ENGINEERING PROPERTIES INVESTIGATION OF STONE MASTIC ASPHALT (SMA) MIXING WITH COCONUT FIBERS

Chandy Chin

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การทดสอบคุณสมบัติทางวิศวกรรมของวัสดุสโตนมาสติกแอสฟัลต์ที่ผสมด้วยเส้นใยมะพร้าว

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Suranaree University of Technology has approved this thesis submitted in partial fulfillment of the requirements for a Master's Degree.

Thesis Examining Committee

(Assoc. Prof. Dr. Kunnawee Kanitpong)

Chairperson

(Dr. Nattaporn Charoentham)

Member (Thesis Advisor)

(Asst. Prof. Dr. Rattaphol Pueboobpaphan)

Member

(Assoc. Prof. Flt. Lt. Dr. Kontorn Chamniprasart)

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and Internationalization

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การศึกษานี้ มีวัตถุประสงค์เพื่อศึกษาคุณสมบัติทางวิศวกรรมซึ่ง ได้แก่ คุณสมบัติเชิงปริมาตร, ค่าเสถียรภาพมาร์แชลล์, การไหลแยกตัว, กำลังรับแรงดึงทางอ้อม และความไวตัวต่อความชื้น ของวัสดุสโตนมาสติกแอสฟัลต์ที่มีขนาดมวลรวมใหญ่สุดเท่ากับ 12.5 มิลลิเมตร โดยผสมด้วยเส้นใยมะพร้าวที่มีความยาวแตกต่างกัน 3 ขนาด (5-20, 20-40, และ 40-60 มิลลิเมตร) และใช้ปริมาณแตกต่างกัน 5 เปอร์เซนต์โดยมวล (0, 0.1, 0.3, 0.5 และ 0.7 เปอร์เซนต์โดยมวล) จากผลการศึกษาพบว่าวัสดุ สโตนมาสติกแอสฟัลต์ซึ่งผสมเส้นใยมะพร้าวที่มีช่วงความยาวเท่ากับ 5-20 มิลลิเมตร ด้วยปริมาณ 0.3 เปอร์เซนต์โดยมวล เป็นไปตามข้อกำหนดการออกแบบวัสดุสโตนมาสติกแอสฟัลต์ตามวิธีมาร์แชลล์ และมีคุณสมบัติทางวิศวกรรมดีที่สุดเมื่อเปรียบเทียบกับส่วนผสมอื่น

สาขาวิชา วิศวกรรมขนส่ง ลายมือชื่อนักศึกษา ____________

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CHANDY CHIN : ENGINEERING PROPERTIES INVESTIGATION OF STONE MASTIC ASPHALT (SMA) MIXING WITH COCONUT FIBERS. THESIS ADVISOR : NATTAPORN CHAROENTHAM, Ph.D., 159 PP.

COCONUT FIBER/ DRAINDOWN/INDIRECT TENSILE STRENGTH/ MARSHALL STABILITY/ STONE MASTIC ASPHALT

The objective of this study is to investigate the engineering properties of SMA including volumetric properties, Marshall Stability, drain down, indirect tensile strength, and moisture susceptibility incorporated with 12.5 mm NMAS and coconut fiber. The properties of SMA mixtures containing with three different coconut fiber lengths (5 - 20, 20 - 40, and 40 - 60 mm-long) and various contents (0, 0.1, 0.3, 0.5, and 0.7% by mass) were investigated. The optimum asphalt binder content was determined for each mixture. The results revealed that SMA mixtures containing 0.3% of 5 - 20 mm-long coconut fiber provided the optimum properties based on SMA specifications for Marshall compacted design and had better performance than the other mixtures.

School of Transportation Engineering Student's Signature ______________

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SYMBOLS AND ABBREVIATIONS

%	=	Percent
^{o}C	=	Degree Celsius
μm	=	Micrometer
ρ_w	=	Water density (997kg/m^3)
AASHTO	=	American Association of State Highway and Transportation Officials
AC	=	Asphalt cement
AC60/70	=	Asphalt cement grade 60/70
ASTM	=	American Society for Testing and Materials
AV	=	Air voids
cm	=	Centimeter
dS/m	=	Decisiemens per meter
g	=	gram
G_s	=	Specific gravity
HMA	=	Hot mix asphalt
in. or (")	=	Inch
ITS	=	Indirect tensile strength
kg	=	Kilogram
kN	=	Kilo newton
kPa	=	Kilo Pascal

SYMBOLS AND ABBREVIATIONS (Continued)

L	=	Liter
Max	=	Maximum
Min	=	Minimum
min	=	Minute
ml	=	Milliliter
mm	=	Millimeter
N	=	Newton
NMAS	=	Nominal maximum aggregate size
No.	=	Number
OAC	=	Optimum asphalt content
PH	=	Hydrogen ion concentration
RPM	=	Revolutions per minute
s	=	Second
SMA	=	Stone mastic asphalt
SSD	=	Saturated surface dry
TSR	=	Tensile strength ratio
VCA_{mix}	=	Voids of coarse aggregate in the compacted mixture
VCA_{drc}	=	Voids of coarse aggregate in dry rod condition
VG	=	Viscous grade asphalt
VMA	=	Void in mineral aggregate

CHAPTER I

INTRODUCTION

Chapter I illustrates a brief background of the present study with special emphasis on SMA. Scopes, objectives and contributions for the present study are also provided and discussed.

1.1 Background

SMA which is a gap-graded hot mix asphalt has been recognized worldwide since the mid-1960s because of its durability, resistant to permanent deformations, and capable of being applied in thin layers. Since then, SMA has been widely used in many countries such as USA, Canada, Japan, Australia and other countries around the world (Cao et al., 2013). Its primary advantage compared to conventional dense-graded HMA is the extended life with the improvement of pavement performance. Beside its primary advantage, it is also good at rutting and fatigue resistance, increase durability, improve skid resistance, and more economical in the long term (NAPA, 2002).

Typically, the required components of SMA mixture are aggregates, binders, and stabilizing agents. As SMA requires stone to stone contact, it therefore needs 70 - 80% of coarse aggregate, 12 - 17% of fine aggregate, and 8 - 13% of filler. Furthermore, SMA mixture requires 6 - 7% of asphalt cements and 0.3 - 0.5% of fiber and/or modifiers (Kumar and Ravitheja, 2019; Shravan, 2017; Rosli et al., 2012).

The main purpose of fibers/and or modifiers is to prevent drainage of asphalt binder from aggregate matrix. Stabilizing agents such as fibers and/or modifiers are required to fulfill the draindown requirement of SMA. Modifiers such as polymer, crumb rubber, natural rubber, plastic wastes, etc. have been used to modify the conventional asphalt (Charoentham and Ngamdee, 2019; Panda et al., 2013). However, these modified asphalt have been reported with the significant increase of toxicity and could expose workers to dangerous health and safety conditions (Charoentham and Ngamdee, 2019; Kriech et al, 2018). Moreover, it is not good in drainage reduction if modified asphalt alone is used (Hassan et al., 2005). Beside modifiers, there are many types of fibers which have been used in asphalt mixtures. Natural fibers, mineral fibers, and polymer fibers are the most commonly used in gap-and open-graded mixes to prevent draindown and to strengthen dense-graded asphalt mixed to resist rutting and cracking (McDaniel, 2015). The advantages of natural fiber compared to mineral and polymer fibers include low cost, acceptable strength and mechanical properties, and sustainability. Natural fibers such as cellulose fiber, banana fiber, sisal fiber, pineapple fiber, and coir/coconut fiber have been used successfully in SMA mixtures (Kumar and Ravitheja, 2019; McDaniel, 2015; Putman et al., 2004). Cellulose, banana, sisal, and pineapple fibers are not strong in tension (diameter in micrometer) and these fiber prone to absorb asphalt content. Conversely, they are well-suited to reduce draindown in gap-and open-graded mixes because of their soft textures and tidy diameter (McDaniel, 2015; Awanti et al., 2012). Based on previous works (Kumar and Ravitheja, 2019; Vale et al., 2013), coir/coconut fiber has the highest toughness which is capable of improving stability and moisture susceptibility of SMA mixtures as compared to cellulose fiber, banana fiber, sisal fiber, and pineapple fiber. Beside the improvement of SMA mixtures properties, Awanti et al. (2013) reported that SMA mixtures with coconut fiber were economical as compared to with cellulose fiber. By seeing the certain advantages of coconut fiber, therefore this study selected coconut fiber for SMA mixtures preparation. However, the disadvantage of all known natural fibers is their tendency to absorb moisture which can cause them to swell during soaking in water (McDaniel, 2015; Abiola et al., 2014). Based on this concern, it is therefore the Marshall stability which is tested to indicate the ability to withstand the deformation of compacted specimens soaking in 60^{o}C water even when the highest load is applied (ASTM D6927) and tensile strength ratio (TSR) which is tested to determine the ability of moisture absorbent of specimens during soaking in 60^{o}C water for 24 hours (ASTM D6931 - 4867) were tested and investigated in this study. Moreover, SMA mixtures require stone on stone contact (need more coarse aggregate) to provide better rutting resistance. The stone on stone contact makes SMA mixture requires of high air voids (4%), which could lead the asphalt binder drain from the aggregate matrix during production period (NAPA, 1996). It is therefore drain down, which is considered to be the portions of fines and asphalt that separate from the aggregate matrix, voids of coarse aggregate in compacted mixture (VCA_{mix}), and voids of coarse aggregate in dry rode condition (VCA_{drc}) were tested to ensure the stone on stone contact for SMA mixture (NCHRP, 1999).

The proportion of coconut fiber using in SMA mixtures is suggested between 0.3 - 0.5% by mass. Previous studies (Kumar and Ravitheja, 2019; Panda et al., 2013; Vale et al., 2013) indicated that the additional 0.3% of coconut fiber was sufficient and provided the superior results. When the additional coconut fiber was lower than

0.3%, the draindown tended to be high. Contrary, Marshall stability and TSR tended to decrease when the additional coconut fiber was higher than 0.3%. It could be indicated that the content of coconut fiber using in SMA mixtures has to be in a proper amount in order to obtain the best results. To obtain a suitable amount of coconut fiber content which could provide the optimum results for SMA mixtures, therefore this present study aimed to vary the coconut fiber content. Moreover, previous studies (Kumar and Ravitheja, 2019; Panda et al., 2013; Vale et al., 2013) commonly used 20 - 40 mm-long of coconut fiber in order to prevent the draindown and also used to investigate the other properties of SMA mixture. This study also considered the effect of variation in length of coconut fiber on SMA mixtures properties.

Therefore, the variations in content (0, 0.1, 0.3, 0.5, and 0.7% by mass) and length (5 - 20, 20 - 40, and 40 - 60 mm-long) of coconut fiber were used to cooperate with the 12.5 mm NMAS, which is the commonly used gradation in Thailand (DOH, 1989) and AC60/70, which is the commonly used asphalt in Thailand (DOH, 1988) in order to prepare for SMA mixtures according to Marshall hammer compacted designs (NCHRP, 1999). The influence of the selected coconut fiber contents and lengths on basic properties of SMA mixtures including volumetric properties, Marshall stability, draindown, and tensile strength ratio (TSR) are investigated in this study.

1.2 Purpose of the research

The purposes of this study are as follows:

1) To investigate on engineering properties including volumetric properties,

Marshall Stability, draindown, ITS, TSR, and moisture susceptibility of SMA mixing with and without coconut fiber.

2) To investigate on influence of various coconut fiber lengths and contents toward SMA mixtures properties.

3) To determine the optimum coconut fiber including length in mm and content in % for SMA mixtures.

1.3 Scope of the research

The scopes of this study are indicated as follows:

1) Gradation: 12.5 mm NMAS

2) Type of aggregates: limestone (12.5 and 9.5 mm) and dust rock

3) Filler: Portland cement passing 0.07 mm sieve of more than 90%

4) Binder: AC60/70 penetration grade of 6 - 7% content (0.5% increment)

5) Coconut fiber: adopted from Sichon district located in the northern part of Si Thammarat province of Thailand (concentration of 0, 0.1, 0.3, 0.5, and 0.7%, and length of 5 - 20, 20 - 40, 40 - 60 mm-long)

1.4 Contributions

The contributions of the study are indicated as follows:

1) To know the properties of SMA containing coconut fiber comparing to no coconut fiber.

2) To know the optimum content and length of coconut fiber for SMA pavement.

3) As coconut fiber is mostly available in tropical regions, it is therefore the local authority can reach it easily so that they will have more alternative materials.

4) Be able to provide more jobs to farmer as the needs of coconut fiber increase.

5) Environmental friendly as it is able to reduce the waste of coconut fruits (ripe).

CHAPTER II

LITERATURE REVIEW

Chapter II critically reviews on previous studies in order to provide better understanding for the present study. The related topics including compositions, advantages and disadvantages, requirements, materials (aggregates and filler, binder, and fibers) and methodology of SMA are discussed. A comprehensive summary of the literature review related with SMA mixtures with stabilized agent such as fibers is also presented.

2.1 Stone mastic asphalt (SMA)

SMA is a gab-graded HMA which consists of higher asphalt binder content and coarse aggregates. There are two parts in SMA structure, stone skeleton and mastic, as shown in Figure 2.1. The stone skeleton consists of coarse and fine aggregate and mineral filler. The stabilizing agents can be either fiber and/or modifier which use to prevent drainage of aggregate matrix.

The SMA mixtures are designed to have a high coarse aggregate content (70 - 80%), a high asphalt content (6 - 7%), and high filler content (approximately 10% by weight). Using high coarse aggregate content results in stone on stone contact that provides highly resistant to rutting. Typically, the coarse aggregate in SMA mixture carries the load while the fine aggregate in the dense-graded mixture must carry the load. This can be figured that the SMA mixtures is more resistant to rutting because coarse aggregate can develop more shear strength than fine aggregate (NAPA, 1996). The advantages, differences, and requirements of SMA mixture are discussed in the following paragraphs.

Figure 2.1 Component of SMA mixtures

2.1.1 Advantages of SMA

The first advantage of SMA compared to HMA is the extended life with the improvement of pavement performance (NAPA, 2002). It is because:

- SMA reduces permanent deformations of about 30 - 40% compared to HMA because SMA consists of higher asphalt content and coarse aggregates.

- As SMA consists of higher asphalt content, it has slower aging which can prolong its service life up to 20%.

- SMA costs more at the first time but it is more economical for long term.

- As SMA consists of higher coarse aggregates and stabilizing agents therefore it helps to increase 3 - 5 times of fatigue life.

