, design and its impact on asphalt pavement performance: a review. International Journal of Pavement Engineering, 20(12), 1408-1424.

Fernandes, S., Costa, L., Silva, H., & Oliveira, J. (2017). Effect of incorporating different waste materials in bitumen. Ciência & Tecnologia dos Materiais, 29(1), e204-e209.

Fernandes, S. R., Costa, L., Silva, H. M. R. D. d., & Oliveira, J. (2015). Utilization of waste materials to improve asphalt mixtures performance.

Fletcher, T., Chandan, C., Masad, E., & Sivakumar, K. (2002). Measurement of aggregate texture and its influence on hot mix asphalt (HMA) permanent deformation. Journal of testing and evaluation, 30(6), 524-531.

Gallo, P., & Valentin, J. (2019). Stone mastic asphalt reinforced by vegetable yarns. International Conference on Sustainable Materials, Systems and Structures (SMSS2019): New Generation of Construction Materials,

Garside, M. (2020). Production of plastics worldwide from 1950 to 2019. Statista 2021.

Gawande, A., Zamre, G., Renge, V., Bharsakale, G., & Tayde, S. (2012). Utilization of waste plastic in asphalting of roads. Scientific Reviews & chemical communications, 2(2), 147-157.

Gholizadeh-Vayghan, A., Bellinkx, A., Snellings, R., Vandoren, B., & Quaghebeur, M. (2020). The effects of carbonation conditions on the physical and microstructural properties of recycled concrete coarse aggregates. Construction and Building Materials, 257, 119486.

Giustozzi, F., & Boom, Y. (2021). Use of road-grade recycled plastics for sustainable asphalt pavements: overview of the recycled plastic industry and recycled plastic types.

Gong, F., Liu, Y., You, Z., & Zhou, X. (2021). Characterization and evaluation of morphological features for aggregate in asphalt mixture: A review. Construction and Building Materials, 273, 121989.

Gudimettla, J., Myers, L. A., & Paugh, C. (2006). AIMS: The Future in Rapid, Automated Aggregated Shape and Texture Measurement. Proceedings of the annual conference-canadian technical asphalt association.

Hasita, S., Hoy, M., Suddeepong, A., Horpibulsuk, S., Yeanyong, C., Arulrajah, A., & Mohammadinia, A. (2021). Performance and toxic leaching evaluation of dense-graded asphalt concrete using steel slag as aggregate. Journal of Materials in Civil Engineering, 33(1), 04020432.

Heydari, S., Hajimohammadi, A., Haji Seyed Javadi, N., & Khalili, N. (2021). The use of plastic waste in asphalt: A critical review on asphalt mix design and Marshall properties. Construction and Building Materials, 309. https://doi.org/10.1016/j.conbuildmat.2021.125185

Howson, J., Masad, E., Little, D., & Kassem, E. (2012). Relationship between bond energy and total work of fracture for asphalt binder-aggregate systems. Road Materials and Pavement Design, 13(sup1), 281-303.

Huang, B., Chen, X., Shu, X., Masad, E., & Mahmoud, E. (2009). Effects of coarse aggregate angularity and asphalt binder on laboratory-measured permanent deformation properties of HMA. International Journal of Pavement Engineering, 10(1), 19-28.

Hunter, R. N., Self, A., Read, J., & Hobson, E. (2015). The shell bitumen handbook (Vol. 514). Ice Publishing London, UK:.

Hussein, Z., Yaacob, H., Idham, M., Abdulrahman, S., Choy, L., & Jaya, R. (2020). Rejuvenation of hot mix asphalt incorporating high RAP content: issues to consider. IOP Conference Series: Earth and Environmental Science,

Ibrahim, B., Wiranata, A., & Malik, A. (2020). The effect of addition of antioxidant 1, 2-dihydro-2, 2, 4-trimethyl-quinoline on characteristics of crepe rubber modified asphalt in short term aging and long term aging conditions. Applied Sciences, 10(20), 7236.

Jayakody, S., Gallage, C., & Ramanujam, J. (2021). Assessment of RCA with RAP materials for pavement applications. IOP Conference Series: Materials Science and Engineering,

Jeong, K.-D., Lee, S.-J., & Kim, K. W. (2011). Laboratory evaluation of flexible pavement materials containing waste polyethylene (WPE) film. Construction and Building Materials, 25(4), 1890-1894.

Kasikitwiwat, P., & Jantarachot, K. (2021). Comparative study of fatigue of asphalt concrete mixed with AC 60-70 and polymer modified asphalt binder. Science & Technology Asia, 39-49.

Kennedy, T. (1979). Practical use of the indirect tensile test for the characterisation of pavement materials. Australian road research board conference proc,

Khurshid, M. B., Qureshi, N. A., Hussain, A., & Iqbal, M. J. (2019). Enhancement of hot mix asphalt (HMA) properties using waste polymers. Arabian Journal for science and Engineering, 44, 8239-8248.

Köfteci, S., Gunay, T., & Ahmedzade, P. (2020). Rheological analysis of modified bitumen by PVC based various recycled plastics. Journal of Transportation Engineering, Part B: Pavements, 146(4), 04020063.

Kuang, D., Wang, X., Jiao, Y., Zhang, B., Liu, Y., & Chen, H. (2019). Influence of angularity and roughness of coarse aggregates on asphalt mixture performance. Construction and Building Materials, 200, 681-686.

Kuang, D., Zhang, B., Jiao, Y., Fang, J., Chen, H., & Wang, L. (2017). Impact of particle morphology on aggregate-asphalt interface behavior. Construction and Building Materials, 132, 142-149.

Kumar, V., Coleri, E., & Obaid, I. A. (2021). Constructing High Performance Asphalt Pavements by Improving in Place Pavement Density.

Leng, Z., Gamez, A., & Al-Qadi, I. L. (2014). Mechanical property characterization of warm-mix asphalt prepared with chemical additives. Journal of Materials in Civil Engineering, 26(2), 304-311.

Ling, T., Lu, Y., Zhang, Z., Li, C., & Oeser, M. (2019). Value-added application of waste rubber and waste plastic in asphalt binder as a multifunctional additive. Materials, 12(8), 1280.

Liu, J., Zhao, S., Li, L., Li, P., & Saboundjian, S. (2017). Low temperature cracking analysis of asphalt binders and mixtures. Cold Regions Science and Technology, 141, 78-85.

Lugo, A., Allex, E., Arámbula, E., Spinel, C., Alvarez Lugo, A., Mercado, E., & Caro Spinel, S. (2008). X-ray computed tomography and aggregate image system (AIMS) for studying hot mix asphalt and aggregates. 1foldr Import 2019-10-08 Batch 5.

Luijsterburg, B. (2015). Mechanical recycling of plastic packaging waste.

Maharaj, R., & Maharaj, C. (2015). Physical properties of low density polyethylene, polyvinylchloride and used engine oil modified asphalt. Progress in Rubber Plastics and Recycling Technology, 31(3), 173-187.

Mamlouk, M. S., & Zaniewski, J. P. (2014). Materials for civil and construction engineers. Pearson London, UK:.

Martin-Alfonso, J., Cuadri, A., Torres, J., Hidalgo, M., & Partal, P. (2019). Use of plastic wastes from greenhouse in asphalt mixes manufactured by dry process. Road Materials and Pavement Design, 20(sup1), S265-S281.

Masson, J. (2008). Brief review of the chemistry of polyphosphoric acid (PPA) and bitumen. Energy & Fuels, 22(4), 2637-2640.

McRae, J. (1962). Development of the gyratory testing machine and procedures for testing bituminous paving mixtures.

Michalica, P., Kazatchkov, I. B., Stastna, J., & Zanzotto, L. (2008). Relationship between chemical and rheological properties of two asphalts of different origins. Fuel, 87(15-16), 3247-3253.

Moghaddam, T. B., Karim, M. R., & Syammaun, T. (2012). Dynamic properties of stone mastic asphalt mixtures containing waste plastic bottles. Construction and Building Materials, 34, 236-242.

Moghaddam, T. B., Soltani, M., & Karim, M. R. (2014). Evaluation of permanent deformation characteristics of unmodified and Polyethylene Terephthalate modified asphalt mixtures using dynamic creep test. Materials & Design, 53, 317-324.

Moghaddam, T. B., Soltani, M., Karim, M. R., & Baaj, H. (2015). Optimization of asphalt and modifier contents for polyethylene terephthalate modified asphalt mixtures using response surface methodology. Measurement, 74, 159-169.

Mohammad, L. N., & Paul, H. R. (1993). Evaluation of indirect tensile test for determining structural properties of asphalt mix.

Moreno, F., Rubio, M., & Martinez-Echevarria, M. (2012). The mechanical performance of dry-process crumb rubber modified hot bituminous mixes: The influence of digestion time and crumb rubber percentage. Construction and Building Materials, 26(1), 466-474.

Movilla-Quesada, D., Raposeiras, A. C., Castro-Fresno, D., & Peña-Mansilla, D. (2015). Experimental study on stiffness development of asphalt mixture containing cement and Ca (OH) 2 as contribution filler. Materials & Design, 74, 157-163.

Naser, M., tasim Abdel-Jaber, M., Al-shamayleh, R., Louzi, N., & Ibrahim, R. (2022). Evaluating the effects of using reclaimed asphalt pavement and recycled concrete aggregate on the behavior of hot mix asphalts. Transportation Engineering, 10, 100140.

Nizamuddin, S., Jamal, M., Gravina, R., & Giustozzi, F. (2020). Recycled plastic as bitumen modifier: The role of recycled linear low-density polyethylene in the modification of physical, chemical and rheological properties of bitumen. Journal of cleaner Production, 266, 121988.

Nouali, M., Derriche, Z., Ghorbel, E., & Chuanqiang, L. (2020). Plastic bag waste modified bitumen a possible solution to the Algerian road pavements. Road Materials and Pavement Design, 21(6), 1713-1725.

Padhan, R. K., Mohanta, C., Sreeram, A., & Gupta, A. (2020). Rheological evaluation of bitumen modified using antistripping additives synthesised from waste polyethylene terephthalate (PET). International Journal of Pavement Engineering, 21(9), 1083-1091.

Pan, T. (2006). Investigation of coarse aggregate morphology affecting hot mix behavior using image analysis. ProQuest.

Pandey, B. (2003). Recent trends on design of bituminous mix design. Seminar on Design of Bituminous Mixes,

Perng, J.-D. (1989). Analysis of crack propagation in asphalt concrete using a cohesive crack model The Ohio State University].

Polacco, G., Filippi, S., Merusi, F., & Stastna, G. (2015). A review of the fundamentals of polymer-modified asphalts: Asphalt/polymer interactions and principles of compatibility. Advances in colloid and interface science, 224, 72-112.

Ponnada, S., & Krishna, K. V. (2020). Experimental investigation on modification of rheological parameters of bitumen by using waste plastic bottles. Materials Today: Proceedings, 32, 692-697.

Qu, X., Wang, D., Wang, L., Huang, Y., Hou, Y., & Oeser, M. (2018). The state-of-the-art review on molecular dynamics simulation of asphalt binder. Advances in Civil Engineering, 2018.

Ragaert, K., Delva, L., & Van Geem, K. (2017). Mechanical and chemical recycling of solid plastic waste. Waste Management, 69, 24-58.

Rajan, B., & Singh, D. (2017). Understanding influence of crushers on shape characteristics of fine aggregates based on digital image and conventional techniques. Construction and Building Materials, 150, 833-843.

Rodríguez-Fernández, I., Baheri, F. T., Cavalli, M. C., Poulikakos, L. D., & Bueno, M. (2020). Microstructure analysis and mechanical performance of crumb rubber modified asphalt concrete using the dry process. Construction and Building Materials, 259, 119662.

Roque, R., Birgisson, B., Drakos, C., & Sholar, G. (2005). Guidelines for use of modified binders.

Sadeq, M., Al-Khalid, H., Masad, E., & Sirin, O. (2016). Comparative evaluation of fatigue resistance of warm fine aggregate asphalt mixtures. Construction and Building Materials, 109, 8-16.

Sewell, A. J. (2017). Crack propagation in high modulus asphalt mixtures University of Nottingham].

Shahane, H. A., & Bhosale, S. S. (2021). E-Waste plastic powder modified bitumen: Rheological properties and performance study of bituminous concrete. Road Materials and Pavement Design, 22(3), 682-702.

Shu, X., Huang, B., & Vukosavljevic, D. (2008). Laboratory evaluation of fatigue characteristics of recycled asphalt mixture. Construction and Building Materials, 22(7), 1323-1330.

Sreeram, A., Leng, Z., Zhang, Y., & Padhan, R. K. (2018). Evaluation of RAP binder mobilisation and blending efficiency in bituminous mixtures: An approach using ATR-FTIR and artificial aggregate. Construction and Building Materials, 179, 245-253.

Stenmarck, Å., Belleza, E. L., Fråne, A., & Busch, N. (2017). Hazardous substances in plastics:–ways to increase recycling. Nordic Council of Ministers.

Suddeepong, A., Buritatum, A., Dasdawan, S., Horpibulsuk, S., Yaowarat, T., Hoy, M., & Arulrajah, A. (2023). Mechanical performance of porous asphalt concrete incorporating bottom ash as fine aggregate. Journal of Materials in Civil Engineering, 35(6), 04023129.

Sun, W. (2015). Quantification of Morphological Characteristics of Aggregates at Multiple Scales Virginia Tech].

Sun, Y., Huang, B., Chen, J., Jia, X., & Ding, Y. (2016). Characterizing rheological behavior of asphalt binder over a complete range of pavement service loading frequency and temperature. Construction and Building Materials, 123, 661-672.

Syrmanova, K., Botashev, E., Tleuov, D., Suleimenova, M., Eshankulov, A., & Kaldybekova, Z. B. (2017). Research of oil road bitumen modification with low density polyethylene. Oriental Journal of Chemistry, 33(1), 470-477.

Tahami, S. A., Mirhosseini, A. F., Dessouky, S., Mork, H., & Kavussi, A. (2019). The use of high content of fine crumb rubber in asphalt mixes using dry process. Construction and Building Materials, 222, 643-653.

Taherkhani, H., & Arshadi, M. R. (2019). Investigating the mechanical properties of asphalt concrete containing waste polyethylene terephthalate. Road Materials and Pavement Design, 20(2), 381-398.

Tangella, S. R., Craus, J., Deacon, J., & Monismith, C. (1990). Summary report on fatigue response of asphalt mixtures.

Tapkın, S., Çevik, A., & Uşar, Ü. (2009). Accumulated strain prediction of polypropylene modified marshall specimens in repeated creep test using artificial neural networks. Expert Systems with Applications, 36(8), 11186-11197.

Vasudevan, R. (2012). Ramalinga Chandra Sekar A, Sundarakannan B, Velkennedy R. A technique to dispose waste plastics in an ecofriendly way-application in construction of flexible pavements. Construction and Building Materials, 28(1), 311-320.

Wang, H.-P., Guo, Y.-X., Wu, M.-Y., Xiang, K., & Sun, S.-R. (2021). Review on structural damage rehabilitation and performance assessment of asphalt pavements. Reviews on Advanced Materials Science, 60(1), 438-449.

Wang, X., Shen, S., Huang, H., & Zhang, Z. (2019). Towards smart compaction: Particle movement characteristics from laboratory to the field. Construction and Building Materials, 218, 323-332.

Wei, J., Liu, Z., & Zhang, Y. (2013). Rheological properties of amorphous poly alpha olefin (APAO) modified asphalt binders. Construction and Building Materials, 48, 533-539.

White, G. (2019). Evaluating recycled waste plastic modification and extension of bituminous binder for asphalt. Eighteenth Annual International Conference on Pavement Engineering, Asphalt Technology and Infrastructure, Liverpool, England, United Kingdom,

White, G., & Reid, G. (2018). Recycled waste plastic for extending and modifying asphalt binders. 8th Symposium on Pavement Surface Characteristics (SURF 2018), Brisbane, Queensland, Australia,

Wu, S., & Montalvo, L. (2021). Repurposing waste plastics into cleaner asphalt pavement materials: A critical literature review. Journal of cleaner Production, 280, 124355.

Yildirim, Y. (2007). Polymer modified asphalt binders. Construction and Building Materials, 21(1), 66-72.

Yu, H., Zhu, Z., Zhang, Z., Yu, J., Oeser, M., & Wang, D. (2019). Recycling waste packaging tape into bituminous mixtures towards enhanced mechanical properties and environmental benefits. Journal of cleaner Production, 229, 22-31.

Zhang, K., & Muhunthan, B. (2017). Effects of production stages on blending and mechanical properties of asphalt mixtures with reclaimed asphalt pavement. Construction and Building Materials, 149, 679-689.

Zhang, M., Hao, P., Dong, S., Li, Y., & Yuan, G. (2020). Asphalt binder micro-characterization and testing approaches: A review. Measurement, 151, 107255.

Zoorob, S., & Suparma, L. (2000). Laboratory design and investigation of the properties of continuously graded Asphaltic concrete containing recycled plastics aggregate replacement (Plastiphalt). Cement and concrete composites, 22(4), 233-242.

CHAPTER III

EVALUATING POLYETHYLENE TEREPHTHALATE IN ASPHALT CONCRETE WITH RECLAIMED ASPHALT PAVEMENT FOR ENHANCED PERFORMANCE

3.1 Introduction

This chapter aims to evaluate the effect of polyethylene terephthalate (PET) content on the Marshall properties and mechanical performance of RAP asphalt concrete. The mechanical performance of RAP asphalt concrete modified with PET was evaluated through various tests, including indirect tensile strength (ITS), indirect tensile resilient modulus (IT_{MR}), indirect tensile fatigue life (ITFL), and rutting resistance tests.

3.2 Materials and Methods

3.2.1 Materials

The PET aggregates were obtained by cleaning and chopping plastic water bottles into smaller pieces. As depicted in Figure 3.1(a), the PET was subsequently passed through a sieve with a mesh size of 2.36 mm. Reclaimed asphalt pavement (RAP) analyzed in Figure 1(b) was prepared in the same manner as in Buritatum et al.'s (2023) study, and a summary of its properties is provided in Table 3.1. Before adding asphalt cement during dry mixing, PET was incorporated into the RAP aggregate. Six distinct percentages of PET were employed, specifically 0%, 0.2%, 0.4%, 0.6%, 0.8%, and 1.0% relative to the total weight of RAP.

(a) (b)

Figure 3.1 Studied PET (a) and RAP (b).

Table 3.1 Properties of RAP aggregate.

Properties	Unit	Specifications (DOH, 1999)	RAP (Buritatum et al., 2023)
Soundness	%	< 9	10.21
Los Angeles abrasion value	%	< 40	47.03
Flakiness index	%	< 35	33.00
Elongation index	%	< 35	34.00
Water absorption	%	-	1.49
Asphalt content in RAP	%	-	5.67

The asphalt cement AC60/70 was used in this study. As shown in Table 3.2, the material's properties were evaluated in relation to the asphalt cement specifications outlined by the standard of Department of Highways, Thailand (DOH, 1988). This standard is similar to the international standard for asphalt cement specifications by the Asphalt Institute (AI, 2014). The properties of the studied asphalt cement were found to satisfy the specified requirements.

Table 3.2 Properties of asphalt cement

Properties	Units	Specifications (DOH, 1988)	AC60/70 (Buritatum et al., 2023)
Penetration	-	60-70	67
Flash point	°C	>232	332
Ductility 25°C	cm	>100	150
Solubility in trichloroethylene	%Weight	>99.0	99.97
Test on residue from thin film oven test (5 hour @ 163°C)			
Weight loss	%	<0.8	0.12
Penetration	% of original	>54	71.1
Ductility 25°C	cm	>50	150

3.2.2 Mix design and sample preparation

Figure 3.2 depicts the gradation curve developed for the RAP aggregate utilized in this study. The curve adheres to the maximum aggregate size mandated for asphalt hot mix recycling, which is 12.5 millimeters, in accordance with DOH (1999).

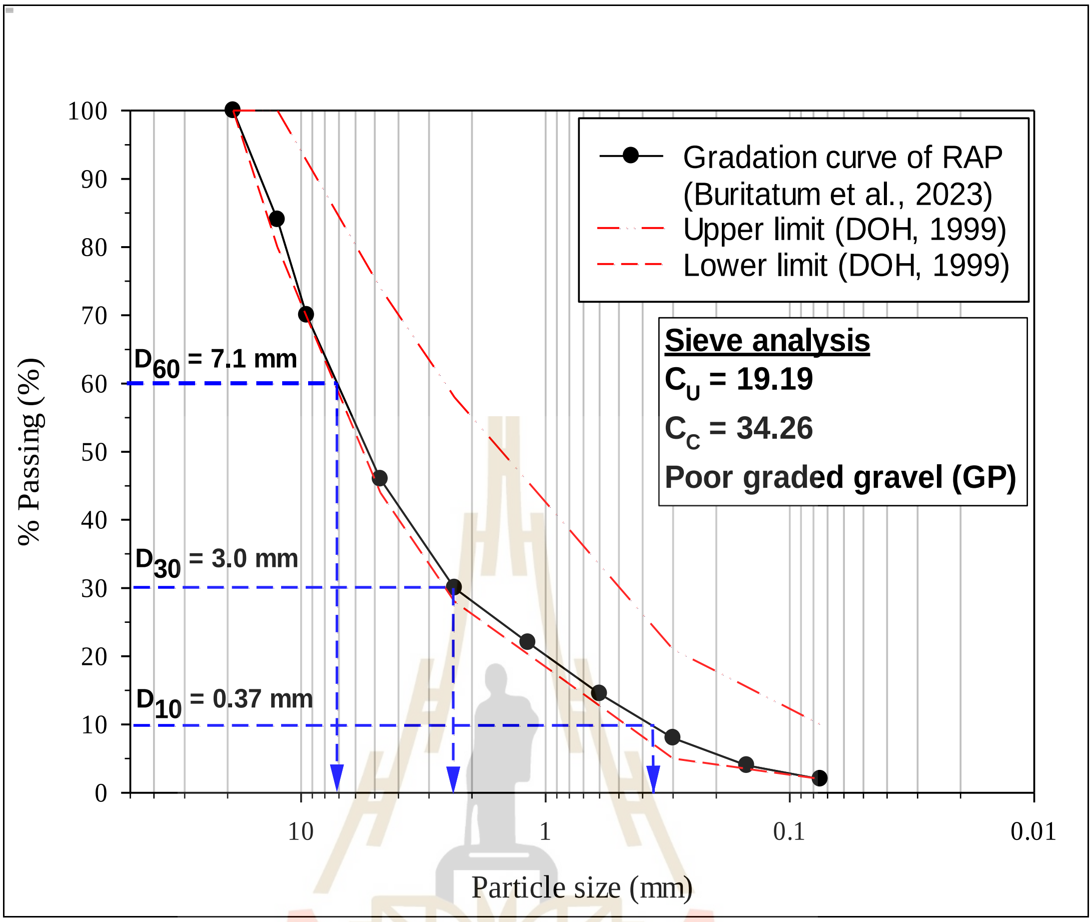

Figure 3.2 Gradation curve of aggregate (Buritatum et al., 2023).

The determination of suitable blend proportions for RAP-asphalt concrete, which has been modified with polyethylene terephthalate (PET), was conducted using the Marshall method as outlined in ASTM standard D 6927 (ASTM, 2015). Both RAP and AC60/70 samples were heated to 180°C and 160°C, respectively. To ensure complete coating of the aggregate, the RAP and AC60/70 mixtures were mixed at 150°C for 60 seconds. Using the Marshall hammer, the mixtures were then densely compacted into metallic molds. Based on the DOH (1999), the surface-wearing course of the recycled asphalt concrete mixture must be prepared by the Marshall method with 75 blows for each side. The referenced standard of DOH (1999) is the present standard for recycled asphalt concrete construction in Thailand, which is still commonly used for field practice. It is similar to the international standard for the recycled asphalt concrete mixture of the Asphalt Institute (AI, 2014). The samples were characterized using standard dimensions, specifically 63.5-mm height and 101.6-mm diameter. The samples were removed from the molds following a 24-hour duration. The Marshall test was developed with the purpose of assessing the characteristic properties of RAP-asphalt concrete that has been modified using polyethylene terephthalate (PET). The aforementioned characteristics encompassed density, void mineral in aggregate (VMA), air void content, voids filled by asphalt concrete (VFA), Marshall stability (MS), and Marshall flow.

RAP-asphalt concrete utilized in the experiment served as the control group, devoid of any PET content. The aggregate properties, aggregate gradation, and asphalt cement properties of this control group were consistent with those outlined in the Buritatum et al. (2023) study. Hence, the asphalt cement that yielded the best results for the asphalt concrete mixture was also the same. The optimal asphalt cement content was determined by assuming a total asphalt cement content ranging from 6 to 9% by total weight of the mixture, which includes both the old asphalt cement in the RAP aggregate and the added AC60/70. The criterion for determining the optimum content was to achieve a 4% air void. When higher quantities of AC60/70 are introduced, there is a reduction in the volume of air voids. To attain an air void percentage of 4%, a total asphalt cement content of 7.07% is required (Buritatum et al., 2023). This total asphalt cement content comprises of 5.67% old asphalt content and an additional 1.40% of AC60/70 asphalt cement.

3.3 Experimental program

3.3.1 Strength index (SI)

The AASHTO T 283 standard (AASHTO, 2007) was adopted for the strength index (SI) tests. The samples were compressed at a constant pressure of 20.7 MPa for 2 minutes. This compression was attained using a double-plunger compactor with dimensions of 63.5-mm height and 101.6-mm diameter. The experiment required the preparation of two test sets. Set 1, comprised of unsoaked samples, was designated the control group. In Set 2, samples were vacuum-saturated with the soaking solution for one hour, followed by a 24-hour soak at 60°C. The SI value was determined through the computation of the ratio between the Marshall stability (MS) of the immersed samples and the MS of the non-immersed samples. The experimental procedure was carried out under controlled conditions with a temperature of 25°C and a loading rate of 50 mm/min.

3.3.2 Indirect tensile strength (ITS)

The indirect tensile strength test samples were prepared using the Marshall technique with 75 hammer blows on each side. The indirect tensile strength of RAP asphalt concretes modified with PET were evaluated according to ASTM D 6931 (ASTM, 2017). The samples were loaded along their vertical diametrical plane at a constant deformation rate (50 mm/min) during testing. Temperatures of 25, 40, 50, and 60°C were used for testing. The sample's ITS value was determined using the observed maximum load and the following equation (3.1).

$$\mathrm{ITS} = \frac{2000P}{\pi t D} \tag{3.1}$$

where ITS stands for indirect tensile strength (kPa), P represents maximum load (N), t denotes the sample thickness (mm), and D is the sample diameter (mm).

3.3.3 Indirect tensile resilient modulus (IT_{MR})

The IT_{MR} was calculated using the ASTM D 4123-82 (ASTM, 1995) standard, which involved subjecting a Marshall sample to dynamic loading while under indirect tensile conditions. A load equivalent to 15% of the sample's initial tensile strength (ITS) was applied along its vertical diameter. The loading frequency was configured at a rate of 1 Hz, accompanied by 0.1-s loading and subsequent 0.9-s resting. The experimental procedure consisted of subjecting the sample to a total of 200 loading pulses, with the testing conducted at 25°C. IT_{MR} was determined by averaging elastic stiffness of the five most recent data points following the initial 150 cycles, as specified in equation (3.2).

$$IT_{MR} = \frac{P(0.27+\nu)}{tH_r} \tag{3.2}$$

where IT_{MR} is indirect tensile resilient modulus (MPa), v is Poisson's ratio, t is the sample thickness, and H_r is recoverable horizontal deformation (mm).

3.3.4 Indirect tensile fatigue (ITF)

Fatigue cracking resulting from the accumulation of damage caused by repeated loads is a major contributor to pavement failure. According to the specifications outlined in BS-EN-12697-24 (BSI, 2004), the stress control method was implemented, with 3 target stresses (namely 250, 300, and 350 kPa). A 12.5-mm wide and curved stainless steel was utilized to apply the load. In this study, a haversine loading pulse was employed to replicate the repetitive traffic loading conditions with loading frequency of 1.0 Hz. The sample was subjected to cyclic loading until failure, and its vertical displacement was recorded at every loading cycle. The vertical displacement can be divided into three separate zones. Due to the rapid reduction in air void caused by the initial cycles of loading, the deformation increment in the initial zone has a relatively high magnitude. Vertical displacement and the loading cycles are positively correlated in the second zone. Throughout the duration of the applied load, microcracks develop as a result of the gradual accumulation of plastic deformation that occurs during this phase. According to Aragao et al. (2008), the propagation of macrocracks is caused by the development of microcracks in the third zone, which originates from the first and second zones, ultimately resulting in complete failure. It is possible to estimate ITFL by locating the point of intersection between the slopes of the second and the third zones.

3.3.5 Rutting resistance by the Hamburg wheel tracking test

According to AASHTO T324 (AASHTO, 2008), the rutting resistance of RAP asphalt concretes modified with PET was evaluated. The Hamburg wheel tracker testing machine, which is specifically designed for wheel track testing, was utilized for this evaluation. The wheel-tracking test samples were prepared with a gyratory compactor based on ASTM D6925 (ASTM, 2015). Two cylindrical specimens, each with 150-mm diameter and 60-mm thickness, were positioned closely together to form the testing sample. These samples were utilized to determine the depth of ruts. Plastic molds were used to securely mount the test sample to ensure stability during loading and minimize movement. In order for the cylindrical specimens to fit the plastic molds precisely, they must undergo precise trimming. A 47 mm wide steel wheel operating at a frequency of 26 cycles per minute exerted a load of 705 N on the sample. The test will end automatically at either 10,000 cycles or 20 mm of rut depth, whichever criterion was met first.

3.4 Test results and discussion

3.4.1 Properties of asphalt concrete

The research results on RAP asphalt concretes (no PET inclusion) by Buritatum et al. (2023) was reanalyzed and used for comparison only in this research. This reanalysis seeks to determine the effect of PET content on RAP-PET-asphalt concrete's optimal AC, Marshall properties, and mechanical performance. Table 3.3 presents the Marshall properties of RAP asphalt concrete with varying percentages of polyethylene terephthalate (PET) content (0, 0.2, 0.4, 0.6, 0.8, and 1%) considered. Taherkhani and Arshadi (2019) revealed that coating PET particles with asphalt cement can result in lower asphalt cement content in the RAP asphalt concrete mixture, leading to increased air void. In order to maintain a consistent 4% air void level, higher asphalt cement content is required.

All RAP asphalt concrete samples have density values ranging from 2.235–2.262 g/cm^3. The density of RAP asphalt concrete decreases with the increased PET content because all PET aggregates were not completely melted during the preparation process (its melting point is 250°C). With higher PET content, the PET particles located between the aggregate particles lead to a larger sample volume and a decreased density (Moghaddam et al., 2014). Moreover, PET having a lower specific gravity (approximately 1.297) than the RAP aggregate (2.274), contributes to the reduction in density of the asphalt concrete mixture (Widojoko & Purnamasari, 2012; Choudhary et al., 2018).

