MECHANICAL PROPERTY AND PERFORMANCE OF ASPHALT CONCRETE USING LIMESTONE, GRANITE AND STEEL SLAG AS AGGREGATE

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สมบัติและสมรรถนะทางกลของแอสฟัลต์คอนกรีตที่ใช้หินปูน หินแกรนิต และตะกรันเหล็กเป็นมวลรวม

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วิทยานิพนธ์นี้ศึกษาความเป็นไปได้ของการประยุกต์ใช้ตะกรันเหล็ก (Steel slag) เพื่อปรับปรุงวัสดุผิวทางที่ยั่งยืน การศึกษาประกอบด้วยงานทดสอบด้านวิศวกรรม และสิ่งแวดล้อม 2 ส่วน เพื่อให้ครอบคลุมความต้องการสำหรับใช้เป็นวัสดุชั้นผิวทาง การทดสอบในส่วนแรกเป็นการศึกษาการพัฒนากำลังของตะกรันเหล็กในแอสฟัลต์คอนกรีต ทั้งคุณสมบัติทางกายภาพ และคุณสมบัติเชิงประสิทธิภาพ การทดสอบในส่วนที่สองเป็นการศึกษาอิทธิพลของขนาดคละมวลรวมที่มีผลต่อคุณสมบัติเชิงประสิทธิภาพ ผลทดสอบแสดงให้เห็นว่าการแทนที่ด้วยตะกรันเหล็กสามารถปรับปรุงค่าเสถียรภาพของแอสฟัลต์คอนกรีต ค่าความเสถียรภาพของการผสมตะกรันเหล็กกับหินปูน มีค่าเสถียรภาพสูงกว่าแอสฟัลต์คอนกรีตที่ใช้หินปูนเป็นมวลรวมเพียงชนิดเดียวทั้งแอสฟัลต์ซีเมนต์ชนิด 60/70 และ PMA แอสฟัลต์คอนกรีตที่ใช้สัดส่วนผสมของหินปูนและตะกรันเหล็กของแอสฟัลต์ซีเมนต์ชนิด AC60/70 มีค่าเสถียรภาพสูงกว่าแอสฟัลต์คอนกรีตที่ใช้สัดส่วนผสมของหินปูนของแอสฟัลต์ซีเมนต์ชนิด AC60/70 และ PMA ชนิดของมวลรวมและแอสฟัลต์ซีเมนต์ไม่มีผลต่อค่าการไหล ค่าความล้า, ค่าโมดูลัสความยืดหยุ่น และค่าความต้านทานต่อการเกิดร่องล้อของแอสฟัลต์คอนกรีตที่ใช้สัดส่วนผสมของหินปูนและตะกรันเหล็ก AC60/70 พบว่ามีค่าสูงกว่าแอสฟัลต์คอนกรีตที่ใช้ส่วนผสมของหินปูน AC60/70 เท่ากับ 1.6, 1.4 และ 1.4 เท่าตามลำดับ ผลการทดสอบความล้า และโมดูลัสความยืนหยุ่นของแอสฟัลต์คอนกรีตที่ใช้สัดส่วนผสมของหินปูนและตะกรันเหล็ก AC60/70 มีค่าใกล้เคียงกับแอสฟัลต์คอนกรีตที่ใช้ส่วนผสมของหินปูน PMA แอสฟัลต์คอนกรีตที่ใช้ส่วนผสมของหินปูนและตะกรันเหล็กมีค่าโมดูลัสความยืดหยุ่นสูงกว่าค่าที่แนะนำโดย AASHTO ซึ่งมีค่าโมดูลัสความยืดหยุ่นมากกว่า 3,100 เมกะปาสคาล แต่แอสฟัลต์คอนกรีตที่ใช้ส่วนผสมของหินปูนไม่ผ่านค่าแนะนำ ผลการทดสอบค่าความคืบและร่องล้อแสดงให้เห็นว่าแอสฟัลต์คอนกรีตที่ใช้สัดส่วนผสมของหินปูนและตะกรันเหล็กมีความต้านทานต่อการเกิดร่องล้อมากกว่าแอสฟัลต์คอนกรีตที่ใช้ส่วนผสมของหินปูน ขนาดของมวลรวมมีผลต่อประสิทธิภาพของแอสฟัลต์คอนกรีตทั้งสองชนิด การใช้มวลรวมขนาดกลางช่วยพัฒนากำลังของแอสฟัลต์คอนกรีตกว่ามวลรวมขนาดใหญ่ จากผลการทดสอบแสดงให้เห็นว่าการแทนที่ด้วยตะกรันเหล็กมีความมั่นคงต่อการพัฒนาผิวถนนแอสฟัลต์คอนกรีต สรุปได้ว่าแอสฟัลต์คอนกรีตที่ใช้สัดส่วนผสมของหินปูนและตะกรันเหล็กสามารถใช้เป็นวัสดุทางเลือกที่มีความคุ้มค่า

ทางสิ่งแวดล้อม และเศรษฐศาสตร์ สำหรับที่จะรองรับปริมาณจราจรสูง มากกว่าใช้หินปูนเป็นมวลรวมแอสฟัลต์คอนกรีต อย่างไรก็ตาม การแทนที่หินปูนด้วยตะกรันเหล็กส่งผลให้แอสฟัลต์คอนกรีตมีอายุการใช้งานที่ยาวนานขึ้น หรือช่วยลดความหนาของผิวทางแอสฟัลต์คอนกรีต

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ลายมือชื่อนักศึกษา เสาวรส หะสิตาะ

ลายมือชื่ออาจารย์ที่ปรึกษา

SAOWAROT HASITA : MECHANICAL PROPERTY AND
PERFORMANCE OF ASPHALT CONCRETE USING LIMESTONE,
GRANITE AND STEEL SLAG AS AGGREGATE. THESIS ADVISOR :
PROF. SUKSUN HORPIBULSUK, Ph.D., 144 PP.

ASPHALT CONCRETE/STEEL SLAG/STABILITY/INDIRECT TENSILE STRENGTH/RUTTING/RESILIEN MODULUS/INDIRECT TENSILE FATIGUE

This thesis studies the feasibility of using steel slag as aggregate to be a pavement material. First, the strength development of these material was investigated, both performance and general test of the using steel slag as aggregate in asphalt concrete. Second, performance test on the effect of gradation of steel slag was conducted. Test result shows that the steel slag replacement can improve the Marshall stability of asphalt concrete mixtures. The Marshall stability of steel slag asphalt concrete is higher than that of limestone asphalt concrete for both AC60/70 and PMA. The flow value was found to be insignificantly affected by type of asphalt cement and aggregate. The fatigue life, resilient modulus, and rut depth resistance of the L:S:S:S-AC60/70 were found to be 1.6, 1.4, and 1.4 times higher than that of L:L:L:L-AC60/70, respectively. The fatigue life and resilient modulus values of the L:S:S:S-AC60/70 concrete were found to be close to those of L:L:L:L-PMA concrete. The resilient modulus of steel slag asphalt concretes were higher than the required value (3,100 MPa) recommended by AASHTO, while limestone asphalt concretes did not meet requirement. In addition, the dynamic creep and wheel tracking test results showed that the steel slag asphalt concretes had superior resistance to permanent deformation and rutting as compared to the limestone asphalt concretes. The aggregate size had a significant effect on the performance of both steel slag and limestone asphalt concretes. The usage of medium-sized steel slag aggregate in developing asphalt concrete was proved to be more sustainable in term of engineering and economical perspectives than the usage of large-sized steel slag aggregate. From a performance and chemical testing perspective, steel slag replacement was found to be suitable for the sustainable development road pavement. This is concluded that the steel slag asphalt concrete can be used as an alternative for limestone asphalt concrete to provide a green and economical pavement surface for a high traffic volume. Also steel slag can improve the service life of the pavement and or reduction in thickness of pavement layers.

School of Civil Engineering　　Student's Signature เสาวรส หะสีตะ

Academic Year 2019　　Advisor's Signature

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Saowarot Hasita

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SYMBOLS AND ABBREVIATIONS

AC60/70 = Asphalt Concrete grade 60/70

AC = asphalt concrete

ACV = Aggregate crushing test

AASHTO = American Association of State Highway and Transportation official

AIV = Soundness test, aggregate impact test

Al_2O_3 = Aluminum oxide

APA = Asphalt pavement analyzer

ASTM = American Society for Testing and Material

BFS = Blast furnace slag

BOFS = Basic oxygen furnace slag

CuO = Copper oxide

CaO = Calcium oxide

CBR = California Bearing Ratio

cm = Centimeter

CO_2 = Carbon dioxide

Cr_2O_3 = Chromium oxide

CSR = Cationic Rapid Setting

DOH = Department of highway

EAFS = Electric arc furnace acid slag

EVA = Ethylene vinyl acetate

SYMBOLS AND ABBREVIATIONS (Continued)

FA = Fly ash

Fe_2O_3 = Iron oxide

FWA = Federal Works Agency

G = Granite

HWTD = Humburg wheel tracking device

HMA = Hot-mix asphalt

IDT = Indirect tensile strength

ITFL = Indirect tensile fatigue life

JMF = Job Mix Formula

kPa = Kilo Pascal

LVDT = Linear variable different transducers

L = Limestone

LAA = Los Angeles abrasion test

LFS = Ladle furnace basic slag

MgO = Magnesium oxide

MnO = Manganese oxide

Mr = Resilient modulus

mm = Millimeter

Na_2O = Sodium oxide

PSV = polished stone test

PMA = Polymer Modified Asphalt Cement

SYMBOLS AND ABBREVIATIONS (Continued)

PSI = Present serviceability index

RLAT = Repeated load axial test

S = Steel slag

SiO_2 = Silicon dioxide

SMA = Stone mastic asphalt

SO_3 = Sulfur trioxide

TiO_2 = Titanium dioxide

UTM = Universal testing machine

SBS = Styrene butadiene

SHRP = Strategic Highway Research Program

XRF = X-Ray Fluorescence

XRD = X-Ray Diffraction

CHAPTER I

INTRODUCTION

1.1 Background and problem statement

Thailand is recognized as one of the fastest growing and most successful developing countries, among ASEAN countries. The national economic expansion causes a large of demands of road infrastructure (DOH, 2012; Nikomborirak, 2004). This results in significant demands of the quality of natural materials such as rock and lateritic soils for use in road construction. Furthermore, using the local resources is needed to minimize the transportation costs. High transportation costs moreover affect total construction cost of the projects when there are no available natural materials nearby the construction site. The transporting materials from a far distance also add the carbon footprint to road construction and increase road wear (VicRoads, 2011). Therefore, it demands the immediate attention of not only Thailand's government, but also all over the world looking for alternative construction materials. Using recycled materials is a good alternative to solve this problem (Hendriks & Pietersen, 2000; Sherwood, 2001).

In recent year, the Thailand's government has encouraged all sectors to use recycled materials to reduce the environmental pollution issues, which is sustainable infrastructure. Sustainable infrastructure is a key initiative in many developed and developing countries. Research on the use of alternative sustainable materials is at the forefront of country development. The utilization of recycled materials derived from industrial waste materials is interesting issues. The recycled materials can be used in pavement applications, which are considered as environmentally friendly construction (Arulrajah et al., 2013; Arulrajah et al., 2015; Disfani et al., 2011; Hu et al., 2014; Jamshidi et al., 2016; Park, 2003). Using recycled materials alternative to conventional waste disposal can help lower greenhouse gas emissions as well as decreases construction cost of highway pavements. However, there is a low rate of application of recycled aggregates in construction of pavement structure due to the limitation of laboratory investigations as well as construction guidelines.

Recently, traffic volume has significanlly increased in Thailand, particularly truck traffic, which becomes main concerns for highway agencies nationwide. Many main roads received repetition overloads and finally permanent deformation (rutting) occurred. Rutting is a problem occurring in asphalt concrete pavement at intersection, where the speed is very low. Stopping and exiting of the car causes high horizontal tensile strain.

The road pavement is separated into two major sections: surface and structure of pavement. The surface is divided to two major types: flexible (asphalt concrete pavements) and rigid (concrete pavements). The previous research reported that recycled materials were able to use in structure pavement. Hoy et al. (2016) informed that the low-carbon geochemical stabilization of RAP for pavement base/ subbase applications. Sas et at. (2015) and Aiban (2006) showed that the steel slag commenced as embankment fill materials and pavement bases/subbase. This research focused on the using of recycled materials on flexibke pavement, which is the most popular pavement surface in Thailand. Asphalt concrete is a uniting of aggregate, asphalt cement and air void (Ahmedzade et al., 2009). The aggregate, including coarse and fine particles consist approximately 90% of volume of asphalt concrete (Huang et al., 2007). The performance of asphalt concrete significantly depends on the properties of aggregate (Kandhal et al., 1997). The aggregate acts as the structural skeleton of the pavement and the asphalt cement as the glue of the mixture. Aggregate in asphalt concrete involves the distress of asphalt concrete; therefore, the aggregate must have high durability against the impact and crushing force, and resistance to abrasion. There are several ways to improve the performance of asphalt concrete, such as addition of mineral filler (gilsonite, lime, fly ash and cement), change of the size of aggregate (Chen et al., 2016), change of the type of asphalt cement from grade 60-70 to 40-50 and modifying asphalt binders (Zhao et al., 2016; Ali et al., 2016; Takaikaew et al., 2018). Some researchers investigated the effect of different types of aggregate on skid resistance. The most commonly using aggregates for surface courses are limestone, basalt, granite, river gravel, sandstone and steel slag. Limestone is very susceptible to polishing and hence not recommended as aggregate in surfaces course which is the most important course, but it can use in lower layers of pavement construction (Dunford, 2013; Senga et al., 2013). Granites, basalt and crushed gravel are reported to have similar polish resistance (Ongel et al., 2009).

Rapid growth of steel industries in Thailand results in growing amount of the steel slag sharply. It constitutes of 13% of the steel output (Shen et al., 2009). There are four broadly different types of steel slag: blast furnace slag (BFS), basic oxygen furnace slag (BOFS), electric arc furnace acid slag (EAFS) and ladle furnace basic slag (LFS), also called as refining slag (Setién et al., 2009). Steel slag has been applied in recent years in a wide range of applications in term of surface pavement. Steel slag was reported to have higher skid resistance, compared with natural aggregates (Beshears et al., 2013). The feasibility of using steel slag as coarse aggregate in asphalt mixture has been well evaluated in literature (Xue et al., 2006; Ahmedzade et al., 2009). Steel slag as coarse aggregate in asphalt mixture can improve mechanical properties and performance such as moisture susceptibility, skid resistance, deformation and crack resistance of stone mastic asphalt (SMA) mixture, porous asphalt mixtures, marshall design method (Wu et al., 2007; Shen et al., 2009; Chen et al., 2012; Chen et al., 2014; Chen et al., 2015; Chen et al., 2016; Birgisson et al., 2016; and Ahmedzade et al., 2009). Even though there are available research works on mechanical properties of slag asphalt concrete, some gaps for optimum designing of slag asphalt concrete are to be addressed (a) the effect of substitution of steel slag at each Bin on the performance of asphalt concrete, (b) the effect of binders on performance of asphalt concrete (AC60/70 and PMA) and (c) the effect of job mix design on performance of asphalt concrete.

This research focuses on the study feasibility of using steel slag as aggregate in asphalt concrete based on the performance tests on Marshall samples. Moreover, the effect of job mix on the performance of asphalt concrete is investigated by the comparison of the different gradation of asphalt concrete samples. This study is significant as utilization of recycled materials is related to environmental concern as well as sustainable development, making roadways more durable, conserving natural resources, decreasing energy use, and reducing greenhouse gas emissions.

1.2 Research objectives and scope

The potential lack of using steel slag as alternative material is interesting. In order to use steel slag in the road construction, a complete laboratory test has to be carried out. The scope of the study is limited to the feasibility of using steel slag as aggregate in asphalt concrete.

The two main objectives of this research are to inscription as follows:

1. To investigate the possibility of using steel slag as aggregate in asphalt concrete based on performance tests (Marshall stability, flow value, strength index, indirect tensile strength, resilient modulus, dynamic creep tests, indirect tensile stiffness test and rutting test.)

2. To study effect of binder and job mix design on performance of steel slag asphalt concrete.

1.3 Structure of thesis

This thesis consists of five chapters as follows:

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

Chapter II presents the literature review of the recent research papers that involve the using of steel slag as aggregate in the asphalt concrete. A brief introduction considering the specification of pavement structures, asphalt concrete properties and performance tests are presented.

Chapter III presents the study of the performance of steel slag asphalt concrete. The performance tests included indirect tensile, fatigue life, resilient modulus, dynamic creep and wheel tracking tests. The properties of the steel slag asphalt concrete were compared with those of limestone asphalt concrete. This chapter aims to investigate the ability of these materials to retain their strength both short-term and long-term on climatic conditions.

Chapter IV presents the engineering and environmental laboratory evaluation of steel slag asphalt concrete which provides a basis for assessing clearly the viability of using these materials in road pavement application. Besides, the study is mostly focuses on the effect type of gradation on the properties of steel slag asphalt concrete.

Chapter V concludes the research work and provides the suggestion as well as recommendation as one of the road construction guidelines for the road decision maker.

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CHAPTER II

LITERATURE REVIEW

2.1 Introduction

This chapter presents the literature on the using of steel slag as aggregate in the asphalt concrete. First, a brief introduction considering the specification of pavement structures, asphalt concrete properties and performance test are presented.

The experience tests have shown that aggregates is main key role of road construction. Especially in asphalt concrete pavement and this was realized by SHRP researchers. The properties of aggregate have directly and significantly effect on the performance of asphalt concrete (Kandhal et al., 1997). Aggregate in asphalt concrete must have high durability against the impact and crushing force and resistance to abrasion. The asphalt concrete pavement mixtures design is composed of aggregate of different sizes according to the defined standards. The stone carries the weight from wheel load after that it distributes the weight to pavement structure. Asphalt cement acts as a binder between aggregates. Currently, the used stones are mostly limestone, which is derived from destroying the natural resource. If we replace limestone with recycled aggregate, it benefits the environment.

As the environmental issue is a severe global concern, the trend to replace the natural aggregate by industrial waste, known as steel slag are then presented. This part provides an overview of using the steel slag as an aggregate in asphalt concrete.

2.2 Specification for pavement structure

There are three major types of pavements: flexible (asphalt concrete pavements), rigid (concrete pavements) and composite pavements (Huang, 1993). In this section, only the flexible pavement is described. Flexible pavements are one of the most popular type pavement which have better quality of materials on top, where the stress is high and inferior materials at the bottom where the intensity of stress is low. The maximum benefit to this design is made possible by using local materials, which makes it more economical. The normally practical in provincial part where high-quality materials are expensive but local materials of poor quality are available. Furthermore, far away resources using, results in increase of transportation costs and also increases the carbon footprint during road construction and a increased rate of road wear. Therefore, it demanded the immediate attention of not only Thailand's government, but also all over the world looking for alternate construction materials. Using recycled construction materials is a good alternate to solve this problem. The reuse and recycling of industry by-products, such as steel slag, as a replacing material in limestone can reduce this problem and also reduce the disposal of steel slag.

The conventional flexible pavement is shown in Figure 2.1 (Typical cross section of flexible pavement). Starting from the top, the pavement consists of seal coat, surface course, tack coat, binder course, prime coat, base course, subbase course, compacted subgrade and natural subgrade respectively. The using of the various courses is based on the economical situation and some of the courses may be omitted.

The seal coat is a treatment asphalt surface layer used to improve skid resistance and or waterproof the surface, where the aggregates in the surface course could be polished by traffic movement and become slippery. Department of Highways of Thailand commonly uses slurry seal and para slurry seal. The criteria for slurry seal and para slurry seal are 405/1999 and DH-S 415/2003, respectively.

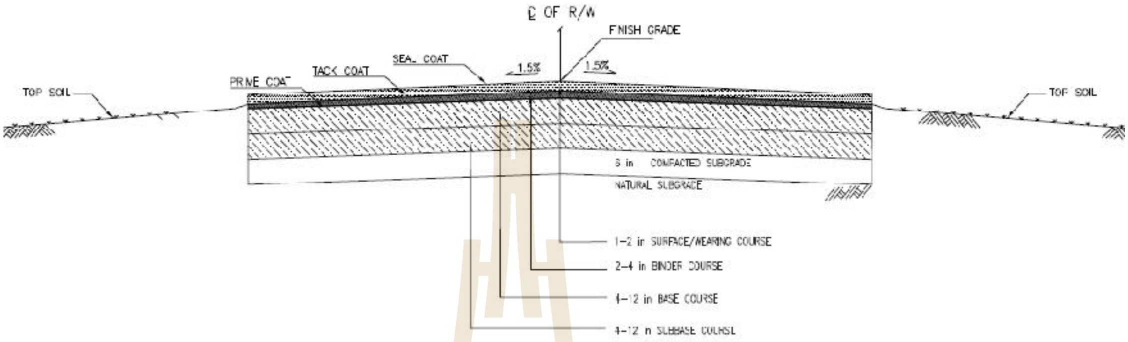

Figure 2.1 Typical cross section of flexible pavement

The surface course, sometimes was called the wearing course is the top course of an asphalt pavement. It must be not only tough to resist distortion under loading of traffic but also must be able to provide a smooth and skid-resistant riding surface. It must also be waterproof, to protect the water from weakening the payment by reaching the subgrade. If the above requirements cannot be met, the use of high quality aggregate of asphalt concrete and seal coat are recommended. Sometimes the wearing course using porous asphalt concrete to improve drainage system (FWA et al., 1999). Department of Highways of Thailand commonly uses two type of asphalt concrete mixture for surface course: asphalt cement penetration grade AC60/70 and polymer-modified asphalt (PMA). The criteria of standard for asphalt concrete is DH-S 408/1989 and standard for modified asphalt concrete is DH-S 409/2006.

The binder course, sometimes was called the asphalt base course, is the asphalt layer below the wearing course. There are two reasons that a binder course is used in addition to the surface course. First, the compacted asphalt concrete layer should not be more than 5-7 cm., so it must be placed in two layers. Second, the binder course generally consists of larger aggregates and less asphalt, so it does not require materials as high-quality as the wearing course, so replacing a part of the wearing course by the binder course results in a more economical design. The standard commonly used for binder course in Thailand is the same as wearing course.

A tack coat is a very light application of asphalt, usually asphalt emulsion, the most popular design used is CRS 1 binder grade, which is used to ensure a bond between the surface being paved and the overlying course. It is an important layer in the asphalt concrete pavement. The criteria of standard in Thailand is DH-S 403/1988.

A prime coat is an application of low to medium-viscosity cutback asphalt to a granular base which is the initial surface course layer of asphalt concrete pavement. The criteria of standard in Thailand is DH-S 402/2014.

The base course is the layer of material beneath the last surface or binder course. It can consists of crushed stone, crushed slag, or other untreated or stabilized materials.

The subbase course is the layer of pavement which builds beneath the base course. Normally, the two different granular material layers are built for economy and easy for compaction at high density. The cheaper and local materials can used as a subbase course on top of the subgrade. The subbase and subgrade should be scarified and compacted to the desirable density near the optimum moisture content.

The subgrade course is the in-situ soil normallty which was compacted or a layer of selected material. Some researchers recommend that subgrade must be higher than ground water content by 2 meters.

The difference between a tack coat and a prime coat is that a tack coat does not require the penetration of asphalt.The prime coat requires the penetration to plugs the voids and forms a watertight seal surface but the track coat is not. However, the type and quantity of asphalt used are quite different, both track and prime coat are used by spray applications.

In the mechanistic-empirical design methods, the properties of materials must be specified, so that the important parameter of the pavement structure(stresses, strains and displacements) in the critical components can be determined. These parameters are used to predict failure criteria of whether failures will occur or the probability that failures will occur.

The following general material properties should be specified for both linear and nonlinear elastic pavement(Huang, 1993). When pavements structure are considered as linear elastic and nonlinear elastic, the elastic modulus and Poisson ratios of the subgrade and each component layer must be specified. The Poisson ratios have relatively small effects on pavement responses, so their values can be reasonably assumed because strength of subgrade and other layer is too high.

The resilient modulus, which was tested for determining the elastic modulus under repeated loads of various material on pavement structure at each time of loading, , must be selected as a load duration corresponding to the vehicle speed to true simulation.

The hot mix asphalt concrete (HMA) is considered linear viscoelastic, the creep compliance, which is the reciprocal of the modulus at various loading times, must be specified. The temperature and loading time at the creep test must be same as the temperature and loading time used for pavement design which indicates the sensitivity of asphalt mixtures.

If the design is based on fatigue cracking, the fatigue properties of asphalt mixtures, must be specified.

If the design is based on rut depth, the permanent deformation parameters of each layer by summing the permanent deformations over all layers must be specified.

If design is based on other distresses such as low-temperature cracking, the appropriate properties which is the asphalt stiffness at the winter design temperature of asphalt concrete are used evaluated as a basic for design.

2.3 Asphalt concrete properties

Asphalt concrete is a mixture of aggregates, binder and filler, which is used for construction and maintenance of surface pavement. Asphalt concrete properties depends on aggregate, binder and air void etc.

2.3.1 Aggregate

When natural materials and recycled materials such as steel slag are used as highway construction, the material characteristics affecting the aggregate behavior include mineralogy, particle size distribution, particle shape, surface texture, angularity, durability (soundness, abrasion resistance) and other engineering properties must be examined.

The used aggregates in highway construction are mostly obtained from local supplies of natural rock. The natural rock occurs either outcrops at or near the surface or gravel deposits usually along old stream beds. The natural rocks are classified by geologists into three groups depending on their origin (igneous, sedimentary and metamorphic). Other types of aggregate that are sometimes used for hot mix asphalt concrete such as lightweight aggregate or steel slag provides good skid resistance. The lightweight aggregate is produced by heating clay at high temperatures and steel slag normally produced in the blast furnace during steel production.

Igneous rocks are type of rocks which occurs from the cooling of molten rock magma as it moves toward to surface of the earth. Igneous rocks was classified based on the size of the crystal grains and composition.

Sedimentary rocks are type of rocks which primarily occurs either by the deposition of insoluble residue from the disintegration of existing rocks or from deposition of the inorganic remains of marine animals which was classified based on the predominant mineral present as calcareous (limestones, chalks, etc.), siliceous (chert, sandstone, etc.), or argillaceous (shale, etc.).