- As SMA consists of higher coarse aggregates it is therefore good at wearing resistant and surface texture.

2.1.2 Disadvantages of SMA

The disadvantages of SMA compared to HMA are as follows (NAPA, 2002):

- SMA costs more because it consists of higher asphalt, filler and stabilizing agents.

- SMA possibly delays the opening traffic after its lay down because it needs to cool down to 40ºC (caused by higher asphalt content) to prevent the flushing (bleeding) of the binder layer.

- SMA requires more mixing time because of additional stabilizing agents which may reduce productivity.

In additionally, SMA provides better strength, improves permanent deformations, and provides better skid resistance; however, it required more cost and produced time.

2.1.3 The differences between SMA and dense-graded HMA mixture

The differences between SMA and HMA (NAPA, 1996) are as follows:

- SMA is a gab-graded while HMA is a well-graded/dense-graded (Figure 2.2).

- SMA is designed with AC between 6 - 7% for all layers while HMA is designed with AC between 3.5 - 6.5% for binder course and 4 - 7% for wearing course.

- SMA requires stabilizing agents while there is no requirement for HMA.

- Requirements of Marshall and volumetric properties are different (Table 2.1).

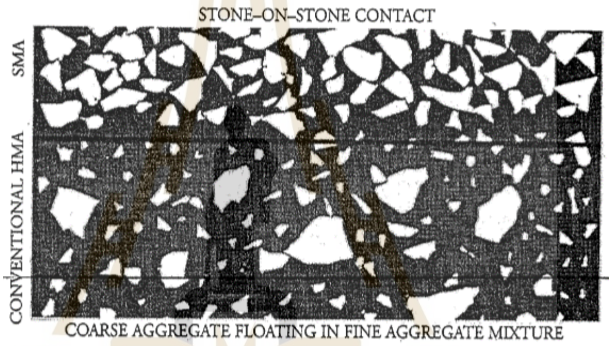


Figure 2.2 Cross-sectional view of a typical SMA and a dense-graded HMA mixture

Source: NAPA (1996)

Table 2.1 The different specifications between SMA and dense-graded HMA mixture

Property	**Unit**	**SMA**	**HMA**
Stability	kN	Min 6.2	Min 8
VMA	%	Min 17	Min 14
AV	%	Max 4	3 - 5
Flow (0.25 mm)	mm	–	8 - 14
Draindown at 170°C	%	Max 0.3	–
VCA_{mix}	%	Less than $\%VCA_{drc}$	–
TSR	%	Min 70	–
No. of blows per side	–	50	75

Source: NAPA (2002, 1996)

2.1.4 Requirement of SMA mixtures in various regions

SMA has been used worldwide and its requirements however are different from place to place as shown in Table 2.2.

Table 2.2 Requirements of SMA in various regions

Country	Aggregate	Fiber	Bitumen (content, %)	Volumetric properties
Germany	High quality chippings	0.3% of cellulose	B65/PMB45 (6.5 - 7)	Not indicated
Czech Republic	Crushed limestone	0.3% of cellulose	PMB45/65 (6.5 - 7.5)	Stability: ≥ 6 kN Voids: ≤ 4.5%
Denmark	100% crushed materials	Not indicated	B65/PMB (6 - 7.2)	Voids: 1.5 - 4% VMA: ≥ 16%
Hungary	100% crushed materials (Filler: 8%)	Cellulose	B50, B65, PMB 80A, PMB80B (6 - 7.5)	Voids: ≤ 4%
Italy	100% crushed materials	Not indicated	PMB50 (5.5 - 7)	Stability: ≥ 13 kN Stiffness: ≥ 2kN Voids: 1 - 4%
The Netherlands	Crushed limestone	0.3% of cellulose	B8 (7)	Voids: ≤ 5%

Source: EAPA (1998)

2.2 SMA Materials

As mentioned above, SMA mixture comprises of aggregates, asphalt, and stabilizing agents. The basic properties of these materials are considered as following.

2.2.1 Aggregates and filler

The largest constituent in SMA mixture is aggregate, which is typically 92 - 96% by mass of mixture. Generally, there are three types of aggregate including coarse aggregate (retained on sieve No.4 or 4.75 mm), fine aggregate (passing sieve No. 4 or 4.75 mm); and filler (at least 70% passing sieve No. 200 or 75 μm).

Aggregates are normally required to be hard, strong and tough, properly grade, durable, clean, and rough. The proportion of coarse aggregate and binder needed for SMA mixtures are higher than HMA mixture. Normally, SMA consists about 70 - 80% of coarse aggregates, higher filler, fiber, and asphalt content which is greater than 6% of the total mixed weight (Sarang et al., 2015). The stone on stone contact of SMA mixture provides better strength and rut-resistance for mixtures. To select a better gradation for SMA mixture, three trial gradations should be initially evaluated. These three trial gradations should have two gradations fall along the coarse and fine limitations and have one gradation fall in the middle limitation as shown in Table 2.3. According to Scherocman (1991), the gradation should consist of 30, 20 and 10% particles passing 4.75, 2.36, and 0.075 mm sieve size, respectively.

Table 2.3 Gradation specification bands for SMA mixture (Percent passing by volume)

Sieve size	**25 mm NMAS**		**19 mm NMAS**		**12.5 mm NMAS**		**9.5 mm NMAS**		**4.75 mm NMAS**	
mm	L	U	L	U	L	U	L	U	L	U
37.5	100	100								
25.0	90	100	100	100						
19.0	30	86	90	100	100	100				
12.5	26	63	50	74	90	100	100	100		
9.50	24	52	25	60	26	78	90	100	100	100
4.75	20	28	20	28	20	28	26	60	90	100
2.36	16	24	16	24	16	24	20	28	28	65
1.18	13	21	13	21	13	21	13	21	22	36
0.60	12	18	12	18	12	18	12	18	18	28
0.30	12	15	12	15	12	15	12	15	15	22
0.075	8	10	8	10	8	10	8	10	12	15

L = Lower limit, U = Upper limit

Source: NCHRP (1999)

Beside a proper gradation selection, aggregates need to be checked its hardness and shape as well as other requirements as shown in Table 2.4.

Table 2.4 The required properties of coarse and fine aggregates

Property	Unit	Aggregate type	
		Coarse	**Fine**
LA abrasion	%	Max 30	
Flat and elongation	%	Max 20	
Absorption	%	Max 2	
Soundness (5 cycles)	%		
Sodium sulfate		Max 15	Max 15
Magnesium sulfate		Max 20	Max 20
Angularity	%		Min 45
Liquid limit	%		Max 25
Plasticity index	-		Non plastic

Source: NAPA (2002)

The aggregates using for SMA mixtures need to be determined the basic properties including specific gravity, particle size distribution, Los Angeles abrasion, flakiness and elongation, and sand equivalent test are presented and discussed as follows.

2.2.1.1 Specific gravity

Specific gravity (G_s) of fine/coarse aggregates according to ASTM C128/127 is used to determine the strength or quality of aggregates themselves. It is the ratio of the fine/coarse aggregate density to that of water. Typically, aggregates within higher specific gravity are stronger than those having lower specific gravity. Aggregates specific gravity and water absorption are determined using different techniques for coarse and fine aggregate. Specific gravity of coarse aggregate is determined using the weight-in-water method as shown in Figure 2.3 (i) while specific gravity of fine aggregate is determined following the pycnometer method as shown in Figure 2.3 (ii). Generally, water has specific gravity of about 1.0, while many construction aggregates have specific gravity values between 2.5 and 3.0 (NASEM, 2011).

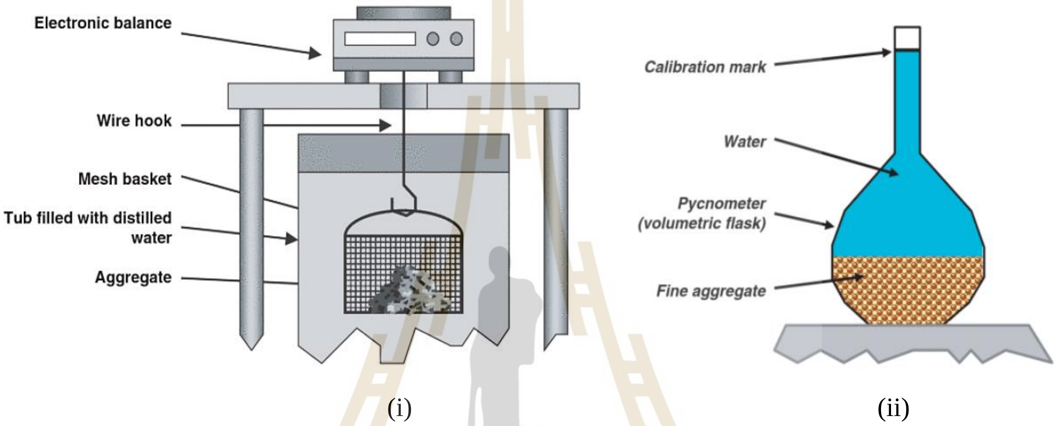


Figure 2.3 Weight-in-water method (i) and Pycnometer method (ii)

Source: NASEM (2011)

Specific gravity (G_s) and water absorption (WA) of fine aggregate can be determined as equation (2.1 - 2.2) while those of coarse aggregate are determined following to equation (2.3 - 2.4).

$$G_s = \frac{A}{A+B-C} \tag{2.1}$$

$$WA\,(\%) = 100 \times \frac{A-D}{D} \tag{2.2}$$

where, A is the weight of SSD sample (g),

B is the weight of pycnometer filled with water to full level (g),

C is the weight of pycnometer filled with water and SSD to full level (g),

D is the weight of sample after oven overnight (g)

$$G_s = \frac{A}{B-C} \tag{2.3}$$

$$WA\,(\%) = 100 \times \frac{B-A}{A} \tag{2.4}$$

where, A is the weight of sample after oven overnight (g),

B is the weight of SSD sample (g),

C is the weight of sample in water (g)

2.2.1.2 Particle size distribution

A particle size analysis (ASTM C136) as shown in Figure 2.4 is used to determine the particle size distribution of soils or aggregates. It presents the relative portions of different sizes of particles. There are two different procedures based on the type of aggregates. The dry method is applied for coarse aggregate while the wet method is for fine aggregate.

Figure 2.4 Apparatus of sieve analysis test

Source: ASTM C136 (2019)

The procedure to test the particle size distribution for coarse aggregate is followed to (1) weigh the desired amount of dried aggregate, (2) select the suitable sieve sizes and nest the sieves in order of decreasing size, and (3) begin to agitate and shake the sample for 10 minutes. On the other hand, the procedure for fine aggregate is followed to (1) wash the desired amount of aggregate over 0.075 mm sieve and (2) transfer the remained part to a container and then keep in oven overnight so that the remained sample from oven can agitate and shake to the desired time. In performing the particle distribution, the weight of the test sample must be large enough to produce reliable results as shown in Table 2.5.

Table 2.5 Minimum test sample size for particle distribution test as a function of nominal maximum aggregate size (NMAS)

NMAS (mm)	**Minimum weight of test sample** (kg)
37.5	15
25.0	10
19.0	5
12.5	2
9.5	1

Source: NASEM (2011)

2.2.1.3 Los Angeles abrasion

Los Angeles abrasion (LA) test according to ASTM C131 is tested to determine the hardness and strength of coarse aggregates. The higher the LA abrasion value, the tougher and stronger of aggregates will be. The desired amount of aggregates will be rotated in abrasion testing machine as shown in Figure 2.5 with the standard steel spheres and the specific duration as given in Table 2.6. Results from the test are reported as a percent loss, which is the mass percentage of aggregate lost during the test due to degradation and abrasion.

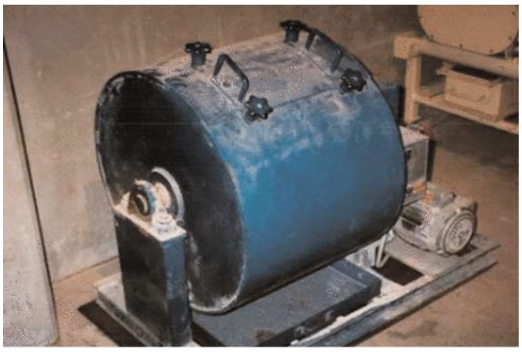


Figure 2.5 LA abrasion testing machine

Source: NASEM (2011)

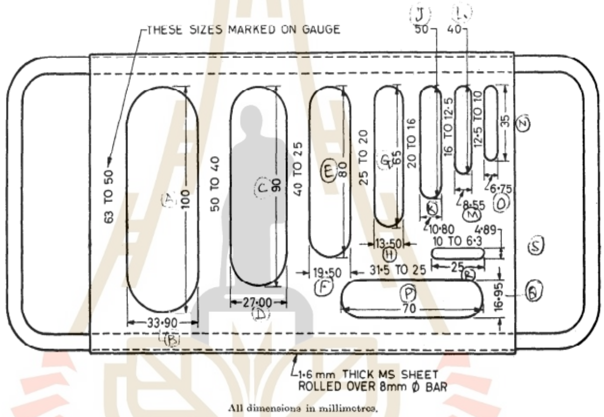
Table 2.6 Grading of test samples

Sieve size (mm)		Mass of indicated size (g)			
Passing	**Retained on**	**Grade A**	**Grade B**	**Grade C**	**Grade D**
35.7 [1½ in.]	25 [1 in.]	1,250 ∓ 25	…	…	…
25 [1 in.]	19 [3/4 in.]	1,250 ∓ 25	…	…	…
19 [3/4 in.]	12.5 [1/2 in.]	1,250 ∓ 10	2,500 ∓ 10	…	…
12.5 [1/2 in.]	9.5 [3/8 in.]	1,250 ∓ 10	2,500 ∓ 10	…	…
9.5 [3/8 in.]	6.3 [1/4 in.]	…	…	2,500 ∓ 10	…
6.3 [1/4 in.]	4.75 [No.4]	…	…	2,500 ∓ 10	…
4.75 [No.4]	2.36 [No.8]	…	…	…	5,000 ∓ 10
Total		5,000 ∓ 10	5,000 ∓ 10	5,000 ∓ 10	5,000 ∓ 10
Number of sphere		12	11	8	6

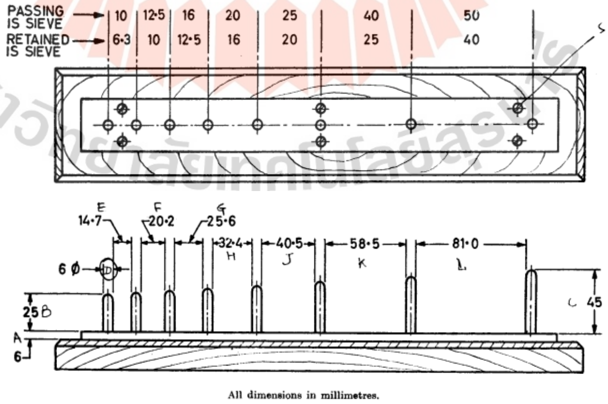
Source: ASTM C131 (2006)

2.2.1.4 Flat and elongated particles

The flat and elongated particles of aggregates are determined using procedure described in ASTM D4791. These two properties indicate the aggregates shapes which have influence on properties of the asphalt mixtures. Generally, 10% of each flat and elongated particles are limited. Apparatus as shown in Figure 2.6 (i, ii) are used to determine the flat and elongated particles of aggregate, respectively.