The range of void mineral in aggregate (VMA) values for RAP asphalt concrete with varying PET contents is 18.70% to 20.87 %. As per the recommendation by DOH, 1999, all RAP asphalt concrete samples exhibited VMA values that exceeded the minimum requirement of 14%. This ensures that RAP asphalt concrete modified with PET contains adequate void space for the asphalt cement filler. Void filled by asphalt cement (VFA) refers to the amount of empty spaces in the compacted RAP asphalt concrete sample, filled with asphalt cement. The VFA values of RAP asphalt concrete at varying PET contents range between 78.60 and 80.90 percent.

Marshall stability (MS) and flow values of PET modified RAP asphalt concrete samples range from 10.5 to 14.0 kN and 8.15 to 8.68, respectively. Without PET, RAP asphalt concrete samples have a lower MS than RAP-PET asphalt concrete samples. The SI values of RAP asphalt concrete samples fall within the range of 71.6% to 90.2%. The addition of PET is seen to contribute to the SI improvement. Notably, the MS, flow, and SI requirements specified by DOH (1999) are met by all RAP asphalt concrete mixtures modified with PET. Due to a lower SI value than the minimum requirement, the RAP asphalt concrete without PET did not meet the requirement, demonstrating the negative effects of aged asphalt cement. The inclusion of PET escalates the asphalt cement content, enhancing adhesion and preventing aggregate surface stripping. In addition, the PET components that melt strengthen the adhesion among the aggregates and asphalt cement (Moghaddam et al., 2014).

Table 3.3 Summary of asphalt concrete’s properties

Description		PET content (%)						Specification (DOH, 1999)
		0.0 (Buritatum et al., 2023)	0.2	0.4	0.6	0.8	1.0	
Composition of asphalt	Total asphalt (%by weight of aggregate)	7.07	7.80	8.04	8.13	8.25	8.34	-
	New Asphalt (%by weight of aggregate)	1.40	2.13	2.37	2.46	2.58	2.67	-
Characteristic values	Air Void (%)	4.0	4.0	4.0	4.0	4.0	4.0	3 - 6
	Bulk Density (g/cm^3)	2.262	2.249	2.243	2.241	2.237	2.235	
	VMA (%)	18.70	19.96	20.37	20.52	20.72	20.87	>14
	VFA (%)	78.60	80.13	80.38	80.59	80.72	80.90	
	Stability (kN)	10.5	11.3	13.4	13.1	13.0	14.0	> 6.7
	Flow (0.25mm)	8.68	8.15	8.57	8.36	8.24	8.63	8 - 16
	Stability/Flow (N/0.25mm)	1,205	1,391	1,559	1,569	1,570	1,622	> 556
	Strength index (%)	71.6	84.2	82.9	85.5	91.0	90.2	> 75

3.4.2 Mechanistic performance

Figure 3.3 illustrates the ITS at different testing temperatures. As the temperature rises, the ITS value decreases due to the reduction in the asphalt cement's adhesion strength. Adding PET to the RAP asphalt concrete mixture improves ITS, with the maximum ITS observed at the optimal PET content of 0.6% for all tested temperatures. The addition of PET to RAP asphalt concrete initially enhances its tensile strength. However, this improvement decreases when the addition of PET exceeds 0.6%. Excessive PET particles occupying a more significant volume reduce overall mixture stiffness, as they have lower stiffness than RAP aggregates (Modarres & Hamedi, 2014b).

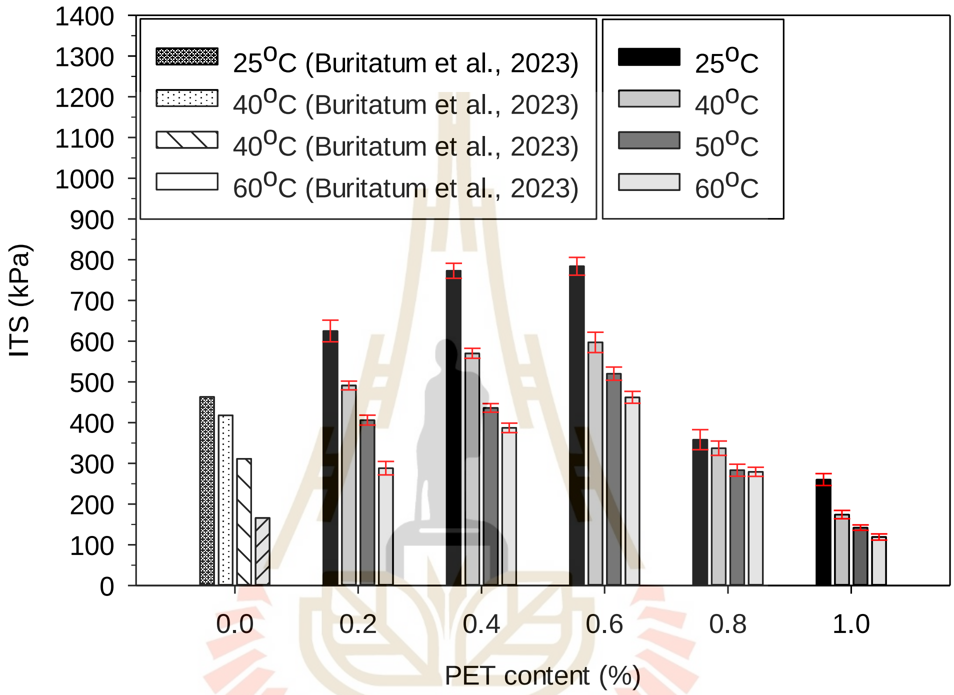

Figure 3.3 ITS of RAP asphalt concrete samples at 25°C, 40°C, 50°C, and 60°C and PET content.

The relationship between IT_{MR} versus PET content is presented in Figure 3.4. The IT_{MR} values of RAP asphalt concrete samples are 1,805.43, 1,927.05, 1,937.36, 2,004.07, 1,791.25, and 1,715.44 MPa for 0, 0.2, 0.4, 0.6, 0.8, and 1.0% of PET contents, respectively. Comparable to the ITS results, the highest IT_{MR} is found at 0.6% PET content. As PET content exceeds 0.6%, the IT_{MR} of RAP asphalt concrete decreases. Incorporating PET into the RAP asphalt concrete mixture enhances the resilient properties of asphalt concrete. The melted PET component can improve adhesion between aggregate and asphalt cement. Meanwhile, the solid PET component can absorb and dissipate energy during loading cycles, hence improving the IT_{MR} (Moghaddam et al., 2012). Beyond the optimum PET content (0.6%), the higher PET content causes a reduction in the IT_{MR}. This excessive PET content reduces mixture stiffness due to the low stiffness of PET particles (Moghaddam et al., 2014; Modarres & Hamedi, 2014).

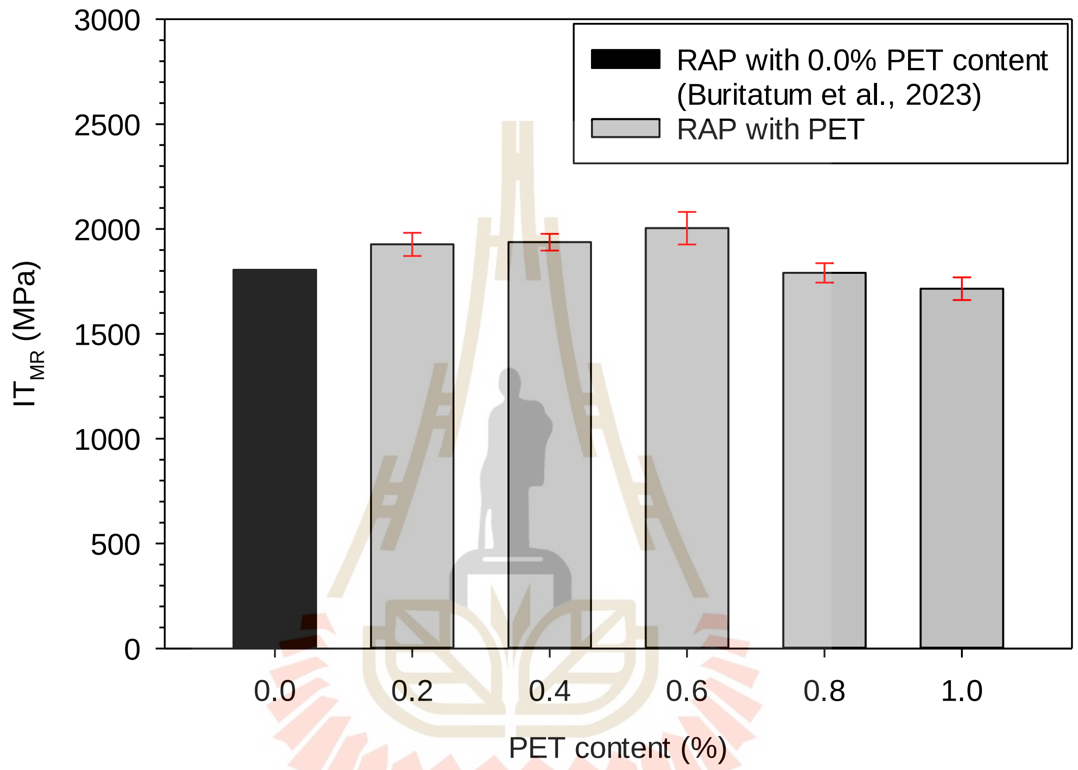

Figure 3.4 IT_{MR} of RAP asphalt concrete samples versus PET content.

Observations indicate a direct proportionality between the improvement in IT_{MR} and ITS versus the PET content (Figure 3.5) and expressed by equation (3.3). When subjected to dynamic tensile stress, the improved ITS results in a greater capacity to withstand permanent deformation. The IT_{MR} of PET-modified RAP asphalt concrete can be determined using ITS values with a significant reliability coefficient of 0.94.

$$IT_{MR} = 0.487(ITS) + 1599 \quad (3.3)$$

where IT_{MR} is expressed in MPa and ITS is expressed in kPa.

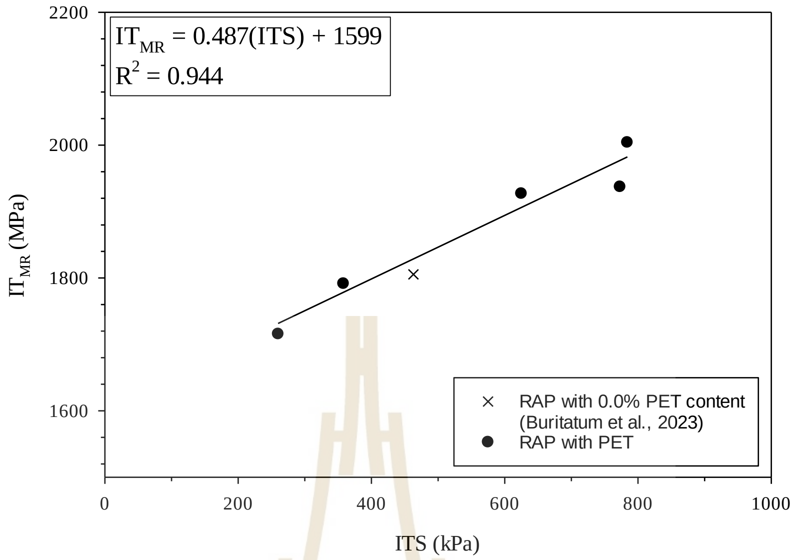

Figure 3.5 Relationship between IT_{MR} and ITS of RAP asphalt concrete samples.

Figure 3.6 depicts the correlation between the polyethylene terephthalate (PET) content and the indirect tensile fatigue life (ITFL) of RAP asphalt concrete modified with PET for various stresses. A notable observation is that as the applied stress is augmented, there is a corresponding decrease in the ITFL across all samples. The inclusion of PET in RAP asphalt concretes has been observed to enhance their resilient properties, resulting in increased ITFL under equivalent stress conditions. The findings for ITFL are consistent with those for ITS and IT_{MR}. The maximum ITFL is observed when the PET content reached 0.6% across all stress levels that were examined. The ITFL values of RAP asphalt concretes modified with 0.6% PET content are 3,002, 2,203, and 1,200 cycles at 250, 300, and 350 kPa stress levels, respectively.

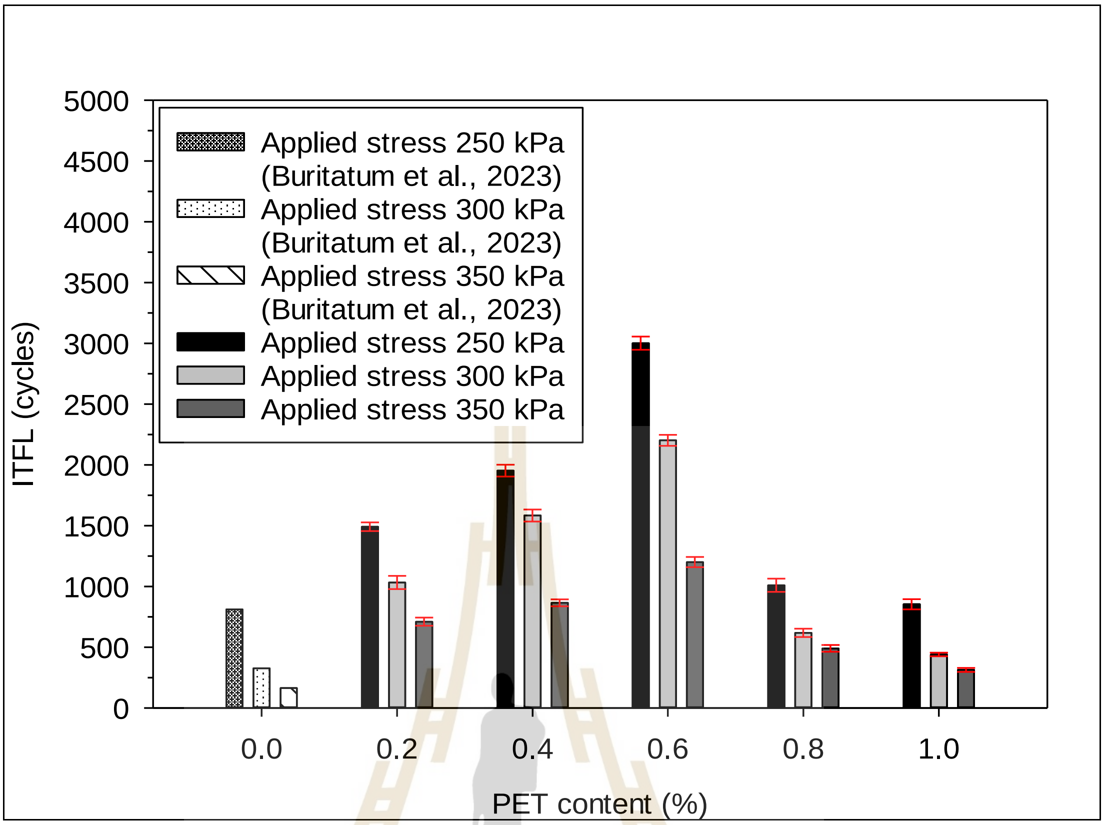

Figure 3.6 ITFL of RAP asphalt concrete samples versus applied stress at different PET content.

Based on the standard BS EN 12697-24 (BSI, 2004), a fatigue law is derived that demonstrates a linear relationship on a logarithmic scale between the fatigue life versus the initial tensile strain (ε_t). On the basis of the aforementioned law, it is possible to formulate a fatigue distress model by incorporating the initial tensile strain as a decisive parameter in the following manner:

$$ITFL = a\left[\frac{1}{\varepsilon_t}\right]^b \quad (3.4)$$

where *a* and *b* (fatigue parameters) represent the regression coefficients that are dependent on the material characteristic and ε_t is expressed in micro-strain.

It should be noted that the initial tensile strain can be derived from the applied stress level, Poisson's ratio, and IT_{MR}, which are obtained through experimental measurements (Kennedy, 1979; Mohammad & Paul, 1993). The initial tensile strain can be determined by employing the subsequent equation:

$$\varepsilon_t = \frac{\sigma(1+3v)}{IT_{MR}} \tag{3.5}$$

where σ is applied stress level (kPa) obtained from ITF test, v is conventionally taken as 0.35 as specified in the BS EN 12697-24 standard.

A distress model was developed for RAP asphalt concrete with and without PET, utilizing fatigue law and analyzing data from dynamic testing. As shown in Figure 3.7, the ITFL decreases as initial tensile strain increases for all asphalt concrete mixtures. At a particular initial tensile strain, the highest ITFL is observed at the PET content of 0.6%. The result supports Modarres and Hamedi's (Modarres & Hamedi, 2014b) findings that PET-modified asphalt concrete shows better ITFL than unmodified asphalt concrete at the same initial tensile strain. Different pavement materials show varying amounts of tensile strain for an equal number of cycles because of variations in their material characteristics. These differences in tensile strain response result in the variable potential to resist fatigue damage.

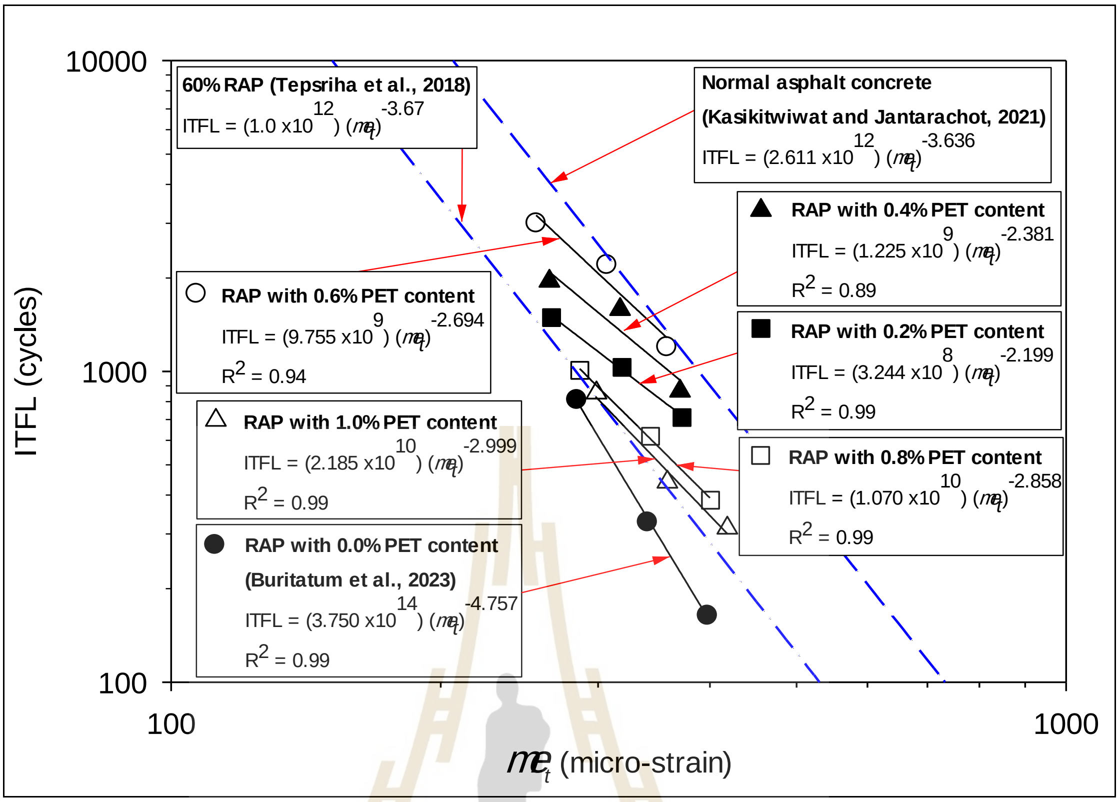

Figure 3.7 Relationship between ITFL and ε_t of RAP asphalt concrete with and without PET samples.

Figure 3.8 and Figure 3.9 show the parameters *a* and *b* of RAP asphalt concrete modified with PET, respectively. An augmentation in the polyethylene terephthalate (PET) content results in an elevation of the magnitude of parameter *a* and a reduction in the magnitude of parameter *b*. As determined by the experimental study, parameters *a* and *b* are a function of the PET content as established through the linear regression analysis presented in equations (3.2) and (3.3), respectively.

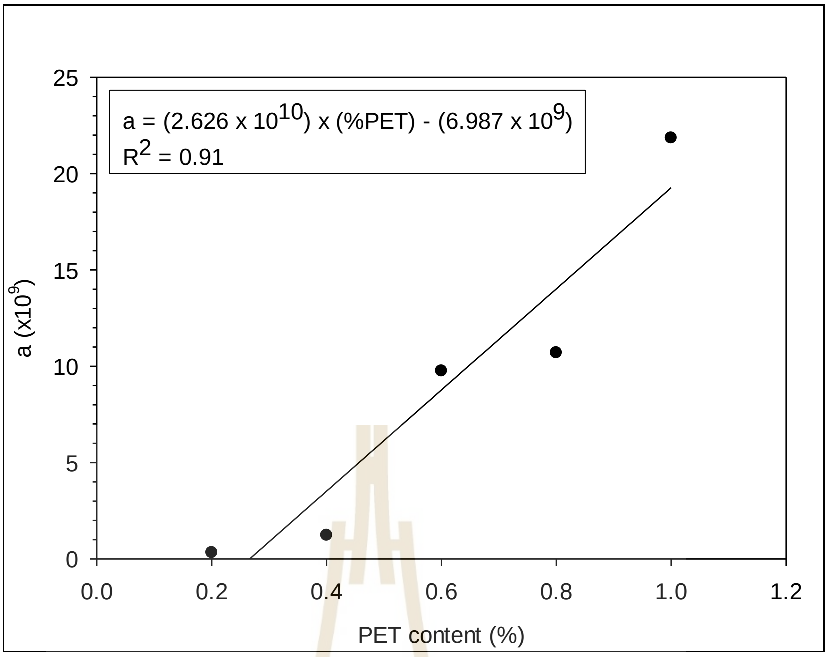

Figure 3.8 Fatigue parameter (*a*) of RAP asphalt concrete with PET samples versus PET content.

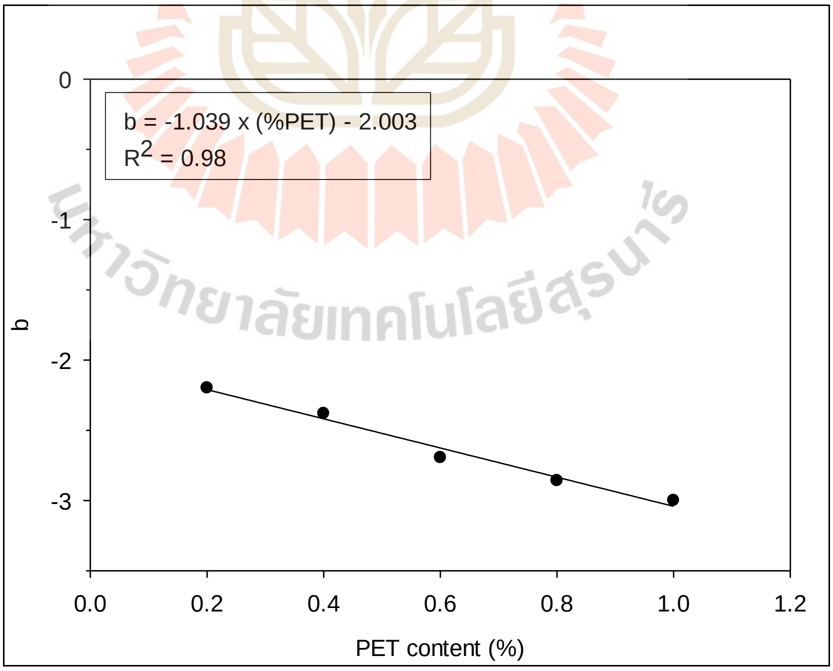

Figure 3.9 parameter (*b*) of RAP asphalt concrete with PET samples and PET content.

The aforementioned equations offer a valuable method for estimating the service life of RAP asphalt concrete that is modified with PET, with given PET content.

$$a = (2.626 \times 10^{10}) \times (\%PET) - (6.987 \times 10^{9}) \quad (3.2)$$

$$b = -1.039 \times (\%PET) - 2.003 \quad (3.3)$$

The comparison of the relationship between ITFL and initial tensile strain of RAP asphalt concrete modified with PET to that reported in previous studies in Thailand, as shown in Figure 3.7. It is revealed that different materials result in distinct fatigue distress models. At the same range of studied initial tensile strain, all RAP asphalt concretes modified with PET have higher fatigue resistance than that of the 60% RAP modified asphalt concrete studied by Tepsriha et al. (2018). Moreover, RAP asphalt concrete modified with 0.6% of PET content is comparable to that of the asphalt concrete using natural aggregate studied by Kasikitwiwat and Jantarachot (2011).

Figure 3.10 shows the rut depth of RAP asphalt concrete at various PET content versus number of cycles. The rut depths observed for the RAP asphalt concretes are 9.69, 5.19, 2.94, 3.19, and 3.63 mm for 0.2, 0.4, 0.6, 0.8, and 1.0% of PET contents, respectively. The lowest rut depth of 2.94 mm is observed at 0.6% PET content.

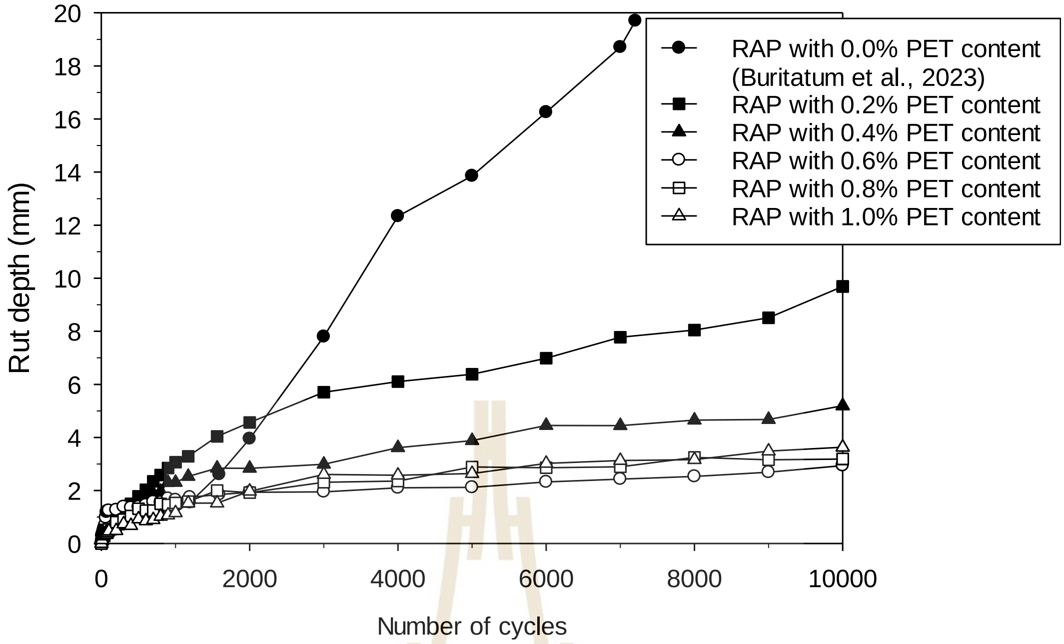

Figure 3.10 Rut depth of RAP asphalt concrete at various PET content versus number of cycles.

Without PET, the RAP asphalt concrete failed at a rut depth of 20 mm under the wheel load after 7,203 cycles, not reaching the desired 10,000 cycles, as presented in Figure 3.11(a). When PET is added to RAP asphalt concrete, it improves its ability to resist rutting, as depicted in Figure 3.11(b-f). The findings of this discovery are consistent with the research conducted by Moghadam et al. (2014b), which determined that the incorporation of PET in asphalt concrete resulted in superior resistance to rutting compared to unmodified asphalt concrete, when subjected to comparable conditions. The PET-modified RAP asphalt concrete exhibits improved rutting resistance due to PET particles’ ability to absorb wheel load, thereby delaying rutting failure (Ziari et al., 2016).

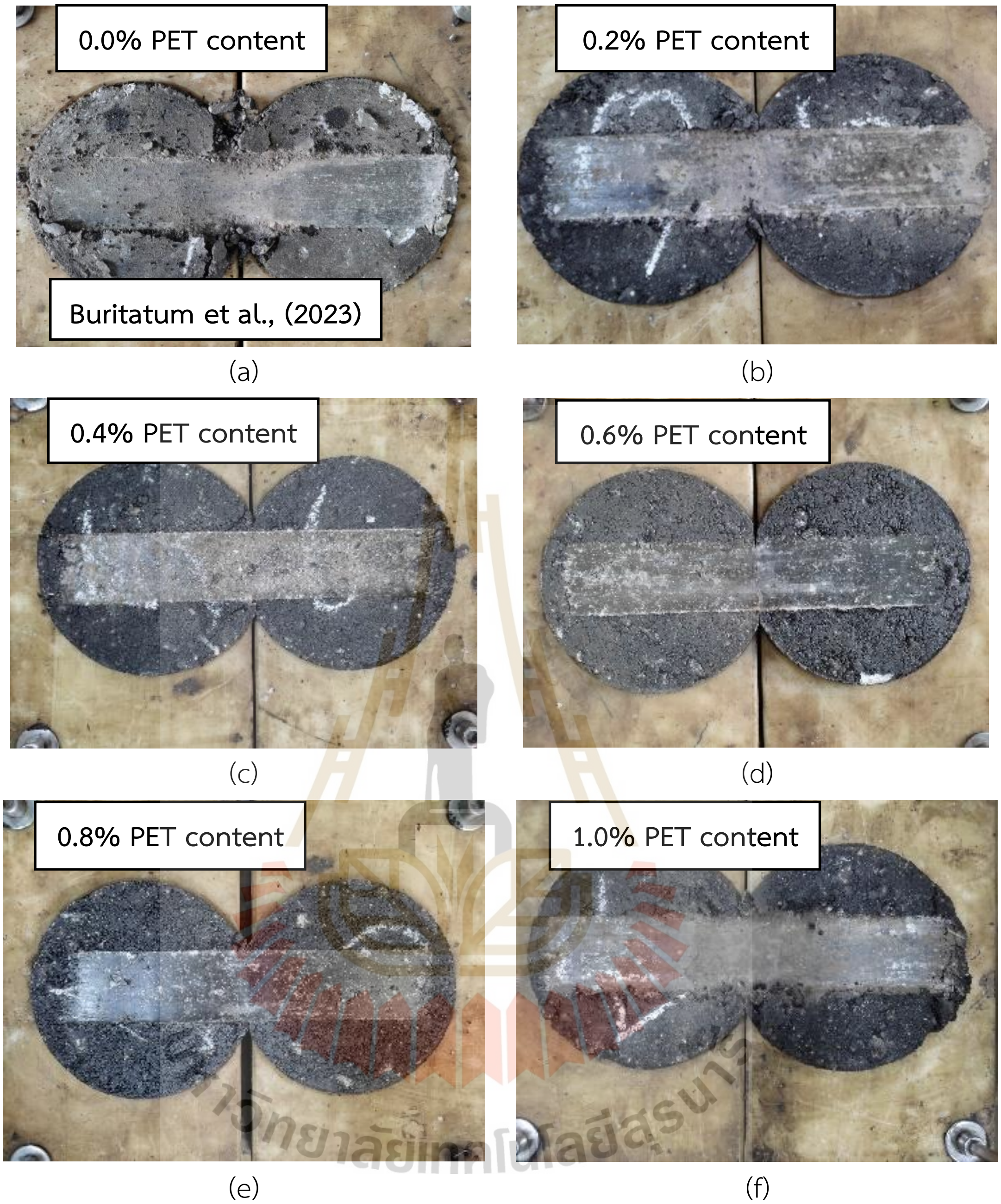

Figure 3.11 Failure characteristics of RAP asphalt concrete modified with (a) 0% PET content (Buritatum et al., 2023), (b) 0.2% PET content, (c) 0.4% PET content, (d) 0.6% PET content, (e) 0.8% PET content, and (f) 1.0% PET content.