Metamorphic rocks are type of rocks which is sedimentary rocks that have been occurs from heat and/or pressure sufficient to change their mineral structure so it is different from the original rock. Metamorphic rocks is generally crystalline in nature with grain size from fine to coarse.

Gravel was occur from the breakdown of any natural rock. Gravel particles are found in existing or ancient waterway and the particle are usually smooth and typically rounded or subrounded by wear, as the material is moved along the waterway by the action of water. Gravel is usually required to be crushed prior to use in hot mix asphalt concrete.

Steel slag is a byproduct of metallurgic processing and is typically produced from processing of steel, tin and copper. It constitutes of 13% of the steel output

(Shen et al., 2009). There are four broadly different types of steel slag: blast furnace slag (BFS), basic oxygen furnace slag (BOFS), electric arc furnace acid slag (EAFS) and ladle furnace basic slag (LFS), also called as refining slag (Setién et al., 2009). Steel slag has been applied in recent years in a wide range of applications such as embankment fills, pavement bases/subbase and building masonry units (Pellegrino et al., 2013; Sakai et al., 2000; and Zhang et al., 2012) Steel slag has also been used as a raw material in cement production, road constructions, fertilizer and etc. (Sas et al., 2015; Aiban, 2006; Kim et al., 2015; Li, 2010; Li et al., 2016) BOFS and EAFS have been used in asphaltic mixes for road-base layers. The feasibility of using steel slag as coarse aggregate in asphalt mixture has been well evaluated in literature. Steel slag as coarse aggregate in asphalt mixture can improve mechanical properties and performance such as moisture stability, skid resistance, deformation and crack resistance of pavement (Chen et al., 2016; Ahmedzade et al., 2009; Chen et al., 2014). Blast furnace slag produced during the processing of steel is the most widely used of the slags for pavement construction applications. This aggregate produces a high quality asphalt mix with good skid resistance. The absorption of slag is often high; hence, the amount of asphalt binder required when slag aggregates are used is usually higher than that for naturally occurring aggregates (Kogbara et al., 2016). Qiushi et al., (2016) shows replacing 25% of asphalt concrete by steel slag, elastic deformation can significantly reduce, the dynamic stiffness can remarkably increase and also the ability to resist deformation can notably increase.

For highway construction purposes, the geologic information about the rocks must be specified. The important characteristics of the rocks relate to how well the materials serve in the various applications such as subbases, bases, or in the various surface courses used in pavement construction. Therefore, for the most part, it is the mechanical properties of the rocks which are important for highway construction. The chemical properties are less important, since the natural rock material coming from different areas within a quarry or gravel pit can vary, so it is important to sample and test the material on a regular basic to ensure that aggregate properties are consistent and meet the specified standards.

The popular testing mechanical properties of the aggregate in Thailand include Los Angeles abrasion test (LAA), soundness test, aggregate impact test (AIV), aggregate crushing test (ACV) and polished stone test (PSV).

A majority of natural aggregates is composed of a combination of minerals. The most important minerals found in aggregates are silica minerals (quartz), feldspars, ferromagnesian minerals (vermiculite), carbonate minerals (calcite, dolomite) and clay minerals (illites, kaolinites, montmorillonites). Since minerals have definite chemical composition and usually specific crystalline structure, the physical and chemical properties of aggregates can be expected to be associated with mineralogy of the aggregates.

The mineral composition of coarse aggregates also affects the skid resistance of asphalt concrete mixture (Roberts et al., 1991). Quartz and feldspar are harder and more polish resistant minerals, which are normally found in igneous rocks such as basalt. On the other hand, calcite and dolomite, which occur in limestone, are examples of soft minerals. Limestone that have high percentage of soft materials tend to polish more rapidly than most other aggregate types. The acid in soluble residue test (ASTM D3042) has been used to measure the amount of harder materials present in carbonate aggregates. Many highway agencies specify a minimum of 10 percent acid in soluble to assure acceptable frictional properties. Other agencies use a polishing test (ASTM D3319 or E660 and E303) or petrographic examination (ASTM C295) to evaluate the polishing potential of an aggregate. According to the criterion of asphalt concrete in Thailand, PSV value should be > 47 for modified asphalt concrete. Most aggregates are composed of several minerals, often with variable compositions. Nevertheless, the aggregates have uniform mineralogy, the properties may be altered by oxidation, hydration, leaching, weathering and foreign coatings. Therefore, mineralogy cannot provide a basic for predicting the behavior of an aggregate in service. The petrographic examinations can be helpful in evaluating aggregates under similar environmental and loading conditions.

Another factor, which affects an aggregate’s usefulness in HMA, somewhat related to mineralogy, is the presence of surface coatings and other deleterious substances. These deleterious substances may include clays, shale, silt, iron oxides, gypsum, water-soluble salts, and other soft particles that affect proper bonding with asphalt binder. Unfavorable materials may also increase the moisture susceptibility of an asphalt concrete mixture. Aggregates with unfavorable substances are undesirable for asphalt concrete mixture and should not be used unless the amount of foreign matter is reduced by washing or other means.

One of the most important effects of aggregate mineralogy on the performance of asphalt concrete mixture is its influence on adhesion and moisture damage. The better bonds of asphalt cement with certain mineral types such as carbonate aggregates (limestone) better bond than to siliceous aggregates (gravel).

The petrographic examination is a petrographic examination of an aggregate is a visual investigation of individual aggregate particles by using an optical microscope, sometimes supplemented by X-ray diffraction, differential thermal analysis, electron microscope, or chemical analysis (Chen et al., 2015). The petrographic examination can be used to measure the relative abundance of rock and mineral type, the physical and chemical attributes (such as particle shape, surface texture, hardness, pore characteristics and chemical activity) and the presence of harmful contaminants. The test has been used for many years to evaluate aggregates for use in concrete but has not been widely used for aggregates for HMA. However, The mineralogy of an aggregate has a greater effect on performance of concrete mixes than asphalt concrete mixtures.

There has been evidence to indicate that some aggregates appear to have a greater affinity for water than for asphalt cement and asphalt films on these aggregate particles may become detached or stripped after exposure to water. These aggregates are called hydrophilic (water-loving) and they tend to be acidic in nature. On the other hand, aggregates having an affinity for asphalt cement are called hydrophobic (water-hating) and they tend to be basic in nature. It is commonly accepted that water significantly affects the adhesion between the aggregate and the asphalt cement and its resistance to moisture damage. Most siliceous aggregates such as quartz, sandstone, and siliceous gravel is become negatively charged in the attendance of water, while limestone and other calcareous materials is a positive charge in the attendance of water. Many aggregates contain both types of charges because they are composed of minerals such as silica with negative charges and also calcium, magnesium, aluminum, or iron with positive charges. Since stripping is one of the major distresses affecting HMA performance, the effect of aggregates on the moisture sensitivity of HMA must be evaluated.

The physical properties of aggregates for HMA are usually classified by size of aggregate as coarse aggregate, fine aggregate or mineral fillers. The asphalt institute defines the No.8 (2.36 mm) sieve or the No.10 (2.00 mm) sieve as the dividing line between coarse and fine aggregates. ASTM defines coarse aggregate as particles retained on a No.4 (4.75 mm) sieve, fine aggregate as that passing a No.4 sieve (4.75 mm) and mineral filler as material with at least 70 percent passing the No.200 (75µm) sieve which is same as the standard used in Thailand.

The required aggregate for HMA are generally to be tough, hard, strong, durable, clean, rough, hydrophobic surfaces and properly graded to consist of cubical particles with low porosity.. The suitability of aggregates for use in asphalt concrete is determined by evaluating material characteristics such as size and gradation, cleanliness/deleterious materials, toughness/hardness, durability/soundness, surface texture, particle shape, absorption and affinity for asphalt.

In addition, the various types of specific gravity of aggregates are discussed since these are used to calculate voids in mix design. This is also the most important characteristics of aggregates for HMA.

The los angles abrasion (L.A.) test is most often used to indication of the design toughness and abrasion characteristics of aggregate. The internal friction of aggregate must support the wheel loads and also be resistant to abrasion and polishing of traffic. In addition, aggregate should be able to receive impact and crushing during manufacturing. They must be hard and tough to resist degradation, crushing and disintegration when stockpiled, fed through a HMA facility, placed with paver, compacted with rollers and travelled over with trucks. In Thailand, the maximum wear for coarse aggregate used in HMA is typically limited by specifications of 35 to 40 percent (DH-S 408/1989 and DH-S 409/2006).

The soundness test (ASTM C88-13) is an empirical screening test that provide an indication of durability due to weathering which is useful for evaluating new sources of aggregate which is not records are available. Aggregate must be breakdown resistant or disintegration under wetting and drying and/or freezing and thawing (weathering) condition. This test involves submerging the aggregate in a solution of sodium or magnesium sulfate. During this test salt crystals grows in the aggregate pores and causes particle to disintegrate in some aggregates. The sulfate soundness test has been an accepted method of testing for many years. Despite this acceptance, it has been widely criticized and numerous reports have appeared which describe its inability to accurately predict field performance for specific aggregates. Many researchers believe that freezing and thawing cycles do not create problems with aggregates in HMA (Roberts et al., 1991). The aggregate is initially dried during production and hence should have little or no moisture in the pores immediately after production. During HMA production, the aggregates are coated with a film of asphalt binder which should prevent the aggregate from absorbing a significant amount of moisture during the life of the mixture. Since there is little or no moisture in the aggregate, freezing and thawing it should not be a problem.

In terms of particle shape and surface texture, the suitable aggregate particles for using in asphalt concrete should be select cubical rather than flat, thin or elongated. The angular-shaped particles of asphalt concrete mixtures compaction exhibits greater interlock and internal friction as a results the greater mechanical stability than rounded particles. Furthermore, the mixture containing rounded particles such as most natural gravels and sands which have better workability and require less compaction effect to obtain the optimum density. However, the rutting resistance affects low voids and plastic flow which must be consider.

The surface texture also influences the workability, adhesion of asphalt cement and strength of asphalt concrete mixture. A rough, sandpaper surface texture such as found on most crushed stones which tends to increase strength and requires additional asphalt cement to overcome the loss of workability as a result the high voids of compacted mixture occurs. Smooth-textured aggregates may be not only easier to coat with an asphalt film but also high void space and low interlocking.

Cleanliness and deleterious materials, Washing the dirty aggregates can usually reduce the amount of this problem to an acceptable level. The typical objective materials include shale, soft particles, clay coating on aggregate particle and sometimes excess dust from the crushing operation. In addition to the petrographic examination described earlier, the following tests can be used to identify and measure the quantity of deleterious materials.

Sand equivalent test DH-T. 203/1972. (modifile from AASHTO T 176-70) is used to determine the relative proportions of plastic fines and dust in fine aggregates. The sand equivalent is the ratio of the height of sand to the height of clay times 100. The cleaner aggregate will have a higher sand equivalent value. The specifications for aggregates in asphalt concrete mixture often specify a minimum sand equivalent 60 percent for modified asphalt concrete.

One of the most important asphalt concrete properties is the specific gravity of an aggregate, which is useful in terms of making weight-volume conversions and in calculating the void content in a compacted asphalt concrete mixtures. The specific gravity of an aggregate is the ratio of the weight of unit volume of the material to the weight of an equal volume of water at approximately 23^0C. When the weight is in grams and the volume is in ml. there are four different aggregate specific gravities used for HMA base on the method used to define the volume of the aggregate particles as following:

1. Apparent specific gravity;
2. Bulk specific gravity;
3. Effective specific gravity;
4. Bulk impregnated specific gravity;

The apparent specific gravity include only the volume of the aggregate particle. It does not include the volume of any pores or capillaries which become filled by water after a 24 hour soaking. The bulk specific gravity include the overall volume of the aggregate particle as well as the volume of the pores that become filled with water after a 24 hour soaking. The effective and bulk-impregnated specific gravity include the overall volume of the aggregate, plus the pore that become filled with water after a 24 hour soaking, minus the volume of the larger pore that absorb asphalt. The volume of solids (V_s) contains internal pores that are impermeable to both water and asphalt. Since the volume of the impermeable pores cannot be accurately determined, for all practical purposes they are considered as part of the volume of the solids. Reducing the aggregate size by crushing exposes some of these internal voids and thus increase the apparent specific gravity of the aggregate.

Air voids in the compacted HMA appears throughout the mix as small pockets of air between the asphalt coated aggregate particles. The choice of an aggregate specific gravity to be used in asphalt mix calculation can have a substantial effect upon the calculated amount of air voids in the compacted HMA. The effect of specific gravity of the aggregate in the mixture depends upon the degree to which the aggregate absorbs asphalt. When the apparent specific gravity is used in the calculations, the voids between the asphalt film and the aggregate (pores not filled with asphalt) are included in the calculated voids. If bulk specific gravity is used, it is assumed that no asphalt is absorbed by any of the water permeable pores, the measured voids include the voids between the aggregate coated particles minus the volume of the absorbed asphalt. Except in rare cases, neither the bulk or the apparent specific gravity provides a correct measure of air voids in the HMA mixture. The concept of effective specific gravity more nearly describes the true case for asphalt absorption when calculating the voids in a compacted asphalt paving mix. In this case, the calculated voids are truly those voids between the asphalt coated particles and do not include the voids in the pores between the asphalt and aggregate. The effective specific gravity is equal to or higher than the bulk specific gravity and equal to or lower than the apparent specific gravity. When the aggregate absorption is zero, all four types of aggregate specific gravity are theoretically equal.

The bulk and apparent specific gravities of coarse and fine aggregates can be determined by ASTM C127 and C128, respectively. The effective specific gravity can be calculated from the theoretical maximum specific gravity (rice specific gravity) using ASTM D2041. The bulk-impregnated specific gravity is used by the U.S. Corps of Engineers to design and control HMA when using aggregates with a water absorption greater than 2.5 percent. The bulk-impregnated specific gravity is similar to the effective specific gravity in concept but involves immersion of aggregate in asphalt, whereas the rice specific gravity is obtained by testing the actual HMA mixture.

When the sample is tested in separate size fractions (for instance, coarse and fine), the average specific gravity value can be computed, after than can be used to calculate the average specific gravity of an aggregate blend.

Gradation is determined by sieve analysis each Bin of gradation. The passing the material through a series of sieves stacked with progressively smaller openings from top to bottom, after then weigh of the material retained on each sieve was weighed. The gradation of an aggregate is normally expressed as total percent passing various sieve sizes.

The gradation of an aggregate can be plot in graphically which represented a gradation curve for which the ordinate is the total percent by weight passing a given size on an arithmetic scale, while the abscissa is the particle size plotted to a logarithmic scale. Sieves typically used for sieve analysis and gradation specifications for asphalt concrete mixtures are 2 inches, 1 ½ inches, 1 inch, ¾ inch, ½ inch, 3/8 inch, No.4, No.8, No.16, No.30, No.50, No.100 and No.200 (50.8 mm, 38 mm, 25.4 mm, 19mm, 12.5mm, 9.5mm, 4.75mm, 2.36mm, 1.18mm, 0.6mm, 0.3mm, 0.15mm and 0.075 mm) respectively. A 3/8 inch sieve is openings equal to 3/8 inch. A No.8 sieve is 8 openings per inch. The openings in a No.8 sieve are smaller than 1/8 inch since the diameter of the wire must be considered in determining the opening size. The sizes of successive sieves usually differ by a factor of approximately 2 therefore, when plotted on a logarithmic scale, the distances between near sieve sizes are usually about equal. Type of gradation are described as dense or well-graded, uniformly-graded (open) and gap-graded.

Gradation is the most important property of an aggregate in asphalt concrete mixtures. It affects directly to asphalt concrete mixtures including stiffness, stability, durability, permeability, workability, fatigue resistance, frictional resistance and resistance to moisture damage. Therefore, gradation is a primary consideration in asphalt mix design and some state like limits specifications on the aggregate gradations that can be used in asphalt concrete mixtures design.

Theoretically, it would seem reasonable that the best gradation for asphalt concrete mixture is the dense particle packing. The dense gradation has maximum density which provides increase of stability through increase interparticle contacts and reduce voids in the mineral aggregate. However, there must be sufficient air void space to provice enough asphalt cement to ensure durability, while still leaving some air space of the asphalt concrete mixture to avoid the bleeding and/or rutting. The tightly packed aggregate in asphalt concrete mixture (low voids in mineral aggregate) also results in a mixture has more sensitive to slight changes in asphalt cement content.

Gradations of maximum density may not provide sufficient voids in the aggregate for enough asphalt cement to provide adequate film thickness for maximum durability without bleeding. The maximum density curves are necessary in order to increase the total voids in the mineral aggregate (VMA). The minimum VMA requirements and the maximum nominal aggregate size have been suggested. The asphalt paving agencies prefer that the gradation be approximately parallel to the maximum density grading, but that it be offset a few percentage points either above or below the line. The two lines will intersect at the nominal maximum size and be a few percentage points different on the middle sieves. The Superpave mix design developed by the Strategic Highway Research Program (SHRP) requires a selected number of control points on the gradation chart.

The maximum particle size in asphalt concrete mixture is important which ensure good properties of asphalt concrete. If the maximum particle size is too small, the asphalt concrete mixtures may be unstable. If they is too large, the workability and segregation may be a problem. There are two designation for maximum particle size (ASTM C125) as following:

1. Maximum size, which designated as the smallest sieve through which 100 percent of the aggregate sample particles pass.
2. Nominal maximum size, which designated as the largest sieve that retains some of the aggregate particles, but generally not more than 10 percent.

Normally, the maximum aggregate size is normally limited to about one-half of the lift thickness. In recent year, there has been an increase in the use of large stone mixes (SMA) to minimize rutting resistance potential of asphalt concrete. The larger stone size increases the volume concentration of the aggregate which was designed to a reduction of both asphalt content and cost of the asphalt concrete mixture. The large stone mixture shows more resistant to rutting than the smaller aggregate size mixtures. The study to investigate the rutting of basalt and basalt–limestone aggregate are done by a combination of coarser and finer of SMA mixtures with a LCPC wheel tracking test (İskender, 2013). The decreasing of maximum aggregate size is the most importance on rutting resistance, according to the gradation and mineralogical factors of aggregate. Rutting resistance of SMA mixture relatively decreased in the incorporation of limestone aggregate in the SMA mixture, but basalt has high rutting resistance than limestone. However, the use of a maximum aggregate size greater than 1 inch (25.4 mm) often results in harsh mixes that tend to segregate during placement. Therefore, special attention must be given to mix design, mat thickness, material handling, mixing and paving procedures when these larger maximum aggregate size mixtures are used.

The typical specification bands and tolerances of aggregate gradation specifications for HMA have been developed through accumulated field experiences. In many cases they are established by trial and error to reflect local conditions. The generally specifications for asphalt concrete mixtures in Thailand which require well or dense-graded aggregate gradations with the middle portion of the curves approximately parallel to the maximum density curves. Table 2.1 contains the gradation limits recommended in DH-S 408/1992 and 409/2006.

Table 2.1 Gradation requirements for aggregate and asphalt (DH-S 408/1992 and 409/2006).

Standard sieve size		mm	9.5	12.5	19.0	25.0
		(in)	(3/8)	(1/2)	(3/4)	(1)
Type course			Wearing Course	Wearing Course	Binder Course	Base Course
Thickness		mm	25 - 35	40 - 70	40 - 80	70 - 100
sieve size	(mm)	(in)	% passing			
	37.5	(1 1/2)				100
	25.0	(1)			100	90 -100
	19.0	(3/4)		100	90 - 100	-
	12.5	(1/2)	100	80 - 100	-	56 – 80

Table 2.2 Gradation requirements for aggregate and asphalt (DH-S 408/1992 and 409/2006).

9.5	(3/8)	90 - 100	-	56 - 80	-
4.75	(# 4)	55 - 85	44 - 74	35 - 65	29 -59
2.36	(# 8)	32 - 67	28 - 58	23 - 49	19 - 45
1.18	(# 16)	-	-	-	-
0.600	(# 30)	-	-	-	-
0.300	(# 50)	7 - 23	5 - 21	5 - 19	5 - 17
0.150	(# 100)	-	-	-	-
0.075	(# 200)	2 - 10	2 - 10	2 - 8	1 - 7
Quantity of asphalt cement (%)		4.0 – 8.0	3.0 – 7.0	3.0 – 6.5	3.0 – 6.0

The gradation of an aggregate is determined by a sieve analysis (ASTM C136 and C117). The aggregate blending are to meet the specifications. For various reasons, mostly associated with achieving maximum density and desired void properties, certain desirable gradation limits are usually required from aggregates for HMA. Because it is unlikely that a single natural or quarried material will meet these specifications, two or more aggregates of different gradations are typically blended to meet specifications limits. The aggregates are also separated into sizes to improve handling characteristics. The mixing of coarse and fine aggregate in one stockpile results in segregation hence, aggregates should be separated into sizes for example ¾ inch-3/8 inch (19 mm-9.5 mm), 3/8 inch-No. 4 (9.5 mm-4.75 mm) and minus 4 (4.75 mm) prior to hauling and stockpile. Another reason for bleeding aggregates is that it is often more economical to combine naturally occurring and processed materials to meet specifications than to use all processed materials.

The most common method of determining the aggregate proportions to meet specification requirements is the trial-and-error method. The trial blend is considered by experience and plots of individual gradation curves specification limits after that calculation to determine the percent passing each sieve size for the blend which stay in medium of specification limits. The grading that is calculated from this trial is compared with the specification requirements. Adjustments are made for the second trial blend and the calculations repeated for the critical sieves until a satisfactory or optimum blend is obtained. This method, guided by a certain amount of reasoning, mathematics and experience is the most widely used method and is the easiest procedure to determine a satisfactory blend.

The trial-and-error method involves the following steps:

1. Selecting critical sieves for the aggregates in the blend.
2. Determining an initial set of proportion a, b, c, etc., which will meet the specification requirements for the critical sieves.
3. Checking the calculated blend using the proportions determined for all sieves in the specification requirements.
4. Adjusting the proportions, as necessary, to ensure that the percentages for all sieves are within specification limits.

2.3.2 Asphalt cement

Asphalt concrete is brown to black material that is either naturally occurring or produced by petroleum distillation which is used principally in the United States in pavement applications.. In different parts of the world, the term “asphalt” has different meanings. In Europe, asphalt is synonymous with what is called hot mix asphalt (HMA) or asphalt concrete (AC). In the U.S., asphalt is “bitumen” sometime is called asphalt cement or asphalt binder. In this thesis it will be called “asphalt cement”. Asphalt cement and tar are considered bituminous materials. Tar is primarily manufactured from the destructive distillation of bituminous coal and has a very distinct odor which is hardly ever used in paving because of (a) some undesirable physical characteristics such as very high temperature susceptibility and (b) significant health hazards such as severe eye and skin irritation when exposed to its fumes. Its adhesive and waterproofing properties are known from the very early ages. However, asphalt cement and tar are two distinctly different materials with different origins and different chemical and physical characteristics. The commercial types of asphalt cement can be classified into two categories:

1. Natural Asphalts:
2. Petroleum Asphalts

Some agency defines asphalt concrete that have been used in paving like,

1. Native asphalts obtained from asphalt lakes in Trinidad and other Caribbean areas, these were used in some of the earliest pavement in North America.
2. Rock asphalts. These are rock deposits containing bituminous material that have been used for road surfaces in localities where they occur.

3. Tars are bituminous materials obtained from the distillation of coal.
4. Petroleum asphalts. These are products of the distillation of crude oil. These asphalts are by far the most common bituminous paving materials in use today and are the only type discussed in this thesis.

The performance of asphalt cement as a binder in asphalt concrete pavements is determined by its physical properties which effect directly by chemical composition. An understanding of the chemical composition factors effect physical properties which controls asphalt concrete performance.

Asphalt cement is refined from the crude petroleum which is primarily formed by nature from plant life. The process of transformation from plant life to crude oil occurs over millions of years under varied temperature and pressure conditions. Although all petroleums are basically hydrocarbons (chemical combinations of carbon and hydrogen), the amount and nature of hydrocarbons varies from crude to crude. Since the asphalt cement is obtained by distillation from the crude, its chemical composition and properties also vary from source to source.

The asphalt cement composition are genrally considered to be made up from asphaltenes, resins and oils as following:

Asphaltenes are insoluble (or precipitated) which are generally brown dark, brittle solids. The asphaltenes is a major role as the viscosity-building component of asphalt cements.

Resins are generally dark and semi-solid or solid in character. They are fluid when heated and become brittle when cold. They work as agents that disperse.

Oils are usually colorless or white liquids. They are soluble in most solvents.

The asphaltenes is mixed with oil to provide a homogeneous liquid. The asphalt cement is dissolved in a nonpolar solvent such as pentane, hexane, or heptane. The component which is dissolved is called “maltenes” or “petrogenesis” and it is comprised of resins and oils. The type of nonpolar solvent used to precipitate the asphaltenes affects the determination of its total amount in the asphalt cement.

Asphalts most commonly used in flexible pavement construction in Thailand can be divided into the following four types:

1. Asphalt cements
2. Emulsified asphalts
3. Cutback asphalts
4. Polymer modified asphalt concrete.

Physical testing of asphalt cements can be categorized as follows: consistency tests, durability tests, purity tests, safety tests and other tests.

2.3.3 Asphalt cement grading system

The penetration grading system has the following advantages:

1. Grading is based on the consistency of the asphalt cement at 7°F (25°C), which is close to the average pavement service temperature. Testing at 7°F (25°C) may provide a better correlation with low temperature properties than the viscosity grading system test which is measured at 140°F (60°C).
2. Testing time is relatively short.
3. Penetration testing is adaptable to field conditions.
4. Equipment costs are relatively low.
5. Precision limits for the penetration test are well established.

6. Temperature susceptibility (change in asphalt cement consistency with corresponding change in temperature) of the asphalt cement can be determined by measuring penetration at temperatures other than 7°F (25°C).

However, the penetration grading system has the following disadvantages:

1. Penetration is an empirical test and does not measure the consistency of asphalt cement in fundamental units such as viscosity.