(i)



(ii)

Figure 2.6 (i) flakiness and (ii) elongation gauge

Source: Indian standard (1997)

2.2.1.5 Sand equivalent

Sand equivalent test (ASTM D2419) is used to determine the fineness materials and clay soil presented in the aggregate. The procedure is conducted on the aggregate fraction of the blend that passes the 4.75 mm sieve. The high sand equivalent is desirable as this indicates that the aggregate is relatively free of dust and clay particles. The result as illustrated in Figure 2.7 is used to identify the quality of the aggregates during production and construction.

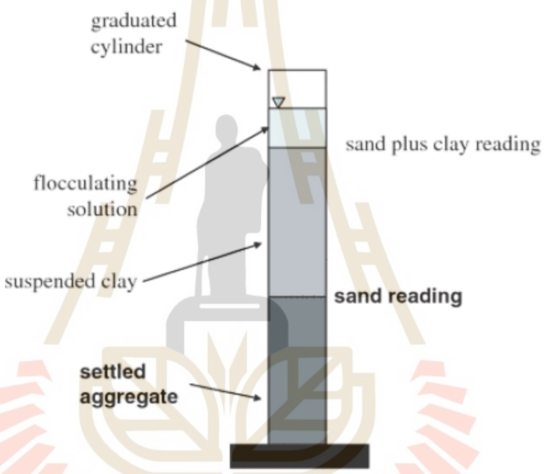


Figure 2.7 Sand equivalent test

Source: NASEM (2011)

2.2.2 Asphalt types

There are three types of asphalts including asphalt cements, emulsified asphalts, and cutback asphalts commonly used in flexible pavement construction. Asphalt cements, mostly used in HMA are produced using different refining techniques from crude petroleum. There are five available grades of asphalt cements which are 40 - 50, 60 - 70, 85 - 100, 120 - 150, and 200 - 300. The numerical values indicate the softness and hardness of asphalt cement. It is therefore the 40 - 50 grade is the hardest grade while 200 - 300 is the softest grade (NAPA, 1996). For tropical regions, AC50/70 or AC60/70 is mostly used for pavements construction. Jitsangiam et al. (2013) used AC60/70 to determine the suitability of Supperpave and Marshall asphalt mixture related to Thailand’s climate conditions. Other work from Siswanto (2017) conducted a case study in Indonesia also used AC60/70 in their study. Table 2.7 shows the properties of the penetration graded for asphalt cement.

Table 2.7 Specification of penetration graded asphalt cements

Test	**Penetration grade**									
	40 - 50		**60 - 70**		**85 - 100**		**120 - 150**		**200 - 300**	
	A	**B**	**A**	**B**	**A**	**B**	**A**	**B**	**A**	**B**
Penetration at 25°C, 100 g, 5 s	40	50	60	70	85	100	120	150	200	300
Flash point, °C	450	–	450	–	450	–	425	–	350	–
Ductility at 25°C, 5 cm/min, cm	100	–	100	–	100	–	100	–	100	–
Solubility in trichloroethylene, %	99	–	99	–	99	–	99	–	99	–
Retained penetration after thin-film oven test, %	55^{+}	–	52^{+}	–	47^{+}	–	42^{+}	–	37^{+}	–
Ductility at 25°C, 5 cm/min, after thin-film oven test, cm	–	–	50	–	75	–	100	–	100	–

Note: A is minimum value and B is maximum value

Source: NAPA (1996)

The basic properties of asphalt (penetration, flash and fire point, softening point, ductility, and Brookfield viscosity) used in SMA mixture are presented and discussed as follows.

2.2.2.1 Penetration

Penetration test in accordance with ASTM D5 is used to determine the degree of asphalt cements at a particular temperature (25^{o}C), standard needle (100 g), and time (5 sec). This property can be determined by curing an asphalt container approximately 30 min at 25^{o}C in a controlled water baht, then place that asphalt cement container under a standard needle and immediately allow the needle to penetrate into the sample for 5 sec. The value of penetration is the distance (measured in one tenths of a millimeter) which the standard needle can penetrate into the asphalt cement as shown in Figure 2.8. The higher the penetration value, the softer is the asphalt cement will be. The penetration of an asphalt cement shall have the difference between the highest and lowest and the sample container needs to be considered as shown in the respective Table 2.8 - 2.9.

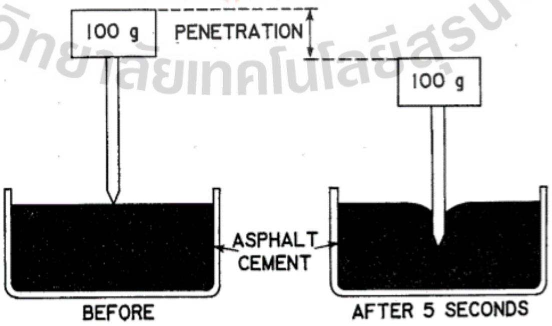


Figure 2.8 Penetration test

Source: NAPA (1996)

Table 2.8 The allowable difference between the highest and lowest penetration

Penetration	**0 - 49**	**50 - 149**	**150 - 249**	**250 - 500**
Maximum difference between the highest and lowest penetration	2	4	12	20

Source: ASTM D5

Table 2.9 Sample container for penetration test

Container (mm)	**Penetration**			
	Below 40	**Below 200**	**200 - 350**	**350 - 500**
Diameter	33 - 50	48 - 56	55 - 80	55 - 70
Internal depth	8 - 16	34 - 40	45 - 70	70 - 80

Source: ASTM D5

2.2.2.2 Flash and fire point

Flash and fire point test following Cleveland Open Cup method (ASTM D92-90) is used to determine the temperature of asphalt cements when it ignites and fires as shown in Figure 2.9.

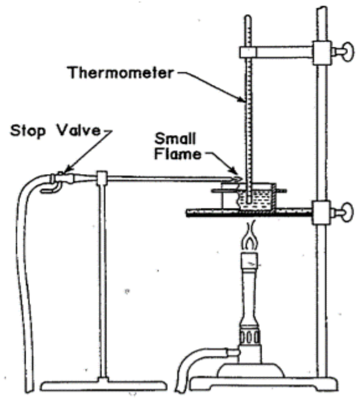


Figure 2.9 Flash and fire point test

Source: NAPA (1996)

The flash point is the temperature at which the vapor of asphalt cements temporarily ignites during heating whereas the fire point is the temperature at which asphalt cements starts to burn. This test is a very important test which can be used to indicate the safety temperature of asphalt cements during the production and construction.

2.2.2.3 Softening point

Ring and ball method (ASTM D36) is used to determine the temperature which is able to change the state of asphalt cements from semi-solid into liquid. A couple of rings filled with asphalt cement are cured in 5^{o}C controlled water bath for 30 min. After curing, the samples are placed on top center with standard steel balls and then heated in the controlled rate of 5^{o}C per minute (Figure 2.10). Temperature when the samples soften and touch the bottom plate by sinking of steel balls, is recorded as the softening point of asphalt. It is necessary to note that the difference between the two temperatures must not exceed 1^{o}C, otherwise the test must be retested.

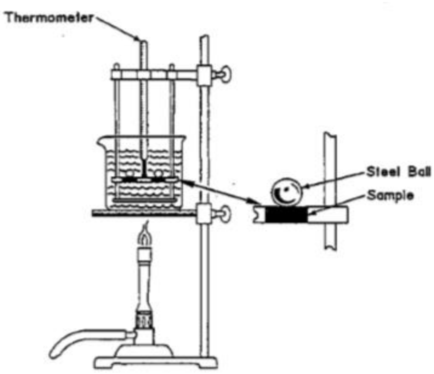


Figure 2.10 Softening point test

Source: NAPA (1996)

2.2.2.4 Ductility

Ductility test (ASTM D113) is defined as the distance measured in centimeter of asphalt cement which will elongate before tearing apart when it is pulled at a specific speed (5 cm/min) and temperature (25^{o}C) as shown in Figure 2.11. In case when the sample is going to touch to the bottom of water bath, alcohol is added. Conversely, salt is added when the sample is going to float.

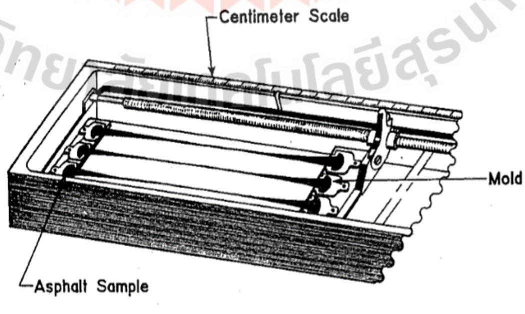


Figure 2.11 Ductility test

Source: NAPA (1996)

2.2.2.5 Brookfield viscosity

Brookfield viscosity test (ASTM D4402-02) is used to determine the opposition to flow of asphalt cement at high construction temperature which is above 100^{o}C. Bitumen sample should be heated and pour into the sample chamber between 8 - 10 g and then the samples are rotated in the desired temperature and the torque is required to maintain in a constant speed of 10, 20, 50 or 100 RPM as shown in Figure 2.12 (i). The Brookfield viscometer apparatus is shown in Figure 2.12 (ii).

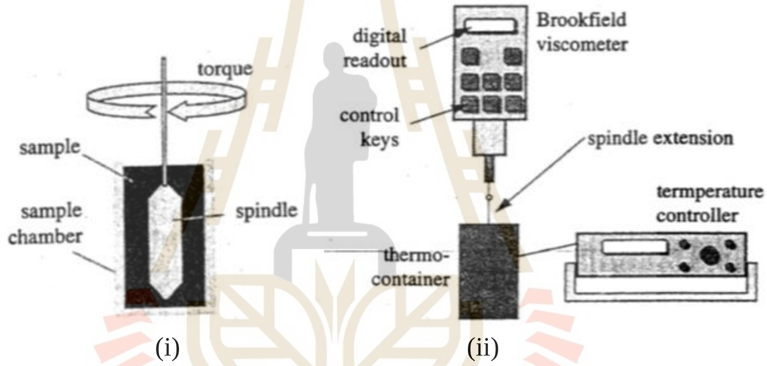


Figure 2.12 (i) rotational viscometer and (ii) Brookfield viscometer

Source: NAPA (1996)

2.2.3 Fibers

A wide variety of fiber types (Figure 2.13) has been used in asphalt mixtures, including cellulose, mineral, synthetic polymer, and glass fibers, as well as some less common fiber types. Recycled fiber materials such as newsprint, carpet fibers, and recycled tire fibers have also been used. These different types of fibers have benefits and disadvantages (Table 2.10) that make them better suited for some applications than others (McDaniel, 2015; Peltonen, 1991; Busching et al., 1970).

Figure 2.13 Type of fibers

Source: Indiamart (Available at https://www.indiamart.com/)

Table 2.10 Advantages/disadvantages of common fiber types

Fiber	**Advantages**	**Disadvantages**
Cellulose	- Stabilized binder in SMA mixtures - Absorbs binder, allowing high binder content for more durable mixture - May be made from a variety of plant materials or recycled materials such as newsprint	- High binder absorption which could increase binder cost - Not strong in tensile mode
Mineral	- Stabilized binder in SMA mixtures - Not as absorptive as cellulose - Promote healing of cracks	- Some may corrode or degrade because of moisture conditions
Polyester	- Resists cracking, rutting, and potholes - Increases strength and stability of mixtures - High tensile strength	- Cost-effectiveness not proven/varies

Table 2.10 Advantages/disadvantages of common fiber types (Continued)

Fiber	Advantages	Disadvantages
Polypropylene	- Reduce rutting, cracking, and shoving - Strongly bound with asphalt - Disperses easily in asphalt - Resistant to acids and salts	- Lowe melting point than some other fiber materials requires control of production temperature - Begins to soften at 300°F (148°C)
Aramid	- Resists cracking, rutting, and potholes - Increases mix strength and stability - High tensile strength	- Cost effectiveness not proven/varies
Aramid and polyolefin	- Controls rutting, cracking, and shoving - Combines benefits of aramid and polyolefin (polypropylene)	- Cost effectiveness not proven/varies
Fiberglass	- High tensile strength and low elongation - High elastic recovery and softening point	- Brittle - Fibers may break where they cross each other - May break during mixing and compaction - Cost-effectiveness not proven or varies

Source: McDaniel (2015)

2.2.3.1 Natural fibers

Natural fibers such as cellulose, hemp, coir/coconut, jute, sisal and flax are a new class of materials which have good potential in bituminous mixes. The advantages of natural fibers over traditional reinforcing materials, such as glass fibers, talc and mica are the acceptable specific strength and other mechanical properties, low cost, low density, non-abrasivity, good thermal properties, enhanced energy recovery and biodegradability. However, its one disadvantage is their tendency to absorb moisture which can cause them to swell (Busching et al., 1970). Depending on their origin, natural fibers can be grouped into bast (jute, banana, flax, hemp, kenaf, and mesta), leaf (pineapple, sisal, henequen, and screw pine), seed or fruit fibers (coir/coconut, cotton, and palm). The reinforcement of the bituminous mixes is one approach to improve the tensile strength and fibers are the most suitable reinforcing material (Abiola et al., 2014).

2.2.3.1.1 Utilization of natural fibers in bituminous mixes

- **Cellulose fibers** are plant-based fibers obtained most commonly from woody plants, although some are obtained from recycled newspaper. These fibers tend to be branching with fairly high absorption which could hold on to high binder contents in mixtures. It therefore allows mixtures to have more durability (McDaniel, 2005). However, the concern on using these fiber is that it would absorb water and cause moisture-related damage to the pavements (Cooley et al., 2000).