The findings of this study suggest that a novel waste management strategy can be presented in the form of PET additives to RAP asphalt concrete, leading to significant performance improvements. Utilizing these two materials provides an economically and environmentally viable alternative for pavement applications.

3.5 Conclusions

The goal of this chapter was to evaluate the PET-modified RAP asphalt concretes as a sustainable pavement surface. Notable findings included the following:

1) The incorporation of polyethylene terephthalate (PET) into the RAP asphalt concrete led to a rise in both the air void and the optimal asphalt cement content in the mixture. The augmentation of asphalt cement content resulted in an enhancement of both adhesion strength and resistance to separation from the aggregate surface. This, in turn, led to improvements in the Marshall properties and SI values.

2) The inclusion of PET enhanced the thickness of the asphalt cement film that envelops the aggregates, which has resulted in the enhancement of adhesion strength, as well as the improvement of tensile properties and resistance to rutting in RAP asphalt concrete. These improvements were evidenced through ITS, IT_{MR}, ITFL, and wheel-tracker tests, with the most significant improvement observed at 0.6% PET content. The addition of PET influenced both the static and dynamic performance of the RAP asphalt concrete up to the best performance value at the optimum PET content of 0.6% for all experimental tests. At the optimum PET content, asphalt concrete was found to have the highest percentage improvement in both static and dynamic performances compared to the 0% of PET content. For static tests, the percentage improvement of Marshall stability, SI, and ITS were 25%, 19%, and 69%, respectively. For dynamic tests, the percentage improvement of IT_{MR}, ITF, and rutting resistance were 11%, 270%, and 80%, respectively. The excessive PET content (> 0.6%) had an adverse effect on the RAP asphalt concrete stiffness due to their lower stiffness compared to RAP aggregates, and the excessively thick film on PET particles caused a susceptible zone, leading to decreased mechanical properties.

3) The distress model of RAP asphalt concrete modified with PET was developed based on experimental data. The fatigue parameters of RAP asphalt

concrete modified with PET were found to vary depending on the PET content. A distress model was proposed to accurately forecast the service life of the material, taking into consideration its specific PET content. The proposed model demonstrates its utility in facilitating mechanistic approaches to pavement design, thereby promoting the adoption of sustainable construction practices both within Thailand and on a global scale.

3.6 Reference

AASHTO. (2007). Standard Method of Test for Resistance of Compacted Asphalt Mixtures to Moisture-Induced Damage. AASHTO T283. Washington, DC: American Association of State Highway and Transportation Officials.

AASHTO. (2008). Standard method of test for Hamburg wheel-track testing of compacted hot-mix asphalt (HMA), AASHTO T324. Washington, DC: American Association of State Highway and Transportation Officials.

Abraham, S. M., & Ransinchung, G. D. (2018). Strength and permeation characteristics of cement mortar with Reclaimed Asphalt Pavement Aggregates. *Construction and Building Materials, 167*, 700-706.

Ahmadinia, E., Zargar, M., Karim, M. R., Abdelaziz, M., & Shafigh, P. (2011). Using waste plastic bottles as additive for stone mastic asphalt. *Materials & Design, 32*(10), 4844-4849.

Al-Qadi, I. L., Elseifi, M., & Carpenter, S. H. (2007). Reclaimed asphalt pavement—a literature review. *FHWA-ICT-07-001*.

Ameri, M., & Nasr, D. (2016). Properties of asphalt modified with devulcanized polyethylene terephthalate. *Petroleum Science and Technology, 34*(16), 1424-1430.

Aragao, F. T. S., Kim, Y.-R., & Lee, J. (2008). Research on Fatigue of Asphalt Mixtures and Pavements in Nebraska.

Aragao, F. T. S., Kim, Y.-R., & Lee, J. (2008). Research on Fatigue of Asphalt Mixtures and Pavements in Nebraska.

ASTM. (1995). Standard test method for indirect tension test for resilient modulus of bituminous mixtures. ASTM D4123-82. West Conshohocken, PA: ASTM.

ASTM. 2015. Standard test method for marshall stability and flow of asphalt mixtures. ASTM D6927-15. West Conshohocken, PA: ASTM.

ASTM. 2017. Standard test method for indirect tensile (IDT) strength of asphalt mixtures. ASTM D6931. West Conshohocken, PA: ASTM.

Badejo, A. A., Adekunle, A. A., Adekoya, O. O., Ndambuki, J. M., Kupolati, K. W., Bada, B. S., & Omole, D. O. (2017). Plastic waste as strength modifiers in asphalt for a sustainable environment. *African Journal of Science, Technology, Innovation and Development, 9*(2), 173-177.

BSI (British Standards Institution). 2004b. Bituminous mixtures. Test methods for hot mix asphalt. Resistance to fatigue. BS-EN12697-24. London: BSI.

BSI. (2004). Bituminous mixtures. Test methods for hot mix asphalt part 24: Resistance to fatigue. BS-EN12697-24.

Buritatum, A., Suddeepong, A., Akkharawongwhatthana, K., Horpibulsuk, S., Yaowarat, T., Hoy, M., Arulrajah, A., & Rashid, A. S. A. (2023). Hemp Fiber-Modified Asphalt Concretes with Reclaimed Asphalt Pavement for Low-Traffic Roads. Sustainability, 15(8). https://doi.org/10.3390/su15086860

Buritatum, A., Suddeepong, A., Horpibulsuk, S., Akkharawongwhatthana, K., Yaowarat, T., Hoy, M., Bunsong, C., & Arulrajah, A. (2022). Improved Performance of Asphalt Concretes using Bottom Ash as an Alternative Aggregate. *Sustainability, 14*(12), 7033.

Copeland, A. (2011). *Reclaimed asphalt pavement in asphalt mixtures: State of the practice*.

DOH (Department of Highways). 1988. Specification for asphalt cement. [In Thai.] Standard No. DH-SP. 401/1988. Ratchathewi, Thailand: DOH.

DOH (Department of Highways). 1999. Standard for Asphalt Hot-Mix Recycling. [In Thai.] Standard No. DH-S 410/1999. Ratchathewi, Thailand: DOH.

DOH. (1999). Standard for Asphalt Hot-Mix Recycling. [In Thai.] Standard No. DH-S 410/1999. Ratchathewi, Thailand: DOH.

Hagos, E., van de Ven, M., & Merine, G. (2012). Investigation into tensile properties of polymer modified Bitumen (PMB) and mixture performance. 7th RILEM International Conference on Cracking in Pavements, Kennedy, T. (1979). Practical use of the indirect tensile test for the characterisation of pavement materials. Australian road research board conference proc,

Kennedy, T. (1979). Practical use of the indirect tensile test for the characterisation of pavement materials. Australian road research board conference proc,

Leng, Z., Sreeram, A., Padhan, R. K., & Tan, Z. (2018). Value-added application of waste PET based additives in bituminous mixtures containing high percentage of reclaimed asphalt pavement (RAP). *Journal of cleaner Production, 196*, 615-625.

McDaniel, R. S., Soleymani, H., & Shah, A. (2002). Use of reclaimed asphalt pavement (RAP) under Superpave specifications. *Washington, DC: Federal Highway Administration (FHWA/IN/JTRP-2002/6).*

Modarres, A., & Hamedi, H. (2014). Effect of waste plastic bottles on the stiffness and fatigue properties of modified asphalt mixes. Materials & Design, 61, 8-15.

Modarres, A., & Hamedi, H. (2014a). Developing laboratory fatigue and resilient modulus models for modified asphalt mixes with waste plastic bottles (PET). *Construction and Building Materials, 68*, 259-267.

Modarres, A., & Hamedi, H. (2014b). Effect of waste plastic bottles on the stiffness and fatigue properties of modified asphalt mixes. *Materials & Design, 61*, 8-15.

Mogawer, W. S., Austerman, A. J., Bonaquist, R., & Roussel, M. (2011). Performance characteristics of thin-lift overlay mixtures: High reclaimed asphalt pavement content, recycled asphalt shingles, and warm-mix asphalt technology. *Transportation research record, 2208*(1), 17-25.

Moghaddam, T. B., Karim, M. R., & Syammaun, T. (2012). Dynamic properties of stone mastic asphalt mixtures containing waste plastic bottles. *Construction and Building Materials, 34*, 236-242.

Moghaddam, T. B., Soltani, M., & Karim, M. R. (2014). Evaluation of permanent deformation characteristics of unmodified and Polyethylene Terephthalate modified asphalt mixtures using dynamic creep test. *Materials & Design, 53*, 317-324.

Moghaddam, T. B., Soltani, M., & Karim, M. R. (2014). Evaluation of permanent deformation characteristics of unmodified and Polyethylene Terephthalate modified asphalt mixtures using dynamic creep test. Materials & Design, 53, 317-324.

Moghaddam, T. B., Soltani, M., Karim, M. R., & Baaj, H. (2015). Optimization of asphalt and modifier contents for polyethylene terephthalate modified asphalt mixtures using response surface methodology. *Measurement, 74*, 159-169.

Mohammad, L. N., & Paul, H. R. (1993). *Evaluation of indirect tensile test for determining structural properties of asphalt mix*.

Mohammad, L. N., & Paul, H. R. (1993). Evaluation of indirect tensile test for determining structural properties of asphalt mix.

Noferini, L., Simone, A., Sangiorgi, C., & Mazzotta, F. (2017). Investigation on performances of asphalt mixtures made with Reclaimed Asphalt Pavement: Effects of interaction between virgin and RAP bitumen. *International Journal of Pavement Research and Technology, 10*(4), 322-332.

Salman, B., Salem, O. S., Garguilo, D. T., & He, S. (2017). *Innovative maintenance, repair, and reconstruction techniques for asphalt roadways: A survey of state departments of transportation*.

Shukla, S., & Harad, A. M. (2006). Aminolysis of polyethylene terephthalate waste. *Polymer degradation and stability, 91*(8), 1850-1854.

Sreeram, A., Leng, Z., Zhang, Y., & Padhan, R. K. (2018). Evaluation of RAP binder mobilisation and blending efficiency in bituminous mixtures: An approach using ATR-FTIR and artificial aggregate. *Construction and Building Materials, 179*, 245-253.

Taherkhani, H., & Arshadi, M. R. (2019). Investigating the mechanical properties of asphalt concrete containing waste polyethylene terephthalate. *Road Materials and Pavement Design, 20*(2), 381-398.

Tepsriha, P., Nukui, T., Chen, W. (2018). Engineering Evaluation and Production Cost Reduction of The Recycling of Reclaimed Asphalt Concrete Pavement Materials to be Used as Components of New Asphalt Concrete Pavement Materials Using a Central Plant Mixed Plant. [In Thai.]. Ratchathewi, Thailand: DOH.

Zaumanis, M., Mallick, R. B., & Frank, R. (2014). 100% recycled hot mix asphalt: A review and analysis. *Resources, Conservation and Recycling, 92*, 230-245.

Zhang, K., & Muhunthan, B. (2017). Effects of production stages on blending and mechanical properties of asphalt mixtures with reclaimed asphalt pavement. *Construction and Building Materials, 149*, 679-689.

Ziari, H., Kaliji, A. G., & Babagoli, R. (2016). Laboratory evaluation of the effect of waste plastic bottles (PET) on rutting performance of hot mix asphalt mixtures. *Petroleum Science and Technology, 34*(9), 819-823.

Ziari, H., Kaliji, A. G., & Babagoli, R. (2016). Laboratory evaluation of the effect of waste plastic bottle (PET) on rutting performance of hot mix asphalt mixtures. Petroleum Science and Technology, 34(9), 819-823.

CHAPTER IV

MECHANICAL PERFORMANCE OF POLYETHYLENE TEREPHTHALATE MODIFIED ASPHALT CONCRETE WITH BLENDED RECYCLED AGGREGATES

4.1 Introduction

The increasing demand for sustainable construction materials has led to a surge in using recycled materials in infrastructure projects. This chapter focuses on incorporation of reclaimed asphalt pavement (RAP) and recycled concrete aggregate (RCA) in asphalt concrete mixtures. This chapter explores using RAP as the total aggregate, replacing RCA in coarse RAP, and enhancing the mixture with polyethylene terephthalate (PET). The performance of this innovative RAP-RCA-PET asphalt concrete is compared to conventional asphalt concrete, which utilizes natural aggregate. The comparison is based on asphalt concrete performance, including indirect tensile strength (ITS), indirect tensile resilient Modulus (IT_{MR}), indirect tensile fatigue (ITF), and rutting resistance. Based on the critical analysis of the cyclic test data, the fatigue distress model of RAP-RCA-PET asphalt concretes has been developed for the mechanistic-empirical pavement design.

4.2 Materials and Methods

4.2.1 Asphalt cement (AC)

The properties of AC penetration grade of 60/70 (AC60/70) were the same as that studied by Buritatum et al. (2023), as shown in Table 3.2 in Chapter 3.

4.2.2 Aggregates

Studied RAP and RCA were produced by crushing and grinding the demolished asphalt concrete and concrete pavements. As the same in Chapter 3, RAP was studied by Buritatum et al. (2023) as shown in Figure 3.1(a). The studied RCA is shown in Figures 4.1(a). The RCA was obtained from Thailand's Local Administration

Department. Properties of RAP and RCA were evaluated based on the local standard (DOH, 1999). The studied natural aggregate (NA) is limestone, which was sourced from Sakon Nakhon province, Thailand, as shown in Figure 4.1(b). Summarized properties of RAP, RCA and NA are depicted in Table 4.1.

(a) (b)

Figure 4.1 Studied (a) RCA and (b) NA.

Table 4.1 Properties of aggregates

Properties	Unit	Test method	Specifications (DOH, 1999)	NA	RAP (Buritatum et al., 2023)	RCA
Soundness	%	DH-T 213	≤ 9	3.31	10.21	3.84
Los Angeles abrasion value, LA	%	DH-T 202	≤ 40	30.4	47.03	33.13
Flakiness index	%	DH-T 210	≤ 35	15	33.00	28.00
Elongation index	%	DH-T 211	≤ 35	9	34.00	27.00
Water absorption	%	DH-T 207	-	0.47	1.49	9.10
Specific gravity	-	DH-T 207	-	2.753	2.274	2.790
Asphalt content in RAP	%	ASTM D 2172	-	-	5.67	-

4.2.3 Polyethylene terephthalate (PET)

In this study, the same PET, as shown in Figure 3.1(b) in Chapter 3, was used. The PET was added using the dry process at different weight percentages of 0.0, 0.2, 0.4, 0.6, 0.8, and 1.0% by weight of aggregate.

4.2.4 Mix design and sample preparation

Before preparing RAP-RCA-PET asphalt concrete, the RAP aggregate was cleaned using trichloroethylene agents. The cleaned RAP aggregate was then sieved, and the gradation curve was altered in compliance with the pavement surface wearing course specifications outlined by the local authority (DOH, 1999), as illustrated in Figure 4.2. The gradation curves of RAP-RCA and RAP were adjusted to be the same. In this study, the coarse RAP aggregate (4.75 mm to 19 mm) was replaced with RCA at various RAP/RCA ratios of 100/0, 90/10, 80/20, and 60/40 by weight of aggregate. The gradation curve of the NA asphalt concrete is also shown in Figure 4.2

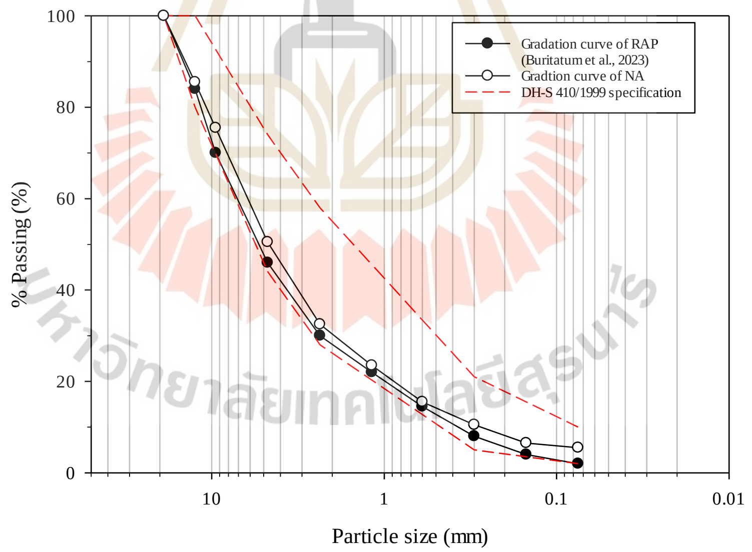

Figure 4.2 Gradation curve of aggregates

The appropriate mix proportions of RAP-RCA-PET asphalt concrete and NA asphalt concrete were acquired using the Marshall method following ASTM D 6927 (ASTM, 2015a). Before mixing, the aggregate and AC were warmed at 180°C and

160°C, respectively. The heated aggregate and AC were blended at 150°C for 1 minute. The PET was then added during the mixing process for RAP-RCA-AC. The mixture was then compacted in a standard 101.6-mm mold with 75 blows to each side by a Marshall hammer. The sample was next de-molded after 24 hours at room temperature. The Marshall test was carried out to obtain the common Marshall properties of the asphalt concrete, including density, void mineral in aggregate (VMA), air void, void filled by AC (VFA), Marshall stability, and Marshall flow.

The influence of the RAP/RCA ratio and PET content on the mechanical performances of RAP-RCA-PET asphalt concretes and NA asphalt concretes was evaluated through various performance tests, including ITS, IT_{MR}, ITFL, and rutting resistance. The performance-tested samples were prepared at a constant air void of 4% based on the local authority standard (DOH, 1999). For RAP-RCA-PET asphalt concretes, the optimum AC content (AC content providing 4% air void) was determined by assuming the total AC content (aged AC in RAP aggregate + added AC60/70).

The strength index (SI) of the studied asphalt concretes was calculated in line with AASHTO T 283 (AASHTO, 2007). The SI samples were prepared by compression under a constant pressure of 20.7 MPa for 2 minutes using a double plunger compactor with a 63.5-mm height and a 101.6-mm diameter. Two sample groups were made, including group 1 (unsoaked samples), which was designated as a control group, and group 2 (soaked samples), which was vacuum-saturated with the sodium chloride solution for 60 minutes and then soaked at 60°C for 1 day. The ratio between Marshall stability of soaked and unsoaked samples is the SI value. The test was run at 25°C using a compression speed of 50 mm/min. The Department of Highways, Thailand (DOH, 1999) specified that the SI value of asphalt concrete should be above 75%.

4.3 Experimental program

4.3.1 Indirect tensile strength (ITS)

The tensile properties of RAP-RCA-PET asphalt concrete were analyzed using the ITS test, which followed the ASTM D 6931 (ASTM, 2017). The Marshall samples were tested by loading at a 50 mm/min deformation rate at 25, 40, 50, and 60°C. The ITS value of the sample was determined using the observed maximum load and the following equation (4.1).

$$\mathrm{ITS} = \frac{2000P}{\pi t D} \tag{4.1}$$

where ITS stands for indirect tensile strength (kPa), *P* represents maximum load (N), *t* denotes the sample thickness (mm), and *D* is the sample diameter (mm).

4.3.2 Indirect tensile resilient modulus (IT_{MR})

The IT_{MR} was evaluated following the ASTM D 4123-82 (ASTM, 1995). A vertical load equivalent to 15% of the sample's ITS was applied during the experiment. The test consisted of 200 loading pulses at a temperature of 25°C. The IT_{MR} was calculated using the average elastic stiffness obtained from the last five values after the initial 150 cycles, as per equation (4.2).

$$IT_{MR} = \frac{P(0.27+\nu)}{tH_r} \tag{4.2}$$

where IT_{MR} is indirect tensile resilient modulus (MPa), *v* is Poisson's ratio, *t* is the sample thickness, and H_r is recoverable horizontal deformation (mm).

4.3.3 Indirect tensile fatigue (ITF)

According to BS-EN-12697-24 (BSI, 2004), the stress control method was chosen with target stress levels of 250, 300, and 350 kPa. A loading strip made of 12.5 mm wide curved stainless steel was used to apply the load. Repetitive traffic loading was simulated at 1 Hz using a haversine loading pulse with a 0.1-second load and 0.9-second rest period. The Marshall sample was repeatedly loaded until it failed, and its vertical deformation was recorded concerning the number of loading pulses.

4.3.4 Rutting resistance by the Hamburg wheel tracking test

According to AASHTO T324 (AASHTO, 2008), the Hamburg wheel tracker testing machine was used to determine the resistance of RAP asphalt concrete samples against rutting. The test involved two adjacent cylindrical specimens with a diameter of 150 mm and a thickness of 60 mm to measure rut depth. The test will automatically stop after 10,000 cycles or if the rut depth reaches 20 mm. The rutting resistance of the RAP asphalt concrete sample was measured by recording the rut depth.

4.4 Results and discussions

4.4.1 Aggregate properties

Properties of studied RAP (Buritatum et al., 2023), RCA, and NA are depicted in Table 4.1 and benchmarked with the hot mix recycling standard (DOH, 1999). NA has the lowest values of soundness, Los Angeles abrasion, flakiness index, and elongation index compared to RAP and RCA. This implies that NA has the highest resistance to corrosion, abrasion, and particle breaking. RCA has superior properties to RAP as shown by its lower values for soundness, Los Angeles abrasion, flakiness index, and elongation index. However, the RCA has greater water absorption than NA and RAP due to its larger porosity, indicating that the RCA has a higher ability to absorb AC. It was evident that all properties of NA and RCA pass the standard requirement.

4.4.2 Marshall properties

The studied results of RAP asphalt concretes (RAP/RCA ratio of 100/0 and 0.0% PET content) by Buritatum et al. (2023) were diagnosed for investigating the influence of RAP/RCA ratios on the optimum AC content, Marshall properties, and mechanical performances of RAP-RCA-PET asphalt concretes. The optimum AC contents of the RAP-RCA-PET asphalt concretes at different PET contents, and NA asphalt concrete are summarized in Table 4.2. The optimum AC content for the RAP asphalt concrete was determined to be 7.07% by weight (5.67% old AC + 1.40% new AC content) (Buritatum et al., 2023). The optimum AC content of NA asphalt concrete is 5.1%. The lower RAP/RCA ratio (higher RCA replacement content) contributes to the decreased old AC content in the RAP-RCA-PET asphalt concretes at a particular PET content. As such, the lower RAP/RCA ratio (higher RCA) results in a higher optimum AC content (De Farias & Sinisterra, 2012; Hou et al., 2014; Pasandín & Pérez, 2013; Wong et al., 2007). At identical RAP/RCA ratio, the more PET content contributes to a greater optimum AC content due to the coating of PET particles with AC, resulting in the increased air void of the mixture (Taherkhani & Arshadi, 2019).

Table 4.2 Optimum AC content of asphalt concrete.

AC content	RAP-RCA-PET asphalt concrete							NA asphalt concrete
	RAP/RCA ratio	%PET						
		0.0	0.2	0.4	0.6	0.8	1.0	
Old AC	100/0	5.67	5.67	5.67	5.67	5.67	5.67	0.0
	90/10	5.14	5.14	5.14	5.14	5.14	5.14	
	80/20	4.63	4.63	4.63	4.63	4.63	4.63	
	60/40	3.61	3.61	3.61	3.61	3.61	3.61	
New AC	100/0	1.40	2.13	2.37	2.46	2.58	2.67	5.1
	90/10	2.70	2.95	3.00	3.10	3.13	3.43	
	80/20	3.40	4.07	4.13	4.23	4.49	4.60	
	60/40	4.68	5.35	5.37	5.54	5.70	5.71	

The Marshall properties of RAP-RCA-PET asphalt concretes and NA asphalt concrete are presented in Table 4.3 and compared with the requirements specified by the local authority (DOH, 1999). At the same PET content, the lower RAP/RCA ratio causes a higher density of asphalt concretes due to RCA having higher specific gravity than RAP. At a given RAP/RCA ratio, the more PET content results in a lower density of the RAP-RCA-PET asphalt concrete. The VMA and VFA values of the RAP-RCA-PET asphalt concretes range from 18.7 to 21.21% and 77.55 to 82.06%, respectively. The Marshall stability and SI values of the RAP-RCA-PET asphalt concretes range from 10.5 to 20.7 kN and 81.6 to 92.8%, respectively. The lowest Marshall stability and SI values are observed in RAP asphalt concrete (no RCA and PET). The highest Marshall stability and SI values are observed in the asphalt concrete with a 80/20 RAP/RCA and 06% PET content. The Marshall flow values range from 8.15 to 15.1. The NA asphalt concrete has 2.456 g/cm^3 density, 15.1% VMA, 73.8 VFA, 15.2 kN stability, 12.8 flow, and 78.2% SI. The Marshall properties, including VMA, stability, flow, and SI for all mix proportions, meet the requirements of the DH-S-

410/1999 standard, except for the SI value of RAP asphalt concrete (RAP/RCA ratio of 100/0 and PET content of 0%).

Table 4.3 Marshall properties of studied asphalt concrete mixtures at 4% air void.

Properties	RAP-RCA-PET asphalt concrete							NA asphalt concrete	Specification (DOH, 1999)
	RAP/RCA ratio	%PET							
		0.0	0.2	0.4	0.6	0.8	1.0		
Density (g/cm^3)	100/0	2.262	2.249	2.243	2.241	2.237	2.235	2.456	-
	90/10	2.275	2.254	2.249	2.244	2.241	2.237		
	80/20	2.281	2.259	2.252	2.247	2.244	2.240		
	60/40	2.290	2.267	2.261	2.256	2.252	2.248		
VMA (%)	100/0	18.70	19.96	20.37	20.52	20.72	20.87	15.1	min 14
	90/10	19.52	19.99	20.06	20.24	20.29	20.79		
	80/20	19.41	20.54	20.64	20.82	21.24	21.41		
	60/40	19.49	20.56	20.07	20.36	20.62	20.65		
VFA (%)	100/0	78.60	80.13	80.38	80.59	80.72	80.90	73.8	-
	90/10	79.50	79.99	80.05	80.22	80.27	80.81		
	80/20	79.39	80.53	80.62	82.06	81.23	81.31		
	60/40	78.85	77.55	80.07	80.35	80.59	80.72		
Stability (kN)	100/0	10.5	11.3	13.4	13.1	12.9	14.0	15.2	min 6.7
	90/10	12.4	13.1	13.8	16.4	15.6	15.1		
	80/20	18.8	17.5	19.1	20.7	20.6	18.4		
	60/40	16.0	16.8	17.3	18.4	17.8	17.5		
Flow (0.25 mm)	100/0	8.7	8.2	8.6	8.4	8.2	8.6	12.8	8-16
	90/10	10.2	10.8	11.3	11.8	12.3	13.1		
	80/20	11.0	11.8	12.1	13.6	14.5	14.8		
	60/40	11.9	12.6	13.9	14.2	15.1	15.0		
SI (%)	100/0	71.6	84.2	82.9	85.5	91.0	90.2	78.2	min 75
	90/10	81.6	85.6	86.8	91.9	91.7	91.2		
	80/20	86.3	87.4	87.8	92.8	92.5	89.7		
	60/40	83.7	84.1	85.1	86.4	84.5	84.2		

4.4.3 Mechanistic performance

The ITS of RAP-RCA-PET asphalt concretes at various temperatures, RAP/RCA ratios and PET contents are compared with that of NA asphalt concrete as demonstrated in Figure 4.3. The raised temperature results in a decrease in ITS for all asphalt concretes due to a reduction of AC adhesion strength. The lower RAP/RCA ratio causes a more ITS until the maximum ITS value at the optimum RAP/RCA = 80/20 at a given PET content for RAP-RCA-PET asphalt concretes. Li et al. (2018) reported that RCA particles have rough surfaces and angular shapes (Hou et al., 2018), resulting in a higher mechanical interlocking than RAP aggregate. The improved interlocking strength at the optimum RAP/RCA therefore contributes to the improved adhesion strength between aggregate and AC for all PET contents and temperatures. Although the RCA has superior basic and engineering properties than RAP, the elastic modulus of the interfacial transition zone between AC and RCA particles gets lower than that of other recycled materials and NA, as reported by Huang et al. (2021). Hence, the excessive RCA in the asphalt concretes generates weak interfacial transition zones within the asphalt concrete matrix, reducing the ITS of asphalt concretes.

At the same RAP/RCA ratios, adding PET in the RAP-RCA-PET asphalt concretes can improve ITS. The highest ITS is observed at the optimum PET content of 0.6% for all tested temperatures. The inclusion of PET enhances the ITS of RAP-RCA-PET asphalt concretes by improving cohesive strength between the aggregate and AC through the melted components of PET during the hot mixed process (Moghaddam et al., 2012). However, the ITS decreased as the PET content exceeded 0.6% for all RAP/RCA ratios and temperatures. Modarres and Hamedi (2014) revealed that the excessive volume of un-melted PET particles, which have lower stiffness than RAP and RCA, leads to the a weak structure in asphalt mixture (Modarres & Hamedi, 2014b). Compared to NA asphalt mixture, the RAP asphalt mixture (no RCA) with 0% PET content has a lower ITS at 25°C. However, ITS of RAP asphalt concretes with 0.0% PET content is higher than that of NA ones at 40, 50, and 60°C. In other words, the RAP asphalt concrete has a less significant loss of ITS than the NA asphalt concrete because of aged AC in the RAP aggregate, providing greater stiffness to the mixtures under high-temperature conditions (Marín-Uribe et al., 2022). Reducing the RAP/RCA ratio and increasing PET improves the ITS of RAP-RCA-PET asphalt concretes. Therefore, RAP-RCA-PET asphalt concretes with the optimum RAP/RCA = 80/20 and 0.6% PET content have higher ITS values than NA asphalt concretes for all temperatures.