2. Shear rate is high during the test.

3. Shear rate is variable because it depends on the consistency of the asphalt cement.

4. Similitude at 7°F (25°C) can be deceptive to performance at higher and lower service temperatures.

Viscosity Grading System, which is based on the viscosity of original (as supplied) asphalt cement, is most widely used in the United States. The poise is the standard unit of measurement for viscosity. The lower the number of poises shows the less viscous the asphalt cement. AC-2.5 shows asphalt cement with a viscosity of 250 poises at 140°F or 60°C is "softer" than AC-40 which is an asphalt cement with a viscosity of 4000 poises at the same temperature. AC-20 grade is most commonly used for paving in the United States. AC-30 grade was recently added to the specifications and is used by some southeastern states. Other test requirements such as penetration at 77°F (25°C), viscosity at 275°F (135°C), viscosity at 140°F (60°C) and ductility at 7°F (25°C) of the residue from thin film oven test (TFOT) and flash point are also given in the specifications. The penetration at 7°F (25°C) controls the consistency of the asphalt cement near the average service temperature and the viscosity at 275°F (135°C) controls its consistency near the mixing and compacting temperatures.

The viscosity grading system has the following advantages:

1. Viscosity is a fundamental property, rather than an empirical test and therefore is independent of the test system and the sample size.

2. It is suitable to a wide range of environments (pavement temperatures 77 to 140°F or 25 to 60°C).

3. It is based on viscosity at 140°F (60°C) which is near the maximum pavement surface temperature generally experienced in the United States. This temperature is critical for pavement performance during hot summer days.

4. Test standards are available with established precision limits.

5. Temperature susceptibility of the asphalt cement can be determined since the consistency is measured at three temperatures.

The disadvantages of the viscosity graded system are listed below:

1. It is not adequate to safeguard against low temperature cracking although within the specifications are superior to those. The test system is slightly more expensive than the penetrometer.

2. Testing time is longer.

3. TFOT residue viscosity can vary considerably within the same grade. For example, AC-20 asphalt cements from two different sources can have TFOT residue viscosities of 3,500 and 10,000 poises. These asphalts are likely to behave differently during and after construction.

There are mainly two type of additives used to improve asphalt concrete mixture, they are fiber and polymer. Fiber such as polyester fiber, carpet fibers, waste tire, mineral fiber, algea, carbon fiber, glass fiber and cellose fiber ect. Those change the viscoelasticity of mixture to improve performance while significantly lower the amount of draindown of asphalt concrete mixture (Mokhtari et al., 2012). Polymer such as styrene butadiene styrence (SBS), ethylene vinyl acetate (EVA), aramid, gilsonite and polyethylene or polypropylene ect. Those helps decrease the binder draindown. Mokhtari et al., (2012) examined the laboratory properties and service life of different SMA mixtures using SBS, cellulose and mineral. The result showed that using SBS is the highest Marshall stability and service life. SBS could significantly improve the performance and service life of SMA mixture. Mario Manosalvas Paredes et al., (2016) using cellulose fiber has precautions for construction, asphalt binder show flow behavior and high cost. Some researcher used algea fiber, which is a new stabilizer additive to enhance the SMA mixture but using algea increases the cost of construction (Teresa Real Herraiz et al., 2016). As presented by Takaikaew et al., (2018), investigated the effect of fiber reinforcement (a combination of polyolefin and aramid fiber 0.05% by mass of total mixture) with AC60/70 to improve the performance of asphalt concrete which is successfully for the utilization of fiber reinforcement in asphalt concrete, can be used instead of PMA mixture.

2.4 Performance pavement related to asphalt concrete

Previous section explained in terms of how selection aggregate and binder increases the performance of asphalt concrete. This section will explain the related effect on asphalt concrete.

Ravelling is one type of distress in asphalt concrete which usually caused by one or a combination of the following factors, such as insufficient amount of both coarse aggregate to handle the fine aggregate particles together, inadequate asphalt content (lean mix), lacking of compaction (high air void content) and excessively aged (oxidized/brittle) asphalt cement binder. It was mentioned earlier that age hardening of asphalt cement in pavement results in progressively lower penetration or higher viscosity, this causes a progressive increase in the brittleness of asphalt cement, thus causing ravelling. High air void contents in the HMA pavements, when constructed, accelerate the age hardening and premature ravelling results. Increased asphalt film thickness can significantly reduce the rate of aging and offset the effects of high air voids.

Over the years, engineers have been able to categorize cracking under two broad groups: load associated and nonload associated (changing of temperature), although most pavement cracks can be described according to their geometry such as longitudinal, transverse, polygon (also alligator and map)blocks or by the mechanism that causes the cracking such as slippage, shrinkage and reflection. Load-associated cracking principal class of load-associated cracking has been described as fatigue cracking (alligator cracking), the occurring of fracture under repeated load have a maximum value less than the tensile strength of the material. Numerous researchers have conducted fatigue tests on HMA mixes. However, laboratory test results have been influenced by the mode of testing (constant stress or constant strain) and the failure criteria. In general, constant stress tests will respond with an increasing fatigue life which shows an increases in the stiffness of HMA. For thin asphalt pavement, mixture of low stiffness should be evaluated by the fatigue life in the constant strain mode of testing. For thick pavements (more than 5 cm), the mixture of high stiffness should be evaluated by the fatigue life in the constant stress mode of testing (Freddy

L et al., 1991). Obviously, the stiffness should not be too low to cause rutting in the surface courses. Nonload associated cracking such as low temperature cracking which is of considerable interest and concern to highway engineers. It shows by itself such as transverse shrinkage cracking in the pavement layer. In field measurements and observations have indicated the cracking starts at the surface and progresses down with time because surface pavements are in high cooling rates and low temperatures develop tensile stresses due to shrinkage. If these stress exceed the fracture strength of the pavement layer, transverse cracking develops. Lopes et al., (2015) found that the present of RAP improves the fatigue life of asphalt concrete mixture.

Rutting is one important type of distress which is caused by the progressive movement of aggregate and asphalt cement under repeated loads either in the asphalt pavement layers or the other layer (Abdulshafi, 1988). It can occur either through consolidation or through plastic flow. In terms of consolidation, it occurs when compaction is poor. The rutting can occur if very thick asphalt layers are consolidated by the repeated load of traffic in contract areas. Rutting also results from plastic flow (permanent deformation) of the asphalt concrte under the wheel tracking. The using of excessive asphalt cement is the most common cause for this. If it is too much asphalt cement in the mixture, it causes the loss of internal friction between aggregate particles. The plastic flow can be solved by using large size of aggregate. Several laboratory tests exist to evaluate characterize of rutting performance of asphalt concrete mixture, such as the Hamburg wheel tracking, Asphalt pavement analyzer, Superpave shear, Georgia loaded wheel tester (GLWT), LCPC (French) wheel tracking and the Asphalt mixture performance tester (AMPT) tests. Each of these laboratory rutting tests has its own advantages and disadvantages in predicting the field performance of a mix (İskender, 2013). Haifang et al., 2013 shows that the indirect tensile test can also be used to predict rutting potential, if the mixture is tested at high temperatures and using a single load test to evaluate more than one primary distress of asphalt concrete would significantly reduce the time and costs. Hui, (2009) shows that the studying of pavement design in Chana, the asphalt surface course is 4 cm thick with a nominal maximum aggregate size of 16 mm. The asphalt intermediate course is 6 cm thick with a nominal maximum aggregate size of 19 mm and the asphalt base course is 6 cm thick with a nominal maximum aggregate size of 26.5 mm. The semirigid base consists of a 20 cm thick 6% cement-stabilized aggregate base course and a 36 cm thick 4% cement-stabilized aggregate subbase course. It is recommended that modified asphalt mixes with great resistance to rutting should be used in the construction of the asphalt intermediate course for freeway pavements in regions with heavy truck traffic and hot weather. Therefore, special attention should be paid to the design, material selection and construction of the asphalt intermediate course.

Stripping can be defined as the weakening or eventual loss of the adhesive bond usually in the presence of moisture between the aggregate and the asphalt cement in the asphalt concrete mixture. The strength of the mixture depands on the cohesional resistance of the binder and aggregate which makes the interlock and frictional resistance of the aggregate and binder. Stripping depend on many variables including the type asphalt cement and aggregate, environment, traffic, construction practice. Some research use antistrip additives to improve stripping. The chemistry of both the asphalt and aggregate at the asphalt aggregate interface plays an important and primary role in the stripping phenomenon. The high viscosity binders have generally been observed to resist displacement by water, better than those of low viscosity because the low viscosity fluid has more wetting power than one of high viscosity.

Objectives of mix design

Asphalt concrete mixture design should be developed as the following.

1. Permanent deformation resistance

The mix should not distort when receiving heavy traffic loading. The resistance to permanent deformation (or rutting) becomes critical at elevated temperatures during hot summer months when the viscosity of the asphalt cement binder is low and the traffic load is primarily carried by the mineral aggregate structure. The permanent deformation resistance was controlled by selecting quality aggregates with proper gradation and selecting the asphalt cement content so that adequate voids exist in the mix. Test methods such as static or dynamic creep may be more suitable for predicting permanent deformation.

2. Fatigue resistance.

The mix should not crack when receiving repeated loads over a period of time. Complex repeated load (either constant stress or constant strain controlled) tests can be run to estimate the number of cycles failure cracking in asphalt concrete mixtures.

3. Low temperature cracking.

Low temperature cracking is usually associated with flexible pavements which happen when asphalt cement becomes harder by aging. The most occurs at temperatures as below as -10^{o}F (-23^{o}C) Durability.

The asphalt concrete mixture must contain asphalt cement to ensure an adequate film thickness around the aggregate particles, thus the consideration must evaluate asphalt cement hardening or aging during production and in service. The compacted mixture should not have very high air voids which is increased permeability.

4. Moisture damage resistance

Moisture damage is when subjected to moisture or water, adhesion loss occurs between the aggregate surface and asphalt cement binder. The aggregate properties are primarily responsible for this occurring, although some asphalt cements are more moisture damage (stripping) than others. If a asphalt concrete mixture is stripping, then anti-stripping agents should be used to make the mix impermeable to water and also minimizes the problem.

5. Skid resistance.

This requirement is only applicable for pavement surface which must be designed to provide sufficient resistance skidding in normal turning and braking movements. Aggregate characteristics such as texture, shape, size and resistance to polish are primarily responsible for skid resistance. However, the mixture should also not contain too much asphalt cement binder which cause the asphalt concrete mixture to flush and create a slippery surface. Skid resistance is discussed by Kogbara et al., 2016 that the coefficient of friction is significantly affected by the gradation of aggregates which is used in the production of asphalt concrete mixtures. The pavement surface will provide adequate skid resistance, which depends largely on the aggregate polishing properties. There are some aggregates for pavement surface courses such as basalt (trap rock), dolerite, granite, greywacke, river gravel, glacial gravel, dolomite, sandstone, quartzite and steel slag. The limestone is not included here as it is very susceptible to polishing and hence it is not used as an aggregate in surfaces courses. Nevertheless, it is used in lower layers of pavement construction. Granites, basalts and crushed gravels are reported to have similar microtexture and comparable polish resistance. Sandstone has a uniform and high texture and is able to retain its microtexture (recovery to its original asperity) with time. In contrast, aggregates such as dolomite and dolerite, which include minerals of similar hardness are more prone to polishing than gabbro (a type of trap rock) and sandstone. It was observed that sandstone possesses the most uniform texture and higher skid resistance, compared with quartzite and river gravel. Steel slag is a recycle aggregate, often added when high frictional properties are required. Gap-graded or Stone matrix asphalt (SMA) aimed at creating stone-to-stone contact within mixture, to improve skid resistance. It contains more durable aggregates, higher (polymer-modified) asphalt content (6–9%), fillers and fibers. Hence, it is more expensive than others. The larger coarse aggregate sizes in the mix gives better performance. Open-graded HMA or Open-graded friction course (OGFC), which are designed to be water permeable. Hence, It uses mostly coarse aggregates, small percentage of sand/mineral filler and 3–6% asphalt binder and contain more than 15% air voids (Asi, I.M., 2007).

6. Workability.

The mixture must be capable of placing and compacing to easy for workingwith reasonable effort. It don’t have testing method. The workability problems are most frequently discovered during the paving operations. However, suitable for the working is made quickly to overcome the workability problems. There are many technologies to produce sustainable asphalt pavements that may affect various phases (raw material processing, manufacturing, utility to recycling) of pavement life. Therefore, it is difficult to choose the most appropriate technology that addresses all the engineering requirements, especially if the technologies produce identical outputs.

2.5 Summary

The widely great detail literature reviews, including existing theories and applications of asphalt concrete and steel slag are illustrated in this chapter. It covers all from the past to recent research publications. It not only concerns with the engineering properties and engineering construction application, but also the perspectives of the environmental and sustainable development are included. The structure of this chapter (literature review) is summarized and demonstrated as the following:

Initially, the basic properties and characteristic of asphalt concrete is briefly descripted. Furthermore, both existing traditional and modified methods are reviewed. Then, the green technology of using steel slag for construction applications is reported by many researchers. The literature, lastly concludes by the pavement performance related to asphalt concrete to assess the possibility of steel slag utilization in the pavement structures.

All in all, based on the review of literatures, it is observed that there are still knowledge gaps in the current understanding of properties of steel slag for their proper applications in construction such as the high asphalt absorb, bleeding at high temperature. This shortcoming, hence encouraged the author to develop a novel mechanical properties of asphalt concretes using limestone and steel slag blend as an aggregate.

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CHAPTER III

PERFORMANCE IMPROVEMENT OF ASPHALT CONCRETES USING STEEL SLAG AS AGGREGATES

3.1 Introduction

The increased proportion of traffic volumes results in distress (rutting, cracking) to all elements of the pavement structure, inclusive of the wearing course, binder course, base, subbase and subgrade layers (Tayfur et al. 2007). Rutting is one of the most common forms of distress on asphalt concrete pavements (flexible pavement). Rutting occurs from traffic volume loads as indicated by the rut depth along the wheel paths (Abdulshafi 1988; Balghunaim et al. 1988; Matthews and Monismith 1992). Fatigue cracking on the other hand occurs from tensile strain, which develops from the bottom of asphalt concrete. Solutions to pavement distress include adding filler (Ali et al. 1992; Zhao et al. 2016), changing the type and size of aggregates (Chen et al. 2016; Iwański and Mazurek 2016; Matthews and Monismith 1992; Wu et al. 2007) and modifying the asphalt cement (Herráiz et al. 2016; Kaloush et al. 2010; Manosalvas-Paredes et al. 2016; Mokhtari and Nejad 2012; Putman and Amirkhanian 2004). Takaikaew et al. (2018) reported that fiber reinforcement (a combination of polyolefin and aramid fiber 0.05% by mass of total mixture) in asphalt concrete penetration grade AC60/70, improved the performance (indirect fatigue life, resilient modulus, dynamic creep, and rutting resistance) of asphalt concrete comparable to the polymer modified asphalt (PMA).

Some research applications of solid waste materials in road construction projects have been conducted in recent years (Kandhal and Hoffman 1997; Robinson Jr et al. 2004; Su and Chen 2002; Tam and Tam 2006; Wu et al. 2007). Steel slag (S) is a by-product obtained during the steel making procedure and comprises 13% waste materials generated from the production of steel (Shen et al. 2009). Steel is a valuable resource material required for economic development of developed and developing countries alike, however, the manufacture of steel from iron ore results in waste, such as S which requires disposal. The usage of S as a construction material in civil infrastructure projects would significantly reduce the landfilling of this waste material and furthermore lead to an avoidance of landfill levies. In recent year, S has been used as a raw material in civil engineering applications such as embankment fills, pavement bases/subbase, building masonry units, cement production, road constructions, fertilizer, etc. (Aiban 2006; Kim et al. 2014; Li et al. 2016; Li 2010; Pellegrino et al. 2013; Sakai and Hiraoka 2000; Sas et al. 2015; Zhang et al. 2012). The utilization of S as a coarse aggregate in asphalt concrete pavements results in pavements with enhanced properties, particularly in terms of durability and stability (Ahmedzade and Sengoz 2009; Setién et al. 2009; Xie et al. 2012; Zhu et al. 2012). S has also been found to possess the required high friction properties often required for pavement materials (Beshears and Tutumluer 2013).

The chemical composition of S mainly comprises CaO, SiO_2, Al_2O_3, MgO and Fe_2O_3. S has high strength and other desirable properties required for road surfacing applications (Feng et al. 2015). Using S as a coarse aggregate in asphalt mixtures can improve the mechanical characteristics and performance of pavements, in terms of moisture, stability, skid resistance, permanent deformation and crack resistance (Chen et al. 2014; Chen et al. 2014; Wang et al. 2009; Zhao et al. 2016). The heat retention characteristics of S can be advantageous for repair work in cold weather conditions (Ahmedzade and Sengoz 2009). The principal issue associated with S is volume expansion due to the hydration of free lime or magnesia which can result in pavement cracking. This can however be effectively mitigated by aging and washing S before placement of this material in pavements (Kneller et al. 1994). The magnesia content in S of Thailand was however found to be 1.38%, which is very low and eliminates this issue (Hasita et al., 2019), which can be considered as low volume expansion and is possibly used as aggregate in asphalt concrete (Wang et al. 2011).

The performance of asphalt concrete depends essentially on the type of aggregate, asphalt cement and gradation (Kandhal and Hoffman 1997). In Thailand, most asphalt concrete uses limestone (L) and granite (G) as the source of aggregates. Asphalt cement of penetration grade 60/70 (AC60/70) is mostly used as the asphalt binder. For some highways with heavy traffic loads, polymer modified asphalt (PMA) is normally specified as an asphalt binder, though this binder is relatively costly. To minimize cost, strong and durable S can be used as a replacement aggregate in AC60/70 concrete, to develop a high performance pavement surface comparable to limestone-PMA (L-PMA) or granite-PMA (G-PMA) concretes. Kara et al. (2004) reported that the S asphalt pavement can be used as a bitumen base, and binder and wearing courses whose mechanical properties satisfied the road authority requirements. Currently, the rapid growth of steel industries in Thailand results in increasing amounts of the steel slag waste. The Iron and Steel Institute of Thailand (2018) reported that the annual output of steel product is close to 22 million tons in Thailand, which results in the generation of 2.86 million tons of S waste. The rate of using steel slag in asphalt concrete is quite low in Thailand, therefore affects the disposal of steel slag, occupies a significant portion of landfills and causes many serious environmental problems.

Even with the available research on the performance of blended S asphalt concrete, there has been little attempt to investigate the role of S replacement at various aggregate sizes which is the focus of this study. This research will also use the unique characteristics of L and S to enhance the development of L/S asphalt concrete when using conventional AC60/70.

This study aims to evaluate the performance of limestone-AC60/70 concrete, limestone-PMA concrete, granite-AC60/70 and granite-PMA concrete, and compared with L/S blends-AC60/70 concrete and L/S blends-PMA concrete. The advantage of S replacement was evaluated by performance tests which included indirect tensile strength, resilient modulus, dynamic creep, indirect tensile fatigue and rutting tests. To avoid the effect of gradation and to consider unique characteristics of L and S in development of better performance of L/S asphalt concrete using conventional AC60/70, all mixed aggregates (L, G and L/S blends) were prepared with similar gradation, in accordance 154 with the Department of Highways’ standard, Thailand.

To the authors’ best knowledge, the comparison of the performance of L and G asphalt concretes has not been previously evaluated for Asian countries, including

Thailand. The performance of asphalt concrete using S as a replacement material has also yet to be reported on to date. This research is novel, innovative and of international significance, as it seeks to promote the usage of S to develop sustainable asphalt concrete pavement systems, resulting in the conservation of natural resources, decreased energy use, and reduced greenhouse gas emission.

3.2 Materials and methods

3.2.1 Materials

3.2.1.1 Aggregates

The aggregates used in this research were limestone (L), granite (G) and steel slag (S). The asphalt cement comprised a penetration grade of 60/70 and polymer modified asphalt (PMA). Table 3.1 presents the mechanical properties of L, G and S including Los Angeles (LA) abrasion [ASTM C131/C131M-1 (ASTM 2014)], soundness [ASTM C88-13 (ASTM 2013)], aggregate impact value (AIV) [BS 812: Part 112: 1990 (BS 1990a)], aggregate crushing value (ACV) [BS 812: Part 110: 1990 (BS 1990b)] and polished stone value (PSV) [BS 812: Part 114 (BS 1989)]. These results indicated that most properties of the aggregates used were in accordance with the criteria for asphalt concrete and modified asphalt concrete in Thailand [DH-S 408/1989 (DOH 1989); DH-S 409/2006 (DOH 2006)]. The PSV value of limestone was found to be slightly lower than the requirement for PMA.

Table 3.1 Basic properties of the tested aggregate.

Test type	Type of aggregate			Criteria for asphalt concrete (AC60/70 binder)	Criteria for modified asphalt concrete (PMA binder)
	Limestone	Granite	Steel slag	(DOH 1989)	(DOH 2006)
Los Angeles abrasion value, LA (%)	22.90	19.70	17.10	40%max	35%max
Soundness (%)	1.60	1.70	0.60	9%max	9%max
Aggregate impact value, AIV (%)	13.60	18.20	13.90	-	25%max
Aggregate crushing value, ACV (%)	18.90	18.30	18.40	-	25%max
Polished stone value, PSV	45.80	50.50	50.60	-	47min

3.2.1.2 Asphalt cements

The properties of asphalt cement are summarized in Table 3.2 and these were compared with the specific requirements for asphalt cement in

Thailand [DH-SP 401/1988 (DOH 1988); DH-SP. 408/1993 (DOH 1993)]. Both the asphalt cements used met the requirements for asphalt cement specified by road authorities in Thailand.

Table 3.2. Test results for asphalt cement.

Parameter	AC60/70		PMA	
	Result	Requirements in Thailand [42]	PMA	Requirements in Thailand [43]
Penetration at 25^{o}C (0.1 mm)	65	60-70	64	55-70
Ductility (cm)	>100	≥100 at 25^{o}C	95.4	≥55 at 13^{o}C
Flash point (^{o}C)	326	≥232	326	≥220

3.2.2 Mix design

In order to evaluate the performance of asphalt concrete with different asphalt cements, aggregate types and S replacement, 10 mixtures of asphalt concrete were prepared according to the Marshall mix design method [ASTM D6927 (ASTM 2015); DH-T. 604/1974 (DOH 1974)] which is also specified in Thailand. To avoid the effect of gradation, all mix proportions were prepared to have essentially the same gradation. The mix proportions were prepared by separating each original aggregate:

S, L and G into 4 bins including bin No.1 (<4.75 mm), bin No.2 (<12.50 mm), bin No.3 (<19.00 mm) and bin No.4 (<25.00 mm) and trial mixing them together. Bin No.1 is the stone dust which is commonly made up from L, as its particles are suitable for milling when compared to granite (G) and steel slag (S). The milled particles of L are smaller than those of G and S because of their low abrasion resistance. As such, when trial mixed with materials from other bins, the final aggregates produced can meet the DOH requirements (DH-S408/1989), whereby % finner than sieve #200 is between 2% and 8%. As such, aggregate of bin No.1 for all studied mixtures was L.

Five types of aggregate evaluated included L:L:L:L, L:G:G:G, L:S:S:S, L:L:S:S and L:L:L:S where the 1st, 2nd, 3rd and 4th letters are the types of aggregates present in bins No. 1 to 4, respectively. Particle size distribution curves of all aggregates used in this study are shown in Fig. 3.1 which was prepared according DH-S408/1989 (DOH 1989). In this study, air void was fixed at 4% for all mix proportions because in Thailand, asphalt concretes are designed at 4% air voids according to Department of Highways Standards. Roberts et al. (1991) reported that the physical property and permanence of asphalt concrete is dependent upon air voids in mixture. When the air voids values decrease to less than 3-4 percent, rutting of the asphalt mixture is likely to occur, due to plastic flow. The mix proportions prepared are shown in Table 3.3. The samples for Marshall test were prepared at optimum asphalt cement content in accordance with ASTM D6927 (ASTM 2015) and DS-T. 604/1974 (DOH 1974). The sample dimension was 63.5 mm height and 101.5 mm diameter.

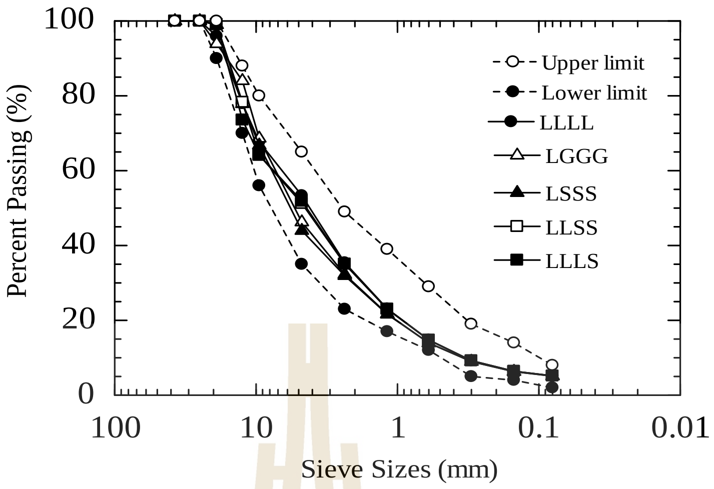


Figure 3.1 Particle size distribution curves of all aggregate.

Table 3.3 Type aggregate and binder in this research.

Mix Proportion	Type of aggregate				Type of Binder	Optimum asphalt cement content
	Fine	Coarse				
	Bin 1 (filler)	Bin 2 (1/2”)	Bin 3 (3/4”)	Bin 4 (1”)		
L:L:L:L+AC60/70	L	L	L	L	AC 60/70	5.00
L:G:G:G+AC60/70	L	G	G	G	AC 60/70	5.00
L:S:S:S+AC60/70	L	S	S	S	AC 60/70	5.00
L:L:S:S+AC60/70	L	L	S	S	AC 60/70	5.00
L:L:L:S+AC60/70	L	L	L	S	AC 60/70	5.00
L:L:L:L+PMA	L	L	L	L	PMA	5.00
L:G:G:G+PMA	L	G	G	G	PMA	5.00
L:S:S:S+PMA	L	S	S	S	PMA	5.00
L:L:S:S+PMA	L	L	S	S	PMA	5.00
L:L:L:S+PMA	L	L	L	S	PMA	5.00

Note: L = Limestone, G = Granite and S = Steel Slag

The aggregates were first heated at 160 ^{o}C. Subsequently, the heated asphalt cement at 160 ^{o}C for AC60/70 and 170 ^{o}C for PMA binder was added into the aggregate and mixed thoroughly to get a well coated and evenly distributed mixture. The mixture was next placed in a Marshall mold and compacted with the standard hammer, with 75 blows imparted on each side of the sample at 145 ^{o}C. After being cooled at room temperature for 1 day, the samples were next soaked in water at a constant temperature of 60 ^{o}C for 30 min prior to Marshall compactor testing. Compressive loading was applied on the sample at a rate of 50.8 mm/minute until it was broken. Two values were measured: the stability which is the required load to fail the sample, and the flow, which is the vertical distortion at the time of failure. The reported results were obtained from an average of three test samples. The results of laboratory Marshall test for various aggregates are presented in Table 3.4.