- **Jute fiber** has an erect stalk with leaves that thrives in hot and humid climate, especially in areas where there is a lot of rainfall. The advantage of jute material is its strength, excellent absorbency, environmental compatibility, biodegradability and annual renewability (Abiola et al., 2014). Jute is also known to have good adhesion with asphalt as evident from the widespread application of asphalt-impregnated jute fabric. Kumar et al. (2004) conducted a research on coated jute fibers as an alternative to synthetic fibers that used conventionally in the construction of SMA in bituminous pavements. The results as shown in Table 2.11 indicated that the jute fibers can replace synthetic fibers in SMA mixture. The low value of creep modulus indicates high permanent deformation and therefore, SMA with jute fiber has slightly lower resistance to permanent deformation. Moreover, there is a reduction of 18% in construction cost per metric ton of the mix of the SMA with natural fiber than the mixes prepared with synthetic fiber as shown in Table 2.12. On the other hand, a jute-based product may not last long enough when subjected to elements of nature, due to its bio-degradability (Banerjee and Ghosh, 2008).

Table 2.11 Creep modulus of synthetic and jute fibers

Creep modulus	**Synthetic fibers (Mpa)**	**Jute fiber (Mpa)**
at 3600 point and 40^{o}C	7.1	6.8
at 3600 and 50^{o}C	6.7	6.2

Source: Kumar et al. (2004)

Table 2.12 Cost comparison of synthetic and jute fiber in SMA mixtures

	Synthetic fiber	**Jute fiber**
Total cost of asphalt at Rs. 11/kg in 1 mT of mix	666.5	605
Cost of 4.5 kg synthetic fiber in 1 mT of the mix including the preparation of fiber at Rs. 90/kg	405	-
Cost of 9.0 kg jute fiber in 1 mT of the mix including the preparation of fiber at Rs. 30/kg	-	270
Total cost per mT of mix	1070.5	875

Note: 1 USD = 45 Indian Rupees (Rs.)

Source: Kumar et al. (2004)

- **Sisal fiber** is one of the most widely used natural fibers and is very easily cultivated. Sisal fiber is a hard fiber extracted from leaves of the sisal plant. The advantages of sisal fiber are (1) they have good resistance against moist, and (2) heat and short fiber delay restrained plastic shrinkage thereby controlling crack development at early ages (Obiola et al., 2013). According to Oda et al. (2012), the results of fatigue analysis of cellulose, sisal, and coconut fiber were not significantly different.

- **Coir/coconut fiber** is a product which is extracted from the outer shell of the coconut fruit. Coir fiber is 100% natural and originates in the husk of coconuts; it comes from part of the seed pod of the coconut palm. Table 2.13 shows the comparison of draindown of various types of fiber using in SMA mixes. The draindown test results clearly suggested that coconut fiber can be used in SMA mixtures as a replacement for cellulose fiber in order to prevent draindown during production (Vale et al., 2013; Oda et al., 2012).

Table 2.13 Draindown of various fibers in SMA mixes

Fiber	**Fiber content (%)**	**Draindown value (%) at 180ºC**
Without fiber	0	0.70
Coconut fiber	0.3	-
	0.5	0.03
	0.7	0.09
Cellulose fiber	0.3	0.03
	0.5	0.02
Polyester	0.3	0.21
	0.5	0.03
Sisal fiber	0.3	0.21
	0.5	0.05

Source: Vale et al. (2013); Oda et al. (2012)

Moreover, SMA mixtures with coconut fiber presented a lower fatigue life than other SMA mixtures (improved fatigue life of bituminous mixes) (Narayan, 2010). Moreover, SMA mixtures with coconut fiber increased stability and TSR as compare to cellulose, sisal, pineapple, and banana fibers (Kumar and Ravitheja, 2019). Apparently, the addition of coconut fiber did not improve the cracking resistance of the SMA mixtures; in fact, for coconut fiber the numbers of cycles to failure were consistently lower than SMA mixtures with cellulose. The drawbacks of SMA mixtures with coconut fiber are (1) presented difficulty in workability, (2) and could absorb moisture so it maybe causes moisture-related damage to the pavements (Vale et al., 2013).

Additionally, fibers are used to provide a need for improving the tensile strength and flexibilty of the bituminous mixtures. Reinforcement with natural fibers has been shown to possess certain advantages over, such as their ease availability, low density, and acceptable specific properties enhanced energy recovery and biodegradability as compared to other fibers. Moreover, the use of natural fibers in bituminous mixes could improve the fatigue life by increasing the resistance to cracking and permanent deformation. The main drawbacks in the use of natural fibers in bituminous mixes are the inherent high moisture absorption (Obiola et al., 2013). Based on the above mention, the advantages and disadvantages of natural fibers in SMA mixtures can be summarized as shown in Table 2.14.

Table 2.14 The summary of advantages/disadvantages of natural fiber in SMA mix

Fiber type	**Advantages**	**Disadvantages**
Cellulose	- High asphalt absorption which could permit more durability	- It would absorb water and cause moisture-related damage to the pavements
Jute fiber	- Jute fibers can replace synthetic fibers in SMA mixture - SMA with jute fiber had slightly lower resistance to permanent deformation as compare to synthetic fiber - SMA with jute fiber was 18% cost lower than SMA with synthetic fiber	- A jute-based product may not last long enough when subjected to elements of nature, due to its bio-degradability
Sisal	- Had good resistance against moist, - Could delay restrained plastic shrinkage thereby controlling crack development at early ages - Had similar fatigue resistance as cellulose, sisal, and coconut	-
Coir/coconut	- Coconut fiber can be used in SMA mixtures as a replacement for cellulose fiber - Increased stability and TSR as compare to cellulose, sisal, pineapple, and banana fibers - Presented a lower fatigue life as compared to other natural fibers	- Presented difficulty in workability - Could absorb moisture so it may be causes moisture-related damage to the pavements

2.3 SMA mixture properties

Fundamentally, the mix design for SMA mixture is meant to determine the volume of bitumen binder and aggregates necessary to produce a mixture with the desired properties (NAPA, 1996). The requirement criteria as shown in Table 2.15 have been set to ensure that the SMA mixture can be selected (NCHRP, 1999). The requirements to be considered as shown in Table 2.15 are discussed as follows.

Table 2.15 SMA mixture specifications for Marshall hammer compacted designs

Property	**Requirement**
Air voids (%)	4.0 [1]
VMA (%)	17 min
VCA_{mix} (%)	Less than VCA_{drc}
Stability (N)	6,200 min [2]
TSR (%)	70 min
Draindown at production temperature (%)	0.30 max

Note: [1] For low traffic volume roadways or colder climates, air void contents less than 4.0% can be used, but should not be less than 3.0%. [2] Successful SMA mixtures have been designed with Marshall Stability values below 6,200 N, therefore this requirement can be waived based on experience.

Source: NCHRP (1999)

2.3.1 Volumetric properties

Volumetric properties of an asphalt cement mixture are referred to the volume of aggregates and bitumen binders needed to make a mixture of desired properties (Kumar and Ravitheja, 2019). These properties are essential for pavement to have a long life of serving with remained durability. The required properties to be considered are specific gravity of compacted mixture (G_{mb}), specific gravity of uncompact mixture (G_{mm}), the voids in mineral aggregate (VMA), air voids (AV), and voids of coarse aggregate in the compacted mixture (VCA_{mix}).

- **G_{mb}** (ASTM D2726) is defined as the ratio of the weight in air of compacted mixture including permeable voids at a room temperature to the weight of gas-free distilled water at a room temperature (equation 2.5).

$$G_{mb} = \frac{W_D}{W_{SSD} - W_{sub}} \tag{2.5}$$

where, W_D is the dry weight (g),

W_{SSD} is the saturated surface dry weight (g),

W_{sub} is the saturated surface dry weight submerged in water (g)

- **G_{mm}** (ASTM D 2041) is the ratio of the weight in air of an uncompacted mixture at a room temperature to the weight of gas-free distilled water at a room temperature as shown in Figure 2.14. The specific of uncompacted mixture, G_{mm}, is determined as shown in equation (2.6).

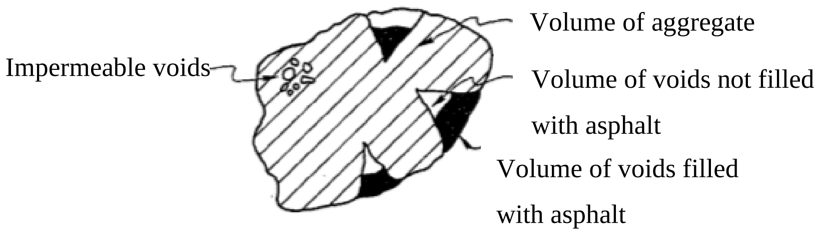


Figure 2.14 Diagram illustrating G_{mm} of mixture

Source: NAPA (1996)

$$G_{mm} = \frac{P_{mm}}{\frac{P_s}{G_{se}} + \frac{P_b}{G_b}} \tag{2.6}$$

where, P_{mm} is the total weight of mixture,

P_s is the weight of aggregate,

P_b is the weight of asphalt,

G_{se} is the effective specific gravity of aggregate coated with asphalt,

G_b is the specific gravity of asphalt

- **AV** (ASTM D3203-94) is the total volume of the small air pockets between the asphalt-coated aggregate particles throughout a compacted mixture. Generally, AV content of not greater than 4% of the total mixture is specified for SMA. The strength of the asphalt mixture is decreased when the AV content is too low. On the other hand, the density of the asphalt mixture is decreased when the AV content is too high (Sun, 2016). It is therefore the sufficient AV content does increase strength, stability, and durability of mixture. The AV is equal to:

$$AV(\%) = 100 \times \frac{G_{mm} - G_{mb}}{G_{mm}} \tag{2.7}$$

- In compacted mixture, the voids space between the aggregate particles including the air voids and volume of effective asphalt is known as VMA. The designed NMAS and air voids content, both are the two factors affecting to VMA percentage in mixture (Asphalt Institute, 1997). The mixture resulting with low VMA could decrease air voids content, it is therefore the durability of mixture is affected as the asphalt film is not thick enough (Dhir et al., 2019). The formula for VMA is found as shown in equation (2.8).

$$VMA\,(\%) = 100\left(\frac{G_{sb} - G_{mb}\left(1 - P_b\right)}{G_{sb}}\right) \tag{2.8}$$

- **VCA$_{\mathbf{mix}}$** defined as the voids of coarse aggregate in the compacted mixture can be determined as shown in equation (2.9) after the extraction of trial samples have been compacted and allowed to cool to room temperature for 24 hours.

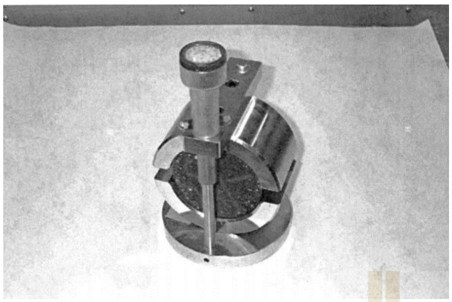
$$VCA_{mix}\,(\%) = 100 - \left(P_{ca} \times \frac{G_{mb}}{G_{ca}}\right) \tag{2.9}$$

where, P_{ca} is the percent coarse aggregated in the total mixture

G_{ca} is the specific gravity of the coarse aggregate fraction

2.3.2 Stability

The stability test (ASTM D 6927) is performed for laboratory mix design and evaluation of the strength of asphalt mixtures. The Marshall Test can be conducted with two different types of equipment: (i) Method A (Traditional Method) - using a loading frame with a load ring and a dial gauge for deformation or flow meter or (ii) Method B (Automated Method) - using a load-deformation recorder in conjunction with a load cell and linear variable differential transducer (LVDT) or other automatic recording device (Figure 2.15).



(i) Method A

(ii) Method B

Figure 2.15 Example of Flowmeter (Used in method A) and assembly using compression machine with LVDT and Plotter (Typical of method B)

Source: ASTM D6927 (2015)

2.3.3 Draindown

Draindown test is performed to insure the holding ability of the binder inside the SMA mixture during the production, transportation, and construction. There are many methods which can be used to determine the draindown characteristic of SMA mixes. Schellenberg method as specified by ASTM D6390 (Figure 2.16) is one of many methods used to determine the draindown characteristics of approximately 1,200g of uncompacted mixture. The uncompacted mixture is poured into a 1,000 ml glass beaker and then kept in oven at mixing temperature for 60 ± 1 min. Then, the mixture is removed from the glass beaker without any shaking force and the final weight of the remaining mixture is recorded. According to NCHRP (1999), the draindown of SMA mixtures should not be exceed 0.3% by weight of the mixture.

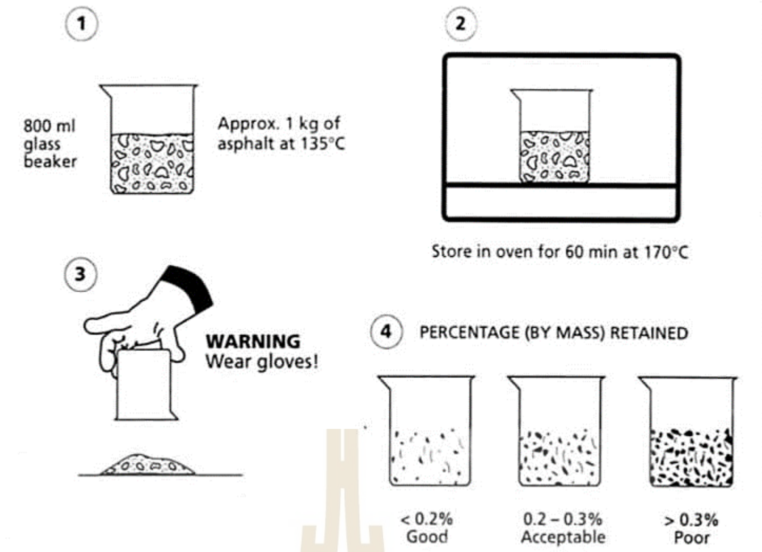


Figure 2.16 Draindown test by Schellenberg method

Source: APRG (1999)

2.3.4 Indirect tensile strength (ITS)

The tensile strength of asphalt pavement is related with cracking problems. The ITS test is performed to ensure that the mixtures have enough resistance encounters with cracking. A higher ITS value indicates a stronger cracking resistance, (Tayfur et al., 2007). To determine the strength of the asphalt mixture, a cylindrical specimen is loaded across its vertical diameter at a standard deformation rate (51 mm/minute) and test temperature (ASTM D6931). The highest load is recorded and used to determine the ITS (S_t) as derived in equation (2.10) and TSR as in equation (2.11).

$$S_t = 2000P / \pi tD \tag{2.10}$$

$$TSR = S_{tconditioned} / S_{tunconditioned} \tag{2.11}$$

where, P is the peak load of the sample (N),

t is the thickness of the sample (mm),

D is the height of the sample (mm),

TSR is the tensile strength ratio of the sample (%)

2.4 Previous works related to SMA

The previous works reviewed in this study can be separated into three topics including gradation, coconut fiber versus other fibers in SMA mixes, and coconut fiber in SMA mixes.