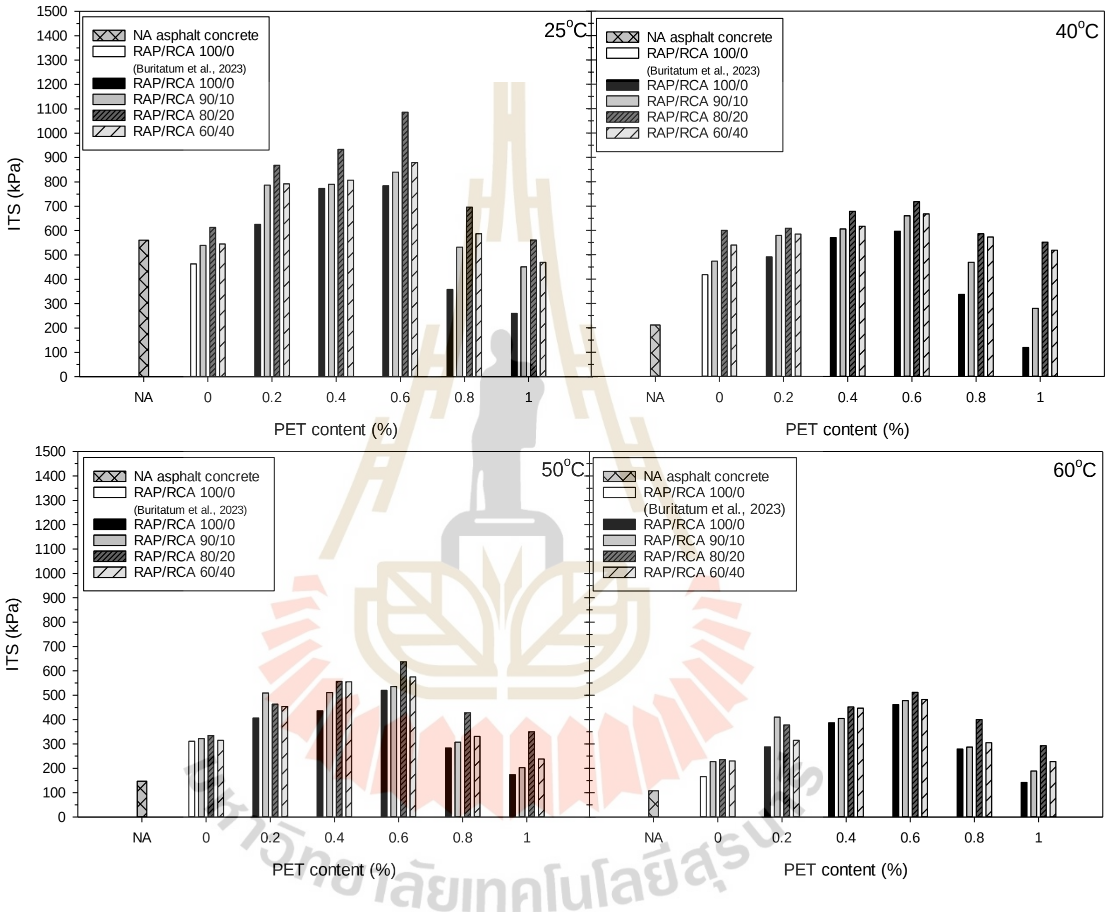

Figure 4.3 ITS of RAP-RCA-PET asphalt concrete at 25, 40, 50, and 60°C versus PET content.

The IT_{MR} of RAP-RCA-PET asphalt concretes at various temperatures, RAP/RCA ratios, and PET contents are compared with that of NA asphalt concretes, as illustrated in Figure 4.4. Like the ITS test results, the highest IT_{MR} of RAP-RCA-PET asphalt concretes comes across at the optimum RAP/RCA = 80/20 for all PET contents. At a given RAP/RCA ratio, the highest IT_{MR} of RAP-RCA-PET asphalt concrete is observed at the optimum PET content of 0.6%. Beyond the optimum PET content, IT_{MR} decreases as the PET content increases. RAP-RCA-PET asphalt concretes have smaller IT_{MR} than NA asphalt concrete, except the RAP-RCA-PET asphalt concretes with RAP/RCA = 80/20 and 0.2, 0.4, and 0.6% PET contents. The RAP-RCA-PET asphalt concrete with a RAP/RCA = 80/20 and 0.6% PET content has a superior IT_{MR} of 14.1% compared to NA asphalt concrete.

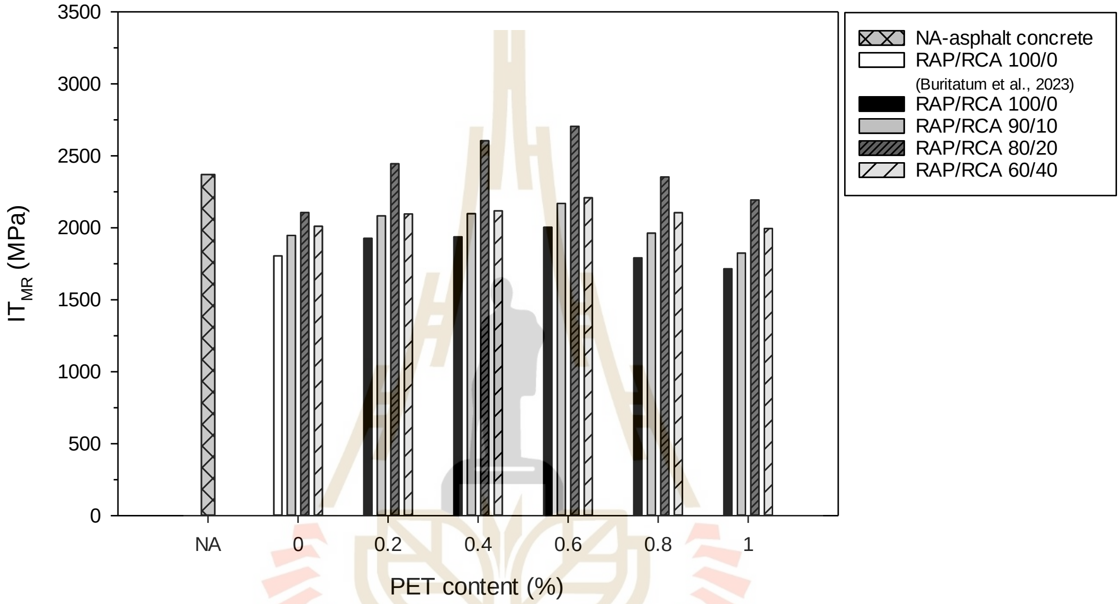

Figure 4.4 IT_{MR} of RAP-RCA-PET asphalt concrete versus PET content.

Both IT_{MR} and ITS improvement is influenced by the mixture stiffness (the addition of RCA) and the AC adhesion improvements (the addition of PET). The relationship between IT_{MR} and ITS of RAP-RCA-PET asphalt concretes is therefore directly related as depicted in Figure 4.5. The relationship is found to be dependent upon the RAP/RCA ratio. The increased ITS enhances the endurance to plastic strain under cyclic tensile stress. At the same ITS value, the asphalt concrete with a smaller RAP/RCA ratio exhibits a larger IT_{MR} due to a higher mixture stiffness. PET additives show the most significant improvement in mechanical properties at the optimum RAP/RCA = 80/20, observed by the steepest gradient of the relationship.

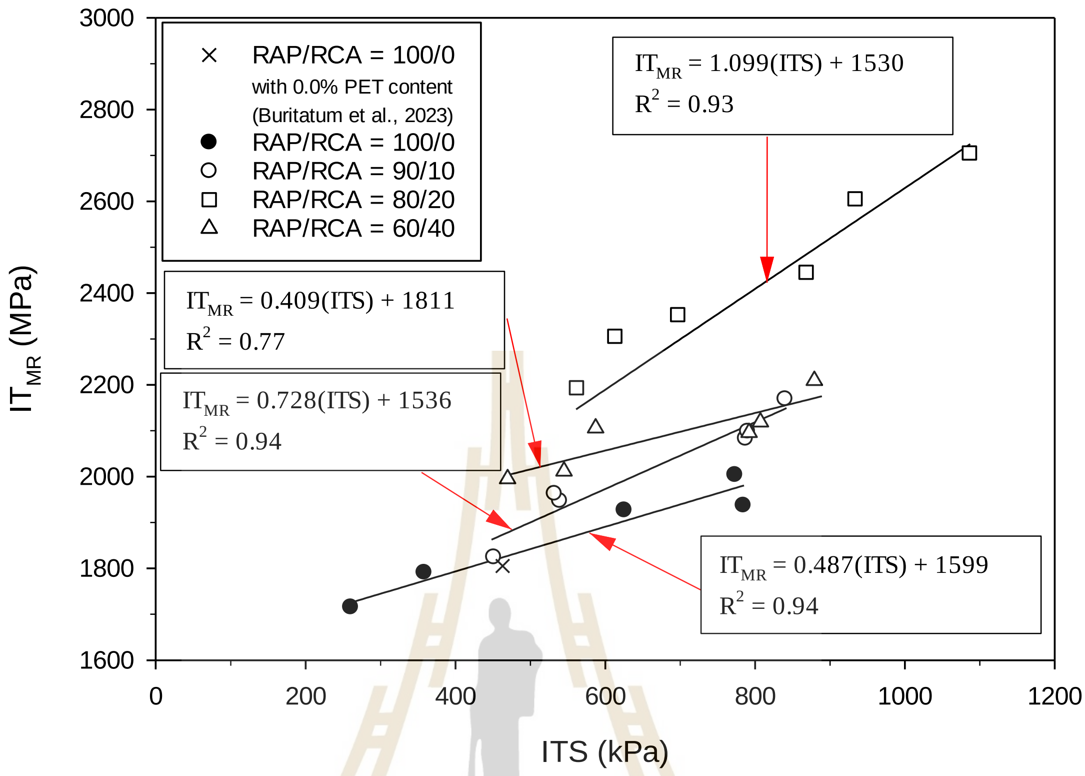

Figure 4.5 Relationship between IT_{MR} and ITS of RAP-RCA-PET asphalt concrete.

The ITFL values of RAP-RCA-PET asphalt concretes with RAP/RCA ratios and PET contents under different applied stresses of 250, 300, and 350 kPa are compared with those of NA asphalt concretes and illustrated in Figure 4.6. The ITFL decreases with the increased applied stress for all asphalt concretes due to the higher plastic deformation. At the same applied stress, without PET, the RCA inclusion can improve the ITFL of RAP-RCA-PET asphalt concretes. Like the ITS and IT_{MR} results, the maximal ITFL is observed at the optimum RAP/RCA ratio of 80/20 for all applied stresses and PET contents. Increasing PET content can advance the ITFL of RAP-RCA-PET asphalt concretes up to the maximal value at the optimum PET content of 0.6% for all RAP/RCA ratios. Moghaddam et al. (2012) revealed that the solid components of PET (which were not melted during the hot mixed process) had the potential to absorb or dissipate energy from loading cycles, further contributing to the improvement of ITFL of asphalt concretes. Compared to NA asphalt concretes, the RAP asphalt concretes have lower ITFL values for all applied stresses. Increasing PET and RCA content improves the ITFL of RAP-RCA-PET asphalt concretes for all applied stresses. The RAP-RCA-PET asphalt concretes with the optimum RAP/RCA ratio and PET content have superior ITFL values of 125, 243, and 379% compared to NA asphalt concretes for applied stresses of 250, 300, and 350 kPa, respectively.

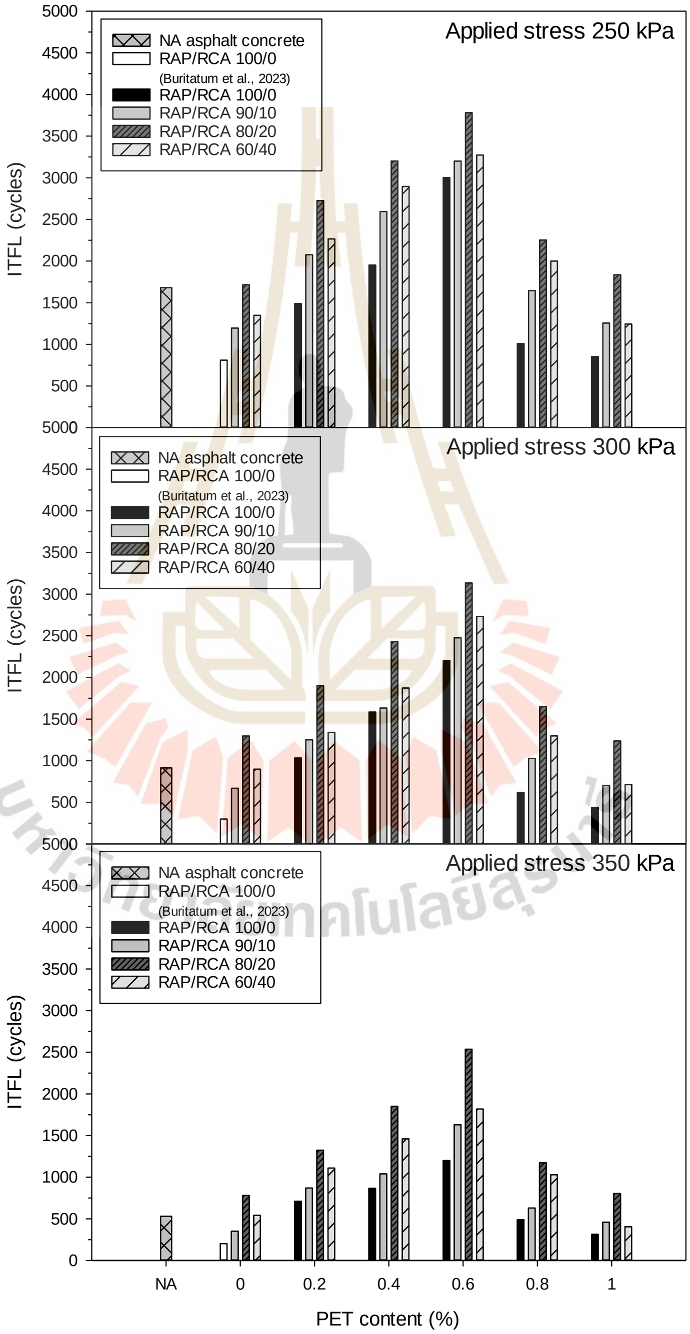

Figure 4.6 ITFL of RAP-RCA-PET asphalt concrete versus PET content.

As per BS EN 12697-24 (BSI, 2004), the initial tensile strain (ε_t) influences the fatigue life (N_f) (fatigue law). The asphalt concrete with a lower ε_t generally presents a higher N_f. The N_f of the asphalt concrete pavement can be estimated using the ε_t based on the fatigue law as follows:

$$N_f = a\left[\frac{1}{\mu\varepsilon_t}\right]^b \tag{4.3}$$

where a and b are the fatigue parameters, which can be determined from the regression analysis.

Kennedy (1979) and Mohammad and Paul (1993) revealed that the applied stress and IT_{MR} influence the ε_t in the following equation:

$$\varepsilon_t = \frac{\sigma(1+3v)}{IT_{MR}} \tag{4.4}$$

where σ is applied stress (kPa) obtained from the indirect tensile fatigue test, and v is Poisson's ratio (taken as 0.35 suggested by BS EN 12697-24).

ε_t of RAP-RCA-PET asphalt concretes and NA asphalt concrete, which are calculated from Eq. (2.4), versus PET content under different applied stresses, is illustrated in Figure 4.7. At the same RAP/RCA ratios and PET contents, the higher applied stress causes a higher ε_t. Asphalt concrete with a superior IT_{MR} has a predominant resistance to plastic strain under applied stress (Gupta & Veeraragavan, 2009). At the same applied stress, the replacement of RCA and addition of PET contribute to a reduction in ε_t, and the lowest value for specific applied stress is found at 80/20 RAP/RCA and 0.6% PET content. Compared to NA asphalt concrete, all RAP-RCA-PET asphalt concretes have higher ε_t except RAP-RCA-PET asphalt concretes with RAP/RCA ratios of 80/20 and 0.2, 0.4, and 0.6% PET content for all applied stresses.

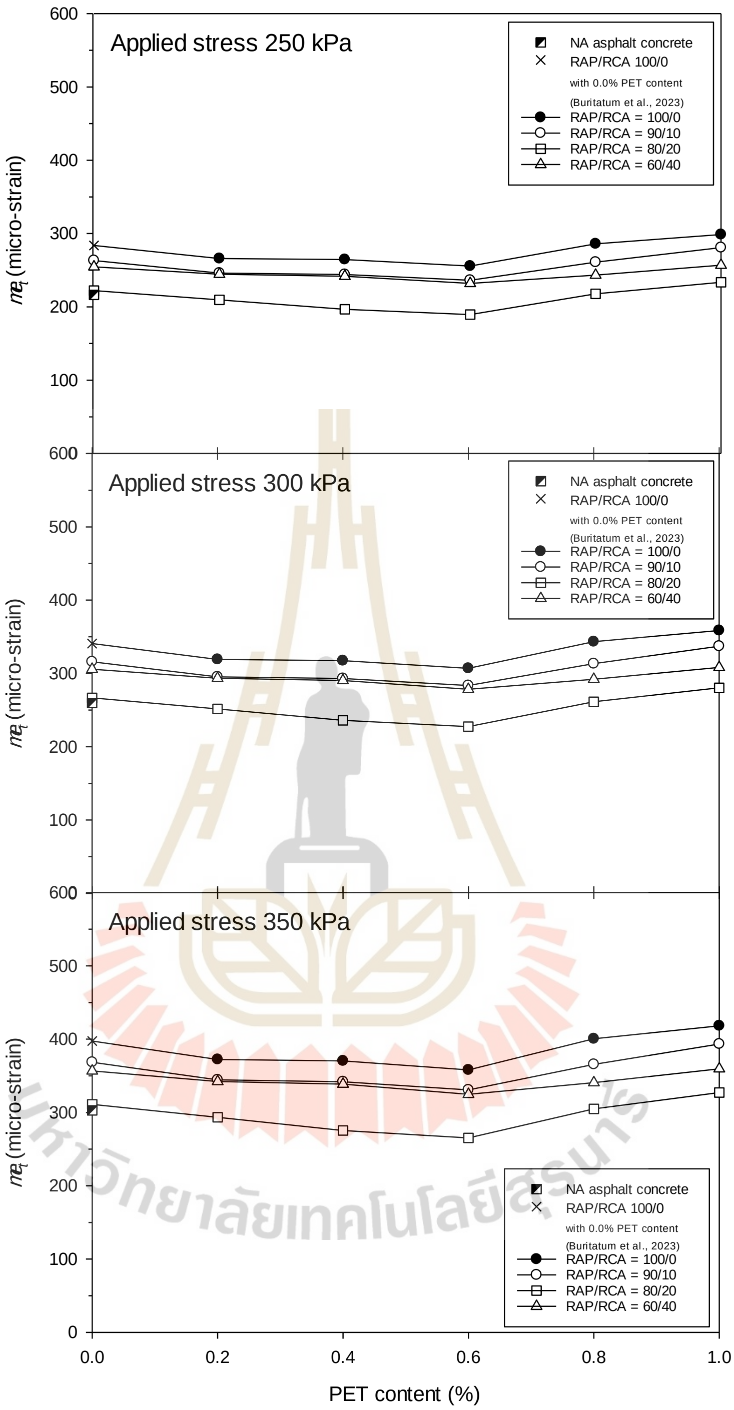

Figure 4.7 ε_t of RAP-RCA-PET asphalt concrete versus PET content.

The relationship between the ITFL and the ε_t in the logarithmic scale of RAP-RCA-PET asphalt concretes, and NA asphalt concrete is illustrated in Figure 4.8. Asphalt concrete with a larger initial tensile strain presents a lower fatigue life

(Modarres & Hamedi, 2014a). In other words, the ITFL decreases as the ε_t increases for all asphalt concretes. The PET content is found to significantly affect in the position and the slope of ITFL-ε_t relationship. Without PET, the ITFL-ε_t relationship exhibits the steepest slope, whereas the gentlest slope is found at the optimum PET content of 0.6%, regardless of the RAP/RCA ratios. It is noted that, in the range of studied strains, the ITFL-ε_t relationships of RAP-RCA-PET asphalt concretes are above the ITFL-ε_t relationship of NA asphalt concrete. However, the ITFL-ε_t relationships of RAP-RCA-PET asphalt concretes and NA asphalt concrete are below the ITFL-ε_t relationship of the Asphalt Institute (AI, 2014). The AI's model was developed based on the assumption that wheel loads on actual pavements are not applied at the same location and have longer rest periods; hence the higher fatigue life.

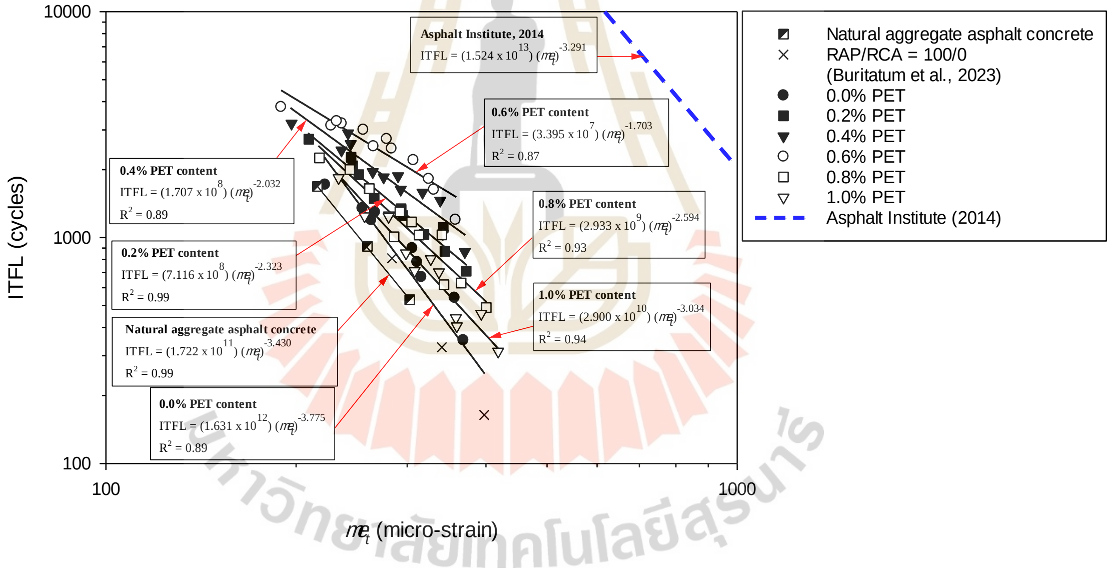

Figure 4.8 Relationship between ITFL and $\boldsymbol{\varepsilon_t}$ of RAP-RCA-PET asphalt concrete.

Different pavement material properties cause a difference in tensile strain response, resulting in different resistance to fatigue damage, expressed in terms of fatigue parameters *a* and *b*. The fatigue parameters of RAP-RCA-PET asphalt concretes versus PET content are given in Figure 4.9. Evidently, the value of parameter *a* decreases as the PET content increases and the lowest value is observed at 0.6% PET content. After that, the value of parameter *a* increases with the raised PET content.

However, the value of parameter b rises with the increased PET content, and the largest value is noted at 0.6% PET content. Then, the value of parameter b declines with the increased PET content. Based on a linear regression analysis, the values of parameters a and b for RAP-RCA-PET asphalt concretes can be calculated in terms of PET content using Eq. (4.1) and (4.2), respectively. These equations can facilitate the ITFL estimation of RAP-RCA-PET asphalt concretes at different PET contents.

$$\log(a) = -7.333 \times (\%PET) + 11.4 \qquad \text{for } 0.0 \leq \%PET \leq 0.6 \qquad (4.1.1)$$

$$\log(a) = 9.029 \times (\%PET) + 1.6 \qquad \text{for } 0.6 \leq \%PET \leq 1.0 \qquad (4.1.2)$$

$$b = 3.254 \times (\%PET) - 3.4 \qquad \text{for } 0.0 \leq \%PET \leq 0.6 \qquad (4.2.1)$$

$$b = -4.068 \times (\%PET) - 1.0 \qquad \text{for } 0.6 \leq \%PET \leq 1.0 \qquad (4.2.2)$$

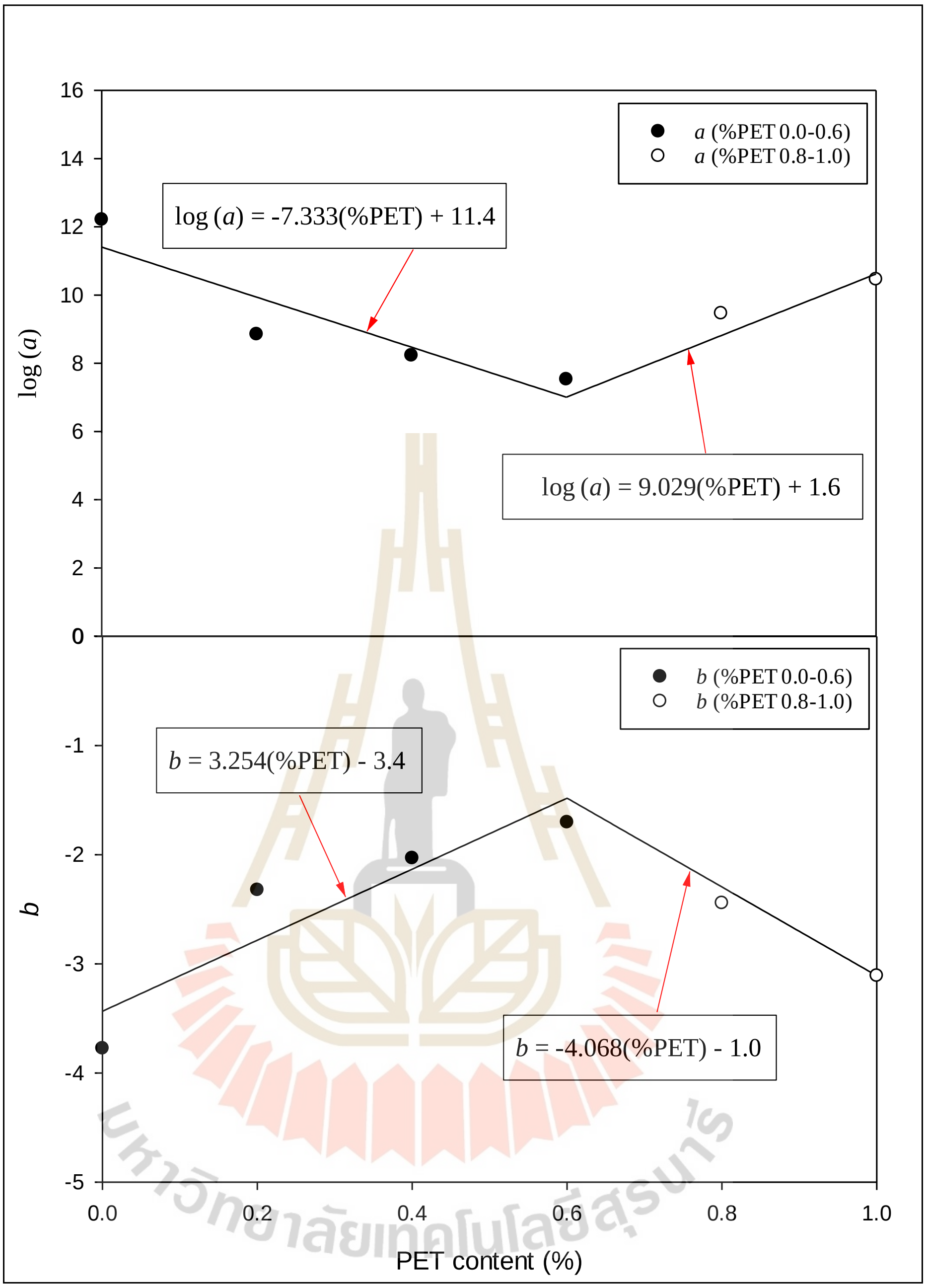

Figure 4.9 Fatigue parameters of RAP-RCA-PET asphalt concrete versus PET content.

The advantages of PET-modified RA asphalt concretes compared to NA asphalt concrete can be explained by Figure 4.8 and Table 4.4. It is interesting to mention that both the fatigue law and the IT_{MR} control the stability of asphalt concretes. The material with the location of ITFL versus ε_t relationship on more right does not always exhibit a longer service life. For instance, although the position of the ITFL-ε_t relationship of RAP-RCA asphalt concrete is above NA asphalt concrete, the RAP-RCA asphalt concrete has lower ITFL than the NA asphalt concrete at a given applied stress of 300 kPa due to its lower IT_{MR} (higher ε_t). However, when 0.6% PET content is added to RAP-RCA-PET asphalt concrete, its ITFL is greater than that of NA asphalt concrete due to its larger IT_{MR} and higher position of ITFL-ε_t relationship. This comparison highlights the potential of PET-modified RA asphalt concrete as an alternative material that can provide a longer fatigue life than natural materials.

Table 4.4 Comparison of ITFL of NA asphalt concrete and RAP-RCA-PET asphalt concrete.

Asphalt concrete mixtures	Applied stress (kPa)	IT_{MR} (MPa)	Strain (micro-strain)	ITFL (cycles)
NA asphalt concrete	300	2,370	259.5	903
RAP-RCA asphalt concrete with RAP/RCA ratio of 100/0 and 0.0% PET content	300	1,805	340.6	450
RAP-RCA asphalt concrete with RAP/RCA ratio of 80/20 and 0.6% PET content	300	2,705	227.3	3,292

Relationship between rut depth and number of wheel cycles of RAP-RCA-PET asphalt concretes at various RAP/RCA ratios and PET contents are compared with NA asphalt concrete and illustrated in Figure 4.10. Figure 4.11 shows rut depth at target cycle of RAP-RCA-PET asphalt concretes and NA asphalt concrete. Without PET, the RAP asphalt concrete (RAP/RCA ratio of 100/0) could not withstand the repetitive wheel load and failed to reach 20 mm of rut depth at 7,203 cycles prior to reaching the target 10,000 cycles, as seen in Figure 4.11(a) (Buritatum et al., 2023). Due to the superior stiffness of RCA benchmarked with that of RAP at a given PET content, the RCA inclusion can enhance the rutting resistance at the same target cycles; the lowest rut depth value is observed at the optimum RAP/RCA = 80/20 (Figure 4.10 and Figure 4.11(c) and (d)). Beyond the optimum RAP/RCA ratio, the low elastic modulus of interfacial transition zones between AC and RCA reduces the mixture stiffness (Huang et al., 2021), increasing rut depth with the decreased RAP/RCA ratio as shown in Figure 4.11(e) and (f).