Table 3.4 Summary of Marshall design results in this research

Parameter	AC 60/70					PMA				
	L:L:L:L	L:G:G:G	L:S:S:S	L:L:S:S	L:L:L:S	L:L:L:L	L:G:G:G	L:S:S:S	L:L:S:S	L:L:L:S
Asphalt cement content (%)	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00
Stability (kN)	10.10	10.30	14.83	13.90	10.85	14.37	14.55	21.56	17.42	14.33
Flow (mm)	3.05	3.05	3.05	3.05	3.05	3.05	3.05	3.05	3.05	3.05
Density (g/cm^3)	2.43	2.37	2.70	2.61	2.61	2.43	2.38	2.70	2.61	2.51
Void content (%)	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00
Voids mineral aggregate (%)	14.73	14.43	15.31	15.31	15.31	14.67	14.39	15.24	15.30	14.91
Voids filled asphalt (%)	73.24	71.78	74.04	73.89	74.22	72.78	72.23	73.58	74.01	73.17

3.2.3 Test methods

The indirect tensile strength (ITS) test was conducted according to ASTM D6931 (ASTM 2017). The sample preparation method was the same as that used for the Marshall test. The ITS test was conducted with a loading rate of 50.80 mm/minute at 25 ^{o}C. The peak load at failure was recorded. The ITS test is related to cracking properties and is the prescribed method to measure the tensile characteristics of asphalt concrete (Takaikaew et al. 2018).

Indirect tensile fatigue test was conducted according to BS-EN-12697-24 (BS-EN 2004) standard at 25 ^{o}C, to investigate the fatigue characteristics of each mixture. The load was applied through a 12.5 mm wide stainless steel curved loading strip. A haversine load was imposed on sample, using a repeated controlled stress pulse to damage the sample and the accumulation of vertical deformation was plotted. The target load pulse rise time was 120 ms. The uniaxial and dynamic load of 400 kPa (58.4 psi) was applied on the samples to represent axle loads applied on the pavement surface, according to the recommendation of Mokhtari and Nejad (2012). Poisson's ratio was assumed to be 0.4. The applied forces on the sample as well as its counting pulses were recorded automatically by the software until sample failed.

The resilient modulus (Mr) test is important for the determination of pavement performance of asphalt concrete mixture when using the mechanistic design procedure, as it measures the pavement response in terms of dynamic stress and the corresponding strain. The Mr test can be used to evaluate the elastic properties of asphalt concrete mixtures (Jiang et al. 2015). The test procedure followed ASTM D4123 (ASTM 1995). The Mr was determined using cylindrical samples (101.6 mm in diameter and 63.5 mm in height) under the indirect tension mode. The test was carried out using the universal testing machine (UTM). Applied loading for each mixture was 15% of ITS on the vertical diameter of the Marshall-prepared samples. The frequency of the load and rest duration was adjusted as 1 Hz: loading for 0.1 s along with a rest period of 0.9 s. The number of repetitions was set at 200 pulses. All samples were kept at 25 ^{o}C for 4 h prior to the test for distributing the temperature throughout the samples evenly. The average last five values of elastic stiffness after the first 150 cycles is defined as Mr. Three samples for each set were tested and the average was presented as Mr.

Dynamic creep and wheel tracking tests are normally used to assess the potential of permanent deformation (rutting) of asphalt mixture (Kaloush et al. 2010). The permanent deformation (rutting) has an important impact on the serviceability index of the pavements during their life service. Dynamic creep test is known as the repeated load axial test and is increasingly used in preference to the uniaxial creep test, as the pulsed load is more simulative of the repeated axle loads applied on the pavement surface. The test can be run at various temperatures and loads. The dynamic creep test was conducted by applying a dynamic load to sample and then measuring the sample’s permanent deformation by linear variable differential transducers (LVDT) after unloading. The loading conditions were selected in order to evaluate the relative performance of different asphalt concrete mixtures in accordance with BS-DD-226 (BSI 1996) for determining the resistance to permanent deformation. The testing conditions and requirements for the dynamic creep test were: conditioning stress = 10 kPa, conditioning period = 30 s, test stress = 100 kPa and test period = 1,800 pulses. All samples were prepared with a Marshall compactor, at 4% air void.

The load shape was rectangular with a loading and rest period of 1s; all samples were placed at 45ºC for 4 h before testing.

The wheel tracking test results can predict rutting characteristic with good correlations with actual field performance. The test was performed in accordance with British and European standard [BS-EN12697-22 (BS-EN 2002)]. The test slabs were prepared using a roller compactor in accordance with British and European standard [BS-EN-12697-33 (BS-EN 2004)]. The slab dimensions are typically 18 cm wide, 50 cm long, and 5 cm thick and compacted to attain 94% of the Marshall density. The test slabs were heated in a 60 ^{o}C temperature controlled chamber for 12 hr prior to the wheel tacking test. The repeated loading in the chamber was applied on the slabs by a steel wheel with rubber tire at a speed of 0.2 m/s forth and back. The tire has 5,000 N loading with a tire pressure of 600 kPa (87 psi). The rut depth on the slabs was measured at various loading wheel passes (N) = 1000, 3000, 4000, 14,000 and 34,000 cycles. The rut depth versus cumulative number of wheel passes was then plotted.

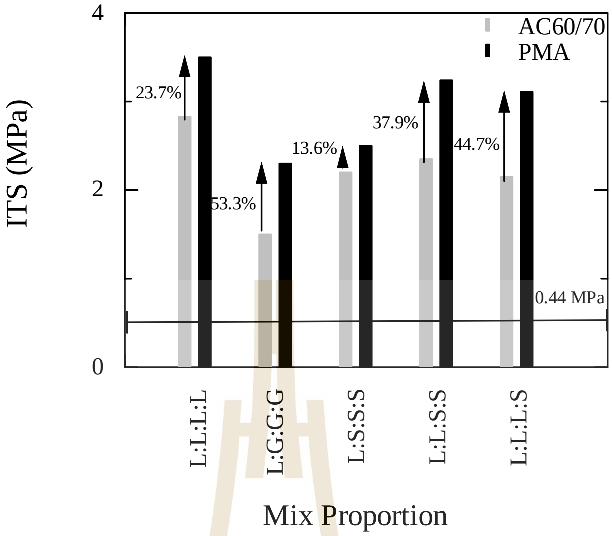
3.3 Test results

Test samples were evaluated with Marshall stability, indirect tensile strength, resilient modulus, indirect tensile fatigue, dynamic creep and wheel tracking tests to investigate the advantage of S replacement in L asphalt concrete. The test results of L/S asphalt concrete were compared with those of G (L:G:G:G) asphalt concrete and L (L:L:L:L) asphalt concrete with both AC60/70 and PMA binders. The effect of asphalt cement was also investigated with two types of asphalt cement including AC60/70 and PMA. The mix proportions of the aggregates studied are presented in

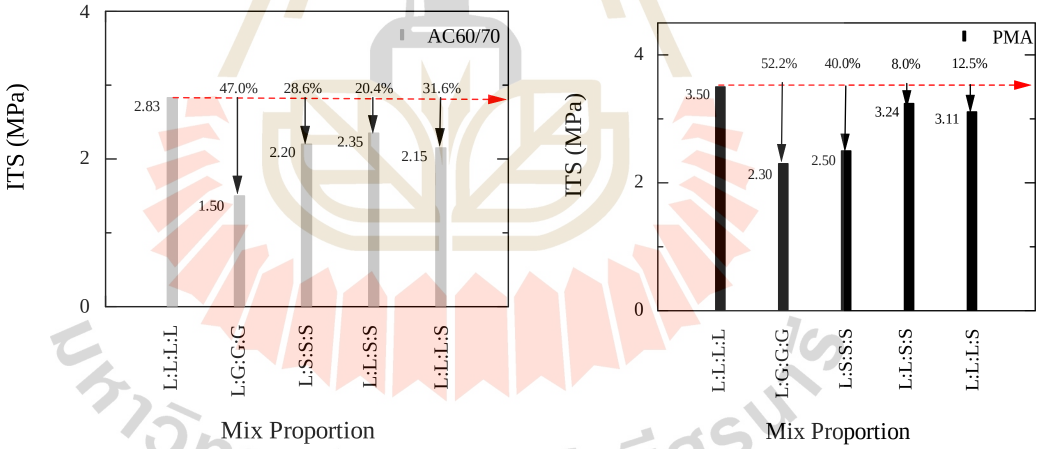
Table 3.3. The Marshall stability test results are shown in Table 3.4. The stability of the each mix proportion is defined as the maximum load carried by a asphalt concrete sample at a standard test temperature of 60 °C. The Marshall stability values of all mix proportions are above the standard (≥ 8.16 kN), and PMA asphalt concrete has higher stability than AC60/70 asphalt concrete with the same aggregate types of between 25.3% – 45.4%. For a given AC60/70 or PMA, the Marshall stability value of L:L:L:L-asphalt concrete and L:G:G:G-asphalt concrete are almost the same. The Marshall stability of L:S:S:S-, L:L:S:S-, and L:L:L:S-AC60/70 concretes is 46.8%, 37.6%, and 7.4% higher than that of L:L:L:L- AC60/70 concrete. The Marshall stability of L:S:S:S- and L:L:S:S-PMA concretes is 50.0% and 21.2% higher than that of L:L:L:L-PMA concrete. The S replacement content improved significantly the Marshall stability, with results similar to those reported by Ahmedzade and Sengoz (2009). Ahmedzade and Sengoz (2009) evaluated the influences of S as a coarse aggregate on the properties of gap graded asphalt concrete and concluded that the strength and stiffness of aggregates control the Marshall stability. It is evident from Table 3.1 that L has higher LA and ACV of L than S, hence S has higher deformation resistance than L. The results also show that the L:S:S:S-AC60/70 concrete is comparable to L- and G-PMA concretes which have a higher cost and consume more natural resource.

The Marshall flow values of all asphalt concretes are shown in Table 3.4. The Marshall flow is the ability to resist the settlements without cracking and plastic flow of bituminous mixtures (Mokhtari and Nejad 2012). The flow values of all mix proportions are almost similar at 3.05 mm. Therefore, all the samples meet the requirement of Department of Highways standards [DH-S408/1989] whereby the flow values of asphalt concrete must be between 2.032-4.064 mm.

ITS of all samples at 25 ^{o}C is shown in Fig. 3.2. For a particular asphalt cement, L:L:L:L asphalt concrete has the highest ITS while L:G:G:G asphalt concrete has the lowest ITS. Unlike the Marshall stability, the S replacement results in the decrease of ITS value. Figure 3.2(a) shows that for a particular aggregate type, the PMA concrete has greater ITS value than the AC60/70 concrete between 13.6% - 53.3%, depending upon the aggregate proportion. Figure 3.2(b) shows that the ITS of L:S:S:S, L:L:S:S- and L:L:L:S-AC60/70 concretes is 28.6%, 20.4%, and 31.6% lower than that of L:L:L:L-AC60/70 concrete, respectively. Figure 3.2(c) shows that the ITS of L:S:S:S-, L:L:S:S- and L:L:L:S-PMA concretes is 40.0%, 8.0% and 12.5% lower than that of L:L:L:L-PMA concrete, respectively. Even with the reduction in ITS with S replacement, the ITS values of L:S:S:S, L:L:S:S and L:L:L:S asphalt concretes are still higher than 0.44 MPa, which is the recommended by Christensen et al. (2000) for pavement design.



(a) the comparison of binder



(b) for AC60/70 (c) for PMA.

Figure 3.2 Indirect tensile strength test results: (a) the comparison of binder (b) for AC60/70 and (c) for PMA.

Fig. 3.3 shows the indirect tensile fatigue modulus test (ITFT) results of all mixtures. The fatigue life values of PMA asphalt concrete are higher than those of AC60/70 asphalt concrete for the same aggregate types. Without S replacement, the fatigue life values of L:L:L:L- AC60/70 and L:L:L:L-PMA concretes are higher than those of L:G:G:G-AC60/70 and L:G:G:G-PMA concretes which is associated to the higher ITS of L:L:L:L-AC60/70 and L:L:L:L-PMA concretes. This implies that the mineralogy in L can react better with asphalt cements rather than G (Siriphun et al. 2019). For a particular asphalt cement, the fatigue life of the asphalt concretes with S replacement are higher than L:L:L:L asphalt concrete and L:G:G:G asphalt concrete whereby the L:S:S:S-asphalt concrete possesses the highest fatigue life. The fatigue life of L:S:S:S-AC60/70 concrete (370 pulses) is 1.6 times higher than that of L:L:L:L-AC60/70 concrete (230 pulses). The fatigue life of L:S:S:S-PMA concrete (2230 pulses) is 5.2 times higher than that of L:L:L:L-PMA concrete (430 pulses). It is evident that S can work well with both asphalt cements, especially PMA.

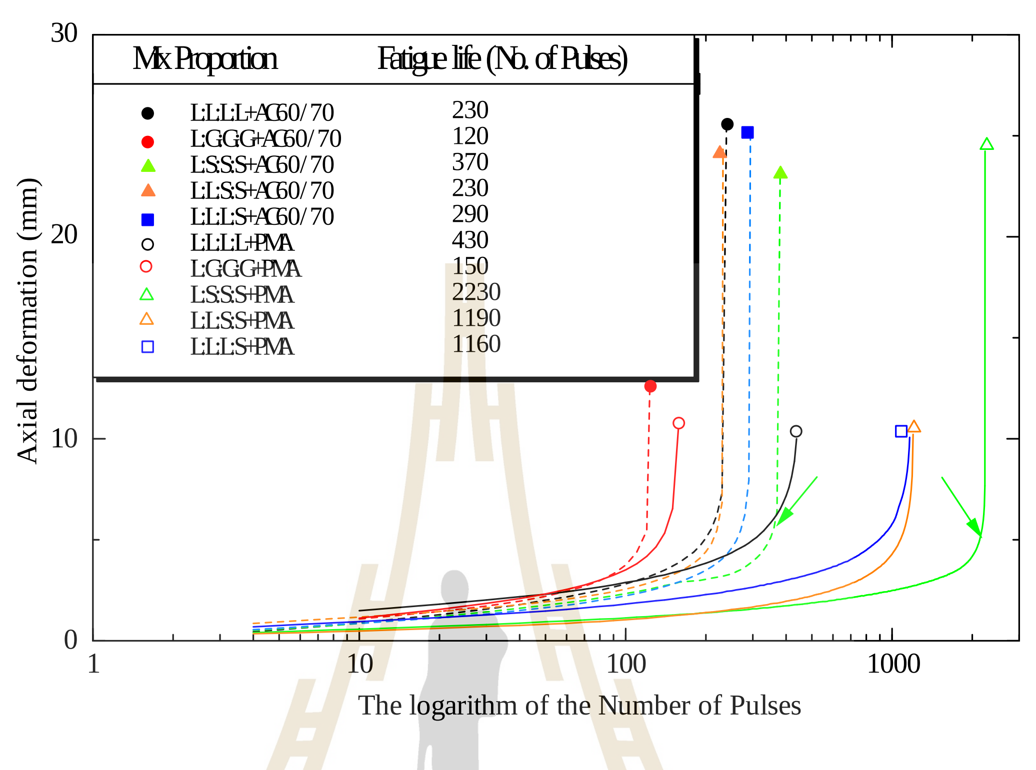
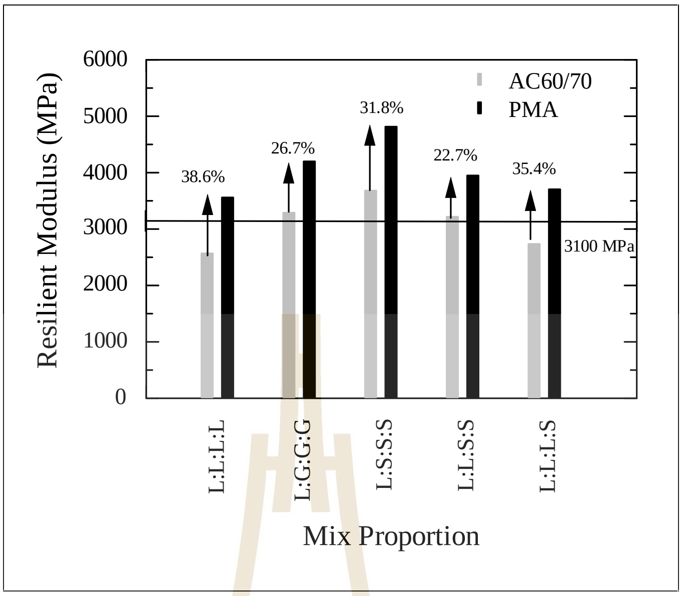


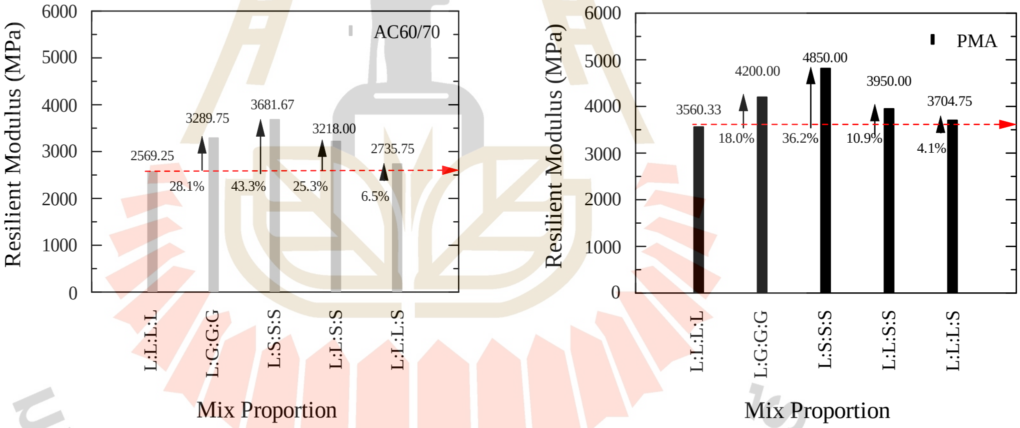
Figure 3.3 The fatigue life of the ten mix proportion.

Figure 3.4 shows relationship between the Mr and mix proportion. Figure 3.4(a) shows that the Mr of PMA concrete is 22.7% – 38.6% higher than that of AC60/70 concrete at the same aggregate types, which is similar to the Marshall stability results. The Mr values of L:G:G:G-AC60/70 and PMA concretes are higher than those of L:L:L:L-AC60/70 and PMA concretes. This implies that L:G:G:G-AC60/70 and PMA concretes have higher rutting resistance than L:L:L:L-AC60/70 and PMA concretes at the service stage but have lower service life. However, the Mr values of L:G:G:G-AC60/70 and PMA concretes are lower than those of L:S:S:S-AC60/70 and PMA concretes.

For a particular asphalt cement, Figure 3.4(b) shows that the Mr values of L:S:S:S-, L:L:S:S- and L:L:L:S-AC60/70 concretes are 43.3%, 25.3%, and 6.5% higher than the Mr value of L:L:L:L-AC60/70 concrete, respectively. Figure 3.4(c) shows that the Mr values of L:S:S:S-, L:L:S:S- and L:L:L:S-PMA concretes are 36.2%, 10.9% and 4.1% higher than the Mr value of L:L:L:L-PMA concrete, respectively. The S replacement content increases the voids mineral aggregate (VMA) of the asphalt concrete (*see* Table 3.3). The high VMA causes the mixtures to have higher deformation resistance and higher strength which causes these mixtures appear to be capable of withstanding stress prior to failure (Neham et al., 2018). As such, the M_r increases with S replacement ratio. Moreover, Mr of L:S:S:S-AC60/70 concrete is 3,681.67 MPa, which is higher than that of L:L:L:L-PMA concrete (3,560.33 MPa) and L:G:G:G-AC60/70 concrete (3,289.75 MPa). In other words, the S replacement improves Mr of L:S:S:S-AC60/70 concrete to be superior to the L:L:L:L-PMA concrete which has a higher cost. The higher Mr leads to the higher rutting resistance of asphalt concrete. Comparing with the requirement of American Association of State Highway and Transportation officials (AASHTO, G. 1993) where Mr > 3,100 MPa, L:L:L:L-PMA, L:G:G:G-AC60/70 and L:G:G:G-PMA concretes met the requirements, while the L:L:L:L-AC60/70 concrete did not. However, the L:S:S:S-AC60/70 and L:L:S:S-AC60/70 concretes meet the requirement, showing the advantage of S replacement.



(a) the comparison of binder

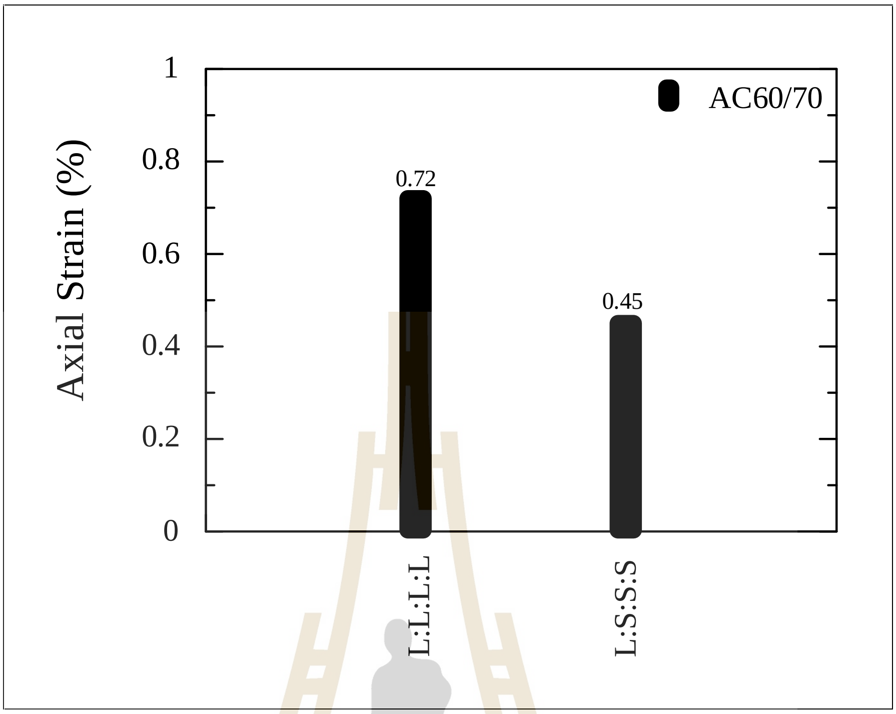


(b) for AC60/70 (c) for PMA.

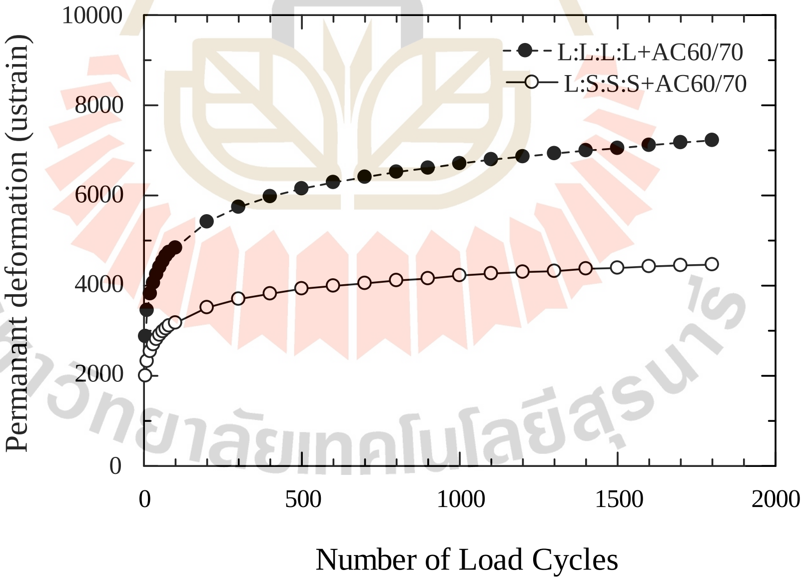
Figure 3.4 Resilient modulus test results: (a) the comparison of binder (b) for AC60/70 and (c) for PMA.

The dynamic creep test is a high reliability test to predict permanent deformation of asphalt mixtures. Figure 3.5(a) shows the permanent axial strain of L:S:S:S-AC60/70 concrete compared with L:L:L:L-AC60/70 concrete.

The permanent axial strains of L:S:S:S-AC60/70 and L:L:L:L-AC60/70 concretes are 0.45% and 0.72%, respectively. In other words, the L:S:S:S-AC60/70 concrete has lower permanent axial strain than the L:L:L:L-AC60/70 concrete approximately 1.62 times which is in agreement with higher Mr value of L:S:S:S-AC60/70 concrete. Figure 3.5(b) shows the relationship between accumulated permanent deformation (μ strain) versus the number of load cycles for L:L:L:L asphalt concrete and L:S:S:S asphalt concrete. The L:L:L:L-AC60/70 concrete has the highest permanent deformation. The results of dynamic creep tests show that the S replacement content leads to lower rut depth which could be attributed to the roughness, hardness and high bearing strength of S aggregates. Therefore, the S replacement improves the machanical interlocking between asphalt cement and aggregates. Though accumulated permanent strain of the tested asphalt concretes increases with the number of load cycles in the similar pattern, the L:S:S:S-AC60/70 concrete has higher resistance to permanent deformation than L:L:L:L-AC60/70 concrete for the same number of load cycles.



(a) axial strain (strain rate)



(b) Permanent deformation (µstrain)

Figure 3.5 Dynamic creep test results: (a) Axial strain (strain rate) and (b) Permanent deformation (µstrain).