2.4.1 Aggregate gradation

Siva and Uma (2018) investigated a study on SMA by comparing two different gradation including 19 and 13 mm NMAS. The Portland cement was used as filler material and VG-30 grade bitumen was used as binder content by weight of aggregates of 5 - 7% (0.5% increment). The result showed that (1) the SMA with 19 mm NAMS had better performance than 13 mm NMAS as the 19 mm NMAS consisted of large size aggregates in gradation, (2) SMA with 19 mm NMAS increased the stability and bulk specific gravity and decreased flow as compared to SMA with 13 mm NMAS.

Sarang et al. (2015) studied on laboratory performance of SMA mixture using two different gradations which were 16 and 13.2 mm NMAS. In their work, they chose polymer modified asphalt as the binder material without adding any fiber. Adding that they prepared the specimen in Superpave Gyratory compactor with the asphalt content from 5 - 7% (0.5% increment). The result indicated that the 16 mm NMAS mixtures had higher density, improved 28 - 31% of stability and tensile strength, improved 0.4 - 0.7 mm of rutting resistance, and improved 21% of fatigue life as compared to 13.2 mm NMAS mixtures. Their work was well done, however the draindown of mixtures should be investigated to ensure that polymer modified asphalt was able to fulfill the draindown requirement.

Imran et al. (2011) evaluated the effect of aggregate gradation with different NMAS (4.75, 9.5, 12.5, and 19 mm) on the stiffness, rutting, and fatigue performance of SMA mixes. A penetration graded (PG) 58-22 asphalt binder and cellulose fiber were used to incorporate with each NMAS. The result revealed that (1) rut resistance of SMA increases with an increase of aggregate size in aggregate gradation, (2) increasing aggregate size in aggregate gradation decreases fatigue life and increases binder drainage, and (3) mix stiffness increase with an increase in aggregate size in aggregate gradation. The result also showed that increasing aggregate size in aggregate gradation increases asphalt binder and VMA and decreases G_{mb} of SMA mixture.

Cooley and Hurley (2004) also studied on the SMA mixture performance using different types of gradations including 9.5 and 4.75 mm NMAS. They utilized unmodified PG 67-22 as the binder material and 0.3% of cellulose fiber as stabilized agent for their study. As the result, they found that the 4.75 mm NMAS reached the OAC at 8.5% while the 9.5 mm NMAS reached the OAC at 7.2%. Adding that the mixtures having 4.75 mm NMAS were difficult to design. They have done several job mixes which were able to prove the availability of using 4.75 and 9.5 mm NMAS in their community. In their works, they just compared about the volumetric properties and made the assumption about the suitability of each NMAS. It is better to include Marshall properties to see which one that have better strength. The

OAC is literally higher than the standard (6 - 7%), it is therefore better to determine another optimum fiber content which is suitable for both NMAS. The previous works related to aggregate gradation in SMA can be summarized as shown in Table 2.16.

Table 2.11 The summary of previous works related to aggregate gradation in SMA

Year	Author	Title	Material	Result	Remark
	Siva and Uma	An experimental investigation on stone matrix asphalt by using coconut fiber and banana fiber.	- 19 and 13 mm NMAS - VG-30: 5 - 7%	- the SMA with 19 mm NAMS had better performance than 13 mm NMAS - SMA with 19 mm NMAS increased the stability and bulk specific gravity and decreased flow as compared to SMA with 13 mm NMAS	Good
2015	Sarang et al.	Laboratory performance of stone matrix asphalt mixtures with two aggregate gradations	- 16 and 13.2 mm NMAS - PMA: 5 - 7% (no fiber)	- 16 mm NMAS provided higher density, stability and tensile strength, improved the rutting resistance and fatigue life compared to 13.2 mm NMAS	Should be performed the draindown test
2011	Imran et al.	An experimental study to select aggregate gradation for stone mastic asphalt	- 4.75, 9.5, 12.5, and 19 mm NMAS - PG 58-22	- 19 mm NMAS provided better rut resistance, decreased fatigue, increased binder drainage, and increased stiffness	Good

2.4.2 Coconut fiber versus other fibers

Kumar and Ravitheja (2019) studied on characteristics of SMA mixtures using different natural fibers (coir/coconut, sisal, and banana fiber). AC 60/70 with the concentration of 5.5 - 7.5 % (0.5% increment) was used. The fiber contents for all fibers were varied between 0.1, 0.2, 0.3, and 0.4% by mass. As the result, the optimum fiber content of coir/coconut, sisal, and banana fiber was 0.3%. The coir/coconut fiber showed the highest result in term of stability as compared to sisal and banana fiber.

Siva and Uma (2018) investigated a study on SMA by using coconut fiber and banana fiber. The engineering properties of SMA mixture without and with fibers such as coconut and banana fibers were studied. The VG-30 grade bitumen is used as binder content by weight of aggregates of 5, 5.5, 6, 6.5, and 7%. The result showed that (1) air voids were less for SMA mixes with coconut fiber when compared to banana fiber, (2) the optimum fiber content of 0.3% and 0.4% were achieved at 0% draindown for coconut and banana fiber, respectively, and (3) stability and specific gravity of SMA mixes with coconut fiber were better as compared to banana and without fiber.

Shravan (2017) studied on SMA performance comparing between cellulose and coconut fiber. The coconut fiber length and diameter used in this work were 10 - 20 mm-long and 0.09 – 0.12 mm, respectively while there was no specific dimensions for cellulose fiber. VG 30 with the concentration from 5.5 - 7% (0.5% increment) were selected as the binder for mixtures. As the result, the OAC of SMA mixtures mixing with coconut and cellulose fiber were 6.23% and 6.43%, respectively.

The optimum fiber content for both fibers was found to be 0.3%. It also showed that the stability of mixtures containing coconut fiber was 10% higher than cellulose fiber.

Satyavathi et al. (2016) investigated a study of SMA with coir/coconut and pineapple fiber. Various percentages such as 5.5, 6, 6.5 and 7% of bitumen were selected for this study. Draindown test is initially performed to find the optimum fiber content and finally to find the optimum bitumen content. The result revealed that the use of coir/coconut fiber reduced the draindown value and increased the stability value of SMA mixes when compared with pineapple fiber.

Vale et al. (2013) studied on behavior of natural fibers in SMA mixtures using two design methods including Marshall and Superpave. The coconut fiber (0.2 - 0.6 mm diameter and 30 - 40 mm-long) concentration using in their work were 0.5% and 0.7% while 0.3% concentration was for cellulose fiber. As the result, the optimum fiber content for cellulose and coconut fiber were 0.3% and 0.5%, respectively. They found that the addition of coconut fibers increased the stability and TSR and reduced the draindown as compared to cellulose fiber. But SMA mixes with coconut fibers did not perform as well in fatigue as mixes with cellulose fiber. This was possibly because the high absorption of the coconut fiber increased the stiffness of the mix. The researchers also noted that long coconut fibers were difficult to mix with the aggregate and could have lowered the strength of the mix by interfering with aggregate interlock. In their study, it is better to cover more concentrations of the coconut and cellulose fibers to see how the trend of stability and draindown percent of the mixtures will be.

Awanti et al. (2012) studied on the characterization of SMA mixtures containing coconut and cellulose fiber by utilizing VG 30 grade as the binder asphalt.

They selected coconut fiber of 3 - 8 mm-long and 0.2 - 0.6 mm diameter while cellulose fiber of 1100 µm-long and 45 µm diameter. As the result, the OAC of coconut and cellulose fiber were found to be 6% and 5.8 %, respectively. Moreover, the draindown of coconut fiber was 60% lower than the cellulose fiber. The authors summed up that SMA containing coconut fiber was economical when compared to SMA containing cellulose fiber. In this study, it is better to include the results of stability of each job mix. The previous works related to coconut fiber versus other fibers in SMA can be summarized as shown in Table 2.17.

Table 2.17 The summary of previous works related to coconut fiber versus other fibers in SMA

Year	Author	Title	Material	Result	Remark
2019	Kumar and Ravitheja	Characteristics of stone matrix asphalt by using natural fibers as additives	- AC60/70: 5.5 - 7.5% - Coir, sisal, banana fiber: 0.1, 0.2, 0.3, and 0.4%	- OAC of all fibers: 6.42% - OFC of all fibers: 0.3% - Coir fiber showed the best performances among other fibers in term of stability	Good
2018	Siva and Uma	An experimental investigation on stone matrix asphalt by using coconut fiber and banana fiber.	- VG-30: 5 - 7% - Coconut and banana fiber	- Air voids were less for SMA mixes with coconut fiber when compared to banana fiber - The optimum fiber content of 0.3% and 0.4% were achieved at 0% draindown for coconut and banana fiber, respectively - Stability and specific gravity of SMA mixes with coconut fiber were better as compared to banana and without fiber	Good
2017	Shravan	A comparative study on performance of stone mastic asphalt with cellulose and coir fiber	- VG30 (5.5 - 7%) - Coconut and cellulose fiber	- OAC of coconut: 6.23% - OAC of cellulose: 6.43% - OFC for both fibers: 0.3% - Coconut fiber had higher stability	Good

Table 2.17 The summary of previous works related to coconut fiber versus other fibers in SMA (Continued)

Year	Author	Title	Material	Result	Remark
2016	Satyavathi et al.	Experimental study of Stone Matrix Asphalt with coir fiber and pineapple fiber	- Coir/coconut and pineapple fiber - VG - 30: 5.5 - 7%	- The use of coir/coconut fiber reduced the draindown value and increased the stability value of SMA mixes when compared with pineapple fiber	Should be considered the variation of fiber content
2013	Vale et al.	Behavior of natural fiber in stone matrix asphalt mixtures using two design methods	- AC50/70 (5 - 7%) - Coconut fiber: 0.5 - 0.7%, - Cellulose fiber: 0.3%	- OFC of coconut: 0.5% - OFC of cellulose: 0.3% - Coconut fiber provided excellent driandown and stability - Coconut fiber presented difficulties in workability	Should be considered fiber concentrations
2012	Awanti et al.	Characterization of stone matrix asphalt with cellulose and coconut fiber	- VG30 (5 -7.5%) - Coconut and cellulose fiber	- OAC for coconut fiber was 6% while for cellulose fiber was 5.8% - Draindown result of coconut fiber was 60% higher than cellulose - Coconut fiber was recommended as its availability and low cost	Should be provided stability results of each job mix

2.4.3 Coconut fiber

Baby et al. (2018) studied the effect of coir/coconut fiber on SMA with marble waste filler. The percentage of bitumen by weight of aggregates was varied as 5, 5.5, and 6% to determine optimum bitumen content by Marshall stability Test. Bitumen (VG-30) percentage corresponding to 4% air voids gives the OAC which was found to be 5.84%. Similarly the percentage of fiber by weight of mineral aggregates was varied as 0.2, 0.3, and 0.4% and the optimum fiber content was found to be 0.3%. The addition of coir/coconut fiber showed increase in stability of the mix, which was found to be maximum at 0.3% of coir/coconut fiber by weight of aggregates.

Panda et al. (2013) studied on utilization of coconut fiber in SMA mixing with viscosity grade 30 asphalt (VG 30) and crumb rubber modified 60 grade asphalt (CRMB 60). They manually extracted the coconut fiber from local ripe coconut fruits. The extracted coconut fiber lengths were in the range of 75 - 200 mm and diameters varied from 0.2 - 0.6 mm. These coconut fibers were then cleaned and cut into 20 - 35 mm-long to ensure proper mixes. In their work, the binder concentrations were varied from 4 to 7% and fiber concentrations were selected as 0%, and 0.3 - 0.7% (0.2% increment). As the result, 0.3% of coconut fiber was the optimum fiber content for all the job mixes in term of stability.

Thulasirajan and Narasimha (2011) presented a study on stability, flow and volumetric properties of the coconut fiber - reinforced bitumen by varying the binder content, fiber content and fiber length. The results indicated that the addition of coconut fiber increased the stability and voids with decrease in the flow rate. Fiber length of 15 mm with a fiber content of 0.52% and a binder content of 5.72%

provided good stability and volumetric properties. It can be said that coconut fiber has the potential to improve the structural resistance to distress occurring in flexible pavement due to traffic loads. The previous works related to coconut fiber in SMA can be summarized as shown in Table 2.18.

According to the literature reviews, it can be concluded that (1) larger gradation of aggregate can lead to higher strength and Marshall stability of SMA mixture, (2) polymer modified asphalt can be used without any fibers while unmodified asphalt must need fibers to prevent draindown of SMA the mixture, (3) coconut fiber shall be used in SMA mixture because it has higher stability and be able to fulfill other requirements, and (4) 0.3% of cellulose fiber and 0.3 - 0.5% of coconut fiber are sufficient to resist the draindown of asphalt in SMA mixture.

Table 2.18 The summary of previous works related to coconut fiber in SMA

Year	Author	Title	Material	Result	Remark
2018	Baby et al.	Effect of coir fiber on stone mastic asphalt with marble waste filler	- VG-30: 5 - 6% - Coir/coconut fiber: 0.2, 0.3, and 0.4%	- OAC was 5.84%. - OFC was 0.3% - The addition of coir/coconut fiber showed increase in stability of the mix	Should be provided more detail results
2013	Panda et al.	Utilization of ripe coconut fiber in stone matrix asphalt mixes	- 19 mm NMAS - VG30 and CRMB60 - Coconut fiber: 0.3, 0.5, and 0.7%	- 0.3% of coconut fiber was the optimum fiber content for all the job mixes in term of stability	Should be provided more range of optimum asphalt content of each job mix
2011	Thulasirajan and Narasimha		- Coconut fiber: 15 mm-long	- OAC was 5.72% - OFC was 0.52% - High stability and volumetric properties - Coconut fiber had the potential to improve the structural resistance to distress occurring in flexible pavement due to traffic loads.	Should be provided more detail of each material

CHAPTER III

MATERIALS AND METHOD

This chapter presents the materials and research methodology which are used in this research work. The overall topics of this chapter are illustrated in Figure 3.1.