Incorporating PET enhances RAP-RCA-PET asphalt concretes’ resistance to rutting failure, as seen in Figure 4.10 and Figure 4.11(b), (d), and (f). The lowest rut depth is observed at the optimum PET content of 0.6% for all RAP/RCA ratios. At the optimal PET content, the rut depth of RAP-RCA-PET asphalt concretes at the target cycles is 2.94 mm, 0.85 mm, 0.42 mm, and 0.83 mm for RAP/RCA = 100/0, 90/10, 80/20, and 60/40, respectively. According to Moghadam et al. (2014b), adding PET into asphalt concretes can improve energy absorption against wheel loading. The improved energy absorption is caused by the higher adhesion of AC film resulting from the melted particles of PET, improving rutting resistance.

The rut depth of NA asphalt concrete at the target cycles is 2.56 mm. Figure 4.10 shows that even with the addition of PET to RAP asphalt concretes (RAP/RCA ratio of 100/0), the rut depth at the target cycles is still larger than that of NA asphalt concrete. For 90/10 and 60/40 RAP/RCA ratios, rut depth at the target cycles of RAP-RCA-PET asphalt concretes is higher than NA asphalt concrete at PET contents of 0.4, 0.6, 0.8, and 1.0%. Meanwhile, the rut depth of the RAP-RCA-PET asphalt concretes with RAP/RCA ratio of 80/20 is lower than that of NA asphalt concrete at PET contents of 0.2, 0.4, 0.6, 0.8, and 1.0%. At the optimum PET content of 0.6% and RAP/RCA ratio of 80/20, RAP-RCA-PET asphalt concrete has a superior rutting resistance of 84% compared to NA asphalt concrete. These results indicated that incorporating RAP, RCA, and PET at the optimum contents in asphalt concrete mixtures can enhance their rutting resistance, superior to NA asphalt concrete.

This research suggests that adding PET additives to RAP-RCA asphalt concretes results in a significant performance improvement, presenting a new method for waste management. Using these materials together offers a cost-effective and environmentally friendly alternative for pavement applications.

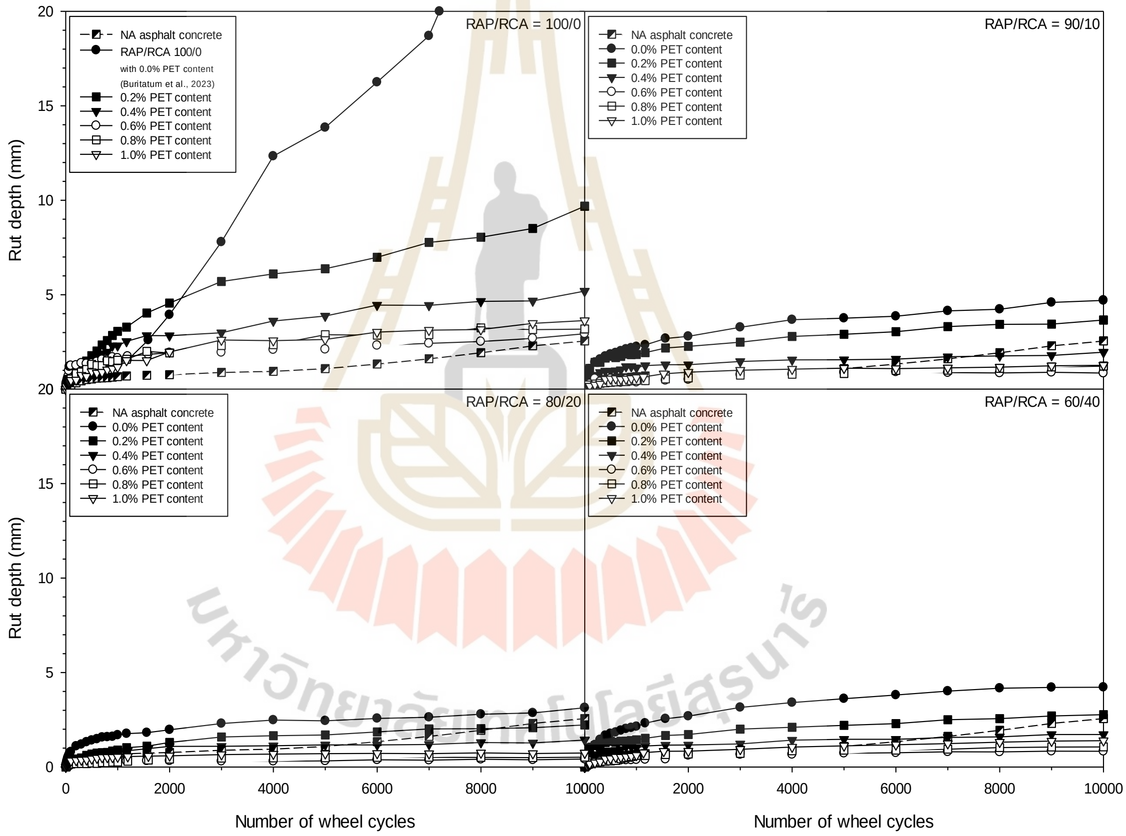

Figure 4.10 Rut depth of RAP-RCA-PET asphalt concrete versus number of cycles.

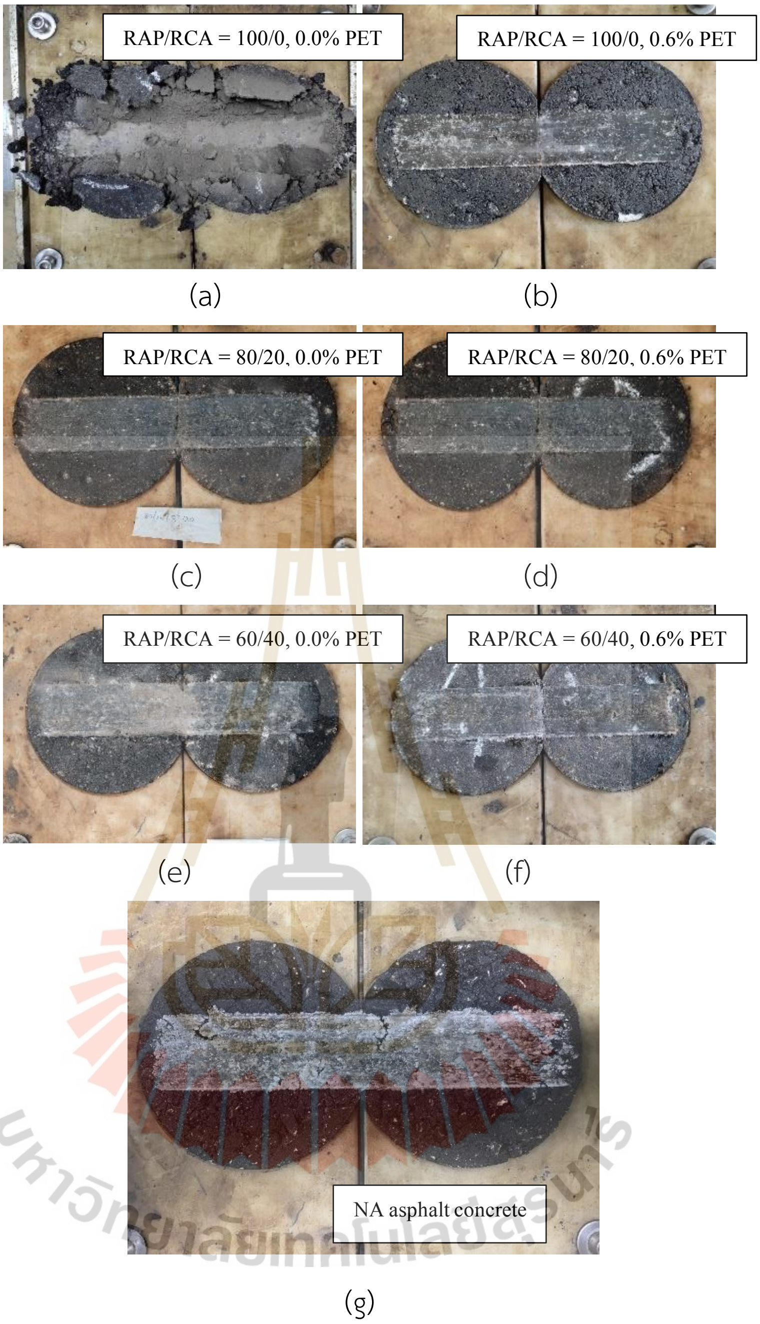

Figure 4.11 Rut depth at target cycle of RAP-RCA-PET asphalt concretes with (a) RAP/RCA = 100/0 with 0% PET content (Buritatum et al., 2023), (b) RAP/RCA = 100/0 with 0.6% PET content, (c) RAP/RCA = 80/20 with 0% PET content, (d) RAP/RCA = 80/20 with 0.6% PET content, (e) RAP/RCA = 60/40 with 0% PET content, (f) RAP/RCA = 60/40 with 0.6% PET content, and (g) NA asphalt concrete.

4.5 Conclusions

This chapter evaluated the mechanical performance of RAP-RCA-PET asphalt concretes. Following significant findings are summarized from the current research:

1) PET addition in asphalt concrete causes the higher asphalt cement required for PET particles coating, hence the higher optimum AC content of RAP-RCA-PET asphalt concretes. The RAP/RCA ratio also significantly influences the optimum AC content of asphalt concretes. Reducing the RAP/RCA ratio increases the optimum AC content due to a higher ability to absorb the AC of RCA. The Marshall properties of RAP-RCA-PET asphalt concretes meet the requirements of DH-S 410/1999 for Marshall stability, Marshall flow, VMA, and SI.

2) The RAP/RCA ratio and PET content significantly affect the performance of RAP-RCA-PET asphalt concretes. The lower RAP/RCA ratio leads to a higher ITS and IT_{MR} until the optimum RAP/RCA ratio of 80/20, where the improved interlocking strength of RCA particles and PET adhesion strength enhance mechanical properties. Beyond the optimum RAP/RCA, the excessive RCA replacement generates weak interfacial transition zones within the asphalt concrete matrix, reducing ITS, IT_{MR}, ITFL, and rutting resistance. Addition of PET to the asphalt concrete mixture improves ITS, IT_{MR}, and ITFL, whereby the highest values are observed at an optimum PET content of 0.6%. These improved properties are due to the melted components of un-melted PET enhancing the bond between the aggregate and AC and the higher energy absorption of un-melted PET particles. However, due to weak structure formation, excessive volume of PET particles (lower stiffness than RAP and RCA) reduces the performance.

3) The IT_{MR} improvement is directly related to the ITS improvement. At the optimum RAP/RCA ratio and PET content, RAP-RCA-PET asphalt concrete has a higher performance when compared to NA asphalt concrete. Adding PET also enhances the resistance to rutting failure, leading to lower rut depth at the target cycle. The lowest rut depth at the target cycle is found at the PET content of 0.6% for all RAP/RCA ratios, which is attributed to the improved energy absorption against wheel loading and thicker AC film due to the addition of PET. With a RAP/RCA ratio of 80/20 and

0.6% PET content, the RAP-RCA-PET asphalt concrete outperforms NA asphalt concrete.

4) According to the critical test results analysis, the fatigue distress model of RAP-RCA-PET asphalt concrete is developed in terms of the ITFL- ε_t relationship. The relationship is unique for all RAP/RCA ratios and the fatigue parameters are dependent on the PET content. Additionally, the ITFL-ε_t relationships of RAP-RCA-PET asphalt concretes are above and gentler than the relationship of NA asphalt concrete, which emphasizes the potential of PET as an additive to enhance the fatigue life of RAP-RCA-PET asphalt concrete alternative to NA asphalt concrete. The proposed fatigue distress model is helpful for the mechanistic design for RAP-RCA-PET asphalt concrete pavement, which supports sustainable construction strategy worldwide.

4.6 Reference

AASHTO. (2007). Standard Method of Test for Resistance of Compacted Asphalt Mixtures to Moisture-Induced Damage. AASHTO T283. Washington, DC: American Association of State Highway and Transportation Officials.

AASHTO. (2008). Standard method of test for Hamburg wheel-track testing of compacted hot-mix asphalt (HMA). AASHTO T324. Washington, DC: American Association of State Highway and Transportation Officials.

Aragao, F. T. S., Kim, Y.-R., & Lee, J. (2008). Research on Fatigue of Asphalt Mixtures and Pavements in Nebraska.

ASTM. (1995). Standard test method for indirect tension test for resilient modulus of bituminous mixtures. ASTM D4123-82. West Conshohocken, PA: ASTM.

ASTM. (2017). Standard test method for indirect tensile (IDT) strength of asphalt mixtures. ASTM D6931. West Conshohocken, PA: ASTM.

ASTM, A. (2015). D6927-15 Standard Test Method for Marshall Stability and Flow of Asphalt Mixtures. ASTM International: West Conshohocken, PA, USA.

BSI. (2004). Bituminous mixtures. Test methods for hot mix asphalt part 24: Resistance to fatigue. BS-EN 12697-24. .

Buritatum, A., Suddeepong, A., Akkharawongwhatthana, K., Horpibulsuk, S., Yaowarat, T., Hoy, M., Arulrajah, A., & Rashid, A. S. A. (2023). Hemp Fiber-Modified Asphalt Concretes with Reclaimed Asphalt Pavement for Low-Traffic Roads. Sustainability, 15(8). https://doi.org/10.3390/su15086860

De Farias, M. M., & Sinisterra, F. Q. (2012). Influence of asphalt rubber on the crushing of recycled aggregates used in dense HMA. Proceeding of Asphalt Rubber.

DOH. (1988). Specification for asphalt cement. [In Thai.] Standard No. DH-SP. 401/1988. Ratchathewi, Thailand: DOH.

DOH. (1999). Standard for Asphalt Hot-Mix Recycling. [In Thai.] Standard No. DH-S 410/1999. Ratchathewi, Thailand: DOH.

Gupta, S., & Veeraragavan, A. (2009). Fatigue behaviour of polymer modified bituminous concrete mixtures. Journal of Indian Road Congress, Hou, Y., Ji, X., Li, J., & Li, X. (2018). Adhesion between asphalt and recycled concrete aggregate and its impact on the properties of asphalt mixture. Materials, 11(12), 2528.

Hou, Y., Ji, X., Su, X., Zhang, W., & Liu, L. (2014). Laboratory investigations of activated recycled concrete aggregate for asphalt treated base. Construction and Building Materials, 65, 535-542.

Huang, Q., Qian, Z., Hu, J., Zheng, D., Chen, L., Zhang, M., & Yu, J. (2021). Investigation on the properties of aggregate-mastic interfacial transition zones (ITZs) in asphalt mixture containing recycled concrete aggregate. Construction and Building Materials, 269, 121257.

Kasikitwiwat, P., & Jantarachot, K. (2021). Comparative study of fatigue of asphalt concrete mixed with AC 60-70 and polymer modified asphalt binder. Science & Technology Asia, 39-49.

Kennedy, T. (1979). Practical use of the indirect tensile test for the characterisation of pavement materials. Australian road research board conference proc,

Modarres, A., & Hamedi, H. (2014). Effect of waste plastic bottles on the stiffness and fatigue properties of modified asphalt mixes. Materials & Design, 61, 8-15.

Moghaddam, T. B., Karim, M. R., & Syammaun, T. (2012). Dynamic properties of stone mastic asphalt mixtures containing waste plastic bottles. Construction and Building Materials, 34, 236-242.

Moghaddam, T. B., Soltani, M., & Karim, M. R. (2014). Experimental characterization of rutting performance of polyethylene terephthalate modified asphalt mixtures under static and dynamic loads. Construction and Building Materials, 65, 487-494.

Mohammad, L. N., & Paul, H. R. (1993). Evaluation of indirect tensile test for determining structural properties of asphalt mix.

Pasandín, A., & Pérez, I. (2013). Laboratory evaluation of hot-mix asphalt containing construction and demolition waste. Construction and Building Materials, 43, 497-505.

Taherkhani, H., & Arshadi, M. R. (2019). Investigating the mechanical properties of asphalt concrete containing waste polyethylene terephthalate. Road Materials and Pavement Design, 20(2), 381-398.

Thephsriha, P., Thipwangmek, R., Chankhao, S., Na Chiangmai, C., Nukui, T., Chen, W., Srithanya, S., & Khiaochotikul, P. (2018). Engineering Evaluation and Production Cost Reduction of The Recycling of Reclaimed Asphalt Concrete Pavement Materials to be Used as Components of New Asphalt Concrete Pavement Materials Using a Central Plant Mixed Plant. [In Thai.]. Ratchathewi, Thailand: DOH.

Wong, Y. D., Sun, D. D., & Lai, D. (2007). Value-added utilisation of recycled concrete in hot-mix asphalt. Waste Management, 27(2), 294-301.

CHAPTER V

PERFORMANCE OF POROUS ASPHALT CONCRETE USING POLYPROPYLENE- MODIFIED ASPHALT CEMENT AC60/70

5.1 Introduction

Porous asphalt concrete (PAC), the surface drainage layer on asphalt pavements, has many application advantages (noise reduction and safety during rainfall) due to its open-graded structure. The water from rainfall is stored and moved horizontally within the layer, which reduces splash and spray effects and thus increases the visibility of drivers during rainfall. However, due to its high air void (approximately 20%) in the mixture, unsuitable asphalt cement (AC) properties may lead the PAC to have a high separation of AC, resulting in low stiffness, high rutting, and low durability. Polymer-modified asphalt (PMA) is mainly used in PAC mixtures because of its superior performance characteristics, including elasticity, resistance to deformation, and durability under varying environmental conditions compared to conventional AC. Unfortunately, PMA costs are higher than those of conventional ACs, such as AC60/70 and AC40/50. Hence, using PAC, which has a higher material cost than conventional asphalt concrete (Dense-graded), is not promoted in Thailand. This chapter aims to assess the utilization of PP to modify asphalt cement penetration grade 60/70. The effect of PP on the asphalt cement properties, its influence on the Marshall properties of PAC, and its effect on the mechanistic performance of PAC were evaluated. The results of this chapter lead to the use of alternative materials that reduce the cost of PAC pavement construction and increase the PAC's use in pavement construction in Thailand.

5.2 Materials and Methods

5.2.1 Aggregate and asphalt cements

The studied aggregate was limestone, which was sourced from Sakhon Nakhon province, Thailand, as shown in Figure 5.1. The aggregate properties were compared to the Thailand PAC standard specified by the Department of Rural Roads (DRR, 2020), as indicated in Table 5.1. It was evident that the studied aggregate met the specifications of the DRR (2020).

Figure 5.1 Studied aggregate

Table 5.1 The aggregate properties

Description	Specifications (DRR, 2020)	Fine Aggregate		Coarse Aggregate			Total
		Passing #200	Retained #200	Retained #4	Retained 3/8”	Retained 1/2”	
Bulk Specific Gravity	-	2.745		2.750	2.755	2.757	2.753
Apparent Specific Gravity	-	2.776		2.790	2.797	2.790	2.790
Water Absorption (%)	≤2	-	0.83	0.52	0.47	0.43	-
Flakiness Index (%)	≤25	-		24	17	17	15
Elongation Index (%)	≤25	-		14	7	11	9
Asphalt Absorption (%)	≤2	Total = 0.24					
Los Angeles Abrasion (%)	≤30	Coarse Aggregate = 30.4					
Soundness (%)	≤5	Fine Aggregate = 4.65, Coarse Aggregate = 1.96					

The studied asphalt cement (AC), including AC60/70 and PMA, was supplied by Zola Asphalt Co., Ltd, Thailand. Both were characterized according to the AC for PAC specifications of the local authorities for each type. The PMA properties were evaluated according to the asphalt cement specifications outlined by the Department of Rural Roads standard (DRR, 2002), while the AC60/70 properties were evaluated following the Thai Industrial Standard Institute standard (TISI, 2017). The properties of PMA and AC60/70 are summarized in Table 5.2.

Table 5.2 Properties of PMA and AC60/70

Properties of asphalt cement	Unit	PMA		AC60/70	
		Specifications (DRR, 2002)	Results	Specifications (TISI, 2017)	Results
Asphalt cement					
Penetration at 25°C, 100 g, 5 sec	0.1 mm	60-70	60	60-70	64.0
Flash point	°C	≥232	340	≥232	327
Softening point (Ring & Ball)	°C	≥60	82.5	-	48.1
Ductility, 5 cm/min - at 13°C - at 25°C	 cm cm	 ≥20 -	 88.6 223	 - ≥100	 - 162
Shear dynamic at 10 rad/s, - at 64°C, G*/sinδ - at 70°C, G*/sinδ - at 76°C, G*/sinδ	 kPa kPa 	 - - ≥1.0	 1.93 1.84 1.71	 ≥1.0 - -	 1.32 1.28 1.09
Toughness/Tenacity test, 25°C - Toughness - Tenacity	 kg.cm kg.cm	 ≥200 ≥100	 218.3 178.4	 - -	 - -
Storage stability at 165°C. 120 hrs. Difference in softening point	°C	≤5	0.4	-	-
Density at 25°C	g/cc	1.00-1.05	1.03	-	1.02
Solubility in trichloroethylene	%wt	≥99	99.78	≥99	99.86

Table 5.3 Properties of PMA and AC60/70 (Continued)

Properties of asphalt cement	Unit	PMA		AC60/70	
		Specifications (DRR, 2002)	Results	Specifications (TISI, 2017)	Results
Test residue thin film oven test					
Weight loss	%Wt.	≤0.5	0.32	≤0.8	0.29
Retained penetration at 25°C, 100 g, 5 sec	%	≥65	90.8	≤54	69.4
Ductility, 5 cm/min					
- at 13°C	cm	≥10	72.0	-	-
- at 25°C	cm	-	181	≥50	132

5.2.2 Polypropylene modified asphalt cement

Figure 5.2 shows the polypropylene (PP) pellets obtained from Epac Groups Company Limited, Khon Kaen, Thailand. PP pellets are cylindrical with a size of approximately 3 mm in length and 2 mm in diameter. The uniform shape and size of the PP pellets ensure a consistent and even distribution within the asphalt mixture, which is crucial for achieving the homogenous and desired modification effects. The PP-modified AC60/70 was prepared by United Asphalt Products Company Limited in Khon Kaen, Thailand. A high-shear homogenizer was employed to incorporate PP into AC60/70 by the wet process. The AC60/70 was first heated adequately and then poured into a mixing container. Subsequently, the PP pellets were added to the warmed AC60/70 and mixed at a shear rate of 3,000 rpm for 2 hours with a constant temperature of 170°C. PP contents of 2%, 4%, and 6% by weight of the asphalt cement were used for the modification. The properties of the PP-modified AC60/70 were assessed through various tests, including penetration, softening point, flash point, dynamic shear, and the residue from the rolling thin film oven test.

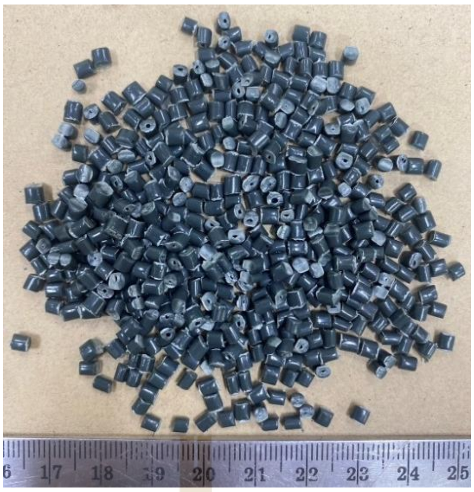

Figure 5.2 Studied PP.

5.2.3 Mix design and sample preparation

Before preparing studied porous asphalt concrete (PAC) mixtures, the aggregate was sieved, and the gradation curve was altered in compliance with the pavement surface wearing course specifications outlined by the local authority (DRR, 2020), as illustrated in Figure 5.3. The aggregate gradation curves were adjusted to fit the DRR (2020) specification.

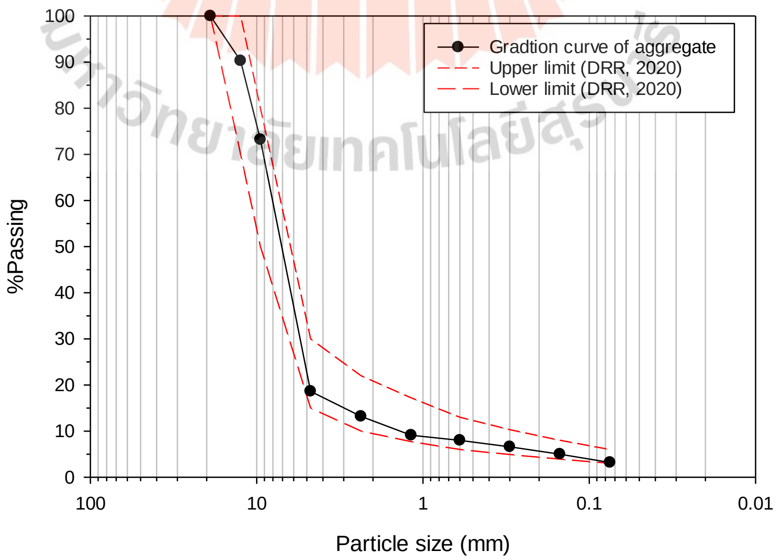

Figure 5.3 Gradation curve of aggregate

The appropriate mix proportion of PACs was acquired using the Marshall method following ASTM D 6927 (ASTM, 2015a). Before mixing, the aggregate and AC were warmed at 180°C and 160°C, respectively. The heated aggregate and AC were blended for 1 minute. The mixture was then compacted at 150°C in a standard 101.6-mm mold with 50 blows to each side by a Marshall hammer. The sample was next de-molded after 24 hours at room temperature. The Marshall test was conducted to determine the typical properties of asphalt concrete, such as density, voids in the mineral aggregate (VMA), air voids, voids filled by asphalt concrete (VFA), stability, and flow value. In addition, PAC samples were tested to assess PAC properties, including drain down and Cantabro abrasion tests.

The influence of PP-modified AC60/70 on the mechanical performances of PAC (AC60/70-PP-PAC) was evaluated through various performance tests, including ITS, ITMR, ITFL, and rutting resistance, compared to PAC using PMA (PMA-PAC). The performance-tested samples were prepared at a constant air void of 20% based on the local authority standard (DRR, 2020). For PACs, the optimum AC content (AC content providing 20% air void) was determined by assuming the AC content.

5.3 Experimental program

5.3.1 Drain down

The drain down test determines the separation of the AC from the asphalt concrete mixture due to the action of gravity. According to EN12697–18:2017 (BSI, 2017), the drain down test is carried out by preparing the uncompacted mixture at 150°C in an 800 ml beaker and after keeping it in an oven at 180°C for 3 hours. The drain down value can be determined by using the following equation:

$$Drain\ down = \frac{W_{fc} - W_{ic}}{W_{is}} \tag{5.1}$$

where W_{fc} = final weight of container(g); W_{ic} = initial weight of container (g); and W_{is} = initial weight of the mixture sample(g). The drain down for the PAC mixture must be less than 0.3%.

5.3.2 Cantabro abrasion loss

The Cantabro abrasion was conducted to evaluate the resistance to particle loss of PAC samples according to ASTM D7064 (ASTM, 2021). The PAC samples were prepared by Marshall method. PAC samples shall be tested in 7 days after de-mold in two conditions, concluding soaked and unsoaked. The soaked PAC sample was submerged in water bath at 25°C for 24 hours and then placed in Los Angeles abrasion machine for 300 rotations with speed of 30-33 rpm. The unsoaked PAC sample was placed directly into the Los Angeles abrasion machine. The test was conducted without steel sphere. After 300 rotations, the broken particle of PAC sample was discarded. The weight of PAC sample before and after test was measured. The loss in PAC sample weight is expressed in percentage of ratio of weight of disintegrated to the initial weight of the specimen shows in equation (5.2).

$$Particle\ loss\ (\%) = \frac{(M_i - M_f)}{M_i} \times 100 \tag{5.2}$$

M_i = weight of PAC sample before test and M_f = weight of PAC sample after test.

5.3.3 Strength index (SI)

The strength index (SI) of the asphalt concretes was determined according to AASHTO T 283 (AASHTO, 2007). The SI samples were prepared by compression under a constant pressure of 20.7 MPa for 2 minutes using a double plunger compactor with a height of 63.5 mm and a diameter of 101.6 mm. Two sample groups were prepared, including group 1 (unsoaked samples), which was set to be a control group, and group 2 (soaked samples), which was vacuum-saturated with the soak solution for 1 hour and then soaked at 60°C for 24 hours. The ratio between Marshall stability of soaked and unsoaked samples determined the SI value. The test was conducted at 25°C using a loading rate of 50 mm/min. The Department of Highways, Thailand (DRR, 2020) specified that the SI value of asphalt concrete should be above 80%.

5.3.4 Indirect tensile strength (ITS)

This study used the ITS test to determine the tensile properties of PACs according to ASTM D 6931 (ASTM, 2017). The ITS value was determined by loading a sample across its vertical diametrical plane at a 50 mm/min deformation rate at testing temperatures of 25, 40, 50, and 60°C. The maximum load at failure was measured and used to determine the ITS value of the Marshall sample. The ITS value can be determined using the following equation (5.3).

$$\text{ITS} = \frac{2000P}{\pi t D} \tag{5.3}$$

where ITS stands for indirect tensile strength (kPa), *P* represents maximum load (N), *t* denotes the sample thickness (mm), and *D* is the sample diameter (mm).

5.3.5 Indirect tensile resilient modulus (IT_{MR})

The IT_{MR} is a crucial factor in evaluating the performance of asphalt concretes for pavement design using the mechanistic-empirical method. The IT_{MR} was determined by subjecting the Marshall sample to dynamic loading under indirect tensile conditions following ASTM D 4123-82 (ASTM, 1995). The IT_{MR} test was performed at a stress level of 15% of ITS with haversine loading (frequency of 1 Hz, with a loading period of 0.1 seconds and a rest period of 0.9 seconds) for 200 pulses at 25°C. The IT_{MR} is determined using the average of the last five elastic stiffness values after the first 150, as described in equation (5.4).

$$IT_{MR} = \frac{P(0.27+\nu)}{tH_r} \tag{5.4}$$

where IT_{MR} is indirect tensile resilient modulus (MPa), ν is Poisson's ratio, *t* is the sample thickness, and H_r is recoverable horizontal deformation (mm).

5.3.6 Indirect tensile fatigue (ITF)

Fatigue failure is a significant distress of the flexible pavement under the accumulated damage caused by repeated loads. According to BS-EN-12697-24 (BSI, 2004), the stress control method was adopted to determine the fatigue resistance of asphalt concrete sample. The target applied stress of 150, 200, and 250 kPa were selected based on the BS-EN-12697-24 recommendation. The haversine loading pulse with a loading frequency of 1.0 Hz, a loading period of 0.1 seconds, and a rest period of 0.9 seconds was applied until the Marshall sample failed.

Theoretically, the deformation behavior under fatigue loading can be divided into three distinct zones of the relationship between horizontal deformation and the number of cycles. In the first zone, the initial loading cycles cause a relatively high deformation increment due to a rapid decrease in air void. In the second zone, the deformation increases linearly with the number of cycles. Throughout the loading period, accumulated plastic deformation gradually developed, leading to the formation of microcracks. In the third zone, the microcracks from the first and second zones propagate the macrocrack, resulting in complete failure (Aragao et al., 2008). The indirect tensile fatigue life (ITFL) is estimated from the intersection point of the slopes of the second and third zones.