The wheel tracking test is widely used to evaluate the rutting potential of pavements. During the testing, the wheel tracking device produced rutting by rolling a steel wheel across the surface of slab samples which is a general description of rutting under traffic loading. The amount of the depression significantly depends on the quality of asphalt concretes (Tapkın 2008). The rut depths that occurred after specified number of wheel passes (N); 1,000, 4,000, 14,000 and 34,000 cycles are presented in Fig.3.6. The L:S:S:S-AC60/70 concrete exhibits smaller rut depth than L:L:L:L-AC60/70 concrete. The rut depth is 0.92, 1.15, 1.66 and 2.24 mm at N = 1,000, 4,000, 14,000 and 34,000 cycles, respectively for L:L:L:L-AC60/70 concrete. While the rut depth is smaller of 0.61, 0.81, 1.22 and 1.60 mm at N = 1,000, 4,000, 14,000 and 34,000 cycles, respectively for L:S:S:S-AC/70 concrete. In other words, at N = 1,000, 4,000, 14,000 and 34,000 cycles, the rut depth of L:S:S:S asphalt concrete is 50.8%, 42.0%, 36.1% and 40.0%, respectively lower than the L:L:L:L asphalt concrete. The wheel tracking and dynamic creep test results show that the Mr is directly related to rutting resistance. The Mr of L:S:S:S-AC60/70 concrete is 43.3% higher than L:L:L:L-AC60/70 concrete (Figure 3.4) and the rut depth of L:L:L:L-AC60/70 concrete is an average of 42.2% higher than L:S:S:S-AC60/70 concrete for all N tested. The rut depth is directly related to the adhesive damage, which is caused by the stripping of asphalt cement at aggregate surface. The mineralogy of L is very susceptible to polishing and the S replacement can improve such a unfavorable characteristic. The L/S blend is therefore recommended as aggregates in the pavement surface courses for heavy traffic load (Dunford 2013; Senga et al. 2013) whereas the L alone can be used in the binder course.

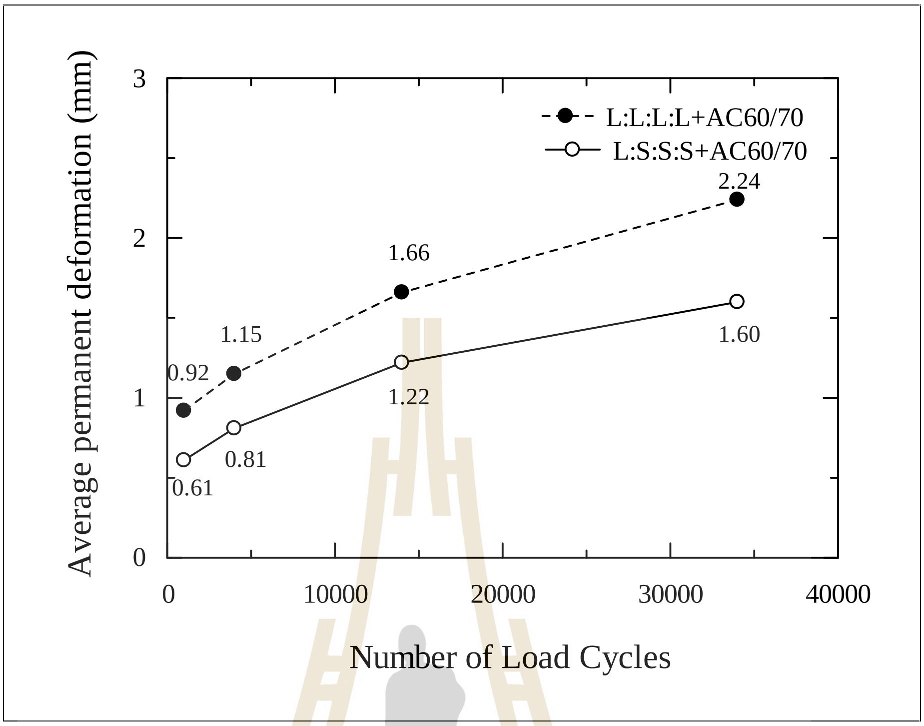


Figure 3.6 Pavement rutting test results.

The ANOVA (F-test) was performed to determine statistical significance of influence factors on the performance of asphalt concrete and the results are shown in Table 3.5. The result shows that the type of binder has a significant effect on stability, ITS, fatigue life and Mr at 95% confidence level, but insignificantly affects the Marshall flow.

Table 3.5 Summary of ANOVA (F-test) for type of asphalt cement.

		Sum of Squares	df	Mean Square	F	Sig.
Stability (kN)	Between Groups	49.51	1	49.51	6.721	0.032
	Within Groups	58.93	8	7.37		
	Total	108.43	9			
Flow (mm)	Between Groups	0.00	1	0.00	1.000	0.347
	Within Groups	0.00	8	0.00		
	Total	0.00	9			
Indirect tensile strength (MPa)	Between Groups	1.31	1	1.31	5.385	0.049
	Within Groups	1.95	8	0.24		
	Total	3.26	9			
Fatigue life (No. of Pulses)	Between Groups	1536640.00	1	1536640.00	4.638	0.063
	Within Groups	2650560.00	8	331320.00		
	Total	4187200.00	9			
Resilient Modulus (MPa)	Between Groups	2275919.68	1	2275919.68	9.927	0.014
	Within Groups	1834065.24	8	229258.16		
	Total	4109984.92	9			

* statistical significance at the level of 0.05 (α = 0.05)

3.4 Conclusions

In this research, the performance tests on asphalt concretes using limestone (L), granite (G) and steel slag (S) as coarse aggregate in asphalt mixture were performed to determine the advantage of replacement with S. The following conclusions can be drawn from this study:

3.4.1 For a particular asphalt cement, the stability of both L:L:L:L-asphalt concrete and L:G:G:G-asphalt concretes was essentially 403 the same. The S replacement enhanced significantly the stability of asphalt concrete. The stability of L:S:S:S-AC60/70 concrete was 46.8% higher than that of L:L:L:L-AC60/70 concrete and the stability of L:S:S:S-PMA concrete was 50% higher than that of L:L:L:L-PMA concrete. Furthermore, the stability of L:S:S:S-AC60/70 concrete was as high as the L:L:L:L- PMA and L:G:G:G-PMA asphalt concrete, which is more expensive and consumes more natural resources. The improvement of Mashall stability by S is due to the lower LA and ACV of S than L, improving the deformation resistance of the asphalt concrete. The flow value was found to be independent of asphalt cement and aggregate.

3.4.2 Indirect tensile strength (ITS) of L:G:G:G asphalt concretes was lower than that of L:L:L:L asphalt concretes for both AC60/70 and PMA. The S replacement reduced the ITS and the L:S:S:S-AC60/70 concrete had the lowest ITS. The ITS of L:S:S:S- AC60/70 concrete was 28.6% lower than that of L:L:L:L-AC60/70 concrete while the ITS of L:S:S:S-PMA concrete was 40.0% lower than that of L:L:L:L-PMA concrete. Even with the reduction in ITS, the ITS values of L:S:S:S, L:L:S:S and L:L:L:S asphalt concretes were still higher than 0.44 MPa, which was recommended by Christensen et al. (2000) for pavement design.

3.4.3 The fatigue life of L:L:L:L-AC60/70 and L:L:L:L-PMA concretes was higher than that of L:G:G:G-AC60/70 and L:G:G:G-PMA concretes, respectively. The S replacement improved the fatigue life significantly. The fatigue life of L:S:S:S-AC60/70 concrete (370 pulses) was 1.6 times higher than that of L:L:L:L-AC60/70 concrete (230 pulses). The fatigue life of L:S:S:S-PMA concrete (2230 pulses) was 5.2 times higher than that of L:L:L:L-PMA concrete (430 pulses). In other words, the S replacement content improves the service life of asphalt concrete for the same traffic loads.

3.4.4 The resilient modulus, Mr of L:L:L:L-AC60/70 and L:L:L:L-PMA concretes was lower than that of L:G:G:G-AC60/70 and L:G:G:G-PMA concretes, respectively. The Mr of L:L:L:L-AC60/70 was 2569.25 MPa, which is lower than 3100.00 MPa, recommended by AASHTO. With the S replacement, the Mr of L:S:S:S-AC60/70 concrete was 3681.67 MPa, which met the recommendations and was also higher than that of L:L:L:L-PMA concrete. This implies that the S replacement can enhance the Mr of the AC60/70 concrete comparable to the L:L:L:L-PMA concrete. The Mr improvement by S replacement is possibly due to the higher void mineral aggregate (VMA) content of S mixture. The high VMA content causes the mixtures to have higher deformation resistance and higher strength which causes the asphalt concretes appear to be capable of withstanding stress prior to failure.

3.4.5 Due to the rougher and stronger aggregates of S, the degree of mechanical interlocking is higher with the S replacement ratio, leading to higher resistance to creep. As such, the L:S:S:S-AC60/70 concrete had higher resistance to permanent deformation than L:L:L:L-AC60/70 concrete for the same number of load cycles. The L:S:S:S-AC60/70 concrete had lower permanent axial strain than the L:L:L:L- AC60/70 concrete approximately 1.62 times at the end of test.

3.4.6 The wheel tracking test results showed that the rut depth of L:S:S:S-AC60/70 concrete had approximately 42.2% lower than that of the L:L:L:L-AC60/70 for all number of wheel passes. The rut depth is associated with Mr as seen that the Mr of L:L:L:L-AC60/70 concrete was 43.3% lower than that of L:S:S:S-AC60/70 concrete. In other words, the L:S:S:S-AC60/70 concrete has a longer service life than conventional L:L:L:L-AC60/70 concrete.

3.4.7 S replacement improves the performance of the asphalt concrete. The fatigue life, Mr and rut depth resistance of the L:S:S:S-AC60/70 was 1.6, 1.4 and 1.4 times higher than those of the L:L:L:L-AC60/70, respectively. In other words, the L:S:S:S-AC60/70 concrete has a longer service life than L:L:L:L-AC60/70 concrete with the same thickness. S is therefore suggested as sustainable aggregate in asphalt concrete, which has a significant engineering, economic and environmental impact.

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CHAPTER IV

EVALUATION OF DENSE-GRADED ASPHALT CONCRETES USING STEEL SLAG AS AGGREGATES

4.1 Introduction

Over decades, a significant amount of waste is generated by industries world-wide due to the growth of the modern industrial sectors. This results in increasing transportation and landfilling costs and negative environmental impacts. The usage of recycled materials in construction projects is a sustainable practice to reduce both the demand for natural resource and reduce waste disposal.

Several researchers have attempted to use recycled waste materials as substitutes to virgin materials in the infrastructure applications, such as in pavements, footpaths, concrete and embankments. The waste materials such as recycled crushed glass (Arulrajah et al. 2014; Disfani et al. 2012; Grubb et al. 2006), melamine debris (Donrak et al. 2016), recycled concrete aggregate (Poon and Chan 2006; Yaowarat et al. 2018; Yaowarat et al. 2019), recycled asphalt pavement (Arulrajah et al. 2014; Taha et al. 2002) have been evaluated for this application.

A large amount of recycled waste materials is often used for road maintenance and reparation work (Asi et al. 2007). Current research and practice concentrates on the usage of waste materials in pavement applications for base and subbase (Hoy et al. 2016; Hoy et al. 2018; Mohammadinia et al. 2016; Sudla et al. 2018) and surface layers (Yaowarat et al. 2020; Yaowarat et al. 2019; Hasita et al. 2019; Hasita et al. 2020), as these courses require large quantities of materials.

The steel industry is crucial to the Thailand economy. As a by-product, 13% of steel slag (S), is generated from the steel output (Shen et al. 2009). S accounts for approximately 2.86 million tons produced annually in Thailand (The Iron and Steel Institute of Thailand 2018). S can be reprocessed into both coarse and fine aggregate materials and used in the road construction. However, not all types of steel slag are suitable for processing as aggregates. Some of them contain high percentages of free lime and magnesium oxides, which are not reacted with the silicate structures and besides can hydrate and expand in humid environments (JEGEL 1993). This problem can be mitigated by aging and washing of steel slag prior to using them in pavements (Kneller et al. 1994).

The performance of asphalt mixtures with S has been investigated via laboratory experimental programs including stability, skid resistance, deformation and crack resistance of pavement. It was reported that the mechanical properties and performance of asphalt concrete can be improved by using S as coarse aggregate (Ahmedzade and Sengoz 2009; Chen et al. 2016; Chen et al. 2015; Chen et al. 2016; Chen et al. 2014).

Over the years, several pavement engineers and agencies worldwide have reported that the escalating proportion of traffic volumes causes distress to the pavement surface course, mainly due to rutting and fatigue cracking. Permanent deformation (rutting) and fatigue tensile tests are therefore important for flexible pavement design. Most of the permanent deformations occur in the pavement surface course, rather than in the base and subbase courses. Fatigue cracking occurs from the tensile stress developed from the bottom of the asphalt concrete.

Ahmedzade and Sengoz (2009) studied the influences of coarse S on the mechanical properties and electrical conductivity of asphalt concrete mixtures in which the asphalt cement (AC-5 and AC-10) mixed with limestone (L) aggregates were used as control materials. The results indicated that mechanical properties of asphalt mixtures were improved by S replacement. The electrical conductivity of steel was also better than that of the controlled mixtures. Similar study conducted by Asi et al. (2007) reported that 25% of S was an optimal replacement of the limestone coarse aggregate for improving the mechanical properties of the asphalt concretes. The mechanochemistry and physical observation of S as aggregate in stone mastic asphalt (SMA) mixtures were studied by Wu et al. (2007), who stated that the utilization of S can contribute to construction cost effectiveness. The high polish stone value (PSV) of steel slag asphalt mixtures exhibited good skid and wear resistance compared to natural aggregates including sandy dolomite and limestone (Parker and Brown, 1992). A recent study reported that S can be used as coarse and fine aggregates in the induction of healing asphalt concrete (Xu et al. 2020). Oluwasola et al. (2016) conducted a feasibility study on dense-graded and gap-graded asphalt mixture consisting of steel slag and copper mine tailings. The Superpave mix design method was employed in the study at a fixed void content of 4%. The experimental program including moisture susceptibility, indirect tensile strength, dynamic creep, rutting test, and leaching test. The combination of S and copper mine tailing asphalt concrete exhibited better rutting resistance and less susceptible to permanent deformation when compared to control granite asphalt mixtures.

Although many research works have studied the possibility of S utility as asphalt concrete aggregate, the comparative performance studies between S- and L-asphalt concretes at different gradations and air voids via complete laboratory are very limited, especially in Southeast Asia and this aspect is the focus of this research. The results will fulfil the gap knowledge on the usage of S in road construction in Thailand. The typical limestone, which contains high CaO and SiO_2, was used as the controlled aggregate and the asphalt AC 60/70, which typical in road construction in Thailand was used as asphalt binder in this study. The asphalt concretes were prepared using dense-graded aggregates according to ASTM D6927 but with different sizes. The complete laboratory performance tests included those simulating fatigue cracking and rutting failures commonly occur in asphalt concrete pavement. The performance tests for fatigue cracking were indirect tensile strength (ITS), indirect tensile fatigue life (ITFL) and indirect tensile resilient modulus (M_R), while in order to assess the rutting behavior dynamic creep and wheel tracking testes were conducted. In addition, an environmental experiment program was carried out to detect the heavy metal of the mixtures and benchmarked with the international specification. The outcome of this research will lead to guidelines for the usage of S to develop sustainable asphalt concrete pavement with long service life and cost-effectiveness in Thailand and other countries.

4.2 Materials and methods

4.2.1 Materials

4.2.1.1 Aggregates

The aggregates used in this research were limestone and steel slag. Their basic and engineering properties are summarized in Table 4.1. Properties of these aggregates were in accordance with the criteria for asphalt concrete and modified asphalt concrete in Thailand [DH-S 408/1989 (DOH 1989)]. The mineral and chemical composition of S and L were obtained by X-Ray Fluorescence (XRF) and X-Ray Diffraction (XRD) analyses and are presented in Table 4.2 and Figure 4.1, respectively. The main chemical compositions detected in steel slag are $Fe_2O_{3,}$ CaO, MnO. The magnesia content of steel slag in this research was found to be 1.38%, which can be considered as low volume expansion and used as aggregate for asphalt concrete (Wang et al. 2011).

Table 4.1 Basic properties of aggregates.

Test Parameters	Type of aggregate			Criteria for AC60/70 binder (DOH 1989)
	Limestone	**Granite**	**Steel slag**	
Los Angeles abrasion value, LAA (%)	22.90	19.70	17.10	40%max
Soundness (%)	1.60	1.70	0.60	9%max
Aggregate impact value, AIV (%)	13.60	18.20	13.90	-
Aggregate crushing value, ACV (%)	18.90	18.30	18.40	-
Polished stone value, PSV	45.80	50.50	50.60	-

Table 4.2 Chemical compositions of steel slag.

Chemical formula	Fe_2O_3	CaO	MnO	Cr_2O_3	SiO_2	Na_2O	Al_2O_3	MgO	TiO_2	SO_3	CuO
Percentage	51.25	28.08	8.64	2.84	2.46	2.16	1.90	1.38	0.76	0.14	0.02

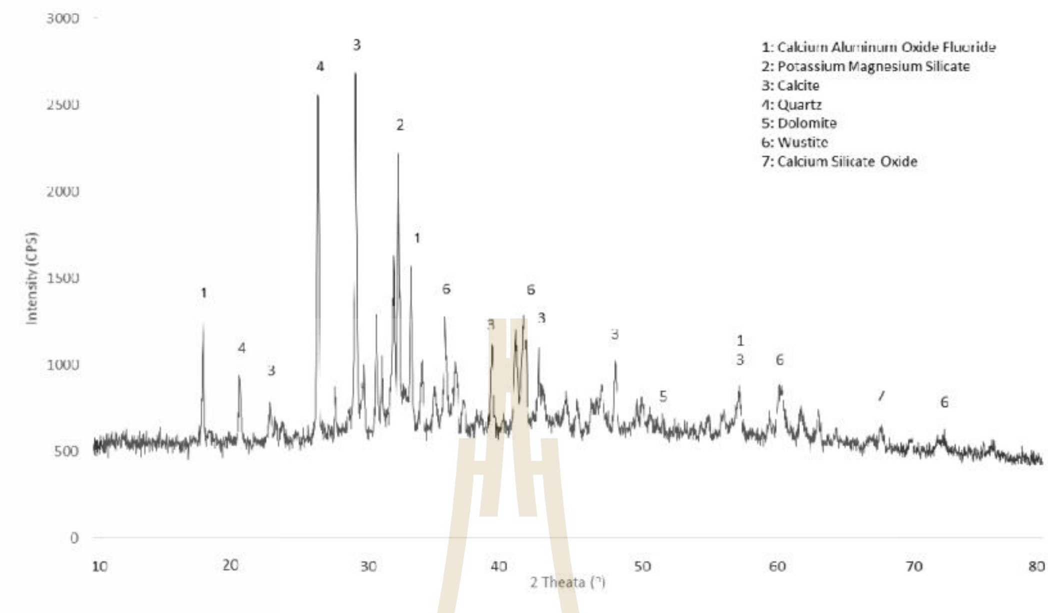


Figure 4.1 X-Ray Diffraction (XRD) pattern of steel slag.

4.2.1.2 Asphalt cements

The asphalt cement AC60/70 obtained from Tipco Asphalt Co., Ltd was used in this study. The physical properties of AC60/70 were penetration 65 (0.1mm) at 25°C, Ductility > 100 cm and flash point 326°C, which are in compliance with the specific requirements for asphalt cement specified by the Department of Highway (DOH), Thailand [DH-SP 401/1988 (DOH 1988)].

4.2.2 Mix design

The Marshall mixture design method ASTM D6927 (ASTM 2015) procedure is commonly used to establish the job mix in Thailand, in accordance with the Department of Highways (DOH) specification (DH-T 604/1974, 1974). The steel slag and limestone were prepared by separating each original aggregate into four bins: bin No.1 (<4.75 mm), bin No.2 (<12.50 mm), bin No.3 (<19.00 mm) and bin No.4

(<25.00 mm) and then trial mixed. To investigate the influence of the aggregate type and gradation on asphalt concrete, four different mixtures were prepared within the aggregate boundaries (ASTM D6927), including large-sized limestone (LL), medium-sized limestone (ML), large-sized steel slag (LS) and medium steel slag (MS). Due to the crushing process of S into fine particle takes much effort, the L aggregate smaller than 4.75 mm (bin No.1) was used to mix in LS and MS. The particle size distribution curves of ML, LL, MS, and LS are shown in Figure 4.2 compared with the upper and lower boundaries. The gradation curves of ML and MS were in the middle of the boundaries while the gradation curves of LL and LS were close to the lower boundary.

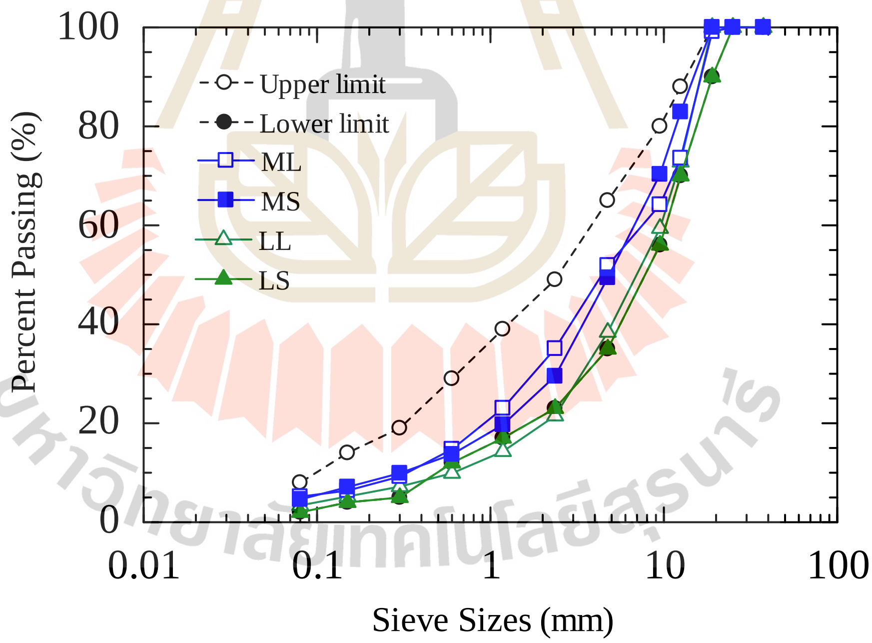


Figure 4.2 Particle size distribution curves of all aggregate.

The aggregates were first heated at 160°C. Subsequently, the heated asphalt binder at 160°C was added into the aggregates and mixed thoroughly to attain well coated and uniformly distributed mixture. The mixture was then placed in a Marshall mold (63.5 mm in height and 101.5 mm in diameter) and compacted with the standard hammer for 75 blows on each side of the sample at 145°C to attain Marshall specimen namely: ML-AC60/70, LL- AC60/70, MS-AC60/70, and LS-AC60/70. The material behavior such as granular interlocking and material density is significantly influenced by the air void content (Dubois et al. 2010). Previous research work indicated that an air void increase of 1% led to a 10% reduction in pavement life (Khan et al. 1998; Linden et al. 1989). However, the mechanical performance of the mixtures could be worse with excessively low air void. Brown and Cross (1991) reported that an air void content of below 3% can lead to premature rutting of the pavement structure. In practice, lower air void was recommended for large- sized aggregate to minimize the effect of large pore space of the aggregate (Kota et al. 2018). Therefore, the air voids were designed to be 4% and 3% for medium-sized and large- sized aggregate mixtures, respectively. Table 4.3 summaries the properties of aggregate for AC 60/70 job mix design.

Table 4.3 Summary the properties of aggregate for Marshall mix design.

Parameter	AC 60/70			
	ML	MS	LL	LS
Asphalt cement content (%)	5.00	5.00	6.10	5.20
Density (g/cm^3)	2.454	2.649	2.418	2.622
Void content (%)	4.00	4.00	3.00	3.00
Voids filled mineral aggregate (%)	15.0	15.1	15.3	15.4
Voids filled asphalt cement (%)	75.3	73.5	78.00	74.54

The Marshall specimens were cured at room temperature (25 ± 2^{o}C) for 1 day and then soaked in water at a constant temperature of 60^{o}C for 30 min prior to the Marshall test in accordance with the DOH speciation. The compressive loading was applied on the specimen at a rate of 50.8 mm/min until the specimen was broken and the maximum loading at failure is the Marshall stability. In addition, the resistance to plastic flow of cylindrical samples was also measured; the associated plastic flow (deformation) of the sample is the flow value.

4.2.3 Test methods

The indirect tensile strength (ITS) test was conducted in accordance with ASTM D6931 (ASTM 2017). The ITS of asphalt mixtures was measured by loading a cylindrical specimen across its vertical diametrical plan at a rate of deformation of 50.80 mm/min at 25^{o}C. The specimen thereby fails along the vertical plane. The peak load at failure was recorded and used to calculate the ITS of the specimen. Three specimens, with a height of 63.5 mm and a diameter of 101.5 mm, were prepared for testing to confirm the consistency. The value of ITS can be used to evaluate the relative quality of asphalt mixtures in job mix design testing and to estimate the potential for rutting or racking in road pavement.

The long-term performance of the asphalt concrete can be evaluated by the characteristics of fatigue properties of the asphalt mixtures. The high fatigue property of the mixture exhibits a long service life of the pavement. The indirect tensile fatigue test (ITFT) was carried out on the studied specimens in accordance with BS-EN-12697-24 (BS-EN 2004c). The specimen (101.5 mm in diameter and 63.5 mm in height) was prepared in accordance with Marshall specimen preparation method. Fatigue test is a specialized mechanical testing method performed by applying cyclic loading to the asphalt mixtures. Fatigue life and crack growth were then observed in the critical locations, which illustrates the safety of the mixtures that may be susceptible to fatigue. The cyclic load test method was performed instead of the static load test as it provides a precise estimation of the fatigue cracking of asphalt mixtures (Moghaddam et al. 2014). The haversine load was imposed on the specimens through a 12.5 mm wide stainless-steel curved loading strip using a repeated controlled stress pulses to damage the specimen. The target load pulse rises time of 120 ms, the target test stress of 400 kPa (axle loads on the pavement surface), and assumed Poisson’s ratio of 0.4 at 25^{o}C were the standard test conditions recommended by Mokhtari and Nejad (2012). The minimum load was set for 0.15 kN in order to attest the data measurement consistency (Guo et al. 2015) The applied forces and the counting pulses were recorded automatically, and the accumulation of vertical deformation against the number of load pulses was then plotted. The total number of the pulses was defined as the fatigue life when the specimen was completely cracked.