3.1 Overall framework

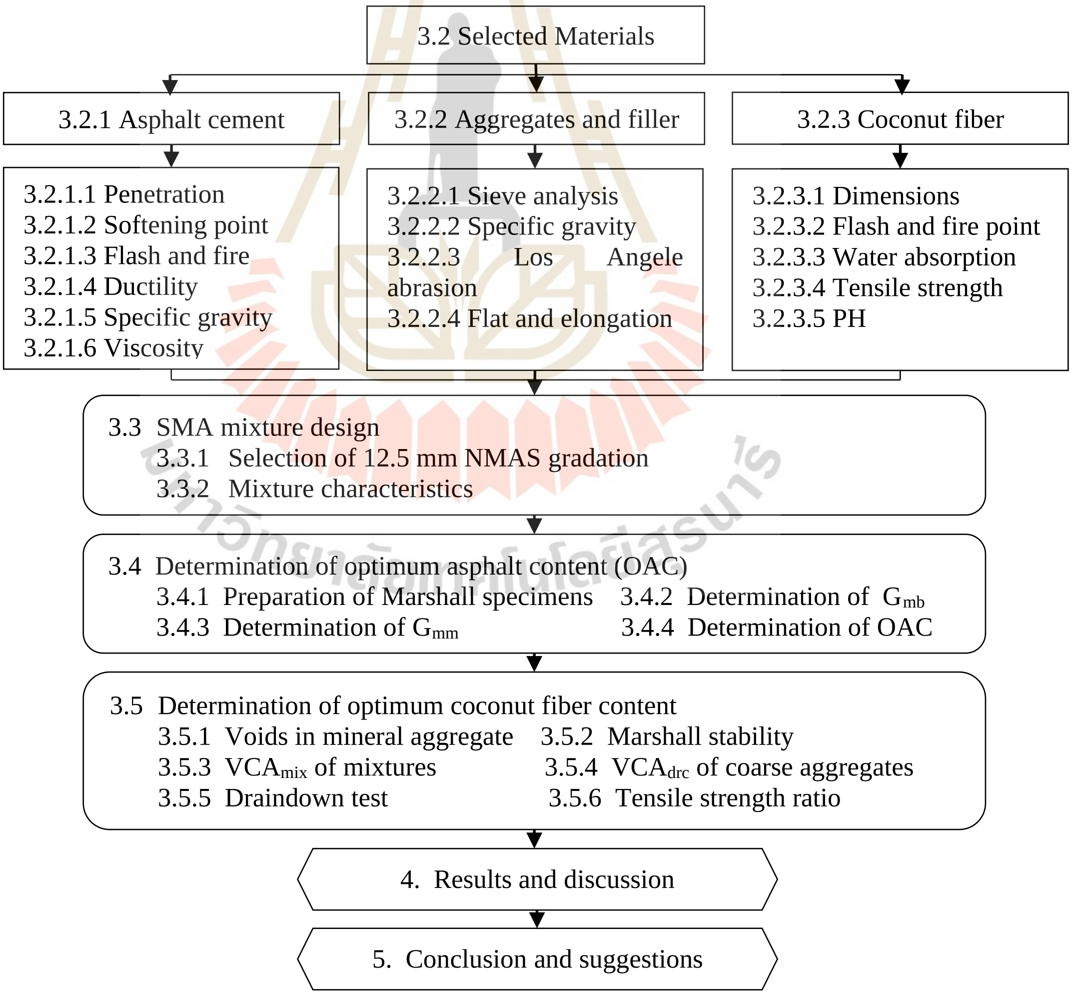


Figure 3.1 Overall framework

The overall framework as shown in Figure 3.1 is used to present all the relevant steps of this research study. The materials selection was the first thing needed to be considered. These materials were selected according to the literature review plus available resources. The properties of each material were also determined to ensure the strength and suitability/fit to the requirements. Then, mix design for SMA mixture according to Marshall hammer compacted method was mad. After then, the optimum asphalt content (OAC) and fiber (% and mm) were determine for each mixture.

3.2 Selected Materials

The selection of testing materials including AC60/70, aggregates and filler, and coconut fiber are presented and discussed in this section. The basic properties of these materials are determine and discussed as follows.

3.2.1 Asphalt cement

AC60/70 was selected for this study because it is the most commonly used asphalt in Thailand (Jitsangiam et al. 2013). AC60/70 was provided by Thai Lube Base Public Company Limited located in Sriracha, Chonburi, Thailand. The evaluation of the selected AC60/70 was conducted to assure that their significant properties complied with the specification of Thai Lube Base Public Company Limited. Penetration, softening point, flash and fire point, ductility, specific gravity and density, and viscosity of AC60/70 were tested and presented as follows.

3.2.1.1 Penetration test

The penetration test following by ASTM D5 was tested with the temperature, load, and time of 25^{o}C, 100 g, and 5 s, respectively. The apparatus including containers (metal cylindrical containers of 35 mm in height and 55 mm in diameter), penetrometer (consisted of a 1/10 mm scale dial gauge, an adjustable screw, a 50 g needle, and a 100 g plunger), water bath (sufficient depth and could maintain the sample at 25^{o}C), thermometer, and transfer dish as shown in Figure 3.2 were used.

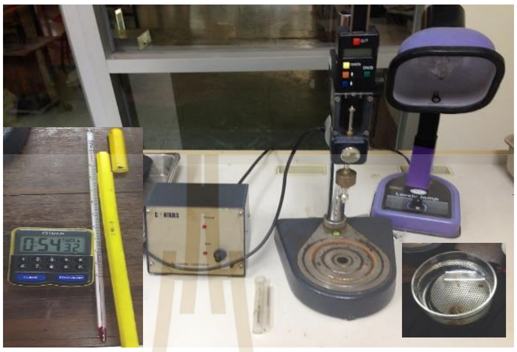


Figure 3.2 Apparatus of penetration test

To obtain penetration value of AC60/70, three samples were prepared as shown in Figure 3.3 and those three samples after cooling to room temperature were kept at 25^{o}C for 30 minutes so that the penetration test could be subjected. Note that these samples were prepared by pouring AC to level 3/4 of container.

Figure 3.3 Sample preparation for the penetration test

The distance penetrating by the needle into AC60/70 sample was called penetration value as shown in Figure 3.4. In this test, three replications as shown in Figure 3.4 (i) were made in each sample and each point was to be at least 10 mm from the side of the container, and the needle need to be cleaned to ensure no asphalt sticks on it before going to retest. Figure 3.4 (ii) is used to present the sample before the penetration test while Figure 3.4 (iii) is used to present the sample after the penetration test.

(i)

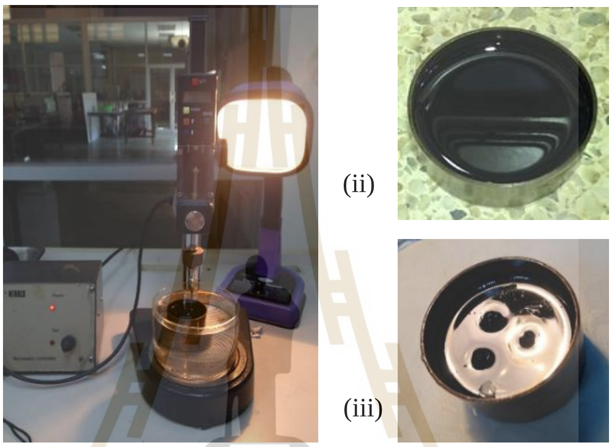


Figure 3.4 (i) penetration test, (ii) sample before, and (iii) after the test

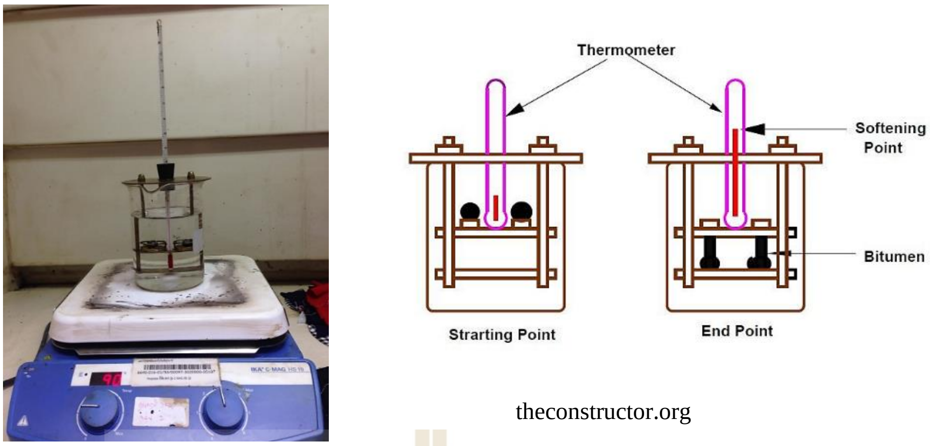
3.2.1.2 Softening point test

Softening point test in accordance with ASTM D36 was used to determine a temperature in which AC60/70 changes its state from semi-solid to liquid state. The apparatus including a couple of ring used to hold the sample, a glass water container, two standard steel balls, pouring plate, ball centering guide, heating plate, thermometer, stop watch, and spatula as shown in Figure 3.5 were used. To obtain the softening point value, AC60/70 was heated at testing temperature (160 - 170^{o}C) and then poured into standard rings and kept until it can cool to room temperature itself. After that, the samples were leveled and cured in 5^{o}C water bath for 30 minutes as illustrated in Figure 3.6.

Figure 3.5 Apparatus of softening point test

Figure 3.6 Sample preparation of softening point test

The softening point of AC60/70 was found by curing the prepared sample in a glass beaker at 5^{o}C for around 30 min prior to the test. After that, setting and warming up the samples on the heating plate with the temperature around 80^{o}C and then let the temperature increased until the inside temperature of the water container was raised 5^{o}C consecutively. AC60/70 therefore softened and eventually deformed slowly with the ball through the ring. At the time when AC60/70 and the ball touch to the base plate, the thermometer temperature was the AC6070 softening point (Figure 3.7). The test was performed twice and the mean of the two measured temperatures were reported.



(i) (ii) (iii)

Figure 3.7 (i) softening point test, (ii) sketch of before and (iii) after the test

3.2.1.3 Flash and fire point test

Flash and fire point test in according with ASTM D92-90 was used to determine the flash and fire temperature of AC60/70. It is an important test because it helps to indicate the flash and fire temperature of asphalt during the testing and construction period. To perform this test, two samples were prepared as shown in Figure 3.8.

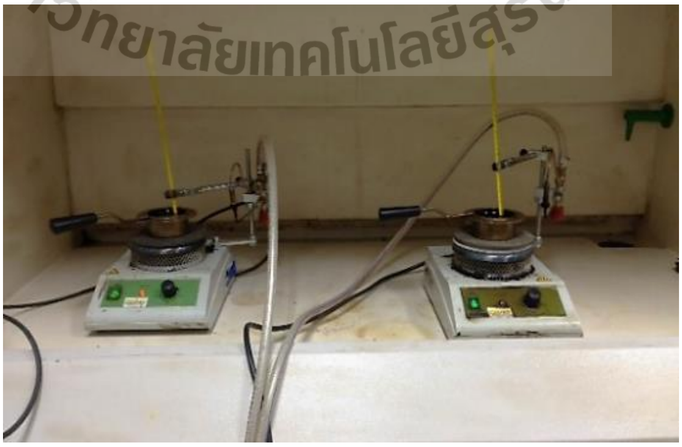


Figure 3.8 Sample preparation of softening and fire point test

The heating plate was used to supply the heat until the AC60/70 was able to ignite. The first occurrence of ignition was recorded as the flash point as shown in Figure 3.9 (i) while the temperature at which the sample supported a flame for a period of at least five seconds was recorded as the fire point as shown in Figure 3.9 (ii).

(i)  (ii) 

Figure 3.9 (i) flash point and (ii) fire point

3.2.1.4 Ductility test

The ductility test in accordance with ASTM D113-07 was used to define the distance in centimeters to which it elongated before breaking (pulled at specified speed of 5 cm/min and at specified temperature of 25°C). At least two samples were prepared for this test. Apparatus including ductility mold, testing machine (consists of a water bath using to maintain a specified temperature, an adjustable steel using to pulling the sample apart, and a scale), thermometer, trimmer, heater, scissor, and a stop watch as shown in Figure 3.10 were needed.

Figure 3.10 Required apparatus of ductility test

For sample preparation, AC60/70 was first heated and then poured in the mold assembly placed on a plate. The prepared samples (2 samples) were then leaved to cool to room temperature. After that, the excess part was cut and its surface was leveled using a hot knife. Then, the prepared samples were cured in water bath at 25^{o}C for 30 min prior to the test as illustrated in Figure 3.11.

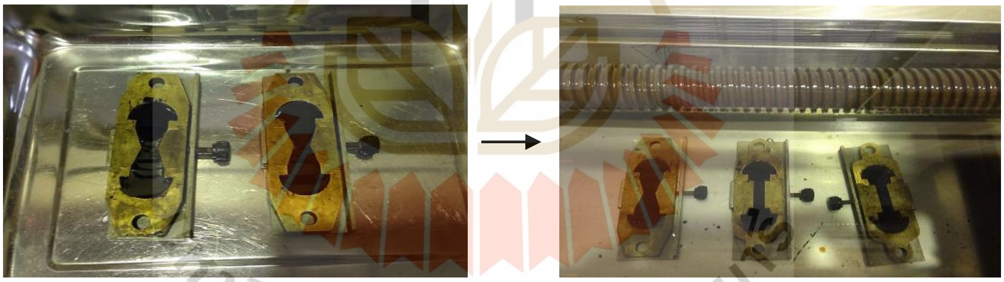


Figure 3.11 Sample preparation of ductility test

To proceed the test, the sides of the molds were removed and then the clips of mold were hooked as shown in Figure 3.12 (i) and then the machine was able to operate as shown in Figure 3.12 (ii). The distance (cm) up to the point of the breaking of thread was recorded as the ductility of AC60/70.