5.3.7 Rutting resistance by the Hamburg wheel tracking test

The rutting resistance of asphalt concrete was evaluated according to AASHTO T324 (AASHTO, 2008) using the Hamburg wheel tracker testing machine. The wheel-tracking test samples were prepared by a gyratory compactor based on ASTM D6925 (ASTM, 2015b). The testing sample comprised two cylindrical specimens, each measuring 150 mm in diameter and 60 mm in thickness, positioned adjacent to each other to measure rut depth. The testing sample was securely mounted using plastic molds, with the cylindrical specimens precisely trimmed to fit the molds. A steel wheel, which is 47 mm wide, applied the 705-N load to the sample at a wheel speed of 26 cycles per minute. The machine automatically terminated the test upon reaching 10,000 cycles of wheel passes or a rut depth of 20 mm, whichever occurs first. The resistance to rutting failure was expressed in terms of the rut depth.

5.4 Test results and discussion

5.4.1 Properties of AC

The properties of PMA and PP-modified AC60/70 are shown in Table 5.3. Based on experimental testing, the 2% PP-modified AC60/70 (AC60/70-2%PP) has been found to meet the AC40/50 standard specified by TISI (2017), while 4% PP-modified AC60/70 (AC60/70-4%PP) and 6% PP-modified AC60/70 (AC60/70-6%PP) do not meet any standard of TISI (2017). According to the specifications for AC40/50 (TISI, 2017), AC's penetration value should be 4.0 to 5.0 mm. The penetration values of

PMA, AC60/70, AC60/70-2%PP, AC60/70-4%PP, and AC60/70-6%PP are 6.00, 6.40, 4.56, 4.11, and 3.80 mm, respectively. The PMA has lower penetration than unmodified AC60/70, indicating a more rigid material. Similar to the previous study by Habib et al. (2011) and Fattah et al. (2021), the penetration value of AC60/70 decreases as the PP content increases, indicating increased stiffness. Compared to PMA, all PP-modified AC60/70 exhibit lower penetration values than PMA.

The flash point indicates the safety of using AC at high temperatures. The flash point should be higher than 232°C (TISI, 2017). The flash point of PMA, AC60/70, AC60/70-2%PP, AC60/70-4%PP, and AC60/70-6%PP are 340, 327, 339, 350, and 361°C, respectively. PMA has a significantly higher flash point than AC60/70. The flash point of PP-modified AC60/70 increases as the PP content increases. The test result shows that PP improves the safety of AC60/70 for high-temperature applications, which is consistent with the findings of Sembiring et al. (2018).

The softening point indicates AC's temperature sensitivity or ability to maintain adhesion as the temperature increases. AC's softening point should be 48 to 58°C (TISI, 2017). The softening point of PMA, AC60/70, AC60/70-2%PP, AC60/70-4%PP, and AC60/70-6%PP are 82.5, 48.1, 51, 67, and 73°C, respectively. PMA has the highest softening point. The softening point of PP-modified AC60/70 increases as the PP content increases. The result indicates that PP reduces the temperature sensitivity of AC, aligning with the findings of Habib et al. (2011) and Fattah et al. (2021).

The ductility value indicates the ability of AC to elongate without breaking. The ductility should be higher than 100 cm (TISI, 2017). The ductility of PMA, AC60/70, AC60/70-2%PP, AC60/70-4%PP, and AC60/70-6%PP are 289, 162, 139, 122, and 110 cm, respectively. PMA has the highest ductility. The ductility of PP-modified AC60/70 decreases as PP content increases. This result shows that adding PP makes the AC stiffer and reduces its elongation ability, correlating with the decrease in penetration values, aligning with the findings of Habib et al. (2011) and Fattah et al. (2021).

Dynamic shear resistance, a term of G*/sind, indicates the ability of AC to resist permanent deformation. G*/sind should be not less than 1 kPa (TISI, 2017). G*/sind of PMA, AC60/70, AC60/70-2%PP, AC60/70-4%PP, and AC60/70-6%PP are 1.84, 1.28, 1.41, 1.52, and 1.57 kPa, respectively. As expected, PMA has the highest G*/sind. G*/sind of PP-modified AC60/70 increases as PP content increases. The result shows that PP makes the AC stiffer, which helps it resist deformation under dynamic loading. These results are consistent with Yeh et al. (2005) and Habib et al. (2011).

According to the specifications for AC40/50 (TISI, 2017), the weight loss of residue AC after heating by rolling thin film oven test (Aged AC) should be less than 0.8%. The weight loss of PMA, AC60/70, AC60/70-2%PP, AC60/70-4%PP, and AC60/70-6%PP are 0.32, 0.29, 0.24, 0.20, and 0.18%, respectively. PMA has the highest weight loss. The weight loss of PP-modified AC60/70 decreases as PP content increases. The result shows that PP reduces the weight loss of AC when subjected to high temperatures aging.

Compared to AC40/50's standard of TISI (2017), the softening point of AC60/70-4%PP does not meet the requirement. Meanwhile, the penetration and softening point values of AC60/70-6%PP do not meet the requirement. In other words, a PP content of 2% is the optimum content for improving the AC60/70 properties to meet the requirement.

Table 5.4 Properties of PMA and PP-modified AC60/70 compared to TISI (2017)

Properties of asphalt cement	Unit	AC40/50 Specifications (TISI, 2017)	Results				
			PMA	PP content (%)			
				0	2	4	6
Penetration at 25°C, 100 g, 5 sec	0.1 mm	40-50	60	64.0	45.6	41.1	38
Flash point	°C	≥232	340	327	339	350	361
Softening point (Ring & Ball)	°C	48-58	82.5	48.1	51	67	73
Ductility at 25°C, 5 cm/min	cm	≥100	289	162	139	122	110
Shear dynamic at 10 rad/s, at 70°C, G*/sinδ	kPa	≥1.0	1.84	1.28	1.41	1.52	1.57
Test on the residue obtained from thin film oven test							
Weight loss	%Wt.	≤0.8	0.32	0.29	0.24	0.20	0.18
Retained penetration at 25°C, 100 g, 5 sec	%	≥58	90.8	69.4	77.2	79.1	82.0
Ductility at 25°C, 5 cm/min	cm	≥48	271	132	123	113	87

5.4.2 Properties of PACs

Table 5.4 presents the properties of PACs, including PMA-PAC, AC60/70-PAC, AC60/70-2%PP-PAC, AC60/70-4%PP-PAC, and AC60/70-6%PP-PAC. At the desired air voids of 20%, all PAC samples have density values ranging from 2.023 to 2.066 g/cm^3. Void mineral in aggregate (VMA) values are 25.5 to 27.4%. The VFA values range from 23.9 to 26.3%.

The stability of PMA-PAC, AC60/70-PAC, AC60/70-2%PP-PAC, AC60/70-4%PP-PAC, and AC60/70-6%PP-PAC are 8.52, 5.49, 7.56, 8.51, and 10.09 kN, respectively. It is fascinating to note that the stability of PP-modified AC60/70-PAC increases as the PP content increases. Using PP-modified AC60/70 leads to a decrease in penetration, thereby enhancing the stiffness of PAC. Compared to PMA-PAC, the AC60/70-PAC, AC60/70-2%PP-PAC, and AC60/70-4%PP-PAC have lower stability. In contrast, AC60/70-6%PP-PAC exhibit higher stability, indicating PP content's significant influence on PAC performance. However, the stability of all PAC samples is higher than 3.56 kN, which meets the requirement specified by DRR (2020). All PAC samples show a flow of approximately 13, which falls in the 8 to 16 range specified by DRR (2020).

The SI values of PMA-PAC, AC60/70-PAC, AC60/70-2%PP-PAC, AC60/70-4%PP-PAC, and AC60/70-6%PP-PAC are 88.9, 82.5, 83.5, 80.0, and 77%, respectively. PMA-PAC has the highest SI value. The SI value of AC60/70-2%PP-PAC is higher than AC60/70-PAC. In contrast, the SI value of AC60/70-4%PP-PAC and AC60/70-6%PP-PAC is lower than AC60/70-PAC. The excessive PP can negatively impact the interaction between the AC and aggregate due to a high stiffness of AC, leading to poor adhesion and cohesion within the mix. The SI value of all PAC samples exceeds 80% specified by DRR (2020), except AC60/70-6%PP-PAC.

The PMA-PAC has the lowest drain down. Meanwhile, the drain down of PP-modified AC60/70-PAC is almost the same. The drain down of all PAC samples is lower than 0.3%, as specified by DRR (2020).

The Cantabro abrasion of unsoaked PAC samples are 6.55, 7.99, 7.83, 21.05, and 31.30% for PMA-PAC, AC60/70-PAC, AC60/70-2%PP-PAC, AC60/70-4%PP-PAC, and AC60/70-6%PP-PAC, respectively. The Cantabro abrasion of soaked PAC samples are 16.99, 18.85, 18.30, 23.67, and 37.64% for PMA-PAC, AC60/70-PAC, AC60/70-2%PP-PAC, AC60/70-4%PP-PAC, and AC60/70-6%PP-PAC, respectively. The unsoaked PAC sample has a lower abrasion loss than the soaked PAC sample due to moisture, reducing internal adhesion. DRR (2020) specified that the Cantabro abrasion loss should be less than 20 and 40% for unsoaked and soaked PAC samples, respectively. It can be seen that all of the PAC samples have the Cantabro abrasion loss less than the requirement except AC60/70-4%PP-PAC and AC60/70-6%PP-PAC.

Table 5.5 Properties of PMA-PAC, AC60/70-PAC, AC60/70-2%PP-PAC, AC60/70-4%PP-PAC, and AC60/70-6%PP-PAC

Properties	Unit	Specifications (DRR, 2020)	Results				
			PMA-PAC	AC60/70-PAC	AC60/70-2%PP-PAC	AC60/70-4%PP-PAC	AC60/70-6%PP-PAC
%AC by weight of Aggregate	%	3-7	3.5	4	3.5	3.5	3.5
Bulk density	g/ml	-	2.034	2.023	2.042	2.066	2.050
VMA	%	-	26.7	27.4	26.4	25.5	26.1
Air voids	%	20±2	20	20	20	20	20
VFB	%	-	23.6	26.3	23.9	25.1	24.1
Stability	kN	≥3.56	8.52	5.49	7.56	8.51	10.09
Flow	0.01 ”	8-16	13.4	12.7	12.5	13	13

Table 5.4 Properties of PMA-PAC, AC60/70-PAC, AC60/70-2%PP-PAC, AC60/70-4%PP-PAC, and AC60/70-6%PP-PAC (Continued)

Properties	Unit	Specifications (DRR, 2020)	Results				
			PMA-PAC	AC60/70-PAC	AC60/70-2%PP-PAC	AC60/70-4%PP-PAC	AC60/70-6%PP-PAC
Strength index	%	≥80	88.9	82.5	83.5	80	77
Drain down	%	<0.3	0.05	0.08	0.08	0.10	0.10
Cantabro abrasion loss							
- Unsoaked sample abrasion loss	%	<20	6.55	7.99	7.83	21.05	31.30
- Soaked sample abrasion loss	%	<40	16.99	18.85	18.30	23.67	37.64

5.4.3 Mechanistic performance

The ITS of PAC samples under different testing temperatures of 25, 40, 50, and 60°C are illustrated in Figure 5.4. The ITS values decrease with increasing temperature for all mixtures, which is expected as asphalt tends to soften at higher temperatures. PMA-PAC shows the highest ITS values across all temperatures, indicating superior tensile strength compared to the other PAC samples. At low temperature (25°C), AC60/70-PAC has lower ITS values than AC60/70-2%PP-PAC but higher than that of the AC60/70-4%PP-PAC and AC60/70-6%PP-PAC. At high temperatures (40, 50, and 60°C), the AC60/70-PAC has a lower ITS than AC60/70-2%PP-PAC, AC60/70-4%PP-PAC, and AC60/70-6%PP-PAC, demonstrating adding PP leads to low-temperature susceptibility of AC due to its higher softening point. Adding 2% of PP content yields the greatest increase in ITS. However, AC60/70-2%PP-PAC has lower ITS than PMA-PAC across all tested temperatures.

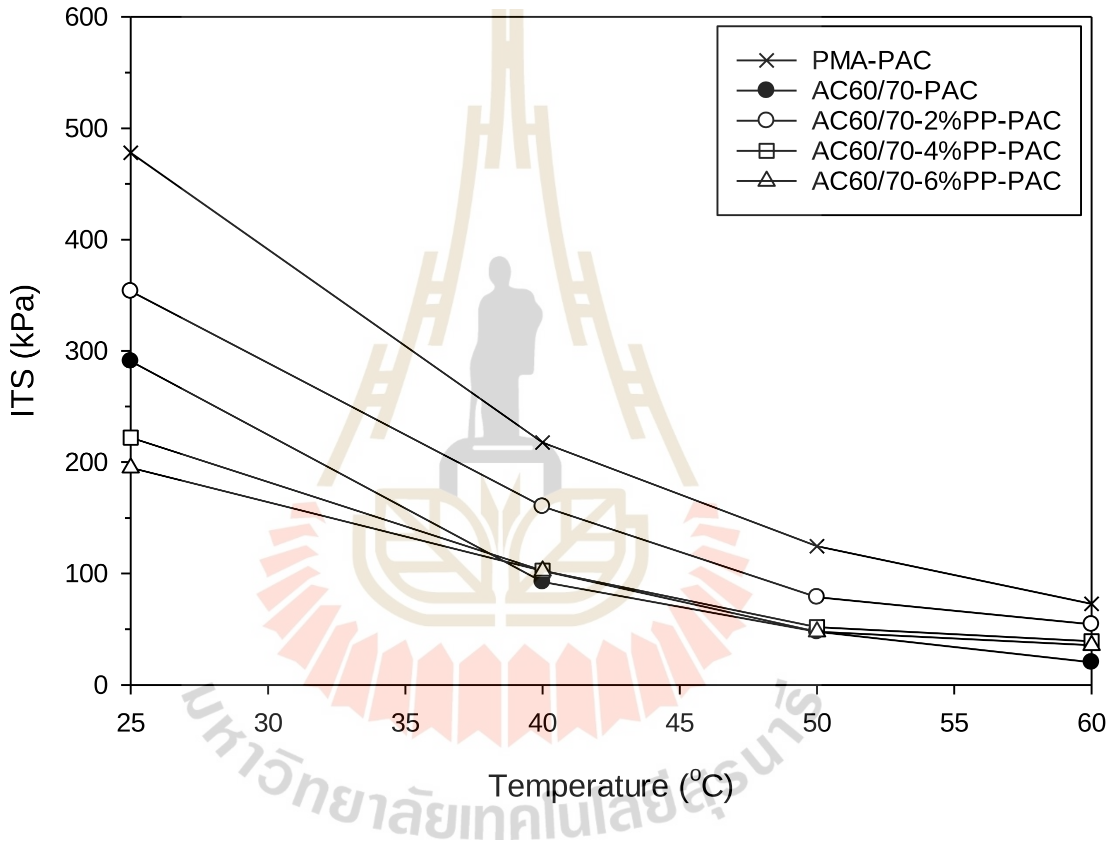

Figure 5.4 The ITS of PAC samples under different testing temperatures of 25, 40, 50, and 60°C

As shown in Figure 5.5, the IT_{MR} of PMA-PAC, AC60/70-PAC, AC60/70-2%PP-PAC, AC60/70-4%PP-PAC, and AC60/70-6%PP-PAC is 2,243.6, 1,457.3, 1,784.4, 589.3, and 477.4 MPa, respectively. PMA-PAC shows the highest IT_{MR} value. Compared to AC60/70-PAC, the IT_{MR} of AC60/70-2%PP-PAC is higher, while the IT_{MR} of AC60/70-4%PP-PAC and AC60/70-6%PP-PAC are lower. Adding PP can enhance the IT_{MR} of PAC, particularly by PP content of 2%. However, when PP content exceeds 2%, the IT_{MR} of PAC decreases as PP content increases. Higher PP content increases the stiffness and reduces the flexibility of AC, as shown in penetration and ductility test results.

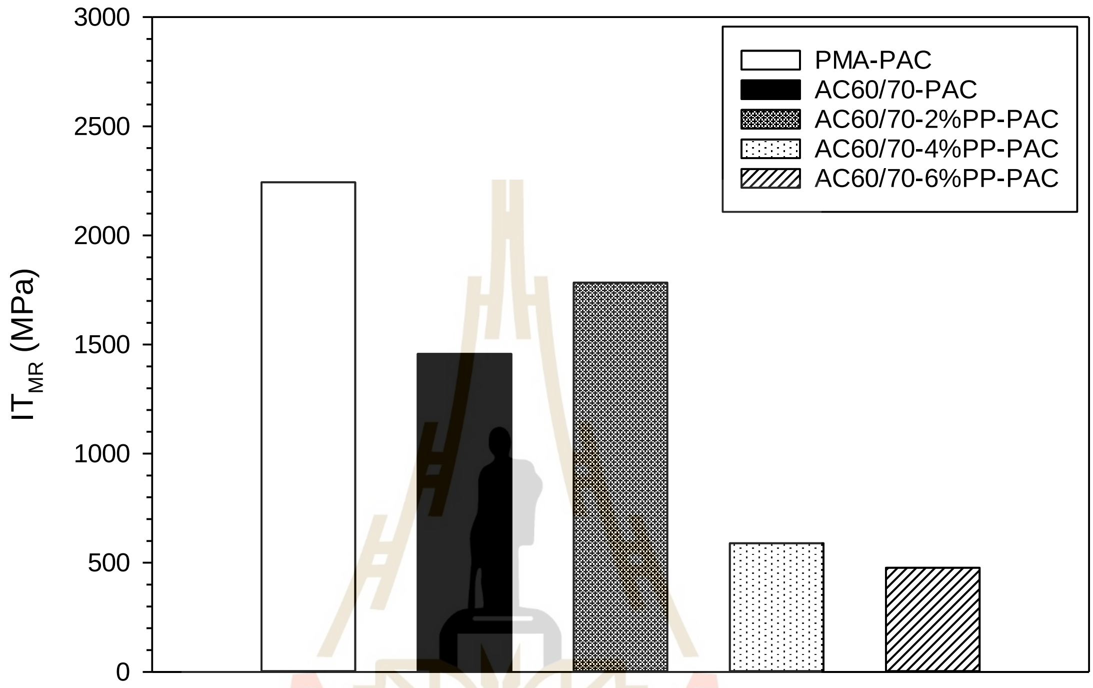

Figure 5.5 The IT_{MR} of PAC samples

Figure 5.6 illustrates the ITFL values of PACs under different applied stresses of 150, 200, and 250 kPa. The ITFL decreases with the increased applied stress for all PACs due to the higher plastic deformation. At the same applied stress, the PMA-PAC has the highest ITFL. Adding PP can enhance the ITFL of PAC, particularly by PP content of 2%. However, when PP content exceeds 2%, the ITFL of PAC decreases as PP content increases. Similar to the IT_{MR} test result, higher PP content increases the stiffness and reduces the flexibility of AC. At the higher applied stress, AC60/70-4%PP-PAC cannot withstand the applied stress at 250 kPa, while AC60/70-6%PP-PAC cannot withstand applied stress at 200 and 250 kPa due to its lower ITS than the applied stress.

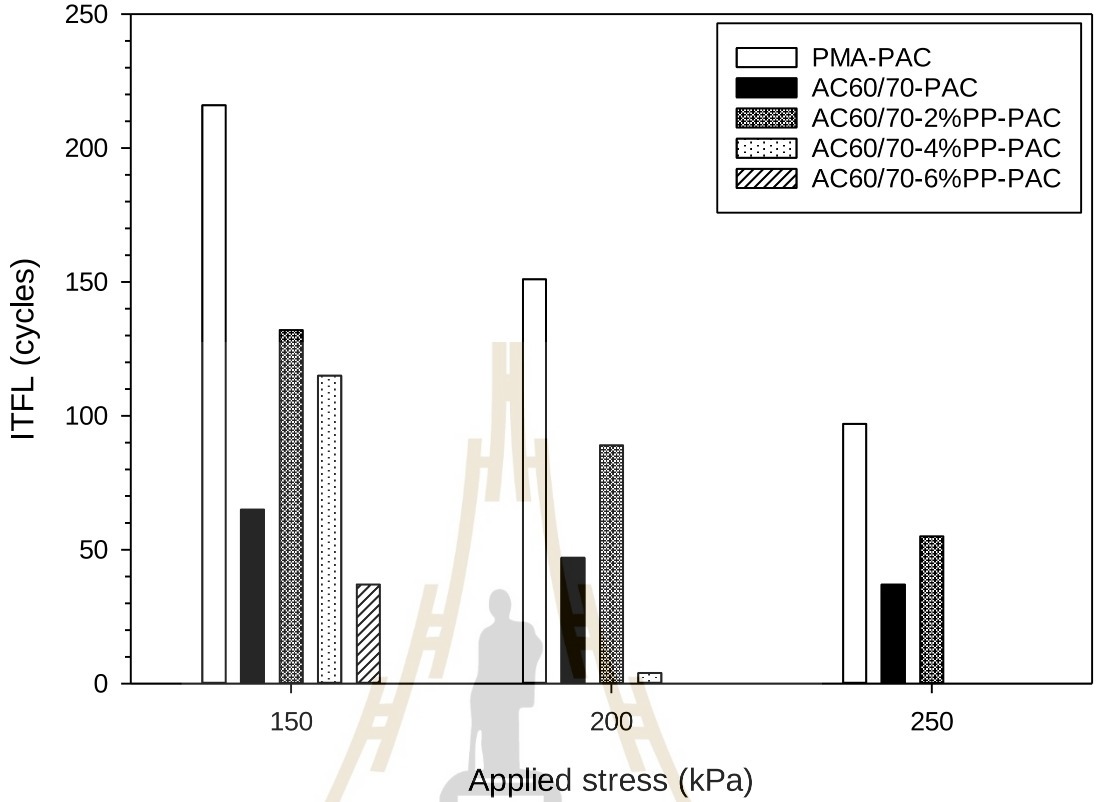

Figure 5.6 The ITFL of PAC samples under difference applied stress of 150, 200, and 250 kPa

As per BS EN 12697-24 (BSI, 2004), the initial tensile strain (ε_t) influences the ITFL (fatigue law). The asphalt concrete with a lower ε_t generally presents a higher ITFL. The ITFL of the asphalt concrete pavement can be estimated using the ε_t based on the fatigue law as follows:

$$\mathrm{ITFL} = a\left[\frac{1}{\mu\varepsilon_t}\right]^b \tag{5.5}$$

where *a* and *b* are the fatigue parameters, which can be determined from the regression analysis.

Kennedy (1979) and Mohammad and Paul (1993) revealed that the applied stress and IT_{MR} influence the ε_t in the following equation:

$$\varepsilon_t = \frac{\sigma(1+3v)}{IT_{MR}} \tag{5.6}$$

where σ is applied tensile stress (kPa), and v is Poisson's ratio (taken as 0.35 suggested by BS EN 12697-24).

ε_t of PMA-PAC, AC60/70-PAC, and AC60/70-2%PP-PAC are calculated from Eq. (2.4). The relationship between the ITFL and the ε_t in the logarithmic scale of PAC samples is illustrated in Figure 5.7. The ITFL reduces as the ε_t increases, consistent with the behavior described by BE EN12697-24. Within the range of studied strains, the ITFL- ε_t relationship for PMA-PAC is positioned highest above those of the other PACs, indicating that PMA-PAC exhibits the longest service life under the same induced strain, highlighting the superior fatigue resistance of PMA-PAC. It can also be revealed that the addition of PP to AC60/70 significantly influences the position and slope of the ITFL- ε_t relationship. Precisely, AC60/70-2%PP-PAC is positioned above AC60/70-PAC and exhibits a gentler slope, suggesting enhanced resistance to strain and a potentially longer fatigue life. The result demonstrates that incorporating 2% PP content into AC60/70 can improve the fatigue performance of PAC.

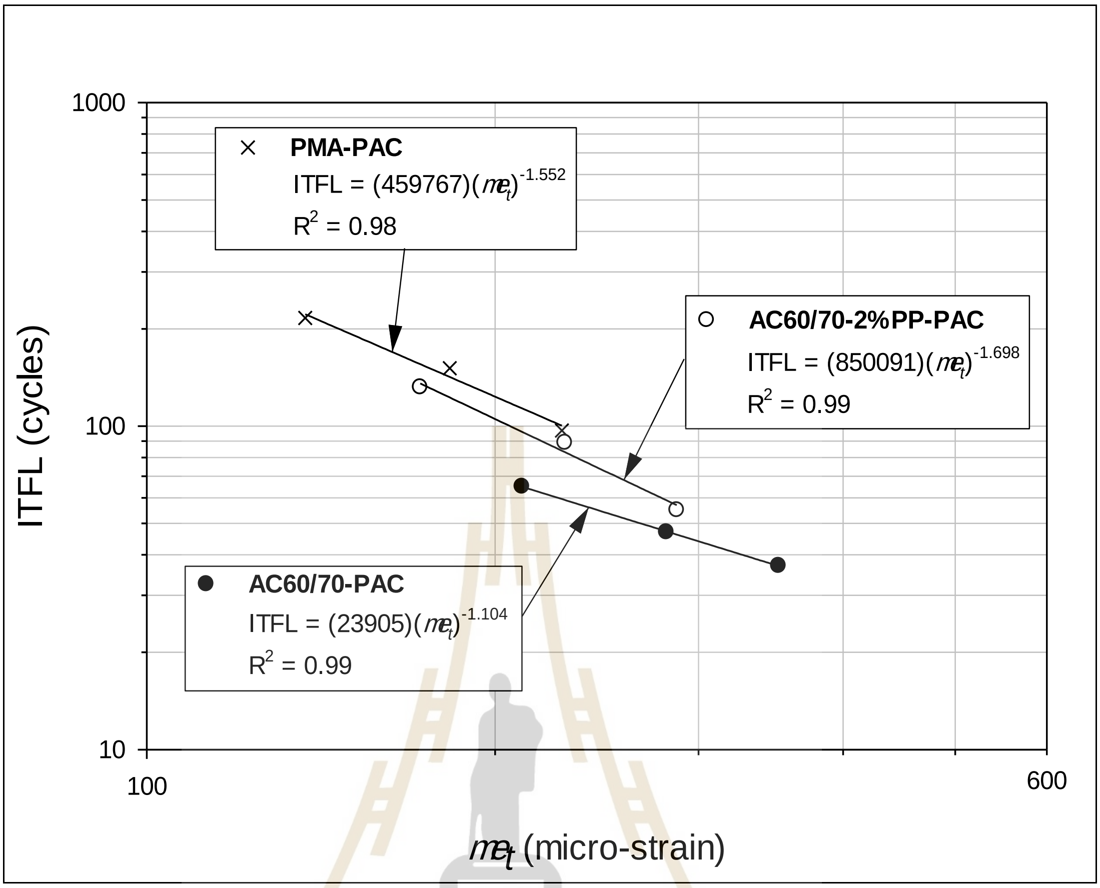

Figure 5.7 Relationship between ITFL and me_t of PMA-PAC, AC60/70-PAC, and AC60/70-2%PP-PAC

Figure 5.8 illustrates the rut depth of PACs under testing wheel cycles. The rut depth at the target 10,000 cycles of PMA-PAC, AC60/70-PAC, AC60/70-2%PP-PAC, AC60/70-4%PP-PAC, and AC60/70-6%PP-PAC are 2.78, 4.11, 3.69, 3.58, and 7.26 mm, respectively. The PMA-PAC has the lowest rut depth. Adding 4% PP can improve the rutting resistance of PP-modified AC60/70-PAC, resulting in the lowest rut depth. When PP content exceeds 4%, the rut depth of PAC increases as PP content increases. AC60/70-6%PP-PAC has the highest rut depth due to the high G*/sind of AC, resulting in lower flexibility under the wheel load.

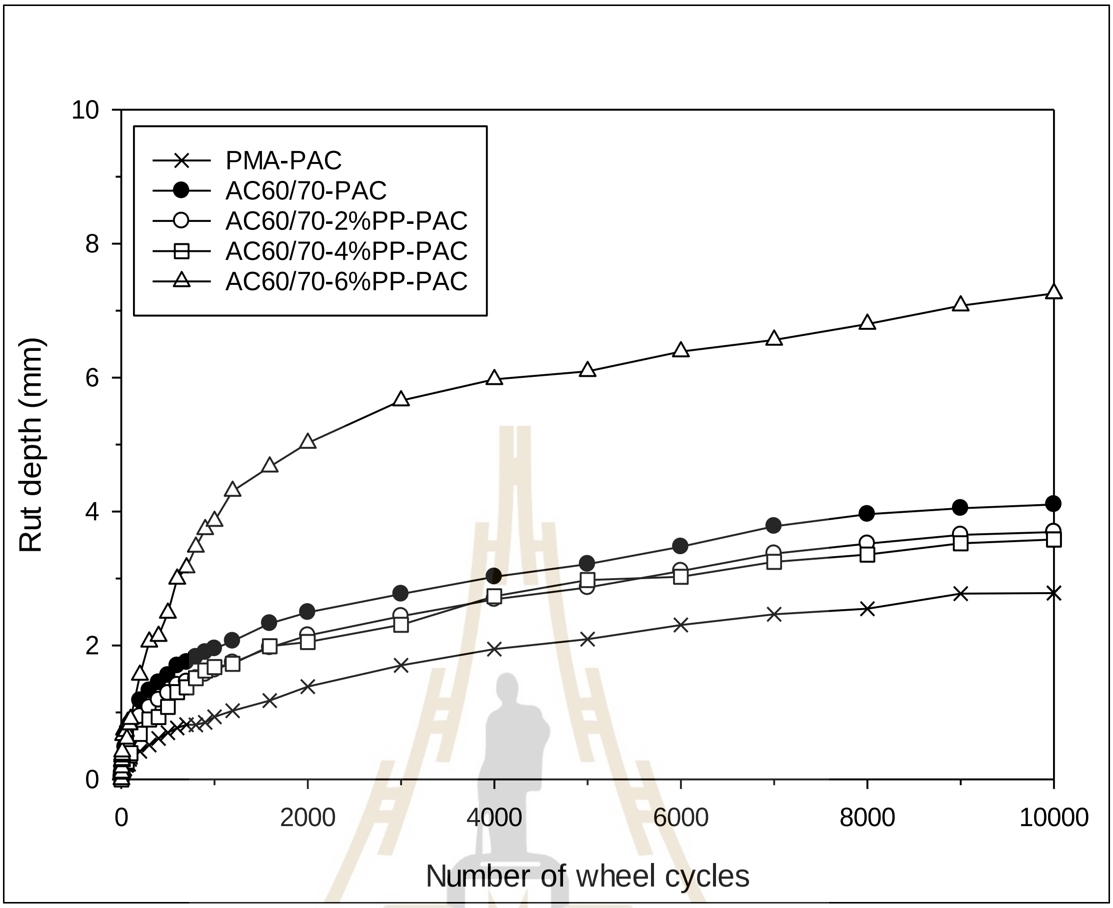

Figure 5.8 The rut depth of PAC samples under testing wheel cycles

5.5 Conclusions

The goal of this chapter was to evaluate the polypropylene (PP)-modified asphalt cement penetration grade of 60/70 (AC60/70) for porous asphalt concrete (PAC) as a sustainable pavement surface. Notable findings included the following:

1) Based on experimental testing, it was found that AC60/70 modified with 2% PP content (AC60/70-2%PP) meets the AC40/50 standard specified by TISI (2017), while AC60/70 modified with 4% PP (AC60/70-4%PP) and 6% PP (AC60/70-6%PP) do not meet TISI standard. PP-modified AC60/70 penetration values decrease as PP content increases, indicating increased stiffness. The flash point temperature increases with higher PP content, enhancing the safety of AC60/70 for high-temperature applications. The softening point temperature increases as PP content increases, showing reduced temperature sensitivity. The dynamic shear resistance (G*/sind) increases with higher PP content, indicating better resistance to deformation. However, ductility decreases with increased PP content, indicating reduced elongation ability. The weight loss after heating also decreases with higher PP content, suggesting better resistance to aging.