Resilient modulus (M_R) is a fundamental material property used to characterize the stiffness of pavement materials under different conditions, including moisture and temperature, density, and stress distribution. The value of M_R is used to evaluate the relative quality of materials and to generate input for pavement design or pavement evaluation and analysis. M_R is also one of the most important properties of the material used in the mechanistic design procedure for pavement structure (Huang 2004).

The procedures for laboratory preparation and testing method based on ASTM D4123 (ASTM 1995) were performed to determine M_R of the studied asphalt mixtures. The prepared Marshall specimens (101.6 mm in diameter and 63.5 mm in height) were cured at 25^{o}C for 4 h prior to M_R test. The repeated load indirect tension test for determining M_R was conducted by applying compressive loads in the vertical diametral plane of the specimens with a haversine frequency of 1 Hz. The target peak pulse compressive load was 15% ITS. The loading period of the pulses, 0.1 s was followed by a rest period of 0.9 s. The number of repetitions was 200 pules. The average last five values of elastic stiffness after the first 150 cycles is defined as M_R. The M_R value was presented by the average triplicated samples.

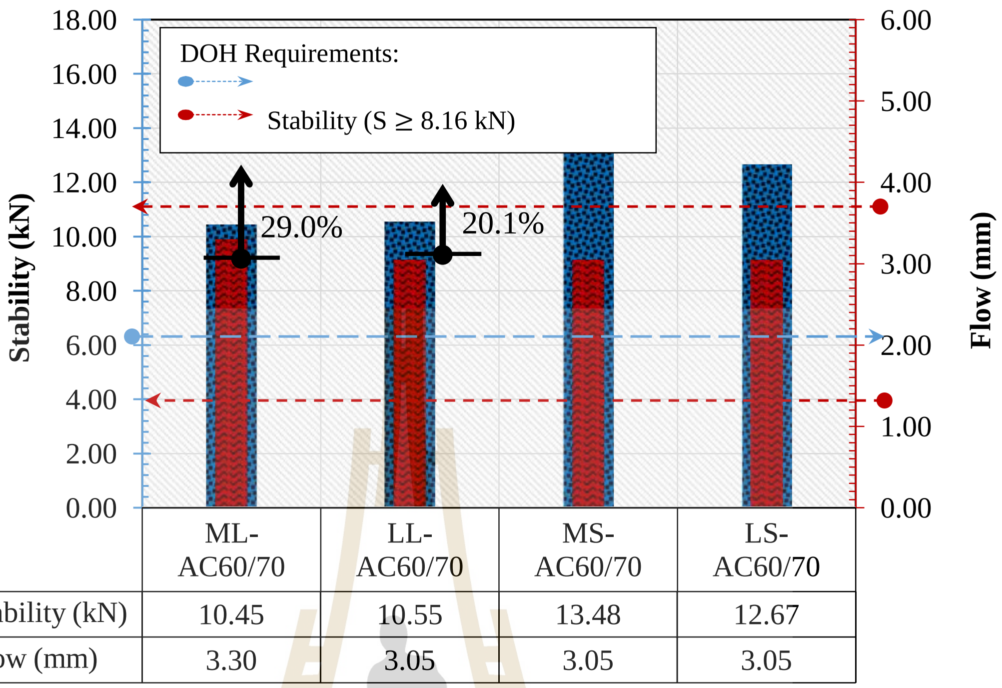
The permanent deformation has an important impact on the serviceability index of the pavements during their life service. The specimens were prepared by Marshall compactor. The test procedure was in accordance with BS-DD-226 (BSI 1996) with the following test conditions: loading level conditioning stress = 10 kPa, test loading stress = 100 kPa, conditioning period = 30 s, terminal pulse count = 1800 pulses. The specimen’s skin and core temperatures during testing were monitored by two thermocouples inserted in a nearby dummy specimen at 45^{o}C. The dynamic creep test applies a repeated pulsed uniaxial stress on an asphalt concrete specimen and uses linear variable different transducers (LVDT) to measure the resulting deformations in the same direction as the unapplied load. It represents the simulative pulsed load of the repeated axle loads applied on the pavement surface.

The French wheel tracking test was designed to qualify bituminous mixtures according to their capacity to resist rutting. This test has been successfully used in France for over 20 years to study the rutting behavior in asphalt concrete. The prediction of rutting characteristic of the pavement using this wheel tracking test indicated the good correlation with the actual field performance (Gabet et al. 2011). In this study, the test was performed in accordance with British and European standard [BS-EN12697-22 (BS-EN 2004a)]. The test slab specimens with dimensions of 18 cm in width, 50 cm long and 5 cm thick were prepared using a roller compactor to attain 94% of Marshall density in accordance with British and European standard [BS-EN-12697-33 (BS-EN 2004b)]. The test slab specimens were heated at 60^{o}C in a controlled chamber for 12 h prior to the wheel tracking test. The repeated loading in the chamber was applied on the slabs by a steel wheel with rubber tire at a speed of 0.2 m/s forth and back. The tire had 5,000 N loading with a tire pressure of 600 kPa (87 psi). The rut depths on the slabs were measured at various loading wheel passes (N) = 1000, 3000, 4000, 14,000 and 34,000 cycles. The relationship between rut depth versus the cumulative number of wheel passes was then plotted.

The Toxicity Characteristic Leaching Procedure (TCLP) is an analytical method to simulate leaching through a landfill. This method was prescribed by the Environmental Protection Agency, the United State (US. EPA) standard (EPA 1992). The Inductively Coupled Plasma – Optical Emission Spectrometry (ICP-OES) tool was used to detect the present heavy metals of S asphalt concrete. The specimens obtained from the studied mixtures were crushed and screened with 9.5 mm sieve. It was then extruded by using an acetic acid solution at a liquid to solid ratio of 20:1 on a weight basis and agitated in a rotary extractor at 30 rpm for a period of 18 h at room temperature (22°C). The suspended solids in the leachate were removed by filtering through a 0.45-micron membrane filter. The results were reported based on the triplicated specimens to ensure data consistency. The total contents of eight heavy metals including arsenic, cadmium, chromium, lead, mercury, selenium, silver, and barium in steel slag asphalt concrete mixtures were examined.

4.3 Test results

Figure 4.3 presents the Marshall stability and flow test results of the S and L asphalt mixtures with different gradations. The Marshall stability values of all studied mixtures are greater than the minimum requirements specified by DOH (stability > 8.16 kN) (DH- S408/1989). The Marshall stability of ML-AC60/70 and LL-AC60/70 are approximately the same, indicating that the gradation has an insignificant effect on the Marshall stability. It was noted that the S replacements in bin 2 to 4 can improve the stability of the controlled mixtures; the stability of MS-AC60/70 and LS-AC60/70 mixtures are 29.0% and 20.1% higher when comparing to the ML-AC60/70 and LL-AC60/70 mixture, respectively. This finding is consistent with previous research in that the asphalt mixture mixed with S indicated the high performance (Chen et al. 2014).



	ML-AC60/70	LL-AC60/70	MS-AC60/70	LS-AC60/70
▨ Stability (kN)	10.45	10.55	13.48	12.67
▨ Flow (mm)	3.30	3.05	3.05	3.05

Figure 4.3 Marshall stability and flow test results

Unlike the L asphalt mixture, the gradation affects the Marshall stability of S asphalt; the MS-AC60/70 mixture exhibits higher Marshall stability than the LS-AC60/70 mixture. The higher Marshall stability of the mixtures indicates a higher rutting resistance under traffic load. The flow values of all mixtures are not significantly different and are within the allowable flow requirement (2.032 mm < flow values < 4.064) specified by DOH (DH- S408/1989). This indicates that S can be used to replace the high-quality natural aggregate to resist the gradual deformation of the pavements. The higher Marshall stability is found for medium-sized aggregate.

The indirect tensile strength (ITS) test results of all mixtures are shown in Figure 4.4. ITS values of the mixtures are found to be dependent upon the type of aggregate and gradation. Similar trends of L- and S-asphalt mixtures are observed in that the medium-sized aggregate provides higher ITS values than the large-sized aggregate. The lower ITS in the mixtures with large-sized aggregate was due to higher voids, causing higher deformation, even with a lower air void. ITS of ML-AC60/70 and MS-AC60/70 mixtures are 15.2% and 13.0% higher than that of LL-AC60/70 and LS-AC60/70 mixtures, respectively. It is worth mentioning that the ITS values of MS-AC60/70 and LS-AC60/70 are 29.0% and 26.5% lower than the ML-AC60/70 and LL-AC60/70 mixtures, respectively. This finding is different from that reported in previous research which showed that the S mixtures had higher ITS than the L mixtures (Masoudi et al., 2017). This might be because L from various sources in Thailand consists of high CaO and SiO_2 (Siriphun et al. 2019), which contribute to the strong chemical compounds of asphalt concrete. Although the ITS values of MS-AC60/70 and LS-AC60/70 are lower than those of ML-AC60/70 and LL-AC60/70 respective, the ITS values of MS-AC60/70 and LS-AC60/70 are found to be higher than the minimum recommended value (0.44 MPa) for pavement design (Christensen et al. 2000).

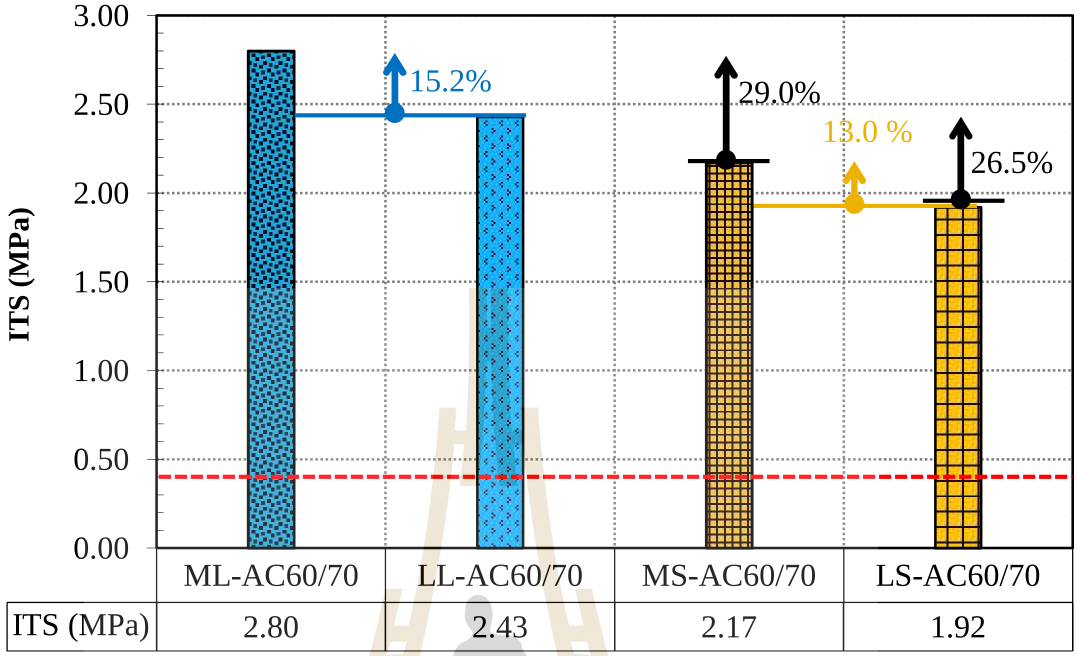


Figure 4.4 Indirect tensile strength test results.

Figure 4.5 shows the indirect tensile fatigue life of all studied asphalt mixtures. It is evident that the fatigue life of S asphalt mixtures is higher than L asphalt mixtures. Even with lower ITS, the fatigue life of MS-AC60/70 and LS-AC60/70 mixtures are 1.27 and 1.95 times greater than that of ML-AC60/70 and LL-AC60/70 mixtures, respectively. In other words, fatigue life is not directly related to the ITS. This better performance might be attributed to S having a lower LAA and soundness properties than L, resulting in higher fatigue load capacity and durability of aggregate. In addition, the low ACV of S can also resist the high impact of crushing force. This finding is similar the previous research conducted by (Marco and Nicola 2013).

For an aggregate, it is evident the fatigue life is governed by the gradation. For instance, the fatigue life of MS-AC60/70 is 17% higher than LS-AC60/70 while the fatigue life of ML-AC60/70 is 46.2% higher than that LL-AC60/70. In other words, even with large air voids, the asphalt mixtures with medium-sized aggregate exhibit the best fatigue life than those with large-sized aggregate.

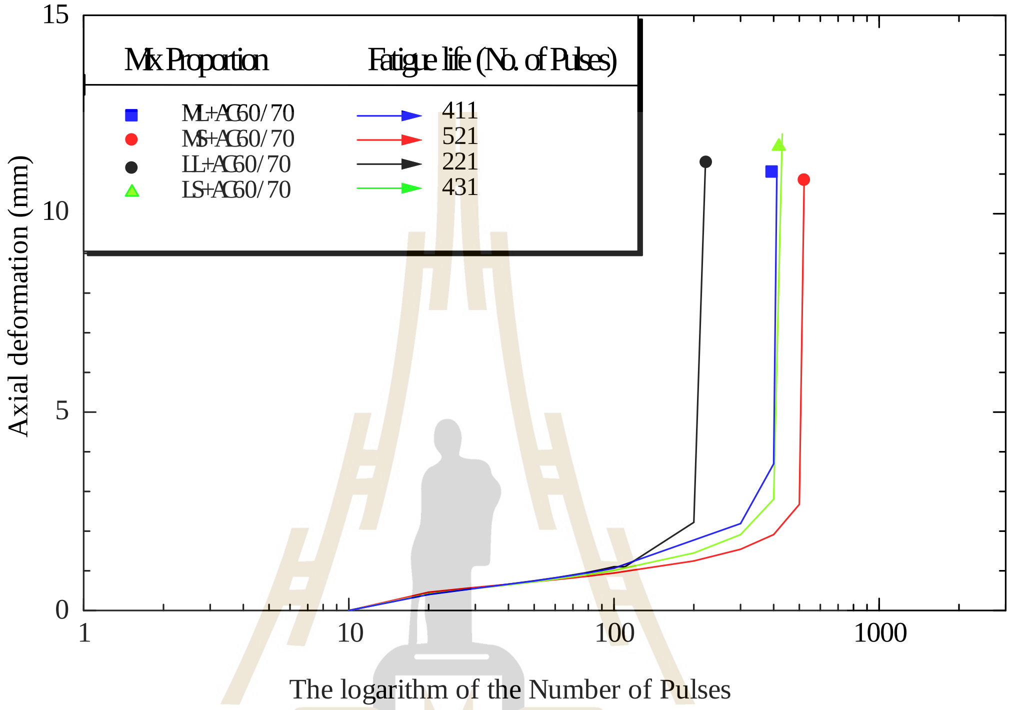
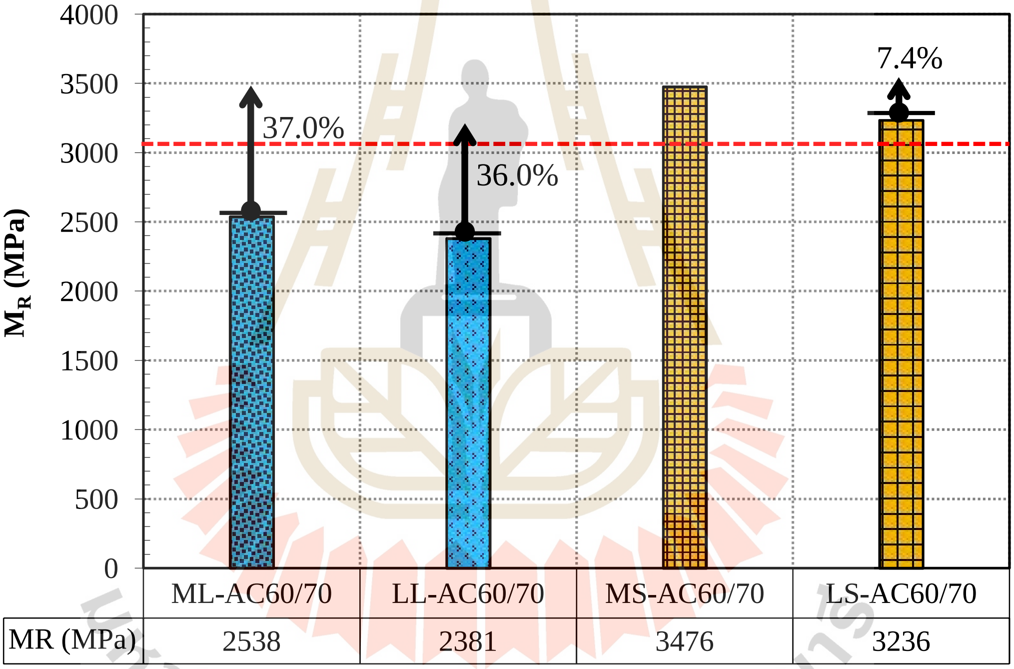


Figure 4.5 The fatigue life of the asphalt mixtures.

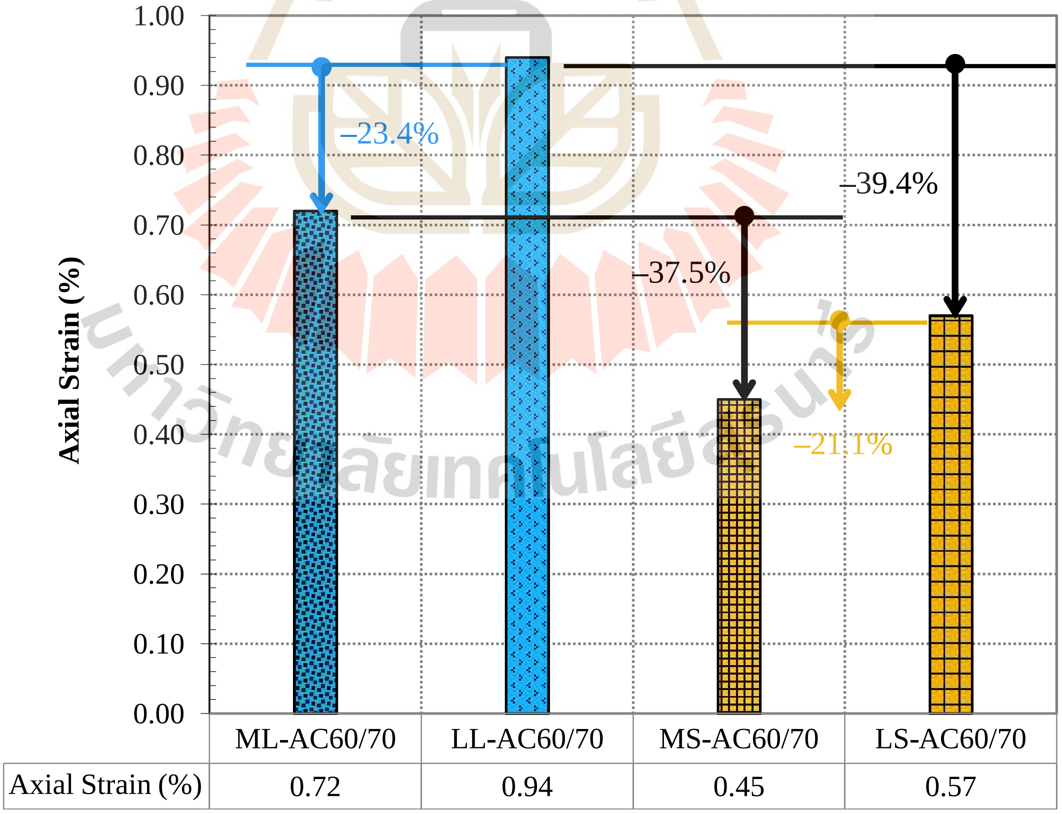
The indirect tensile resilient modulus (M_R) values of all studied asphalt mixtures are presented in Figure 4.6. For a particular type of aggregate, the gradation insignificantly affects the M_R values of L asphalt concrete as seen that ML-AC60/70 and LL-AC60/70 mixtures are more or less the same and the DS-AC60/70 mixture has M_R value of only 7.4% higher than the MS-AC60/70 mixture. However, S asphalt mixtures have higher M_R values than L asphalt mixtures for both gradations. These results are in good agreement with the Marshall stability and fatigue life test results, which indicates that S has good basic properties to resist the fatigue cracking under a high traffic load. Masoudi et al. (2017) reported that the high mechanical properties and angularity physical shape of steel slag enhances interlocking, leading to a higher M_R of the asphalt mixtures. Once this aggregate mixed with the cohesive asphalt binder, it results in better stiffness and higher bearing capacity of mixtures. The S asphalt mixtures have M_R values higher than the requirement (M_R > 3100 MPa) according to AASHTO (1993) for high volume traffic road, whereas L asphalt mixtures do not. This can confirm the advantage of S replacement in the road construction.



	ML-AC60/70	LL-AC60/70	MS-AC60/70	LS-AC60/70
MR (MPa)	2538	2381	3476	3236

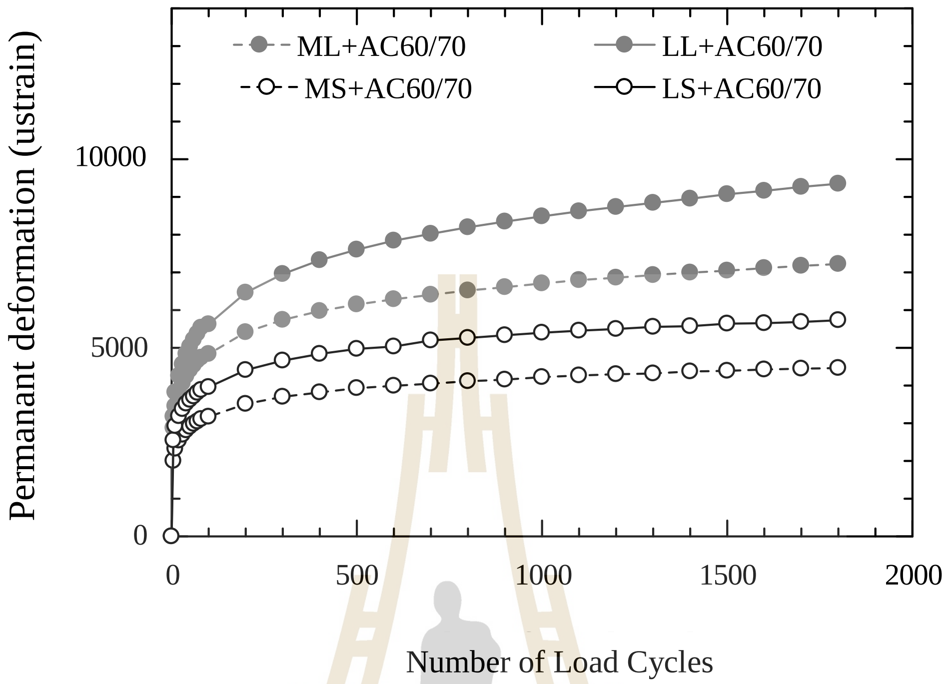
Figure 4.6 Resilient modulus test results.

Dynamic creep test is considered as one of the best procedures to assess the permanent deformation of asphalt concrete mixture (Kalyoncuoglu and Tigdemir 2011; Valkering et al. 1990). The axial strains at the terminal pulse (1800 pulses) for each asphalt mixture are illustrated in Figure 4.7. Figure 4.7a shows that the S asphalt mixtures have lower axial strain than the L asphalt mixtures. For the same gradation, S has higher resistance to permanent deformation; the axial strains of MS-AC60/70 and LS-AC60/70 mixtures are approximately 37.5% and 39.4% lower when compared with ML-AC60/70 and LL-AC60/70 mixtures, respectively. The medium-sized asphalt mixture exhibited better axial strain performance; i.e., the axial strains of ML-AC60/70 and MS-AC60/70 mixtures are 23.4% and 21.1% lower when compared with the LL-AC60/70 and LS-AC60/70 mixtures, respectively. In other words, the mixtures with medium-sized aggregate exhibit better performance than those with large-sized aggregate. Figure 4.7b shows that the mixtures with medium-sized aggregate have higher resistance to permanent deformation under the same number of load cycles.



	ML-AC60/70	LL-AC60/70	MS-AC60/70	LS-AC60/70
Axial Strain (%)	0.72	0.94	0.45	0.57

(a) Axial strain (strain rate)



(b) Permanent deformation (ustrain)

Figure 4.7 Dynamic creep test results: (a) Axial strain (strain rate) and (b) Permanent deformation (µstrain).

The wheel tracking test is widely used to evaluate the rutting potential of pavement materials (Arulrajah et al. 2020). The rolling steel wheel was used to simulate the wheel tracking across the surface of the slab specimens. The rut depths of the mixtures occurred after the specified number of wheel passes (*N*): 1,000, 4,000, 14,000 and 34,000 cycles are recorded by a wheel tracking device. The relationships between rut depth and the number of load cycles of all mixtures are presented in Figure 4.8. The results show that the S asphalt mixtures have lower rut depth than the L asphalt mixtures. For the same *N*, the MS-AC60/70 mixture has the lowest rut depth and followed by LS-AC60/70, ML-AC60/70, and LL- AC60/70. The rut depths of S mixtures are gradually increased with *N*, whereas the sharp increase is observed for the L asphalt mixtures after *N* = 1,000. For a particular type of aggregate, the asphalt mixtures with large-size aggregate might have fewer fine particles to fill the void, leading to increased deformation after cyclic loading, even with reduced air voids. While the lower rut depth of the S asphalt mixtures can be explained by the strong interlocking and greater adhesion in the mixture (Masoudi et al., 2017). This finding shows the best performance of S replacement in asphalt concrete for a high traffic volume road.