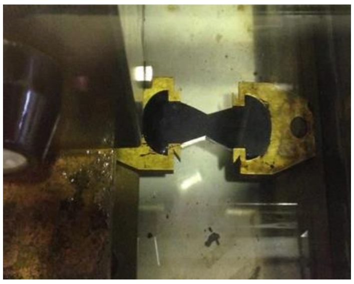
(i)  (ii) 

Figure 3.12 (i) before and (ii) after ductility test

3.2.1.5 Specific gravity and density test

Specific gravity and density test in accordance with ASTM D70-18 was used to determine the specific gravity and density of AC60/70 compared to that of water. Three samples were prepared and tested for specific gravity and density of AC60/70 as shown in Figure 3.13.

(i)  (ii) 

Figure 3.13 Sample preparation of specific gravity of AC60/70

The bottle partially filled with AC60/70 as shown in Figure 3.13 (ii) were then cured at 25^{o}C for 1 hr and after that it was filled to full level with 25^{o}C water. To determine the specific gravity of AC60/70, weight of empty pycnometer (A), pycnometer filled with water (B), pycnometer filled with AC60/70 (C), and pycnometer filled with

AC60/70 and water to the full level (D) were recorded. The specific gravity and density of AC60/70 were determined as shown in equation (3.1, 3.2), respectively.

$$G_s = \frac{C - A}{(B - A) - (D - C)} \tag{3.1}$$

$$Density = G_s \times \rho_w \tag{3.2}$$

3.2.1.6 Viscosity test

Brookfield test in accordance with ASTM D4402 was used to determine the viscosity of AC60/70. This test was determined to insure the resistance to flow of AC60/70. Apparatus including temperature controller (to control the temperature inside the environmental chamber), standard spindle (21 and 27 inch diameter), sample chamber in pouring rack (to carry and make the mold in vertical direction), rotational viscometer (capable of measuring the torque and able to convert the torque measurement to viscosity in centipoise), gripping pliers (to pick the hot mold during the test), standard molds or sample chambers, and readable balance as shown in Figure 3.14 were used.

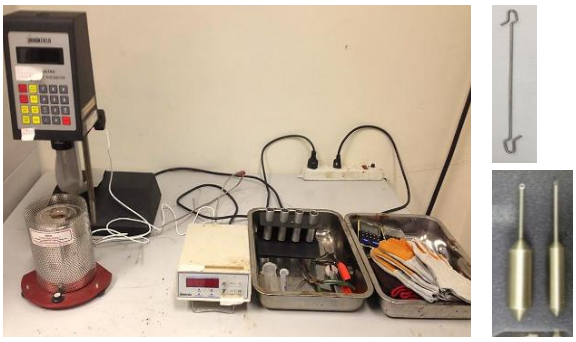


Figure 3.14 Apparatus to test viscosity of AC60/70

For sample preparation, AC60/70 was firstly heated and poured into the sample chambers between 8 -10 g, then samples were kept to cool to room temperature before starting to rotate in the desired temperature (110°C with maintained time 10 min for example). During the test, the rotation was started at a speed which developed a resisting torque between 10 - 98% (maintained to allow the sample to equilibrate for an additional 10 min) of the full-scale instrument capacity. In this test, there were three samples were prepared and tested as shown in Figure 3.15.

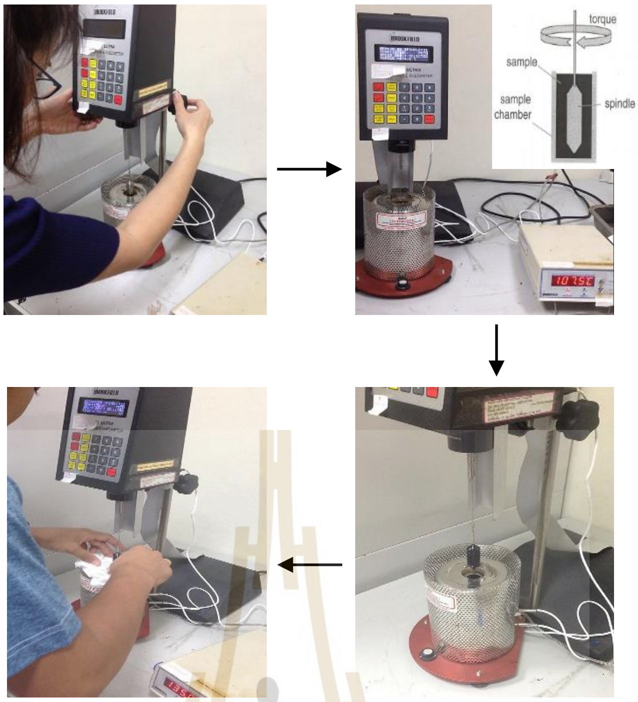


Figure 3.15 Brookfield viscosity test

The properties of AC60/70 are summarized in Table 3.1. The details of obtained test results of penetration, softening point, flash and fire point, ductility, and so on are given in Appendix I.

Table 3.1 Basic properties of AC60/70

Test item	Unit	Test method	Specification	Result
Original asphalt				
Penetration at 25ºC	-	ASTM D5	60 - 70	67
Ductility at 25ºC	cm	ASTM D113-07	Min 100	> 100
Softening point	ºC	ASTM D36	45 - 55	47.6
Flash point	ºC	ASTM D92	Min 232	328
Specific gravity at 25/25ºC	-	ASTM D70-80	1.01 - 1.06	1.056
Solubility in Trichloroethylene	%	ASTM D2042-15	Min 99.0	99.98
Complex shear modulus at 64ºC	kPa	ASTM D7175-15	Min 1.0	1.11
Viscosity at:	Pa.s	ASTM D4402	-	
100ºC				3.97
135 ºC				0.44
165 ºC				0.11
175 ºC				0.08
Residue from thin film oven test (TFOT)				
Mass change	%	ASTM D1754-09	Max 0.8	- 0.065
% of original after TFOT	%	ASTM D5	Min 54	68
Ductility at 25ºC	cm	ASTM D113-07	Min 50	>100

3.2.2 Aggregates and filler

Three sizes of lime stone aggregate (12.5 mm, 9.5 mm, and dust rock) adopted from Roi Et province (Thailand) were used to combine with Portland cement to prepare for all SMA mixtures throughout the study. Portland cement (filler) had more than 90% of particles passing through 0.075 mm sieve and its laboratory bulk specific gravity (ASTM C188) was 2.97. Specific gravity, water absorption, abrasion, flatness and elongation properties of all aggregate types and filler were tested and discussed as follows.

3.2.2.1 Sieve analysis test

Sieve analysis test in accordance with ASTM C136 was used to determine the single gradation of each aggregate and also used to determine the 12.5 mm NMAS gradation for the combined aggregate. Apparatus including standard sieves of 19, 12.5, 9.5, 4.75, 2.36, 1.18, 0.6, 0.3, 0.075 mm and pan, balance (readable to 5 kg), drying oven (capable of maintaining the temperature up to 200°C), metal trays, sieve brushes, and sieve shaker as shown in Figure 3.16 were used. To conduct this test, each aggregate was separated as shown in Figure 3.17 and the opposite sides were selected.

Figure 3.16 Apparatus for sieve analysis test

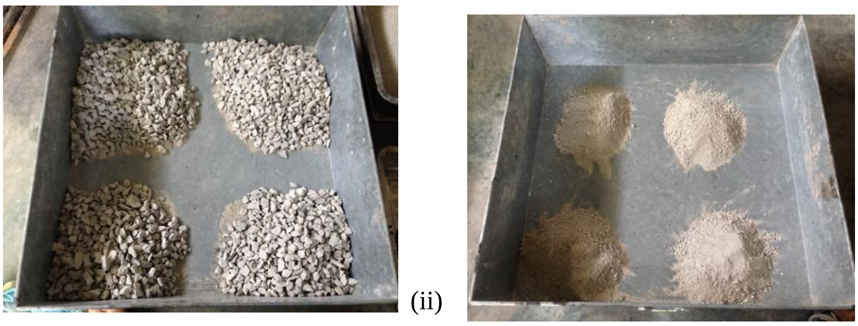
(i)  (ii)

Figure 3.17 (i) sample preparation for coarse and (ii) fine aggregate

The procedure for coarse and fine aggregate were differently. The procedure for coarse aggregate (12.5 and 9.5 mm) was followed to dried method while that of fine aggregates (dust rock and Portland cement) were followed to wet method. The test was done twice for single sieve and triple times for 12.5 mm NMAS. The single curve of each aggregate and filler and the 12.5 mm NMAS (it was made by the combination of 12.5 and 9.5 mm, dust rock, and Portland cement as shown in Figure 3.19) are shown in Figure 3.18 and 3.20, respectively.

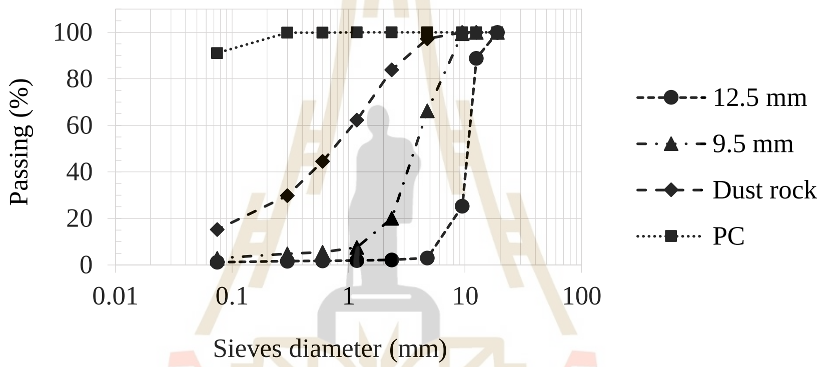


Figure 3.18 Gradation curve of single sieve

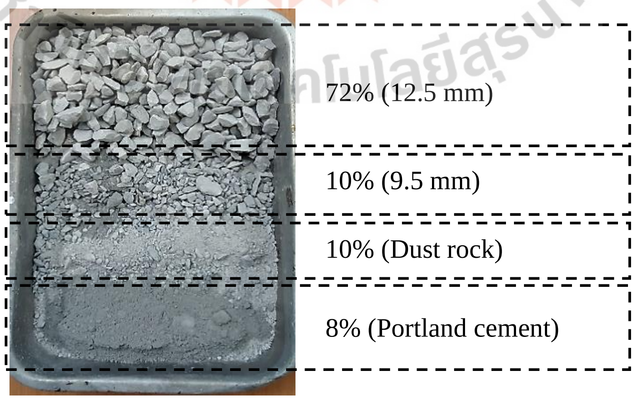


Figure 3.19 The combination for 12.5 mm NMAS

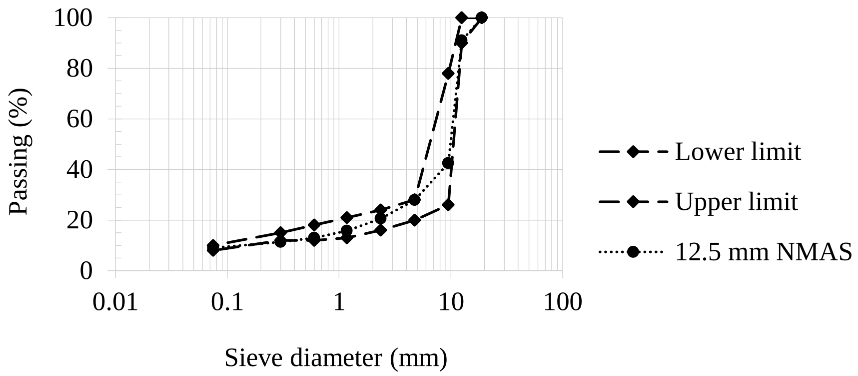


Figure 3.20 Gradation curve of 12.5 mm NMAS

3.2.2.2 Specific gravity and water absorption test

Specific gravity and water absorption test in accordance with ASTM C127/128 was used to determine the specific gravity and water absorption for fine and coarse aggregates. Apparatus as shown in Figure 3.21 (i, ii) were used to conduct the specific gravity of coarse and fine aggregate, respectively. The specific gravity of fine and coarse aggregate were tested differently.

(i)  (ii) 

Figure 3.21 Apparatus of specific gravity test of (i) fine and (ii) coarse aggregate

To obtain the specific gravity of coarse aggregate, at least 2,000 g of aggregate was used and then soaked in 25°C water for 24 hours as shown in Figure 3.22 (i). Then, the aggregate was then drained and placed in the wire basket as shown in Figure 3.22 (ii). Next, immersed the entire sample in distilled water in order to take its weight in water as shown in Figure 3.22 (iii), and then the aggregate was transferred and dried by the absorbent clothes till no further moisture could be removed as shown in Figure 3.22 (iv).

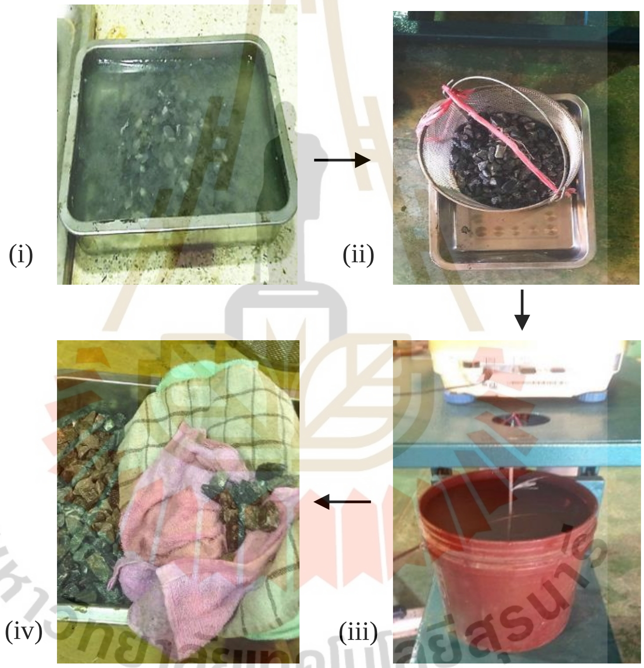


Figure 3.22 Specific gravity test of coarse aggregate

For fine aggregate, the dried aggregate was sieved to pass the 4.75 mm sieve and approximately 500 g was taken. This amount of sample was lately mixed with 6% of water (sample was closely to SSD condition with this percentage) and then leaved for about 2 hours as shown in Figure 3.23 (i). To obtain SSD condition of fine aggregate, slum test was performed as shown in Figure 3.23 (ii) until the sample failed as shown in Figure 3.23 (iii). Once the SSD was obtained, pycnometer filled with water as shown in Figure 3.23 (iv), pycnometer filled with approximately 250 g of SSD sample as shown in Figure 3.23 (v), and pycnometer filled with water and sample to the full level as shown in Figure 3.23 (vi) were recorded. This set was gently agitated for at least 10 min to remove the air bubbles as shown in Figure 3.23 (vii). All contents inside pycnometer were removed and dried in the oven over night.