2) With higher AC properties, PAC using PP-modified AC60/70 performs better than AC60/70-PAC. Adding PP improved AC's temperature susceptibility, stiffness, and dynamic load resistance. At 2% of PP content, it led to the most significant improvement in the ITS of PAC. ITMR, ITFL, and rutting resistance of PAC. In contrast, with an exceeded PP content, PAC's ITMR, ITFL, and rutting resistance were reduced due to the exceeded stiffness of AC, particularly at 6% of PP content. Compared to PMA-PAC, all PP-modified AC60/70-PAC samples have a lower mechanical performance.

3) The distress model of PAC samples was developed based on experimental data. Using PP-modified AC60/70 in PAC can significantly enhance its fatigue life. AC60/70-2%PP-PAC's superior performance in resisting strain-induced fatigue makes it a suitable candidate for applications requiring viscous materials for PAC pavement. The proposed fatigue distress model is helpful for the mechanistic design of AC60/70-2%PP-PAC, which supports a sustainable construction strategy worldwide.

5.6 Reference

AASHTO. (2007). Standard Method of Test for Resistance of Compacted Asphalt Mixtures to Moisture-Induced Damage. AASHTO T283. Washington, DC: American Association of State Highway and Transportation Officials.

AASHTO. (2008). Standard method of test for Hamburg wheel-track testing of compacted hot-mix asphalt (HMA). AASHTO T324. Washington, DC: American Association of State Highway and Transportation Officials.

Aragao, F. T. S., Kim, Y.-R., & Lee, J. (2008). Research on Fatigue of Asphalt Mixtures and Pavements in Nebraska.

ASTM. (1995). Standard test method for indirect tension test for resilient modulus of bituminous mixtures. ASTM D4123-82. West Conshohocken, PA: ASTM.

ASTM. (2015a). Standard Test Method for Marshall Stability and Flow of Asphalt Mixtures. ASTM D6927-15. International: West Conshohocken, PA, USA.

ASTM. (2015b). Standard Test Method for Preparation and Determination of the Relative Density of Asphalt Mix Specimens by Means of the Superpave Gyratory Compactor. ASTM D6925. West Conshohocken, PA: ASTM.

ASTM. (2017). Standard test method for indirect tensile (IDT) strength of asphalt mixtures. ASTM D6931. West Conshohocken, PA: ASTM.

BSI. (2004). Bituminous mixtures. Test methods for hot mix asphalt part 24: Resistance to fatigue. BS-EN12697-24.

BSI. (2017). Bituminous mixtures-Test methods-Part 18: Binder drainage. EN12697-18:2017. London: BSI.

Fattah, M. Y., Abdulkhabeer, W., & Hilal, M. M. (2021). Characteristics of asphalt binder and mixture modified with waste polypropylene. *Engineering and Technology Journal, 39*(8), 1224-1230.

Habib, N. Z., Kamaruddin, I., Tan, I. M., & Napiah, M. (2011). The application of modern analytical techniques to study rheology and morphology of polymer modified bitumen. 2011 National Postgraduate Conference.

Ma, Y., Zhou, H., Jiang, X., Polaczyk, P., Xiao, R., Zhang, M., & Huang, B. (2021). The utilization of waste plastics in asphalt pavements: A review. *Cleaner Materials, 2*, 100031.

Sembiring, F., Purnomo, C. W., & Purwono, S. (2018). Catalytic pyrolysis of waste plastic mixture. IOP Conference Series: Materials Science and Engineering.

CHAPTER VI
CONCLUSION AND RECOMMENDATION

6.1 Summary and conclusions

This thesis consists of three main objectives. The first is to examine the use of recycled PET as an additive to improve the mechanistic performance of RAP asphalt concrete. The second involves using recycled PET to enhance the mechanistic performance of RAP-RCA asphalt concrete. This part also studies the effect of the RAP/RCA ratio on the Marshall properties and mechanical performance. In both the first and second parts, the effectiveness of PET is evaluated using the dry method, which is incorporated into dense-graded asphalt concrete mixtures. The third is to evaluate the use of PP through the wet method, where the properties of asphalt cement are assessed. PP-modified asphalt cement is then evaluated for use in open-graded asphalt concrete mixtures, also called porous asphalt concrete. The results of this study will provide valuable insights into the potential use of waste materials in asphalt concrete pavement to improve waste management and enhance the sustainability of pavement infrastructure.

6.1.1 The effect of PET content on the optimum asphalt cement, the Marshall properties, and the mechanistic performances of RAP asphalt concrete.

Incorporating polyethylene terephthalate (PET) into RAP asphalt concrete increases air voids and optimal asphalt cement content, enhancing adhesion strength and resistance to aggregate separation, ultimately improving Marshall properties and strength indices (SI). The addition of PET thickened the asphalt cement film around the aggregates, boosting adhesion strength, tensile properties, and rutting resistance. The optimal improvement was observed at a 0.6% PET content. At 0.6% PET, the RAP asphalt concrete showed the highest performance improvements: Marshall stability, SI, and ITS improved by 25%, 19%, and 69%, respectively, while IT_{MR}, ITF, and rutting resistance improved by 11%, 270%, and 80%. Excessive PET content (>0.6%) negatively affected stiffness. A distress model for RAP asphalt concrete modified with PET was developed, accurately forecasting service life based on PET content.

6.1.2 The effect of PET content on the optimum asphalt cement, the Marshall properties, and the mechanistic performances of RAP-RCA asphalt concrete.

Adding PET to RAP-RCA asphalt concrete increases the optimum asphalt cement (AC) content for coating PET particles. The RAP/RCA ratio also affects the optimum AC content, with lower ratios requiring more AC due to RCA's higher absorption capacity. The Marshall properties of RAP-RCA-PET asphalt concretes meet DH-S 410/1999 standards. The performance of asphalt concrete is significantly influenced by the RAP/RCA ratio and PET content. An 80/20 RAP/RCA ratio provides optimal interlocking strength and mechanical properties, while excessive RCA reduces performance. PET improves ITS, IT_{MR}, and ITFL, with the best results at 0.6% PET. Beyond this, excessive PET reduces stiffness and performance. The IT_{MR} improvement corresponds to ITS enhancement. At optimal RAP/RCA ratios and PET content, RAP-RCA-PET asphalt concrete outperforms natural aggregate (NA) asphalt concrete. PET enhances rutting resistance, with the lowest rut depth at 0.6% PET. The fatigue distress model developed for RAP-RCA-PET asphalt concrete, based on ITFL-ε_t relationships, shows better fatigue life than NA asphalt concrete, supporting the use of PET for sustainable construction. This fatigue distress model aids in the mechanistic design of RAP-RCA-PET asphalt concrete pavements, promoting sustainable construction globally.

6.1.3 The effect of PP content on the asphalt cement properties and the effect of PP-modified asphalt cement on the optimum asphalt cement, the Marshall properties, and the mechanistic performances of porous asphalt concrete.

Incorporating AC60/70 with PP significantly affects its properties, enhancing its performance in various aspects. The study found that 2% PP content optimally improves the penetration, softening point, flash point, and dynamic shear resistance of AC60/70, making it stiffer and more resistant to high temperatures and deformation. However, higher PP contents (4% and 6%) result in reduced ductility and increased brittleness, negatively impacting the mixture's overall performance. The optimal PP content of 2% balances enhancing stiffness and maintaining adequate flexibility, ensuring improved performance of the AC60/70. Compared to PMA, PP-modified AC60/70 remains the lower performance. The use of PP-modified AC60/70 in PAC shows significant improvements in stability, tensile strength, and resistance to deformation. PAC samples with 2% PP-modified AC60/70 exhibit higher stability and lower rut depth than unmodified PAC samples, meeting the performance criteria specified by DRR (2020). However, higher PP contents (4% and 6%) lead to increased abrasion loss and reduced flexibility, indicating that excessive PP can adversely affect PAC performance. The findings suggest that a 2% PP content is optimal for enhancing the properties of PAC, providing a balance between stiffness and durability while maintaining adequate flexibility. The distress model of PAC samples was developed based on experimental data. The proposed fatigue distress model is helpful for the mechanistic design of AC60/70-2%PP-PAC, which supports a sustainable construction strategy worldwide.

6.2 Recommendations for future work

1) It is advisable to conduct field research for additional study.

2) The construction cost should be assessed for cost-benefit analysis.

3) This study only examined one PET and PP size. Further research should explore other sizes.

4) This study utilized the Marshall method for mix-design. The Superpave method could be considered for future study.

APPENDIX A

PUBLICATIONS

List of Publications

Laomuad, A., Suddeepong, A., Horpibulsuk, S., Buritatum, A., Yaowarat, T., Akkharawongwhatthana, K., Pongsri, N., Phunpeng, V., Chinkulkijniwat, A., & Arulrajah, A. (2024). **Evaluating polyethylene terephthalate in asphalt concrete with reclaimed asphalt pavement for enhanced performance**. Construction and Building Materials, 422, 135749.

Construction and Building Materials 422 (2024) 135749

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Evaluating polyethylene terephthalate in asphalt concrete with reclaimed asphalt pavement for enhanced performance

Apisit Laomuad [a], Apichat Suddeepong [a,*], Suksun Horpibulsuk [a,b,c,**], Apinun Buritatum [a,d], Teerasak Yaowarat [a,d], Kongsak Akkharawongwhatthana [a,e], Nantipat Pongsri [a], Veena Phunpeng [a,f], Avirut Chinkulkijniwat [c], Arul Arulrajah [g]

[a] Center of Excellence in Innovation for Sustainable Infrastructure Development, Institute of Research and Development, Suranaree University of Technology, Nakhon Ratchasima 30000, Thailand
[b] Academy of Science, The Royal Society of Thailand, Bangkok 10300, Thailand
[c] School of Civil Engineering, Institute of Engineering, Suranaree University of Technology, Nakhon Ratchasima 30000, Thailand
[d] Undergraduate Program in Civil and Infrastructure Engineering, Institute of Engineering, Suranaree University of Technology, Nakhon Ratchasima 30000, Thailand
[e] Graduate Program in Civil Engineering and Construction Management, Institute of Engineering, Suranaree University of Technology, Nakhon Ratchasima 30000, Thailand
[f] School of Mechanical Engineering, Institute of Engineering, Suranaree University of Technology, Nakhon Ratchasima, 30000, Thailand
[g] Department of Civil and Construction Engineering, Swinburne University of Technology, Melbourne, Australia

ARTICLE INFO

Keywords:
Polyethylene terephthalate
Reclaimed asphalt pavement
Performance
Waste

ABSTRACT

Reclaimed asphalt pavement (RAP) is widely utilized as a green base/subbase material. Still, this material can only be used in small amounts in asphalt concrete mixtures. Many studies have shown that a large amount of RAP replacement could make asphalt pavements less effective. The goal of this study is to evaluate the mechanical properties of asphalt concrete made with 100% RAP aggregate and crushed polyethylene terephthalate (PET) bottles. The effect of adding PET to RAP aggregate was investigated with PET contents ranging from 0% to 1.0% by weight of RAP aggregate. The improved static and dynamic performances of the RAP asphalt concrete were assessed via the Marshall stability, the strength index (SI), the indirect tensile strength (ITS), the indirect tensile fatigue (ITF), the indirect tensile resilient modulus (IT_{MR}), and the resistance to rutting tests. The optimum PET content of 0.6% provided the best performance across all experimental testing, resulting in a 25% improvement in Marshall stability, 19% in SI, 69% in ITS, 11% in IT_{MR}, 270% in ITF, and 80% in rutting resistance compared to 0% PET content. Furthermore, it has been determined that an increase in ITS results in a corresponding increase in IT_{MR}, exhibiting a linear correlation. After carefully analyzing the cyclic test data, a model for fatigue distress was suggested. This study's results will aid in developing sustainable pavement options, including RAP and PET, from both an economic and environmental standpoint.

1. Introduction

Due to its cost-effectiveness and positive environmental effects, recycled asphalt pavement (RAP) is widely employed in asphalt mixtures. RAP is a product derived from road surfaces that have outlived their usefulness. This material is comprised of asphalt cement and aggregates that have aged over time. The use of this material as a cost-effective alternative to conventional asphalt concrete has been identified as a viable strategy for the development of environmentally sustainable pavements [32,3,34,41]. Its usage in asphalt concrete produces significant economic benefits, as stated by Noferini et al. [31].

RAP has gained widespread recognition and is widely used in pavement projects [18]. Due to concerns about its potential negative impacts on asphalt concrete's long-term performance and properties, RAP use in the surface layer is often restricted to a maximum of 25% in many projects [33]. The European Asphalt Pavement Association (EAPA) has reported that there is a global surplus of recycling of RAP being generated. The report indicates that in 19 developed countries, only 47% of the available RAP has been used for paving despite its widespread availability [40]. Globally, researchers consistently evaluate

* Corresponding author.
** Corresponding author at: School of Civil Engineering, Institute of Engineering, Suranaree University of Technology, Nakhon Ratchasima 30000, Thailand.
E-mail addresses: suddeepong@g.sut.ac.th (A. Suddeepong), suksun@g.sut.ac.th (S. Horpibulsuk).

https://doi.org/10.1016/j.conbuildmat.2024.135749
Received 1 October 2023; Received in revised form 3 February 2024; Accepted 6 March 2024
Available online 15 March 2024
0950-0618/

the benefits of incorporating more significant amounts of RAP into asphalt concrete mixtures. They aim to uphold the highest performance criteria to satisfy growing requirements and regulations [7]. According to the findings of Yu et al. [39], RAP was replaced with new materials at a rate of less than 50 percent. However, it is possible to increase this proportion without compromising the mechanical properties or performance as a whole. The practical potential of rejuvenators, polymer additives, and synthetic fibers to improve the overall performance of RAP asphalt concrete mixture has been established in previous studies (Abilo et al., 2014; [4]).

Sapkota et al. [34] investigated the potential of using recycled concrete aggregate (RCA), recycled glass (RG), and RAP as aggregates in asphalt concretes and compared their performance with the performance of conventional asphalt concretes. They examined three RG:RCA: RAP ratios, namely 10:75:15, 10:65:25, and 10:55:35, based on the total weight of the aggregates. The recycled asphalt concrete was found to have had better performance than conventional asphalt concrete. Using higher RAP content led to greater stiffness of the asphalt concrete. Furthermore, the sample with the highest RAP content demonstrated the highest indirect tensile resilient modulus, Marshall stability, and resistance to water damage. Buritatum et al. [16] observed that the inclusion of hemp fiber as an additive, along with the utilization of 100% RAP as an aggregate in the composition of asphalt concrete mixtures, resulted in enhanced mechanistic performance and extended service life of asphalt concrete mixtures. Nevertheless, there remains a need for enhancements in both the caliber of hemp fiber and the consistent availability of such fiber. Moreover, the widespread implementation of hemp fiber may be hindered by the challenges associated with ensuring its accessibility and ease of use, primarily due to the need for a rigorous treatment process to mitigate potential environmental degradation.

Polymer modification applications have been widely conducted for the fracture resistance enhancement of asphalt concretes. Frequently employed materials include polyethylene terephthalate (PET), ethyl vinyl acetate, polyethylene, polyvinyl chloride, and polyoctenamer [23]. Polymer additives are frequently added to asphalt concrete mixtures to strengthen the adhesion among asphalt cement and aggregates, thereby increasing the pavement's durability. As demonstrated by Mogawer et al. [25], polymers enhance the overall mechanical properties of asphalt concretes with RAP. Taherkhani and Arshadi [37] state that there are three distinct methods for polymers inclusion into asphalt concretes. The wet method entails combining the polymer with asphalt cement before adding aggregates. The following method employs the dry process, in which the polymer and aggregates are mixed together prior to the addition of asphalt cement. The third strategy involves incorporating the polymer into the aggregates and asphalt cement mixture during the mixing process.

PET is the most widely used thermoplastic polyester in the production of plastic bottles [35]. Due to PET's melting temperature of about 250°Cs, it is difficult to achieve homogeneity when incorporating PET into asphalt cement using the wet method. Consequently, the dry method is commonly used in scientific studies to incorporate PET into asphalt concrete mixtures. According to Ahmadinia et al. [5] and Moghaddam et al. [27], crushed PET bottles are frequently added as an aggregate to asphalt concrete mixtures during the dry process in order to minimize the rutting and hence enhances fatigue life. With the PET inclusion, the higher optimum asphalt cement content is required [13,15,28,37,5]. Hassani et al. [21] investigated the impact of incorporating PET, ranging from 5% to 15% by weight of aggregate, into asphalt concrete, identifying that a 5% PET content has the highest Marshall stability to Marshall flow ratios. Moghaddam et al. [26,27] explored the addition of crushed PET bottles, varying from 0.1% to 1.0% by weight of aggregate to asphalt concrete, and demonstrated an increase in fatigue life and rutting resistance with increasing PET content under dynamic loading conditions. Soltani et al. [36] also reported that increasing PET content within the 0.5–1.0% range by weight of aggregate in asphalt concrete correlates with prolonged fatigue life. Mosa [30] assessed the effects of PET contents varying from 0.1% to 1.1% by aggregate weight, finding optimal Marshall stability and rutting resistance at a PET content of 0.5%. The enhancement of the mechanical performance of asphalt concrete by PET due to the melting constituents of PET improves adhesion between aggregate and asphalt cement, whereas the solid constituents absorb or dissipate energy during loading cycles [27]. However, exceeding PET content leads to low stiffness of the mixture due to its lower stiffness particle than the aggregate [24]. The summary of the reviewed literature on the use of PET in asphalt concrete is shown in Table 1. Even in low percentages, the properties and mechanical performance of asphalt concrete are enhanced by adding PET.

Using 100% RAP as aggregate in asphalt concrete mixture may result in insufficient Marshall properties and mechanical performance, failing to meet the local authority's requirements, as Buritatum et al. [16] reported. Hence, incorporating PET into a RAP-asphalt concrete mixture can provide a viable solution and has feasibility in practice. By integrating PET, the weakened aspects of RAP are compensated for, thus improving the Marshall properties and mechanical performances of the RAP asphalt concrete mixture. To the authors' best knowledge, a comprehensive performance evaluation of asphalt concrete containing 100% RAP and modified with PET has yet to be conducted. Therefore, additional research is required in this regard. The impact of incorporating PET as an additive with low content (0%, 0.2%, 0.4%, 0.6%, 0.8%, and 1.0% by weight of aggregate) on the mechanistic behavior of 100% RAP-asphalt concrete is assessed in this research. With much lower density of PET compared with density of RAP, even though the content by weight is small, the content by volume is much larger. This approach aligns with previous research that has investigated using PET at low percentages to improve the properties of asphalt concrete. PET-modified RAP asphalt concrete is evaluated using static and cyclic tests. Outputs of this research will provide valuable insights into the viability of incorporating PET and RAP materials into asphalt concrete pavement, thereby contributing to waste management efforts and improving the overall sustainability of pavement infrastructure.

Table 1
Summary of reviewed research using PET as an additive in asphalt concrete.

Additional method/PET size	PET content	Main findings	Authors
Dry method (3 mm)	0%, 5%, 7.5%, 10%, 12.5%, and 15% by weight of aggregate	The 5% PET content improved the Marshall stability to Marshall flow ratio.	Hassani et al. [21]
Dry method (< 2.36 mm)	0%, 0.2%, 0.4%, 0.6%, 0.8%, and 1.0% by weight of aggregate	– The stiffness of the asphalt concrete mixture increases at lower PET content and decreases at higher PET content. – The fatigue resistance of PET-asphalt concrete is superior to conventional asphalt concrete.	Moghaddam et al. [26]
Dry method (< 2.36 mm)	0%, 0.1%, 0.2%, 0.3%, 0.4%, 0.5%, 0.6%, 0.7%, 0.8%, 0.9%, and 1.0% by weight of aggregate	Under dynamic loading, the permanent deformation of asphalt concrete decreases as the PET content increases.	Moghaddam et al. [27]
Dry method (< 2.36 mm)	0%, 0.5%, and 1.0% by weight of aggregate	The fatigue life of asphalt concrete increases as PET content increases.	Soltani et al. [36]
Dry method (< 2.36 mm)	0.1%, 0.3%, 0.5%, 0.7%, 0.9%, and 1.1% by weight of aggregate	At PET content of 0.5%, the asphalt concrete mixture has the highest improvement in Marshall stability and rutting resistance	Mosa [30]

2. MATERIALS AND SAMPLE PREPARATIONS

2.1. Materials

The polyethylene terephthalate (PET) aggregates were obtained by cleaning and chopping of plastic water bottles into smaller pieces. As depicted in Fig. 1(a), the PET was subsequently passed through a sieve with a mesh size of 2.36 mm. Reclaimed asphalt pavement (RAP) analyzed in Fig. 1(b) was prepared in the same manner as in Buritatum et al.'s (2023) study, and a summary of its properties is provided in Table 2. Before adding asphalt cement during dry mixing, PET was incorporated into the RAP aggregate. Six distinct percentages of PET were employed, specifically 0%, 0.2%, 0.4%, 0.6%, 0.8%, and 1.0% relative to the total weight of RAP.

The asphalt cement AC60/70 was used in this study. As shown in Table 3, the material's properties were evaluated in relation to the asphalt cement specifications outlined by the standard of Department of Highways, Thailand [19]. This standard is similar to the international standard for asphalt cement specifications by the Asphalt Institute [6]. The properties of the studied asphalt cement were found to satisfy the specified requirements.

2.2. Mix design

Fig. 2 depicts the gradation curve developed for the RAP aggregate utilized in this study. The curve adheres to the maximum aggregate size mandated for asphalt hot mix recycling, which is 12.5 millimeters, in accordance with DOH [20].

The determination of suitable blend proportions for RAP-asphalt concrete, which has been modified with polyethylene terephthalate (PET), was conducted using the Marshall method as outlined in ASTM standard D 6927 [10,11]. Both RAP and AC60/70 samples were heated to 180°C and 160°C, respectively. To ensure complete coating of the aggregate, the RAP and AC60/70 mixtures were mixed at 150°C for 60 seconds. Using the Marshall hammer, the mixtures were then densely compacted into metallic molds. Based on the DOH [20], the surface-wearing course of the recycled asphalt concrete mixture must be prepared by the Marshall method with 75 blows for each side. The referenced standard of DOH [20] is the present standard for recycled asphalt concrete construction in Thailand, which is still commonly used for field practice. It is similar to the international standard for the recycled asphalt concrete mixture of the Asphalt Institute [6]. The samples were characterized using standard dimensions, specifically 63.5-mm height and 101.6-mm diameter. The samples were removed from the molds following a 24-hour duration. The Marshall test was developed with the purpose of assessing the characteristic properties of RAP-asphalt concrete that has been modified using polyethylene terephthalate (PET). The aforementioned characteristics encompassed density, void mineral in aggregate (VMA), air void content, voids filled by asphalt concrete (VFA), Marshall stability (MS), and Marshall flow.

RAP-asphalt concrete utilized in the experiment served as the control group, devoid of any PET content. The aggregate properties, aggregate gradation, and asphalt cement properties of this control group were consistent with those outlined in the Buritatum et al. [16] study. Hence, the asphalt cement that yielded the best results for the asphalt concrete

Table 2
Properties of RAP aggregate.

Properties	Unit	Specifications DOH [20]	RAP Buritatum et al., [16]
Soundness	%	< 9	10.21
Los Angeles abrasion value	%	< 40	47.03
Flakiness index	%	< 35	33.00
Elongation index	%	< 35	34.00
Water absorption	%	-	1.49
Specific gravity	-	-	2.274
Asphalt content in RAP	%	-	5.67

Table 3
Properties of asphalt cement.

Properties	Units	Specifications DOH [19]	AC60/70 Buritatum et al., [16]
Penetration	-	60–70	67
Flash point	°C	>232	332
Ductility 25 °C	cm	>100	150
Solubility in trichloroethylene	%Weight	>99.0	99.97
Test on the residue obtained from thin film oven test (5 hour @ 163 °C)			
Weight loss	%	<0.8	0.12
Penetration	% of original	>54	71.1
Ductility 25 °C	cm	>50	150

Fig. 1. Studied (a) PET and (b) RAP.

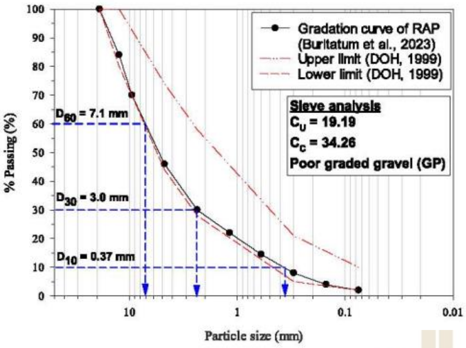

Fig. 2. Gradation curve of aggregate (modified from [16]).

mixture was also the same. The optimal asphalt cement content was determined by assuming a total asphalt cement content ranging from 6% to 9% by total weight of the mixture, which includes both the old asphalt cement in the RAP aggregate and the added AC60/70. The criterion for determining the optimum content was to achieve a 4% air void. When higher quantities of AC60/70 are introduced, there is a reduction in the volume of air voids. To attain an air void percentage of 4%, a total asphalt cement content of 7.07% is required [16]. This total asphalt cement content comprises of 5.67% old asphalt content and an additional 1.40% of AC60/70 asphalt cement.

3. Experimental program

3.1. Strength index (SI)

The AASHTO T 283 standard [1] was adopted for the strength index (SI) tests. The samples were compressed at a constant pressure of 20.7 MPa for 2 minutes. This compression was attained using a double-plunger compactor with dimensions of 63.5-mm height and 101.6-mm diameter. The experiment required the preparation of two test sets. Set 1, comprised of unsoaked samples, was designated the control group. In Set 2, samples were vacuum-saturated with the soaking solution for one hour, followed by a 24-hour soak at 60°C. The SI value was determined through the computation of the ratio between the Marshall stability (MS) of the immersed samples and the MS of the non-immersed samples. The experimental procedure was carried out under controlled conditions with a temperature of 25 °C and a loading rate of 50 mm/min.

3.2. Indirect tensile strength (ITS)

The indirect tensile strength test samples were prepared using the Marshall technique with 75 hammer blows on each side. The indirect tensile strength of RAP asphalt concretes modified with PET were evaluated according to ASTM D 6931 [12]. The samples were loaded along their vertical diametrical plane at a constant deformation rate (50 mm/min) during testing. Temperatures of 25, 40, 50, and 60°C were used for testing. The sample's ITS value was determined using the observed maximum load and the following equation:

$$\mathrm{ITS} = \frac{2000T}{\pi t D} \tag{1}$$

where ITS is expressed in kPa, T is the maximum load (N), t stands for sample thickness (mm), and D stands for sample diameter (mm).

3.3. Indirect tensile resilient modulus (IT_{MR})

The IT_{MR} was calculated using the ASTM D 4123–82 [9] standard, which involved subjecting a Marshall sample to dynamic loading while under indirect tensile conditions. A load equivalent to 15% of the sample's initial tensile strength (ITS) was applied along its vertical diameter. The loading frequency was configured at a rate of 1 Hz, accompanied by 0.1-s loading and subsequent 0.9-s resting. The experimental procedure consisted of subjecting the sample to a total of 200 loading pulses, with the testing conducted at 25°C. IT_{MR} was determined by averaging elastic stiffness of the five most recent data points following the initial 150 cycles, as specified in Eq. (2):

$$IT_{MR} = \frac{P(0.27 + \nu)}{tH_r} \tag{2}$$

where IT_{MR} is indirect tensile resilient modulus (MPa), ν is Poisson's ratio, t is the thickness (mm), and H_r is recoverable radial deformation in millimeters.

3.4. Indirect tensile fatigue (ITF)

Fatigue cracking resulting from the accumulation of damage caused by repeated loads is a major contributor to pavement failure. According to the specifications outlined in BS-EN-12697–24 [14], the stress control method was implemented, with 3 target stresses (namely 250, 300, and 350 kPa). A 12.5-mm wide and curved stainless steel was utilized to apply the load. In this study, a haversine loading pulse was employed to replicate the repetitive traffic loading conditions with loading frequency of 1.0 Hz. The sample was subjected to cyclic loading until failure, and its vertical displacement was recorded at every loading cycle. The vertical displacement can be divided into three separate zones. Due to the rapid reduction in air void caused by the initial cycles of loading, the deformation increment in the initial zone has a relatively high magnitude. Vertical displacement and the loading cycles are positively correlated in the second region. Throughout the duration of the applied load, microcracks develop as a result of the gradual accumulation of plastic deformation that occurs during this phase. According to Aragao et al. [8], the propagation of macrocracks is caused by the development of microcracks in the third zone, which originates from the first and second zones, ultimately resulting in complete failure. It is possible to estimate ITFL by locating the point of intersection between the slopes of second and regions.

3.5. Rutting resistance

According to AASHTO T324 [2], the rutting resistance of RAP asphalt concretes modified with PET was evaluated. The Hamburg wheel tracker testing machine, which is specifically designed for wheel track testing, was utilized for this evaluation. The wheel-tracking test samples were prepared with a gyratory compactor based on ASTM D6925 [10]. Two cylindrical specimens, each with 150-mm diameter and 60-mm thickness, were positioned closely together to form the testing sample. These samples were utilized to determine the depth of ruts. Plastic molds were used to securely mount the test sample to ensure stability during loading and minimize movement. In order for the cylindrical specimens to fit the plastic molds precisely, they must undergo precise trimming. A 47 mm wide steel wheel operating at a frequency of 26 cycles per minute exerted a load of 705 N on the sample. The test will end automatically at either 10,000 cycles or 20 mm of rut depth, whichever criterion was met first.