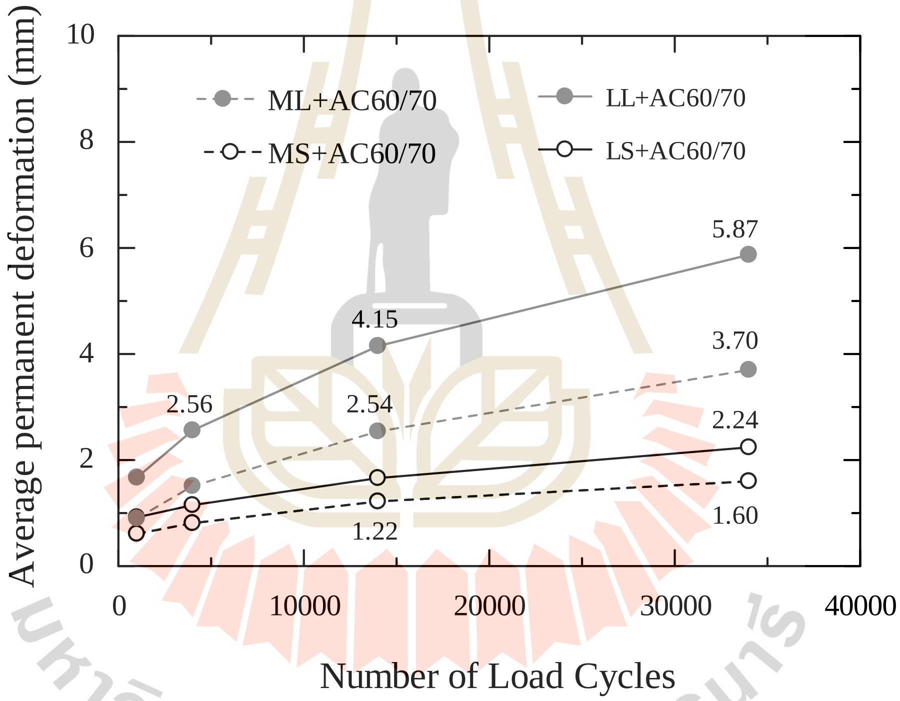


Figure 4.8 Pavement rutting test results.

The leaching assessment of both organic and inorganic are commonly analyzed by the Toxicity Characteristic Leaching Procedure (TCLP) test in the form of solid, liquid and multiphasic materials. The leaching test of the industrial-like steel slag is recommended when it used as the pavement materials (Oluwasola et al. 2016).

Table 4.4 presents the comparison of TCLP results with U.S. EPA requirements and hazardous waste designation (Wartman et al. 2004). Wartman et al. (2004) reported that a certain material is designed as a hazardous waste in according to U.S. EPA if any detected metal is present concentrations > 100 times the drinking water standards. Based on this criterion, the detected concentrations of the heavy metals in S mixtures are within the acceptable limits. Similar findings have been reported by (Nikolić et al. 2016; Oluwasola et al. 2016).

Table 4.4 Comparison of TCLP results with U.S. EPA Requirements.

Contaminant	Drinking water standards (EPA 1999) (mg/l)	Hazardous waste designation (Wartman et al. 2004) (mg/l)	Leachate analysis of steel slag asphalt concrete
Arsenic	0.05	5.0	0.001
Barium	2.0	100.0	4.35
Cadmium	0.005	1.0	<0.001
Chromium	0.1	5.0	<0.001
Lead	0.015	5.0	<0.002
Mercury	0.002	0.2	<0.001
Selenium	0.05	1.0	0.001
Silver	0.05	5.0	<0.001

From a geoenvironmental perspective, it is evident that S replacement can be safely used in asphalt concrete pavement. In addition, the performance test results also confirm that the S asphalt mixtures have superior performance against fatigue cracking and rutting of to the L asphalt mixtures. The medium-sized aggregate provides better performance than the large-sized aggregate at larger air void (lesser asphalt binder). This indicates that the usage of medium-sized S aggregate in developing asphalt concrete is more sustainable in term of engineering and economical perspectives than the usage of large-sized S aggregate.

4.4 Conclusions

This research evaluated the feasibility of using S as aggregate in asphalt concrete pavement by using high-quality limestone as a controlled aggregate material. The following conclusions are made based on data, analyses, and discussion. The basic mechanical properties of S and L can be used as coarse aggregate for asphalt concrete pavement as it meets the criteria for asphalt concrete of Department of Highways standards. The Marshall stability test results indicated that the S asphalt mixtures have higher stability than the L asphalt mixtures. The L asphalt concretes had higher ITS values than the S asphalt mixtures for both medium-sized and large-sized aggregates, which diverted from previous studies. This is possibly due to the strong chemical bonds generated from high calcium and silica in Thailand's limestone. Although lower ITS values of S asphalt concretes were observed, their values were dramatically higher than the requirement (0.44 MPa) for pavement design. Unlike ITS, the indirect tensile fatigue life of the S concrete is significantly higher than that of the L asphalt concretes. The advantage of using S on the fatigue cracking resistance is also noticed from the indirect tensile resilient modulus. The M_R of S asphalt mixtures were higher than the required value (3100 MPa) recommended by AASHTO, while the L asphalt mixtures did not meet this required value.

The dynamic creep and wheel tracking test results showed that the S asphalt concretes had superior resistance to permanent deformation and rutting to the L asphalt concretes. The coarse and rigid S aggregates in asphalt concrete led to higher stiffness and resistance to permanent deformation. The performance test results confirmed that the S asphalt concretes exhibited better performance against fatigue cracking and rutting failure than the L asphalt concretes. The usage of medium-sized S aggregate in developing asphalt concrete is more sustainable in term of engineering and economical perspectives than the usage of large-sized S aggregate.

From a cyclic performance perspective (i.e., indirect tensile fatigue life, M_R and rut depth resistance) and heavy metal leachate properties, it is evident that S can be used as a coarse aggregate for the sustainable development of pavement construction projects in Thailand. The outcomes of this research will have significant contributions in reducing natural resources required for asphalt paving materials, while promoting the sustainability of natural and non-renewable resources with the usage of waste by-product in the road construction projects.

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CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

5.1 Summary

Environmental perspective concerns, which strongly focus on the green technology, is the motivation leading to the study of the possibility of using steel slag as aggregate in the asphalt concrete. This thesis consists of two main objectives. The first is to investigate the possibility of using steel slag as an aggregate in asphalt concrete, based on performance tests. The second is to study effect of binder and job mix design on performance of steel slag asphalt concrete. Chapter 3 focuses on performance improvement of asphalt concretes using steel slag as aggregates. Two types of asphalt cements AC60/70 and polymer-modified asphalt (PMA) were utilized in this research. The mix proportions were prepared by separating each original aggregate (S, L, and G) into four bins, Bin No.1 (<4.75 mm), Bin No.2 (<12.50 mm), Bin No.3 (<19.00 mm), and Bin No.4 (<25.00 mm), and trial mixing them together. Five types of aggregate included L:L:L:L, L:G:G:G, L:S:S:S, L:L:S:S, and L:L:L:S, where the first, second, third, and fourth letters denote the types of aggregates in Bins 1-4, respectively. The asphalt concretes were prepared at 4% air voids by using the Marshall compaction method. The performance tests included indirect tensile strength (ITS), indirect tensile fatigue life (ITFL), resilient modulus (M_R), dynamic creep, and wheel tracking tests.

In chapter 4, to investigate the influence of the aggregate type (L and S) and gradation on performance of asphalt concrete, four different mixtures were prepared within the aggregate boundaries (upper limit and lower limit).The asphalt concrete samples included large-sized limestone (LL), medium-sized limestone (ML), large-sized steel slag (LS) and medium steel slag (MS). The gradation curves of ML and MS were in the middle of the boundaries while the gradation curves of LL and LS were close to the lower boundary. A simulation of laboratory performance tests included those simulating fatigue cracking and rutting failures, which occur in asphalt concrete pavement. The performance tests for fatigue cracking were indirect tensile strength (ITS), indirect tensile fatigue life (ITFL) and indirect tensile resilient modulus (M_R), while in order to assess the rutting behavior dynamic creep and wheel tracking tests were conducted. Though the utilization of recycled waste materials in highway applications can be considered as having significant impacts on resource management, the hazardous compounds can leach out and pollute the water resource. Therefore, this research also be considered as an environmental assessment which is undertaken to verify the risk of using the recycled waste material. The Toxicity Characteristic Leaching Procedure (TCLP) test prescribed by the US Environmental Protection Agency (EPA) guidelines to estimate the contaminant concentration in the seepage water were evaluated on steel slag asphalt concrete, which provide information about the impacts on groundwater in the life cycle of the road construction projects. The conclusions can be drawn as follows:

5.1.1 Chapter 3: performance improvement of asphalt concretes using steel slag as aggregates.

Test results indicated that S replacement improves the stability of limestone asphalt concrete. The flow value was found to be insignificantly affected by type of asphalt cement and aggregate. The fatigue life, resilient modulus, and rut depth resistance of the L:S:S:S-AC60/70 were found to be 1.6, 1.4, and 1.4 times higher than that of L:L:L:L-AC60/70, respectively. The fatigue life and resilient modulus values of the L:S:S:S-AC60/70 concrete were found to be close to those of L:L:L:L-PMA concrete. The performance of L:S:S:S-AC60/70 concrete was found to be comparable to that of the costly L:L:L:L-PMA concrete, and had a longer service life than L:L:L:L-AC60/70 concrete with the same thickness.

5.1.2 Chapter 4: toxic leaching evaluation of dense-graded asphalt concretes using steel slag as aggregates.

The S asphalt concretes had better Marshall's stability than the limestone asphalt concretes even though they had slightly less ITS values. The ITFL and M_R of S asphalt concretes were higher than those of limestone asphalt concretes, indicating higher fatigue cracking resistance. The M_R of S asphalt concretes was higher than the required value (3,100 MPa) recommended by AASHTO, while limestone asphalt concretes did not meet requirement. In addition, the dynamic creep and wheel tracking test results showed that the S asphalt concretes had superior resistance to permanent deformation and rutting as compared to the limestone asphalt concretes. The aggregate size was found to have a significant effect on the performance of both steel slag and limestone asphalt concretes. The usage of medium-sized S aggregate in developing asphalt concrete was proved to be more sustainable in term of engineering and economical perspectives, than the usage of large-sized S aggregate. From a performance and chemical testing perspective, S replacement was found to be suitable for the sustainable development road pavement. The outcome of this research promotes the usage of waste by-product which replaces the natural and non-renewable resources in road construction projects.

5.2 Recommendation for future work

- This study had used only limestone to compare with S. The other natural aggregates such as basalt, and granite can be considered for further study.
- The performance improvement of S asphalt concrete can be considered by scanning electron microscopy (SEM) at different ages for further study.
- The mix design method of S asphalt concrete pavement by Superpave method can be considered by for further study.
- Field research is recommended for further study.
- The life cycle cost analysis and CO_2 equivalent emission is recommended for further study.

APPENDIX A

PUBLICATIONS

List of Publications

INTERNATIONAL JOURNAL PAPERS

Hasita, S., Suddeepong, A., Horpibulsuk, S., Samingthong, W., Arulrajah, A., & Chinkulkijniwat, A. (2020). **Properties of Asphalt Concrete Using Aggregates Composed of Limestone and Steel Slag Blends.** Journal of Materials in Civil Engineering, 32(7), 06020007.

Hasita, S., Rachan, R., Suddeepong, A., Horpibulsuk, S., Arulrajah, A., Mohammadinia, A., & Nazir, R. (2020). **Performance Improvement of Asphalt Concretes Using Steel Slag as a Replacement Material.** Journal of Materials in Civil Engineering.

ASCE

Performance Improvement of Asphalt Concretes Using Steel Slag as a Replacement Material

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Abstract: The increased proportion of traffic volumes on roads is often the cause of distress to the pavement structure. The use of strong and durable steel slag (S) as an aggregate material in asphalt concrete can enhance the load-bearing capacity while at the same time conserving natural resources, resulting in a sustainable asphalt pavement system. This research evaluated the feasibility of using S to replace natural limestone (L) at various aggregate sizes in asphalt concrete. The measured performance of the L-S asphalt concretes was compared with that of L asphalt concretes and granite (G) asphalt concretes. Two types of asphalt cements, Penetration Grade AC60/70 and polymer-modified asphalt (PMA), were utilized in this research project. The mix proportions were prepared by separating each original aggregate (S, L, and G) into four bins, Bin 1 (<4.75 mm), Bin 2 (<12.50 mm), Bin 3 (<19.00 mm), and Bin 4 (<25.00 mm), and trial mixing them together. Five types of aggregate included L:L:L:L, L:G:G:G, L:S:S:S, L:L:S:S, and L:L:L:S, where the first, second, third, and fourth letters denote the types of aggregates in Bins 1–4, respectively. The asphalt concretes were prepared at 4% air voids using the Marshall compaction method. The performance tests included indirect tensile, fatigue life, resilient modulus, dynamic creep, and wheel tracking tests. S was found to improve the Marshall stability properties of the asphalt concrete by a maximum of 50%. The fatigue life, resilient modulus, and rut depth resistance of the L:S:S:S-AC60/70 were found to be 1.6, 1.4, and 1.4 times higher than that of L:L:L:L-AC60/70, respectively. The fatigue life and resilient modulus values of the L:S:S:S-AC60/70 concrete were found to be close to those of L:L:L:L-PMA concrete. The performance of L:S:S:S-AC60/70 concrete was found to be comparable to that of the costly L:L:L:L-PMA concrete, and had a longer service life than L:L:L:L-AC60/70 concrete with the same thickness. The research outcomes of this study will promote the use of S as a sustainable aggregate for pavement concrete construction. **DOI: 10.1061/(ASCE)MT.1943-5533.0003306.**

Author keywords: Asphalt concrete; Resilient modulus; Indirect tensile fatigue; Wheel tracking; Dynamic creep; Steel slag.

Introduction

Increased traffic volumes result in distress (rutting, cracking) to all elements of the pavement structure, inclusive of the wearing course, binder course, base, subbase, and subgrade layers (Tayfur et al. 2007). Rutting is one of the most common forms of distress on asphalt concrete pavements (flexible pavement). Rutting occurs from traffic volume loads, indicated by the rut depth along the wheel paths (Matthews and Monismith 1992; Balghunaim et al. 1988; Abdulshafi 1988). Fatigue cracking, on the other hand, occurs from tensile strain, which develops from the bottom of asphalt concrete. Solutions to pavement distress include adding filler (Ali et al. 1992; Zhao et al. 2016), changing the type and size of aggregates (Chen et al. 2016; Iwański and Mazurek 2016; Matthews and Monismith 1992; Wu et al. 2007), and modifying the asphalt cement (Mokhtari and Nejad 2012; Kaloush et al. 2010; Manosalvas-Paredes et al. 2016; Herráiz et al. 2016; Putman and Amirkhanian 2004). Takaikaew et al. (2018) reported that fiber reinforcement (a combination of polyolefin and aramid fiber 0.05% by mass of total mixture) in asphalt concrete Penetration Grade AC60/70 improved the performance (indirect fatigue life, resilient modulus (M_R), dynamic creep, and rutting resistance) of asphalt concrete comparable to that of polymer-modified asphalt (PMA).

Some research applications of solid waste materials in road construction projects have been conducted in recent years (Wu et al. 2007; Su and Chen 2002; Kandhal and Hoffman 1997; Tam and Tam 2006; Robinson et al. 2004). Steel slag (S) is a by-product obtained during the steel making procedure which comprises 13%

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of waste materials generated from the production of steel (Shen et al. 2009). Steel is a valuable resource material required for economic development of developed and developing countries alike; however, the manufacture of steel from iron ore results in waste, such as S, which requires disposal. The use of S as a construction material in civil infrastructure projects would significantly reduce the landfilling of this waste material and lead to an avoidance of landfill levies. In recent years, S has been used as a raw material in civil engineering applications such as embankment fills, pavement bases/subbases, building masonry units, cement production, road constructions, fertilizer, and so forth (Pellegrino et al. 2013; Sakai and Hiraoka 2000; Zhang et al. 2012; Sas et al. 2015; Aiban 2005; Kim et al. 2015; Li 2010; Li et al. 2016). The utilization of S as a coarse aggregate in asphalt concrete pavements results in pavements with enhanced properties, particularly in terms of durability and stability (Zhu et al. 2012; Ahmedzade and Sengoz 2009; Setién et al. 2009; Xie et al. 2012). S also has been found to possess the required high-friction properties often required for pavement materials (Beshears and Tutumluer 2013).

The chemical composition of S mainly comprises CaO, SiO_2, Al_2O_3, MgO, and Fe_2O_3. S has high strength and other desirable properties required for road surfacing applications (Feng et al. 2015). Using S as a coarse aggregate in asphalt mixtures can improve the mechanical characteristics and performance of pavements, in terms of moisture, stability, skid resistance, permanent deformation, and crack resistance (Wang et al. 2009; Zhao et al. 2016; Chen et al. 2014a, b). The heat-retention characteristics of S can be advantageous for repair work in cold-weather conditions (Ahmedzade and Sengoz 2009). The principal issue associated with S is volume expansion due to the hydration of free lime or magnesia, which can result in pavement cracking. This can be effectively mitigated by aging and washing S before placement of this material in pavements (Kneller et al. 1994). The magnesia content of S in Thailand was found to be 1.38%, which is very low and eliminates this issue (Hasita et al. 2020); therefore S from Thailand can be considered to have low volume expansion, so it possibly can be used as aggregate in asphalt concrete (Wang et al. 2011).

The performance of asphalt concrete depends essentially on the type of aggregate, asphalt cement, and gradation (Kandhal et al. 1997). In Thailand, most asphalt concrete uses limestone (L) and granite (G) as the source of aggregates. Asphalt cement of Penetration Grade 60/70 (AC60/70) mostly is used as the asphalt binder. For some highways with heavy traffic loads, polymer-modified asphalt normally is specified as an asphalt binder, although this binder is relatively costly. To minimize cost, strong and durable S can be used as a replacement aggregate in AC60/70 concrete to develop a high-performance pavement surface comparable to limestone-PMA (L-PMA) or granite-PMA (G-PMA) concretes. Kara et al. (2004) reported that S asphalt pavement can be used as a bitumen base and as binder and wearing courses the mechanical properties of which satisfied the road authority requirements. Currently, the rapid growth of steel industries in Thailand results in increasing amounts of S waste. The Iron and Steel Institute of Thailand (2018) reported that the annual output of steel product is close to 22 million tons in Thailand, which results in the generation of 2.86 million tons of S waste. The rate of using S in asphalt concrete is quite low in Thailand, and therefore the disposal of S occupies a significant portion of landfills and causes many serious environmental problems.

Even with the available research on the performance of blended S asphalt concrete, there has been little attempt to investigate the role of S replacement at various aggregate sizes, which was the focus of this study. This research also used the unique characteristics of L and S to enhance the development of L-S asphalt concrete when using conventional AC60/70.

This study evaluated the performance of limestone-AC60/70 concrete, limestone-PMA concrete, granite-AC60/70, and granite-PMA concrete, and compared them with L-S-AC60/70 concrete and L-S-PMA concrete. The advantage of S replacement was evaluated by performance tests, including indirect tensile strength (ITS), resilient modulus, dynamic creep, indirect tensile fatigue, and rutting tests. To avoid the effect of gradation and to consider unique characteristics of L and S in the development of better performance of L-S asphalt concrete using conventional AC60/70, all mixed aggregates (L, G, and L-S blends) were prepared with similar gradation, in accordance with the Department of Highways' standard, Thailand.

To the authors' best knowledge, the comparison of the performance of L and G asphalt concretes previously has not been evaluated for Asian countries, including Thailand. The performance of asphalt concrete using S as a replacement material also has yet to be reported on to date. This research is novel, innovative, and of international significance, because it seeks to promote the use of S to develop sustainable asphalt concrete pavement systems, resulting in the conservation of natural resources, decreased energy use, and reduced greenhouse gas emissions.

Materials and Methodology

Materials

The aggregates used in this research were limestone, granite, and steel slag. The asphalt cement comprised a Penetration Grade 60/70 and a polymer-modified asphalt. Table 1 presents the mechanical properties of L, G, and S, including Los Angeles (LA) abrasion (ASTM 2014), soundness (ASTM 2013), aggregate impact value (AIV) (BSI 1990a), aggregate crushing value (ACV) (BSI 1990b), and polished stone value (PSV) (BSI 1989). These results indicated that most properties of the aggregates used were in accordance with the criteria for asphalt concrete and modified asphalt concrete in Thailand (DOH 1989; DOH 2006). The PSV value of the limestone was found to be slightly lower than the requirement for PMA.

The properties of asphalt cement are summarized in Table 2, and these were compared with the specific requirements for asphalt cement in Thailand (DOH 1988; DOH 1993). Both the asphalt

Table 1. Basic properties of tested aggregates

	Type of aggregate			Criterion for asphalt concrete (AC60/70 binder)	Criterion for modified asphalt concrete (PMA binder)
Test type	Limestone	Granite	Steel slag	DOH (1989)	DOH (2006)
Los Angeles abrasion value, LA (%)	22.90	19.70	17.10	40% max	35% max
Soundness (%)	1.60	1.70	0.60	9% max	9% max
Aggregate impact value, AIV (%)	13.60	18.20	13.90	—	25% max
Aggregate crushing value, ACV (%)	18.90	18.30	18.40	—	25% max
Polished stone value, PSV	45.80	50.50	50.60	—	47 min

Table 2. Test results for asphalt cement

Parameter	AC60/70 Result	AC60/70 Requirement by DOH	PMA	PMA Requirement by DOH
Penetration at 25°C (0.1 mm)	65	60–70	64	55–70
Ductility (cm)	>100	≥100 at 25°C	95.4	≥55 at 13°C
Flash point (°C)	326	≥232	326	≥220

Note: DOH = Department of Highways, Thailand.

cements used met the requirements for asphalt cement specified by road authorities in Thailand.

Mix Design and Sample Preparation

To evaluate the performance of asphalt concrete with different asphalt cements, aggregate types, and S replacement, 10 mixtures of asphalt concrete were prepared according to the Marshall mix design method (ASTM 2015; DOH 1974), which is specified in Thailand. To avoid the effect of gradation, all mix proportions were prepared to have essentially the same gradation. The mix proportions were prepared by separating each original aggregate (S, L, and G) into four bins, Bin 1 (<4.75 mm), Bin 2 (<12.50 mm), Bin 3 (<19.00 mm), and Bin 4 (<25.00 mm), and trial mixing them together. Bin 1 was stone dust, which commonly is made from L, because its particles are more suitable for milling than are granite and steel slag. The milled particles of L were smaller than those of G and S because of their low abrasion resistance. Therefore, when trial mixed with materials from other bins, the final aggregates produced met the DOH requirements (DH-S408/1989), for which the percentage finer than Sieve #200 is between 2% and 8%. Therefore, aggregate of Bin 1 for all studied mixtures was L.

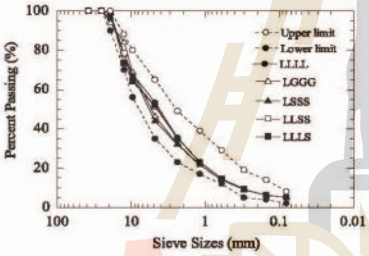

Fig. 1. Particle-size distribution curves of all aggregates.

Five types of aggregate evaluated included L:L:L:L, L:G:G:G, L:S:S:S, L:L:S:S, and L:L:L:S where the first, second, third, and fourth letters denote the types of aggregates in Bins 1–4, respectively. Particle-size distribution curves of all aggregates used in this study are shown in Fig. 1 which were prepared according DH-S408/1989 (DOH 1989). This study investigated the role of S replacement in asphalt concrete at a particular air voids content and similar gradation of blended aggregates. In this study, the air voids content therefore was fixed at 4% for all mix proportions because asphalt concretes in Thailand are designed at 4% air voids according to Department of Highways standards. Roberts et al. (1991) reported that the physical properties and permanence of asphalt concrete is dependent upon the air voids in the mixture. When the air voids decrease to less than 3%–4%, rutting of the asphalt mixture is likely to occur due to plastic flow. The effect of air voids on the performance of asphalt concrete with the blended aggregates can be studied in the future research. The mix proportions prepared are listed in Table 3. Samples for Marshall tests were prepared at optimum asphalt cement content in accordance with ASTM D6927 (ASTM 2015) and DS-T. 604/1974 (DOH 1974). The sample dimensions were 63.5 mm height and 101.5 mm diameter.

The aggregates first were heated at 160°C. Subsequently, the heated asphalt cement at 160°C for AC60/70 and at 170°C for PMA binder was added into the aggregate and mixed thoroughly to produce a well-coated and evenly distributed mixture. The mixture was placed in a Marshall mold and compacted with the standard hammer with 75 blows imparted on each side of the sample at 145°C. After being cooled at room temperature for 1 day, the samples were soaked in water at a constant temperature of 60°C for 30 min prior to Marshall testing. Compressive loading was applied on the sample at a rate of 50.8 mm/minute until the sample broke. Two values were measured: the stability, which is the required load to fail the sample; and the flow, which is the vertical distortion at the time of failure. The reported results were obtained from an average of three test samples. The results of laboratory Marshall test for various aggregates are presented in Table 4.

Performance Tests

In this study, the indirect tensile strength (ITS) test was conducted according to ASTM D6931 (ASTM 2017). The sample preparation

Table 3. Types of aggregate and binders

Mix proportion	Type of aggregate: Fine	Type of aggregate: Coarse			Type of binder	Optimum asphalt cement content
	Bin 1 (filler)	Bin 2 (1/2 in.)	Bin 3 (3/4 in.)	Bin 4 (1 in.)		
L:L:L:L+AC60/70	L	L	L	L	AC 60/70	5.00
L:G:G:G+AC60/70	L	G	G	G	AC 60/70	5.00
L:S:S:S+AC60/70	L	S	S	S	AC 60/70	5.00
L:L:S:S+AC60/70	L	L	S	S	AC 60/70	5.00
L:L:L:S+AC60/70	L	L	L	S	AC 60/70	5.00
L:L:L:L+PMA	L	L	L	L	PMA	5.00
L:G:G:G+PMA	L	G	G	G	PMA	5.00
L:S:S:S+PMA	L	S	S	S	PMA	5.00
L:L:S:S+PMA	L	L	S	S	PMA	5.00
L:L:L:S+PMA	L	L	L	S	PMA	5.00

Note: L = limestone; G = granite; and S = steel slag.