4. Test results and discussion

The research results on RAP asphalt concretes (no PET inclusion) by Buritatum et al. [16] was reanalyzed and used for comparison only in this research. This reanalysis seeks to determine the effect of PET content on RAP-PET-asphalt concrete's optimal AC, Marshall properties, and mechanical performance. Table 4 presents the Marshall properties of RAP asphalt concrete with varying percentages of polyethylene terephthalate (PET) content (0, 0.2, 0.4, 0.6, 0.8, and 1%) considered. Taherkhani and Arshadi [37] revealed that coating PET particles with asphalt cement can result in lower asphalt cement content in the RAP asphalt concrete mixture, leading to increased air void. In order to maintain a consistent 4% air void level, higher asphalt cement content is required. All RAP asphalt concrete samples have density values ranging from 2.235–2.262 g/cm^3. The density of RAP asphalt concrete decreases with the increased PET content because all PET aggregates were not completely melted during the preparation process (its melting point is 250°C). With higher PET content, the PET particles located between the aggregate particles lead to a larger sample volume and a decreased density [27]. Moreover, PET having a lower specific gravity (approximately 1.297) than the RAP aggregate (2.274), contributes to the reduction in density of the asphalt concrete mixture [17,38].

The range of void mineral in aggregate (VMA) values for RAP asphalt concrete with varying PET contents is 18.70–20.87%. As per the recommendation by [20], all RAP asphalt concrete samples exhibited VMA values that exceeded the minimum requirement of 14%. This ensures that RAP asphalt concrete modified with PET contains adequate void space for the asphalt cement filler. Void filled by asphalt cement (VFA) refers to the amount of empty spaces in the compacted RAP asphalt concrete sample, filled with asphalt cement. The VFA values of RAP asphalt concrete at varying PET contents range between 78.60 and 80.90 percent.

Marshall stability (MS) and flow values of PET modified RAP asphalt concrete samples range from 10.5 to 14.0 kN and 8.15–8.68, respectively. Without PET, RAP asphalt concrete samples have a lower MS than RAP-PET asphalt concrete samples. The SI values of RAP asphalt concrete samples fall within the range of 71.6–90.2%. The addition of PET is seen to contribute to the SI improvement. Notably, the MS, flow, and SI requirements specified by DOH [20] are met by all RAP asphalt concrete mixtures modified with PET. Due to a lower SI value than the minimum requirement, the RAP asphalt concrete without PET did not meet the requirement, demonstrating the negative effects of aged asphalt cement. The inclusion of PET escalates the asphalt cement content, enhancing adhesion and preventing aggregate surface stripping. In addition, the PET components that melt strengthen the adhesion among the aggregates and asphalt cement [27].

Fig. 3 illustrates the ITS at different testing temperatures. As the temperature rises, the ITS value decreases due to the reduction in the asphalt cement's adhesion strength. Adding PET to the RAP asphalt concrete mixture improves ITS, with the maximum ITS observed at the optimal PET content of 0.6% for all tested temperatures. The addition of PET to RAP asphalt concrete initially enhances its tensile strength. However, this improvement decreases when the addition of PET exceeds 0.6%. Excessive PET particles occupying a more significant volume reduce overall mixture stiffness, as they have lower stiffness than RAP

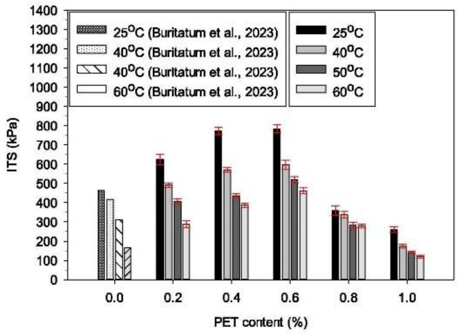

Fig. 3. ITS of RAP asphalt concrete samples at 25°C, 40°C, 50°C, and 60°C and PET content.

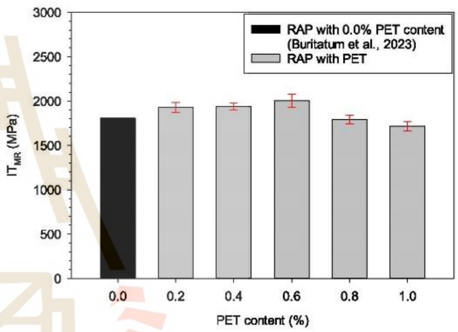

Fig. 4. IT$_{MR}$ of RAP asphalt concrete samples versus PET content.

Table 4
Summary of Marshall design results.

Description		PET content (%) 0 Buritatum et al., [16]	0.2	0.4	0.6	0.8	1.0	Specification DOH [20]
Composition of asphalt	Total asphalt (%by weight of aggregate)	7.07	7.80	8.04	8.13	8.25	8.34	-
	New Asphalt (%by weight of aggregate)	1.40	2.13	2.37	2.46	2.58	2.67	-
Characteristic values	Air Void (%)	4.0	4.0	4.0	4.0	4.0	4.0	**3–6**
	Bulk Density (g/cm^3)	2.262	2.249	2.243	2.241	2.237	2.235	
	VMA (%)	18.70	19.96	20.37	20.52	20.72	20.87	**>14**
	VFA (%)	78.60	80.13	80.38	80.59	80.72	80.90	
	Stability (kN)	10.5	11.3	13.4	13.1	13.0	14.0	**> 6.7**
	Flow (0.25 mm)	8.68	8.15	8.57	8.36	8.24	8.63	**8–16**
	Stability/Flow (N/0.25 mm)	1205	1391	1559	1569	1570	1622	**> 556**
	Strength index (%)	71.6	84.2	82.9	85.5	91.0	90.2	**> 75**

aggregates [24].

The relationship between IT_{MR} versus PET content is presented in Fig. 4. The IT_{MR} values of RAP asphalt concrete samples are 1805.43, 1927.05, 1937.36, 2004.07, 1791.25, and 1715.44 MPa for 0, 0.2, 0.4, 0.6, 0.8, and 1.0% of PET contents, respectively. Comparable to the ITS results, the highest IT_{MR} is found at 0.6% PET content. As PET content exceeds 0.6%, the IT_{MR} of RAP asphalt concrete decreases. Incorporating PET into the RAP asphalt concrete mixture enhances the resilient properties of asphalt concrete. The melted PET component can improve adhesion between aggregate and asphalt cement. Meanwhile, the solid PET component can absorb and dissipate energy during loading cycles, hence improving the IT_{MR} [26]. Beyond the optimum PET content (0.6%), the higher PET content causes a reduction in the IT_{MR}. This excessive PET content reduces mixture stiffness due to the low stiffness of PET particles [24,27].

Observations indicate a direct proportionality between the improvement in IT_{MR} and ITS versus the PET content (Fig. 5) and expressed by Eq. (3). When subjected to dynamic tensile stress, the improved ITS results in a greater capacity to withstand permanent deformation. The IT_{MR} of PET-modified RAP asphalt concrete can be determined using ITS values with a significant reliability coefficient of 0.94.

$$IT_{MR} = 0.487(\mathrm{ITS}) + 1599 \tag{3}$$

where IT_{MR} is expressed in MPa and ITS is expressed in kPa.

Fig. 6 depicts the correlation between the polyethylene terephthalate (PET) content and the indirect tensile fatigue life (ITFL) of RAP asphalt concrete modified with PET for various stresses. A notable observation is that as the applied stress is augmented, there is a corresponding decrease in the ITFL across all samples. The inclusion of PET in RAP asphalt concretes has been observed to enhance their resilient properties, resulting in increased ITFL under equivalent stress conditions. The findings for ITFL are consistent with those for ITS and IT_{MR}. The maximum ITFL is observed when the PET content reached 0.6% across all stress levels that were examined. The ITFL values of RAP asphalt concretes modified with 0.6% PET content are 3002, 2203, and 1200 cycles at 250, 300, and 350 kPa stress levels, respectively.

Based on the standard BS EN 12697–24 [14], a fatigue law is derived that demonstrates a linear relationship on a logarithmic scale between the fatigue life versus the initial tensile strain (ε_t). On the basis of the aforementioned law, it is possible to formulate a fatigue distress model by incorporating the initial tensile strain as a decisive parameter in the following manner:

$$ITFL = a\left[\frac{1}{\varepsilon_t}\right]^b \tag{4}$$

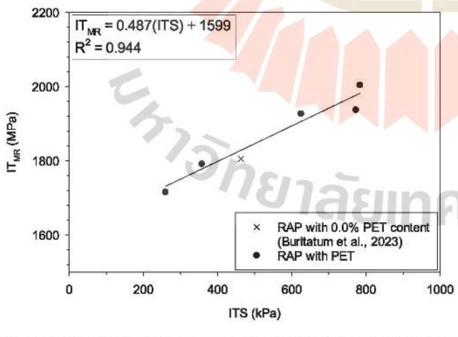

Fig. 5. Relationship between IT_{MR} and ITS of RAP asphalt concrete samples.

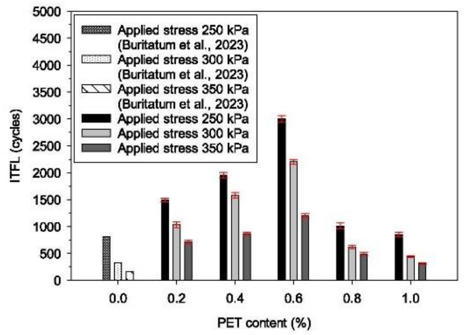

Fig. 6. ITFL of RAP asphalt concrete samples versus applied stress at different PET content.

where a and b (fatigue parameters) represent the regression coefficients that are dependent on the material characteristic and ε_t is expressed in micro-strain.

It should be noted that the initial tensile strain can be derived from the applied stress level, Poisson's ratio, and IT_{MR}, which are obtained through experimental measurements [22,29]. The initial tensile strain can be determined by employing the subsequent equation:

$$\varepsilon_t = \frac{\sigma(1+3\nu)}{IT_{MR}} \tag{5}$$

where σ is applied stress level (kPa) obtained from ITF test, ν is conventionally taken as 0.35 as specified in the BS EN 12697–24 standard.

A distress model was developed for RAP asphalt concrete with and without PET, utilizing fatigue law and analyzing data from dynamic testing. As shown in Fig. 7, the ITFL decreases as initial tensile strain increases for all asphalt concrete mixtures. At a particular initial tensile strain, the highest ITFL is observed at the PET content of 0.6%. The result supports Modarres and Hamedi's [24] findings that PET-modified asphalt concrete shows better ITFL than unmodified asphalt concrete at the same initial tensile strain. Different pavement materials show varying amounts of tensile strain for an equal number of cycles because of variations in their material characteristics. These differences in tensile strain response result in the variable potential to resist fatigue damage.

Fig. 8 and Fig. 9 show the parameters a and b of RAP asphalt concrete

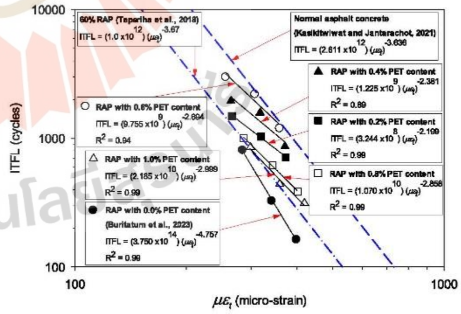

Fig. 7. Relationship between ITFL and ε_t of RAP asphalt concrete with and without PET samples.

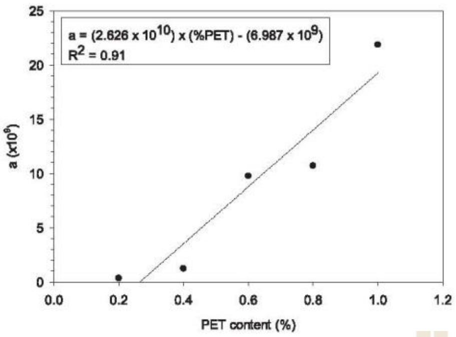

Fig. 8. Fatigue parameter (a) of RAP asphalt concrete with PET samples versus PET content.

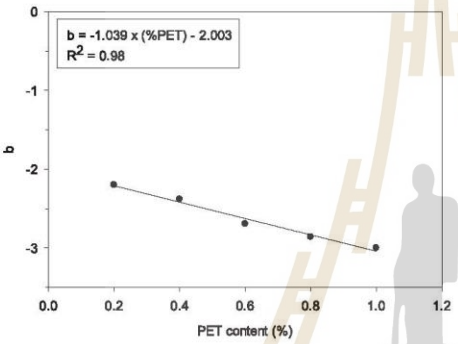

Fig. 9. Fatigue parameter (b) of RAP asphalt concrete with PET samples and PET content.

modified with PET, respectively. An augmentation in the polyethylene terephthalate (PET) content results in an elevation of the magnitude of parameter a and a reduction in the magnitude of parameter b. As determined by the experimental study, parameters a and b are a function of the PET content as established through the linear regression analysis presented in Eqs. (6) and (7), respectively. The aforementioned equations offer a valuable method for estimating the service life of RAP asphalt concrete that is modified with PET, with given PET content.

$$a = (2.626 \times 10^{10}) \times (\%PET) - (6.987 \times 10^{9}) \tag{6}$$

$$b = -1.039 \times (\%PET) - 2.003 \tag{7}$$

The comparison of the relationship between ITFL and initial tensile strain of RAP asphalt concrete modified with PET to that reported in previous studies in Thailand, as shown in Fig. 7. It is revealed that different materials result in distinct fatigue distress models. At the same range of studied initial tensile strain, all RAP asphalt concretes modified with PET have higher fatigue resistance than that of the 60% RAP modified asphalt concrete studied by Tepsriha et al. (2018). Moreover, RAP asphalt concrete modified with 0.6% of PET content is comparable to that of the asphalt concrete using natural aggregate studied by Kasikitwiwat and Jantarachot (2011).

Fig. 10 shows the rut depth of RAP asphalt concrete at various PET

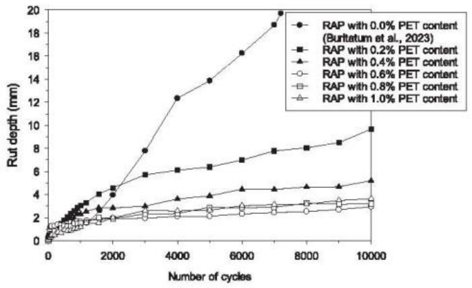

Fig. 10. Rut depth of RAP asphalt concrete at various PET content versus number of cycles.

content versus number of cycles. The rut depths observed for the RAP asphalt concretes are 9.69, 5.19, 2.94, 3.19, and 3.63 mm for 0.2, 0.4, 0.6, 0.8, and 1.0% of PET contents, respectively. The lowest rut depth of 2.94 mm is observed at 0.6% PET content. Without PET, the RAP asphalt concrete failed at a rut depth of 20 mm under the wheel load after 7203 cycles, not reaching the desired 10,000 cycles, as presented in Fig. 11(a). When PET is added to RAP asphalt concrete, it improves its ability to resist rutting, as depicted in Fig. 11 (b-f). The findings of this discovery are consistent with the research conducted by Moghadam et al. (2014b), which determined that the incorporation of PET in asphalt concrete resulted in superior resistance to rutting compared to unmodified asphalt concrete, when subjected to comparable conditions. The PET-modified RAP asphalt concrete exhibits improved rutting resistance due to PET particles' ability to absorb wheel load, thereby delaying rutting failure [42].

The findings of this study suggest that a novel waste management strategy can be presented in the form of PET additives to RAP asphalt concrete, leading to significant performance improvements. Utilizing these two materials provides an economically and environmentally viable alternative for pavement applications.

5. Conclusions

This research evaluates the mechanical performance of PET modified RAP-asphalt concrete to identify common failure modes, including fatigue and rutting failures, in asphalt concrete pavement. The evaluation was conducted through indirect tensile strength, indirect tensile resilient modulus, indirect tensile fatigue, and rutting resistance tests. Adopting this standardized methodology to assess the potential of new material compositions in pavement engineering is essential. The test results showed PET's potential to improve the mechanical performance of RAP-asphalt concrete. Moreover, the fatigue distress model of RAP asphalt concrete modified with PET was developed based on the IT_{MR} and ITF test results and is useful for determining the pavement thickness with the mechanistic-empirical approach. The goal of this research was to evaluate the PET-modified RAP asphalt concretes as a sustainable pavement surface. Notable findings included the following:

The incorporation of polyethylene terephthalate (PET) into the RAP asphalt concrete led to a rise in both the air void and the optimal asphalt cement content in the mixture. The augmentation of asphalt cement content resulted in an enhancement of both adhesion strength and resistance to separation from the aggregate surface. This, in turn, led to improvements in the Marshall properties and SI values.

The inclusion of PET enhanced the thickness of the asphalt cement film that envelops the aggregates, which has resulted in the

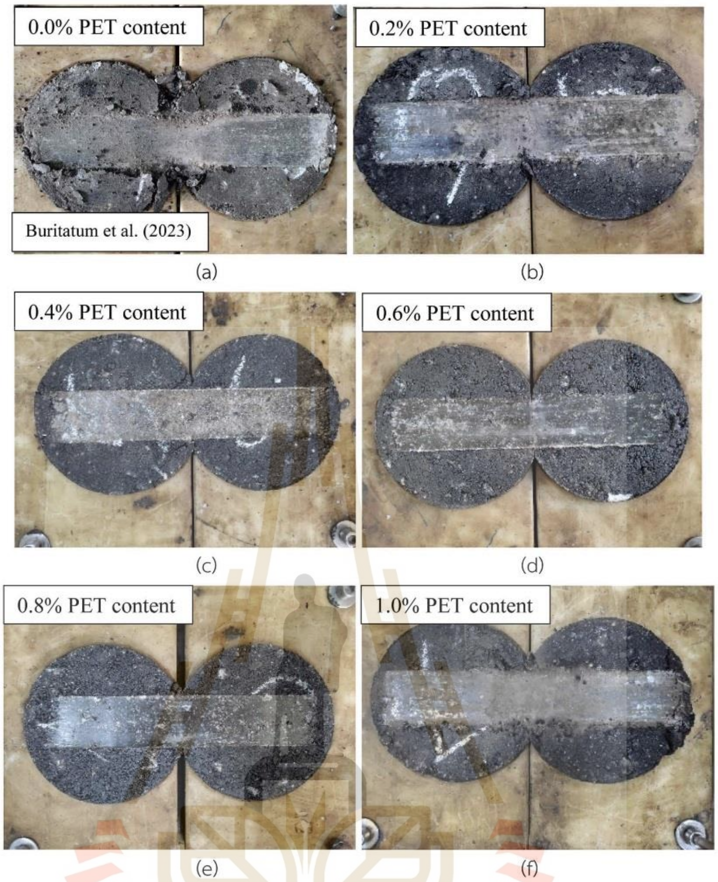

Fig. 11. Failure characteristics of RAP asphalt concrete modified with (a) 0%PET content [16], (b) 0.2%PET content, (c) 0.4%PET content, (d) 0.6%PET content, (e) 0.8%PET content, and (f) 1.0%PET content.

enhancement of adhesion strength, as well as the improvement of tensile properties and resistance to rutting in RAP asphalt concrete. These improvements were evidenced through ITS, IT_{MR}, ITFL, and wheel-tracker tests, with the most significant improvement observed at 0.6% PET content. The addition of PET influenced both the static and dynamic performance of the RAP asphalt concrete up to the best performance value at the optimum PET content of 0.6% for all experimental tests. At the optimum PET content, asphalt concrete was found to have the highest percentage improvement in both static and dynamic performances compared to the 0% of PET content. For static tests, the percentage improvement of Marshall stability, SI, and ITS were 25%, 19%, and 69%, respectively. For dynamic tests, the percentage improvement of IT_{MR}, ITF, and rutting resistance were 11%, 270%, and 80%, respectively. The excessive PET content (> 0.6%) had an adverse effect on the RAP asphalt concrete stiffness due to their lower stiffness compared to RAP aggregates, and the excessively thick film on PET particles caused a susceptible zone, leading to decreased mechanical properties.

The distress model of RAP asphalt concrete modified with PET was developed based on experimental data. The fatigue parameters of RAP asphalt concrete modified with PET were found to vary depending on the PET content. A distress model was proposed to accurately forecast the service life of the material, taking into consideration its specific PET content. The proposed model demonstrates its utility in facilitating mechanistic approaches to pavement design, thereby promoting the adoption of sustainable construction practices both within Thailand and on a global scale.

CRediT authorship contribution statement

Suksun Horpibulsuk: Writing – review & editing, Project administration, Funding acquisition, Conceptualization. **Teerasak Yaowarat:** Validation, Methodology. **Apinun Buritatum:** Writing – original draft, Methodology, Investigation, Formal analysis. **Nantipat Pongsri:** Investigation, Formal analysis. **Kongsak Akkharawongwhatthana:** Investigation, Data curation. **Avirut Chinkulkijniwat:** Writing – review & editing. **Veena Phunpeng:** Writing – review & editing, Visualization. **Arul Arulrajah:** Writing – review & editing. **Apichat Suddeepong:** Writing – original draft, Supervision, Project administration, Funding acquisition, Conceptualization. **Apisit Laomuad:** Methodology, Investigation, Data curation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

Acknowledgements

This work was financially supported by Suranaree University of Technology, Thailand Science Research and Innovation (TSRI), and National Science, Research, and Innovation Fund (NSRF) [Grant No. 160338], National Science and Technology Development Agency under the Chair Professor program [Grant No. P-19-52303] and the NSRF via the Program Management Unit for Human Resources & Institutional Development, Research and Innovation (PMU-B) [Grant No. B13F660067]. The 3rd and the last authors acknowledged the funding support from Australian Research Council's Linkage Projects funding scheme (project number LP200100052).

References

[1] AASHTO. (2007). Standard Method of Test for Resistance of Compacted Asphalt Mixtures to Moisture-Induced Damage. AASHTO T283. Washington, DC: American Association of State Highway and Transportation Officials.
[2] AASHTO. (2008). Standard method of test for Hamburg wheel-track testing of compacted hot-mix asphalt (HMA). AASHTO T324. Washington, DC: American Association of State Highway and Transportation Officials.
[3] S.M. Abraham, G.D. Ransinchung, Strength and permeation characteristics of cement mortar with reclaimed asphalt pavement aggregates, Constr. Build. Mater. 167 (2018) 700–706.
[4] S.M. Abtahi, M. Sheikhzadeh, S.M. Hejazi, Fiber-reinforced asphalt-concrete–a review, Constr. Build. Mater. 24 (6) (2010) 871–877.
[5] E. Ahmadinia, M. Zargar, M.R. Karim, M. Abdelaziz, P. Shafigh, Using waste plastic bottles as additive for stone mastic asphalt, Mater. Des. 32 (10) (2011) 4844–4849.
[6] AI. (2014). 7th edition of MS-2 Asphalt Mix Design Methods. Manual Series No. 2, Asphalt Institute, Lexington, KY.
[7] I.L. Al-Qadi, M. Elseifi, S.H. Carpenter, Reclaimed asphalt pavement a literature review, FHWA-ICT-07-001 (2007).
[8] Aragao, F.T.S., Kim, Y.-R., & Lee, J. (2008). Research on Fatigue of Asphalt Mixtures and Pavements in Nebraska.
[9] ASTM, 1995, Standard test method for indirect tension test for resilient modulus of bituminous mixtures. ASTM D4123-82. West Conshohocken, PA: ASTM..
[10] ASTM, 2015, Standard test method for Marshall stability and flow of asphalt mixtures. ASTM D6927-15. West Conshohocken, PA: ASTM. .
[11] ASTM, 2015, Standard Test Method for Preparation and Determination of the Relative Density of Asphalt Mix Specimens by Means of the Superpave Gyratory Compactor. ASTM D6925. West Conshohocken, PA: ASTM..
[12] ASTM, 2017, Standard test method for indirect tensile (IDT) strength of asphalt mixtures. ASTM D6931. West Conshohocken, PA: ASTM..
[13] A.A. Badejo, et al., Plastic waste as strength modifiers in asphalt for a sustainable environment, Afr. J. Sci., Technol., Innov. Dev. 9 (2) (2017) 173–177.
[14] BSI, Bituminous mixtures. Test methods for hot mix asphalt part 24: Resistance to fatigue. BS-EN 12697-24.BSI, Bituminous mixtures. Test methods for hot mix asphalt part 24, Resist. Fatigue BS-EN12697-24 (2004) 2004.
[15] A. Buritatum, A. Suddeepong, S. Horpibulsuk, K. Akkharawongwhatthana, T. Yaowarat, M. Hoy, C. Bunsong, A. Arulrajah, Improved performance of asphalt concretes using bottom ash as an alternatiVE AGGREgate, Sustainability 14 (12) (2022) 7033.
[16] A. Buritatum, A. Suddeepong, K. Akkharawongwhatthana, S. Horpibulsuk, T. Yaowarat, M. Hoy, A. Arulrajah, A.S.A. Rashid, Hemp fiber-modified asphalt concretes with reclaimed asphalt pavement for low-traffic roads, Sustainability 15 (8) (2023), https://doi.org/10.3390/su15086860.
[17] R. Choudhary, A. Kumar, K. Murkute, Properties of waste polyethylene terephthalate (PET) modified asphalt mixes: dependence on PET size, PET content, and mixing process. Periodica Polytechnica, Civ. Eng. 62 (3) (2018) 685–693.
[18] Copeland, A. (2011), Reclaimed asphalt pavement in asphalt mixtures: State of the practice. 2011, United States. Federal Highway Administration, Office of Research.
[19] DOH. (1988). Specification for asphalt cement. [In Thai.] Standard No. DH-SP. 401/1988. Ratchathewi, Thailand: DOH.
[20] DOH. (1999). Standard for Asphalt Hot-Mix Recycling. [In Thai.] Standard No. DH-S 410/1999. Ratchathewi, Thailand: DOH.
[21] A. Hassani, H. Ganjidoust, A.A. Maghanaki, Use of plastic waste (poly-ethylene terephthalate) in asphalt concrete mixture as aggregate replacement, Waste Manag. Res. *23* (4) (2005) 322–327.
[22] Kennedy, T. (1979). Practical use of the indirect tensile test for the characterization of pavement materials. Australian road research board conference proc.
[23] Z. Leng, A. Sreeram, R.K. Padhan, Z. Tan, Value-added application of waste PET based additives in bituminous mixtures containing high percentage of reclaimed asphalt pavement (RAP), J. Clean. Prod. 196 (2018) 615–625.
[24] A. Modarres, H. Hamedi, Effect of waste plastic bottles on the stiffness and fatigue properties of modified asphalt mixes, Mater. Des. 61 (2014) 8–15.
[25] W.S. Mogawer, A.J. Austerman, R. Bonaquist, M. Roussel, Performance characteristics of thin-lift overlay mixtures: high reclaimed asphalt pavement content, recycled asphalt shingles, and warm-mix asphalt technology, Transp. Res. Rec. 2208 (1) (2011) 17–25.
[26] T.B. Moghaddam, M.R. Karim, T. Syammaun, Dynamic properties of stone mastic asphalt mixtures containing waste plastic bottles, Constr. Build. Mater. 34 (2012) 236–242.
[27] T.B. Moghaddam, M. Soltani, M.R. Karim, Experimental characterization of rutting performance of polyethylene terephthalate modified asphalt mixtures under static and dynamic loads, Constr. Build. Mater. 65 (2014) 487–494.
[28] T.B. Moghaddam, M. Soltani, M.R. Karim, H. Baaj, Optimization of asphalt and modifier contents for polyethylene terephthalate modified asphalt mixtures using response surface methodology, Measurement 74 (2015) 159–169.
[29] Mohammad, L.N., & Paul, H.R. (1993). Evaluation of indirect tensile test for determining structural properties of asphalt mix.
[30] A.M. Mosa, Modification of hot mix asphalt using polyethylene therephthalate (pet) waste bottles, SUST J. Eng. Comput. Sci. *18* (1) (2017) 62–73.
[31] L. Noferini, A. Simone, C. Sangiorgi, F. Mazzotta, Investigation on performances of asphalt mixtures made with reclaimed asphalt pavement: effects of interaction between virgin and RAP bitumen, Int. J. Pavement Res. Technol. 10 (4) (2017) 322–332.
[32] S. Noura, E. Yaghoubi, S. Fragomeni, P. Wasantha, R. Van Staden, Fatigue and Stiffness Characteristics of asphalt mixtures made of recycled aggregates, Int. J. Fatigue 107714 (2023).
[33] B. Salman, O.S. Salem, D.T. Garguilo, S. He, Innovative maintenance, repair, and reconstruction techniques for asphalt roadways, A Surv. State Dep. Transp. (2017).
[34] K. Sapkota, E. Yaghoubi, P. Wasantha, R. Van Staden, S. Fragomeni, Mechanical Characteristics and Durability of HMA Made of Recycled Aggregates, Sustainability 15 (6) (2023) 5594.
[35] S. Shukla, A.M. Harad, Aminolysis of polyethylene terephthalate waste, Polym. Degrad. Stabl. 91 (8) (2006) 1850–1854.
[36] M. Soltani, T.B. Moghaddam, M.R. Karim, H. Baaj, Analysis of fatigue properties of unmodified and polyethylene terephthalate modified asphalt mixtures using response surface methodology, Eng. Fail. Anal. *58* (2015) 238–248.
[37] H. Taherkhani, M.R. Arshadi, Investigating the mechanical properties of asphalt concrete containing waste polyethylene terephthalate, Road. Mater. Pavement Des. 20 (2) (2019) 381–398.
[38] L. Widojoko, P.E. Purnamasari, Study the use of cement and plastic bottle waste as ingredient added to the asphaltic concrete wearing course, Procedia-Soc. Behav. Sci. 43 (2012) 832–841.
[39] S. Yu, S. Shen, X. Zhou, X. Li, Effect of partial blending on high content reclaimed asphalt pavement (RAP) mix design and mixture properties, Transp. Res. Rec. 2672 (28) (2018) 79–87.
[40] M. Zaumanis, R.B. Mallick, R. Frank, 100% recycled hot mix asphalt: A review and analysis, Resour., Conserv. Recycl. 92 (2014) 230–245.
[41] K. Zhang, B. Muhunthan, Effects of production stages on blending and mechanical properties of asphalt mixtures with reclaimed asphalt pavement, Constr. Build. Mater. 149 (2017) 679–689.
[42] H. Ziari, A.G. Kaliji, R. Babagoli, Laboratory evaluation of the effect of waste plastic bottle (PET) on rutting performance of hot mix asphalt mixtures, Pet. Sci. Technol. 34 (9) (2016) 819–823.

BIOGRAPHY

Mr. Kongsak Akkharawongwhatthana was born in October 1992 in Nakhon Ratchasima, Thailand. He obtained a bachelor's degree in civil engineering from the School of Civil Engineering at Suranaree University of Technology in 2017 and a Master's degree in the Master of Engineering Program in Civil, Transportation, and Geo-resources Engineering from the Institute of Engineering at Suranaree University of Technology in 2020. Since June 2021, he has been working as a full-time master's researcher at the Institute of Research and Development, Suranaree University of Technology.