Table 4. Summary of Marshall design results

Parameter	AC 60/70					PMA				
	L:L:L:L	L:G:G:G	L:S:S:S	L:L:S:S	L:L:L:S	L:L:L:L	L:G:G:G	L:S:S:S	L:L:S:S	L:L:L:S
Asphalt cement content (%)	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00
Stability (kN)	10.10	10.30	14.83	13.90	10.85	14.37	14.55	21.56	17.42	14.33
Flow (mm)	3.05	3.05	3.05	3.05	3.05	3.05	3.05	3.05	3.05	3.05
Density (g/cm^3)	2.43	2.37	2.70	2.61	2.61	2.43	2.38	2.70	2.61	2.51
Voids content (%)	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00
Voids mineral aggregate (%)	14.73	14.43	15.31	15.31	15.31	14.67	14.39	15.24	15.30	14.91
Voids filled asphalt (%)	73.24	71.78	74.04	73.89	74.22	72.78	72.23	73.58	74.01	73.17

method was the same as that used for the Marshall test. The ITS test was conducted with a loading rate of 50.80 mm/minute at 25°C. The peak load at failure was recorded. The ITS test is related to cracking properties and is the prescribed method to measure the tensile characteristics of asphalt concrete (Takaikaew et al. 2018).

The indirect tensile fatigue test was conducted according to the BS-EN-12697-24 (BSI 2004C) standard at 25°C to investigate the fatigue characteristics of each mixture. The load was applied through a 12.5-mm-wide stainless steel curved loading strip. A haversine load was imposed on the sample using a repeated controlled stress pulse to damage the sample, and the accumulation of vertical deformation was plotted. The target load pulse rise time was 120 ms. A uniaxial and dynamic load of 400 kPa (58.4 psi) was applied to the samples to represent axle loads applied on the pavement surface, according to the recommendation of Mokhtari and Nejad (2012). Poisson's ratio was assumed to be 0.4. The applied forces on the sample and the number of pulses were recorded automatically by software until the sample failed.

The resilient modulus test is important for the determination of pavement performance of asphalt concrete mixtures when using the mechanistic design procedure, because it measures the pavement response in terms of dynamic stress and the corresponding strain. The M_R test can be used to evaluate the elastic properties of asphalt concrete mixtures (Jiang et al. 2015). The test procedure followed ASTM D4123 (ASTM 1995). The M_R was determined using cylindrical samples (101.6 mm in diameter and 63.5 mm in height) under the indirect tension mode. The test was carried out using a universal testing machine (UTM). The applied loading for each mixture was 15% of ITS on the vertical diameter of the Marshall-prepared samples. The frequency of the load and rest duration was 1 Hz: loading for 0.1 s, and a rest period of 0.9 s. The number of repetitions was 200 pulses. All samples were kept at 25°C for 4 h prior to the test to distribute the temperature throughout the samples evenly. The average of the last five values of elastic stiffness after the first 150 cycles is defined as M_R. Three samples for each set were tested, and the average was presented as M_R.

Dynamic creep and wheel tracking tests normally are used to assess the potential for permanent deformation (rutting) of an asphalt mixture (Kaloush et al. 2010). The permanent deformation (rutting) has an important impact on the serviceability index of the pavements during their life service. The dynamic creep test is known as the repeated load axial test, and it increasingly is used in preference to the uniaxial creep test, because the pulsed load is more simulative of the repeated axle loads applied on the pavement surface. The test can be run at various temperatures and loads. The dynamic creep test was conducted by applying a dynamic load to a sample and then measuring the sample's permanent deformation using LVDTs after unloading. The loading conditions were selected to evaluate the relative performance of different asphalt concrete mixtures in accordance with BS-DD-226 (BSI 1996) to determine the resistance to permanent deformation. The testing conditions and requirements for the dynamic creep test were conditioning stress = 10 kPa, conditioning period = 30 s, test stress = 100 kPa, and test period = 1,800 pulses. All samples were prepared with a Marshall compactor at 4% air voids. The load shape was rectangular, with a loading and rest period of 1 s; all samples were placed at 45°C for 4 h before testing.

The wheel tracking test results can predict rutting characteristics with good correlation with actual field performance. The test was performed in accordance with British and European standards (BSI 2004a). The test slabs were prepared using a roller compactor in accordance with British and European standards (BSI 2004b). The slab dimensions typically are 18 cm wide, 50 cm long, and 5 cm thick, and the slabs are compacted to attain 94% of the Marshall density. The test slabs were heated in a 60°C temperature-controlled chamber for 12 h prior to the wheel tacking test. The repeated back-and-forth loading in the chamber was applied to the slabs using a steel wheel with a rubber tire at a speed of 0.2 m/s. The tire had 5,000 N loading with a tire pressure of 600 kPa (87 psi). The rut depth of the slabs was measured at various loading wheel passes $(N) = 1{,}000$, 3,000, 4,000, 14,000, and 34,000 cycles. The rut depth versus the cumulative number of wheel passes was plotted.

Test Results and Discussion

Test samples were evaluated with Marshall stability, indirect tensile strength, resilient modulus, indirect tensile fatigue, dynamic creep, and wheel tracking tests to investigate the advantage of S replacement in L asphalt concrete. The test results of L-S asphalt concrete were compared with those of G (L:G:G:G) asphalt concrete and L (L:L:L:L) asphalt concrete with both AC60/70 and PMA binders. The effect of asphalt cement also was investigated with two types of asphalt cement, AC60/70 and PMA. The mix proportions of the aggregates studied are presented in Table 3. The Marshall stability test results are listed in Table 4. The stability of the each mix proportion was defined as the maximum load carried by an asphalt concrete sample at a standard test temperature of 60°C. The Marshall stability values of all mix proportions were above the standard (≥8.16 kN), and PMA asphalt concrete had 25.3%–45.4% higher stability than AC60/70 asphalt concrete with the same aggregate types. For a given AC60/70 or PMA, the Marshall stability values of L:L:L:L-asphalt concrete and L:G:G:G-asphalt concrete were almost the same. The Marshall stability of L:S:S:S-, L:L:S:S- and L:L:L:S-AC60/70 concretes was 46.8%, 37.6%, and 7.4% higher than that of L:L:L:L-AC60/70 concrete. The Marshall stability of L:S:S:S- and L:L:S:S-PMA concretes was 50.0% and 21.2% higher than that of L:L:L:L-PMA concrete. The S replacement content significantly improved the Marshall stability, with results similar to those reported by Ahmedzade and Sengoz (2009). Ahmedzade and Sengoz (2009) evaluated the influences of S as a coarse aggregate on the properties of gap-graded asphalt concrete

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and concluded that the strength and stiffness of aggregates control the Marshall stability. L had higher LA and ACV than did S, and hence S had higher deformation resistance than did L (Table 1). The results also show that the L:S:S:S-AC60/70 concrete is comparable to L- and G-PMA concretes, which have a higher cost and consume more natural resources.

The Marshall flow values of all asphalt concretes are listed in Table 4. The Marshall flow is the ability to resist settlement without cracking and plastic flow of bituminous mixtures (Mokhtari and Nejad 2012). The flow values of all mix proportions were similar, 3.05 mm. Therefore, all the samples met the requirement of Department of Highways standards (DH-S408/1989) which specifies that the flow values of asphalt concrete must be between 2.032 and 4.064 mm.

The ITS of all samples at 25°C is shown in Fig. 2. For a particular asphalt cement, L:L:L:L asphalt concrete had the highest ITS, whereas L:G:G:G asphalt concrete had the lowest ITS. Unlike the Marshall stability, the S replacement resulted in the decrease of ITS value. For a particular aggregate type, the PMA concrete had 13.6%–53.3% greater ITS value than the AC60/70 concrete, depending upon the aggregate proportion [Fig. 2(a)]. The ITS of L:S:S:S-, L:L:S:S-, and L:L:L:S-AC60/70 concretes was 28.6%, 20.4%, and 31.6% lower than that of L:L:L:L-AC60/70 concrete, respectively [Fig. 2(b)]. The ITS of L:S:S:S-, L:L:S:S-, and L:L:L:S-PMA concretes was 40.0%, 8.0%, and 12.5% lower than that of L:L:L:L-PMA concrete, respectively [Fig. 2(c)]. Even with the reduction in ITS with S replacement, the ITS values of L:S:S:S, L:L:S:S and L:L:L:S asphalt concretes were higher than 0.44 MPa, which was the value recommended by Christensen et al. (2000) for pavement design.

Fig. 3 shows the indirect tensile fatigue modulus test (ITFT) results of all mixtures. The fatigue-life values of PMA asphalt concrete were higher than those of AC60/70 asphalt concrete for the same aggregate types. Without S replacement, the fatigue-life values of L:L:L:L-AC60/70 and L:L:L:L-PMA concretes were higher than those of L:G:G:G-AC60/70 and L:G:G:G-PMA concretes, which was associated with the higher ITS of L:L:L:L-AC60/70 and L:L:L:L-PMA concretes. This implies that the mineralogy in L can react better with asphalt cements than can G (Siriphun et al. 2019). For a particular asphalt cement, the fatigue life of the asphalt concretes with S replacement was higher than that of L:L:L:L asphalt concrete and L:G:G:G asphalt concrete, and L:S:S:S-asphalt concrete had the highest fatigue life. The fatigue life of L:S:S:S-AC60/70 concrete (370 pulses) was 1.6 times higher than that of L:L:L:L-AC60/70 concrete (230 pulses). The fatigue life of L:S:S:S-PMA concrete (2,230 pulses) was 5.2 times higher than that of L:L:L:L-PMA concrete (430 pulses). It is evident that S can work well with both asphalt cements, especially PMA.

Fig. 4 shows relationship between the M_R and mix proportion. The M_R of PMA concrete was 22.7%–38.6% higher than that of AC60/70 concrete with the same aggregate types [Fig. 4(a)], which was similar to the Marshall stability results. The M_R values of L:G:G:G-AC60/70 and PMA concretes were higher than those of L:L:L:L-AC60/70 and PMA concretes. This implies that L:G:G:G-AC60/70 and PMA concretes have higher rutting resistance than L:L:L:L-AC60/70 and PMA concretes at the service stage but have lower

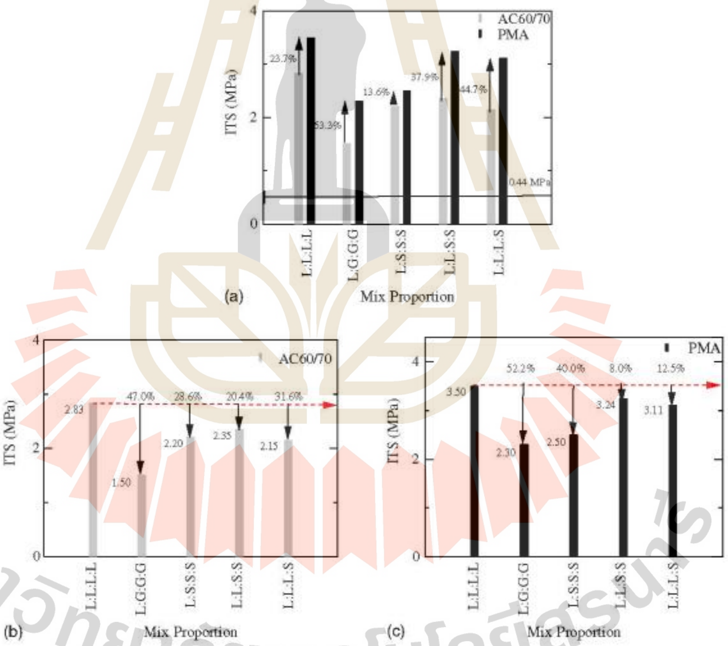

Fig. 2. Indirect tensile strength test results: (a) comparison of binders; (b) for AC60/70; and (c) for PMA.

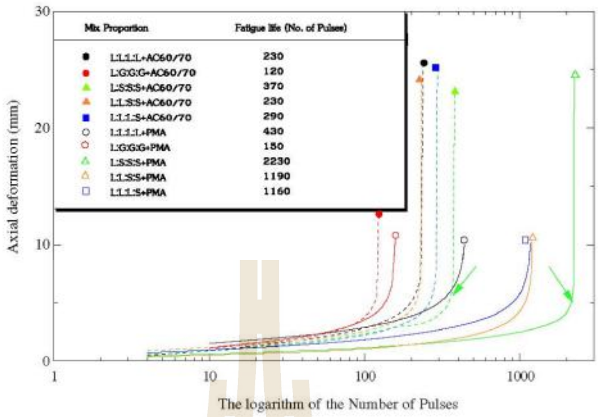

Fig. 3. Fatigue life of the 10 mix proportions.

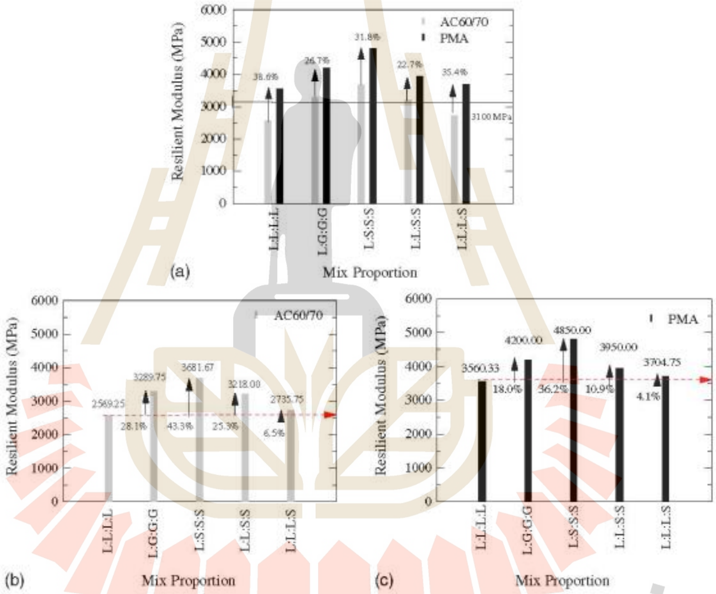

Fig. 4. Resilient modulus test results: (a) comparison of binders; (b) for AC60/70; and (c) for PMA.

service life. However, the M_R values of L:G:G:G-AC60/70 and PMA concretes were lower than those of L:S:S:S-AC60/70 and PMA concretes.

For a particular asphalt cement, the M_R values of L:S:S:S-, L:L:S:S- and L:L:L:S-AC60/70 concretes were 43.3%, 25.3%, and 6.5% higher than the M_R value of L:L:L:L-AC60/70 concrete, respectively [Fig. 4(b)]. The M_R values of L:S:S:S-, L:L:S:S- and L:L:L:S-PMA concretes were 36.2%, 10.9%, and 4.1% higher than the M_R value of L:L:L:L-PMA concrete, respectively [Fig. 4(c)]. The S replacement content increased the voids mineral aggregate

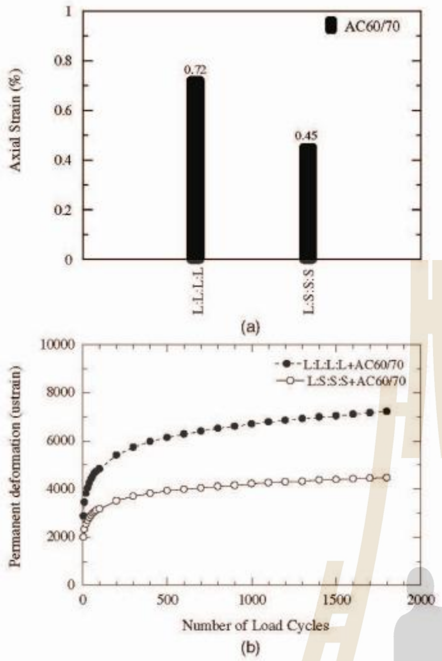

Fig. 5. Dynamic creep test results: (a) axial strain (strain rate); and (b) permanent deformation (μstrain).

(VMA) of the asphalt concrete (Table 3). The high VMA caused the mixtures to have higher deformation resistance and higher strength, which caused these mixtures to be capable of withstanding stress prior to failure (Neham et al. 2018). Therefore, the M_R increased with S replacement ratio. Moreover, the M_R of L:S:S:S-AC60/70 concrete was 3,681.67 MPa, which was higher than that of L:L:L:L-PMA concrete (3,560.33 MPa) and L:G:G:G-AC60/70 concrete (3,289.75 MPa). In other words, the S replacement made the M_R of L:S:S:S-AC60/70 concrete superior to that of the L:L:L:L-PMA concrete, which has a higher cost. Higher M_R leads to higher rutting resistance of asphalt concrete. The L:L:L:L-PMA, L:G:G:G-AC60/70, and L:G:G:G-PMA concretes met the AASHTO requirements of $M_R > 3{,}100$ MPa, whereas the L:L:L:L-AC60/70 concrete did not. However, the L:S:S:S-AC60/70, and L:L:S:S-AC60/70 concretes met the requirement, showing the advantage of S replacement.

The dynamic creep test is a high-reliability test to predict permanent deformation of asphalt mixtures. Fig. 5(a) shows the permanent axial strain of L:S:S:S-AC60/70 concrete compared with that of L:L:L:L-AC60/70 concrete. The permanent axial strains of L:S:S:S-AC60/70 and L:L:L:L-AC60/70 concretes were 0.45% and 0.72%, respectively. In other words, the L:S:S:S-AC60/70 concrete had approximately 1.62 times lower permanent axial strain than the L:L:L:L-AC60/70 concrete, which is in agreement with the higher M_R value of L:S:S:S-AC60/70 concrete. Fig. 5(b) shows the relationship between accumulated permanent deformation (μstrain) versus the number of load cycles for L:L:L:L asphalt concrete and L:S:S:S asphalt concrete. The L:L:L:L-AC60/70 concrete had the highest permanent deformation. Although the accumulated permanent strain of the tested asphalt concretes increased with the number of load cycles in a similar pattern, the L:S:S:S-AC60/70 concrete had higher resistance to permanent deformation than did L:L:L:L-AC60/70 concrete at the same number of load cycles.

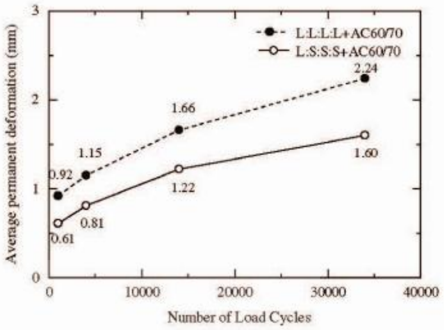

Fig. 6. Pavement rutting test results.

The wheel tracking test is widely used to evaluate the rutting potential of pavements. During the testing, the wheel tracking device produces rutting by rolling a steel wheel across the surface of slab samples, which is a general description of rutting under traffic loading. The depth of the depression significantly depends on the quality of asphalt concretes (Tapkın 2008). The rut depths that occurred after specific numbers of wheel passes (1,000, 4,000, 14,000, and 34,000) are presented in Fig. 6. The L:S:S:S-AC60/70 concrete had shallower rut depth than the L:L:L:L-AC60/70 concrete. The rut depth was 0.92, 1.15, 1.66, and 2.24 mm at $N = 1{,}000$, 4,000, 14,000, and 34,000 cycles, respectively, for L:L:L:L-AC60/70 concrete, whereas the rut depth was 0.61, 0.81, 1.22, and 1.60 mm at $N = 1{,}000$, 4,000, 14,000, and 34,000 cycles, respectively, for L:S:S:S-AC/70 concrete. In other words, at $N = 1{,}000$, 4,000, 14,000, and 34,000 cycles, the rut depth of L:S:S:S asphalt concrete was 50.8%, 42.0%, 36.1%, and 40.0%, respectively, less than that of the L:L:L:L asphalt concrete. The wheel tracking and dynamic creep test results showed that the M_R was directly related to rutting resistance. The M_R of L:S:S:S-AC60/70 concrete was 43.3% higher than that of L:L:L:L-AC60/70 concrete (Fig. 4), and the rut depth of L:L:L:L-AC60/70 concrete was an average of 42.2% greater than that of L:S:S:S-AC60/70 concrete for all N tested. The rut depth is directly related to the adhesive damage, which is caused by the stripping of asphalt cement at the aggregate surface. The results of performance tests showed that the S replacement led to the improvement of fatigue resistance, which could be attributed to the roughness, hardness, and high bearing strength of S aggregates. The S replacement thus improved the mechanical interlocking between asphalt cement and aggregates. The mineralogy of L is very susceptible to polishing, and the S replacement can improve this unfavorable characteristic. The L-S blend therefore is recommended as aggregates in pavement surface courses for heavy traffic loads (Dunford 2013; Senga et al. 2013), whereas L alone can be used in the binder course.

ANOVA version 25 (F-test) was performed to determine the statistical significance of influence factors on the performance of

Table 5. Summary of ANOVA (F-test)

Type of tests	Population	Sum of squares	df	Mean square	F	Significance
Stability (kN)	Between groups	49.51	1	49.51	6.721	0.032
	Within groups	58.93	8	7.37	—	—
	Total	108.43	9	—	—	—
Flow (mm)	Between groups	0.00	1	0.00	1.000	0.347
	Within groups	0.00	8	0.00	—	—
	Total	0.00	9	—	—	—
Indirect tensile strength (MPa)	Between groups	1.31	1	1.31	5.385	0.049
	Within groups	1.95	8	0.24	—	—
	Total	3.26	9	—	—	—
Fatigue life (No. of pulses)	Between groups	1,536,640.00	1	1,536,640.00	4.638	0.063
	Within groups	2,650,560.00	8	331,320.00	—	—
	Total	4,187,200.00	9	—	—	—
Resilient modulus (MPa)	Between groups	2,275,919.68	1	2,275,919.68	9.927	0.014
	Within groups	1,834,065.24	8	229,258.16	—	—
	Total	4,109,984.92	9	—	—	—

Note: Statistical significance at the level of 0.05. df = degrees of freedom.

asphalt concrete (Table 5). The results showed that the type of binder had a significant effect on stability, ITS, fatigue life, and M_R at the 95% confidence level, but insignificantly affected the Marshall flow.

Conclusions

In this research, performance tests of asphalt concretes using limestone, granite, and steel slag as coarse aggregate in asphalt mixtures were performed to determine the advantage of replacement with S. The following conclusions can be drawn from this study:

1. For a particular asphalt cement, the stability of both L:L:L:L asphalt concrete and L:G:G:G asphalt concretes was essentially the same. The S replacement enhanced significantly the stability of asphalt concrete. The stability of L:S:S:S-AC60/70 concrete was 46.8% higher than that of L:L:L:L-AC60/70 concrete, and the stability of L:S:S:S-PMA concrete was 50% higher than that of L:L:L:L-PMA concrete. Furthermore, the stability of L:S:S:S-AC60/70 concrete was as high as that of the L:L:L:L-PMA and L:G:G:G-PMA asphalt concretes, which are more expensive and consume more natural resources. The improvement of Mashall stability by S is due to the lower LA and ACV of S than of L, improving the deformation resistance of the asphalt concrete. The flow value was found to be independent of asphalt cement and aggregate.
2. The indirect tensile strength of L:G:G:G asphalt concretes was lower than that of L:L:L:L asphalt concretes for both AC60/70 and PMA. The S replacement reduced the ITS, and the L:S:S:S-AC60/70 concrete had the lowest ITS. The ITS of L:S:S:S-AC60/70 concrete was 28.6% lower than that of L:L:L:L-AC60/70 concrete, whereas the ITS of L:S:S:S-PMA concrete was 40.0% lower than that of L:L:L:L-PMA concrete. Even with the reduction in ITS, the ITS values of L:S:S:S, L:L:S:S, and L:L:L:S asphalt concretes were higher than 0.44 MPa, which was recommended by Christensen et al. (2000) for pavement design.
3. The fatigue life of L:L:L:L-AC60/70 and L:L:L:L-PMA concretes was higher than that of L:G:G:G-AC60/70 and L:G:G:G-PMA concretes, respectively. The S replacement improved the fatigue life significantly. The fatigue life of L:S:S:S-AC60/70 concrete (370 pulses) was 1.6 times higher than that of L:L:L:L-AC60/70 concrete (230 pulses). The fatigue life of L:S:S:S-PMA concrete (2230 pulses) was 5.2 times higher than that of L:L:L:L-PMA concrete (430 pulses). In other words, the S replacement content improved the service life of asphalt concrete for the same traffic loads.
4. The resilient modulus of L:L:L:L-AC60/70 and L:L:L:L-PMA concretes was lower than that of L:G:G:G-AC60/70 and L:G:G:G-PMA concretes, respectively. The M_R of L:L:L:L-AC60/70 was 2,569.25 MPa, which is lower than the value of 3,100.00 MPa recommended by AASHTO. With the S replacement, the M_R of L:S:S:S-AC60/70 concrete was 3,681.67 MPa, which met the recommendations and also was higher than that of L:L:L:L-PMA concrete. This implies that the S replacement can enhance the M_R of the AC60/70 concrete comparable to the L:L:L:L-PMA concrete. The M_R improvement by S replacement possibly was due to the higher void mineral aggregate (VMA) content of S mixture. A high VMA content causes mixtures to have higher deformation resistance and higher strength, which makes asphalt concretes capable of withstanding stress prior to failure.
5. Due to the rougher and stronger aggregates of S, the degree of mechanical interlocking increases with the S replacement ratio, leading to higher resistance to creep. Therefore, the L:S:S:S-AC60/70 concrete had higher resistance to permanent deformation than did L:L:L:L-AC60/70 concrete at the same number of load cycles. The L:S:S:S-AC60/70 concrete had approximately 1.62 times lower permanent axial strain than the L:L:L:L-AC60/70 concrete at the end of the test.
6. The wheel tracking test results showed that the rut depth of L:S:S:S-AC60/70 concrete was approximately 42.2% less than that of L:L:L:L-AC60/70 for all number of wheel passes. The rut depth is associated with M_R; the M_R of L:L:L:L-AC60/70 concrete was 43.3% lower than that of L:S:S:S-AC60/70 concrete. In other words, the L:S:S:S-AC60/70 concrete had a longer service life than conventional L:L:L:L-AC60/70 concrete.
7. S replacement improves the performance of the asphalt concrete. The fatigue life, M_R, and rut depth resistance of the L:S:S:S-AC60/70 was 1.6, 1.4, and 1.4 times higher than those of the L:L:L:L-AC60/70, respectively. In other words, the L:S:S:S-AC60/70 concrete had a longer service life than the L:L:L:L-AC60/70 concrete with the same thickness. S therefore is suggested as a sustainable aggregate in asphalt concrete, which has a significant engineering, economic, and environmental impact.

Data Availability Statement

Some or all data, models, or code generated or used during the study are proprietary or confidential in nature and may be provided only with restrictions.

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