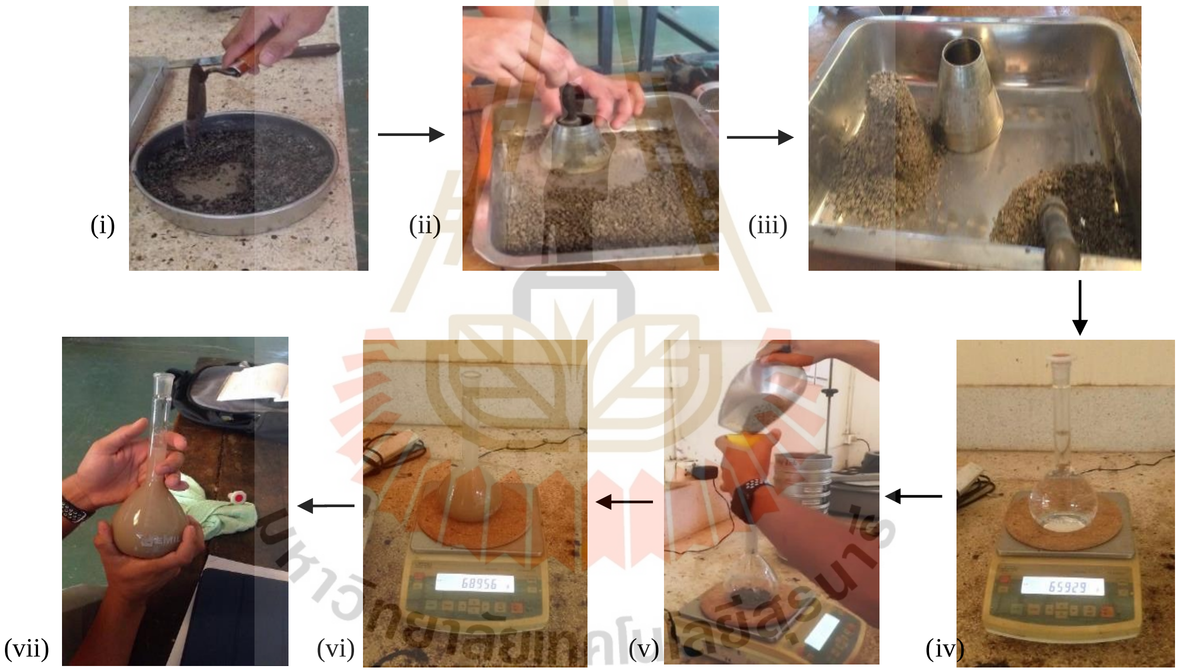
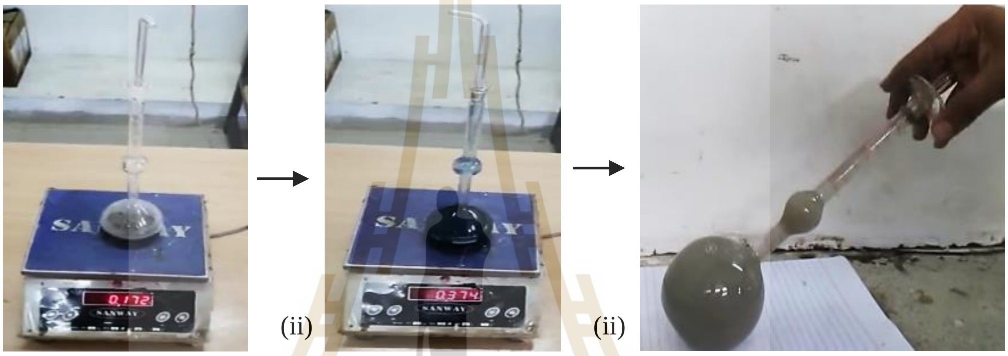


Figure 3.23 Specific gravity test of fine aggregate

Specific gravity of Portland cement was determined (ASTM C136) differently from that of coarse and fine aggregate. Weight of empty pycnometer (A), pycnometer partially filled with Portland cement (B), pycnometer filled with Portland cement and kerosene to full level (C), and pycnometer filled with kerosene to full level (D) were determined as shown in Figure 3.24. After the required values were obtained, specific gravity of Portland cement can be determined as shown in equation (3.3). In this study, two replications were done to obtain the specific gravity of each aggregate and filler.

$$G_s = \frac{B - A}{0.79\left((B - A) - (C - D)\right)} \tag{3.3}$$



(i) (ii) (ii)

Figure 3.24 Specific gravity test of Portland cement

3.2.2.3 Los Angeles abrasion test

Los Angeles (LA) abrasion test in accordance with ASTM C131 was used to determine the strength of 12.5 and 9.5 mm aggregate. Apparatus including standard steel balls, rotating LA machine, 1.7 mm sieve, and containers were used. Grade B method was applied for 12.5 mm aggregate while grade D method was applied for 9.5 mm aggregate. To obtain LA value of each aggregate, the test was performed twice. Figure 3.25 shows the samples after rotating and sieving on 1.7 mm sieve.

(i) 9.5 mm aggregate (ii) 12.5 mm aggregate

Figure 3.25 Samples after rotating

3.2.2.4 Flakiness and elongation test

Flakiness and elongation test (ASTM D4791) were used to determine the flatness and elongation of 12.5 and 9.5 mm aggregate. Apparatus including standard sieves (19, 12.5, 9.5, 4.75, and 2.36 mm), elongation gauge as shown in Figure 3.26 (i), and flakiness gauge as shown in Figure 3.26 (ii) were used.

(i)

(ii)

Figure 3.26 (i) elongation gauge and (ii) flakiness gauge

To conduct these two tests (performed twice), dried aggregates were sieved based on the required standard sieves and then those aggregates were reduced to the desired amount. Approximately 250 particles of 12.5 mm aggregate and 300 particles of 9.5 mm aggregate were carefully selected. Figure 3.27 shows the aggregate separation after flat and elongation test ((i) represents for the elongate particles, (ii) represents for the flat particles, and (iii) represents for the round particles).

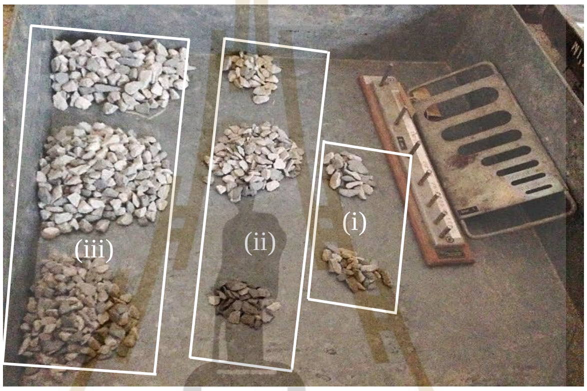


Figure 3.27 Aggregate separation for flakiness and elongation test

The basic properties of aggregates and filler including specific gravity, water absorption, LA abrasion, flakiness and elongation are summarized in Table 3.2 and the detailed as given in Appendix II.

Table 3.2 Basic properties of aggregates and filler

Property	Unit	Test method	Spec.	Aggregates			PC
				1/2''	3/8''	DC	
Proportion	%	ASTM C136	-	72	10	10	8
Specific gravity	-	ASTM C128/127	2.5 - 3.0	2.65	2.66	2.65	2.9
Water absorption	%	ASTM C128/127	2	1.18	1.24	1.23	-
LA abrasion	%	ASTM C131	30	28	28	-	-
Flakiness	%	ASTM D4791	10	8.70	9.47	-	-
Elongation	%	ASTM D4791	10	8.06	8.46	-	-

Note: Spec. = specification, 1/2" = 12.5 mm, 3/8" = 9.5 mm, DC = dust rock, and PC = Portland cement

3.2.3 Coconut fiber

Coconut fiber using in this study was obtained from Sichon district, Nakhon Si Thammarat Province, southern part of Thailand. The color of this fiber was brown and its lengths ranged between 200 - 300 mm-long. Various properties were measured and tested including dimensions, tensile strength, flash and fire point, water absorption, and PH.

3.2.3.1 Dimension measurement

The dimensions of coconut fiber including diameter and length were measured by vernier. The adopted coconut fiber was up to 300 mm as shown in Figure 3.28, and then it was cleaned (shake to take the dust out and select the remained husk out) and cut by scissor into the designed lengths including 5 - 20 mm, 20 - 40 mm, and 40 - 60 mm-long as shown in Figure 3.29.

Figure 3.28 The original coconut fiber

(i) 5 - 20 mm

(ii) 20 - 40 mm

(iii) 40 - 60 mm

Figure 3.29 The designed length of coconut fiber

3.2.3.2 Flash and fire point test

Flash and fire point of coconut fiber were found as those of AC60/70. Approximately 50 g of coconut fiber was weighted and three samples were tested. The coconut fiber was heated over the hot plate in the rate of 10^{o}C/min measuring by sensor. Flash point was the temperature in which the ignition occurred as shown in Figure 3.30 (i) while fire point was the temperature in which the fire occurred as shown in Figure 3.30 (ii). The test was retested when the difference of two average temperatures was more than 5 - 10^{o}C. The flash and fire point test were conducted to ensure the safety during the mixing period. These both temperatures were found to be higher than 200^{o}C which indicated that coconut fiber could be used without causing fire during the mixing period.

(i) (ii)

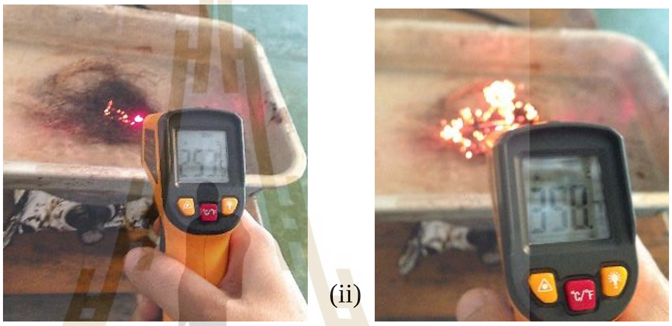


Figure 3.30 (i) flash and (ii) fire point of coconut fiber

3.2.3.3 Water absorption test

Water absorption of coconut fiber was found as that of coarse aggregate. To obtain this property, approximately 100 g of coconut fiber was soaked overnight and were then removed and kept in the oven overnight (80 - 100^{o}C). Three samples were prepared and tested and its results were averaged.

3.2.3.4 Tensile strength test

Tensile strength of coconut fiber (ASTM D3822/D3822-14) was found like the other materials (such as steel) but tensile load and holding specimen equipment were taking in consideration. It was tested by INSTRON machine with the tensile mode of 5 kN load cell and the cross head speed of 0.1

mm/min. This test was applied on 10 mm, 30 mm, and 50 mm-long coconut fiber which were the average length of each designed length and 3 replications were tested for each average length. The tensile load making fiber tear apart as shown in Figure 3.31 was recorded to determine the tensile strength.

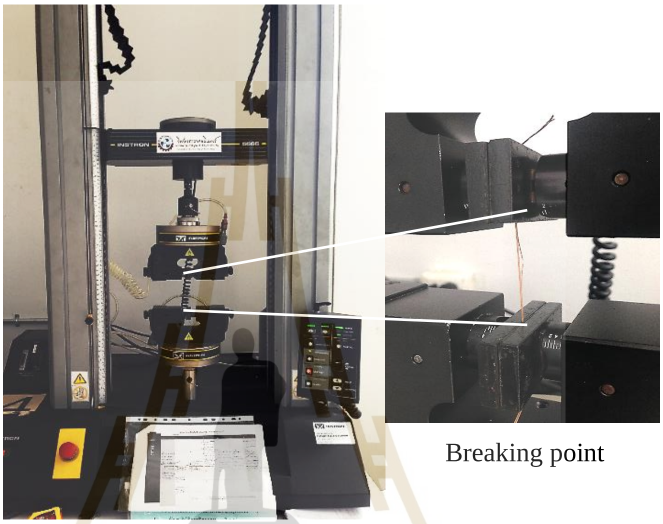


Figure 3.31 Tensile strength test of coconut fiber

The tensile strength of coconut fiber as shown in Table 3.3 was obtained by dividing the maximum tensile load (N) at the breaking point to the breaking area (mm) as in equation (3.4).

$$Tensile\ strength = \frac{Max\ load}{3.14(Diameter)^2} \tag{3.4}$$

The tensile strength was conducted to ensure that coconut fiber has enough strength to prepare for SMA mixtures. As the result, the tensile strength of coconut fiber in this study were found between 100 - 150 kPa, which were similar to Vale et al. (2013) and higher than Panda et al. (2013).

3.2.3.5 PH test

PH was determined according to ASTM D2165. Approximately 20 g of coconut fiber (cut into short length of about 20 mm) was soaked overnight as shown in Figure 3.32 (i). After those soaking periods, PH was measured by OAKTON machine as shown in Figure 3.32 (ii) and its average result was determined as the PH. There were 5 samples were prepared and tested for this property.

(i)

(ii)

Figure 3.32 PH test for coconut fiber

The basic properties of coconut fiber including water absorption, tensile strength, flash and fire point, and PH value are summarized in Table 3.3. The detail of these test results are shown in Appendix III. Table 3.4 shows the summary of materials using in this study.

Table 3.3 Basic properties of coconut fiber

Properties	**Unit**	**Test method**	**Test result**
Water absorption	%		1.29
Tensile strength	N/mm^2	ASTM D3822/D3822-14	100 - 150
Flash point	^{o}C	-	> 200
Fire point	^{o}C	-	> 200
PH	-	ASTM D2165-94(2002)e14	5.65

Table 3.4 The summary of the materials using in this study

Material	**Detail**
AC60/70	Designed content: 6, 6.5, and 7%
Coconut fiber	Length: 5 - 20, 20 - 40, and 40 - 60 mm-long
	Designed concentration: 0, 0.1, 0.3, 0.5, and 0.7%
Gradation	12.5 mm NMAS
Filler	Portland cement (8% of 1,200 g)
Aggregates	12.5 mm (72% of 1,200 g), 9.5 mm (10% of 1,200 g) and dust rock (10% of 1,200 g)

3.3 SMA mixtures design

In this section, the selection of 12.5 mm NMAS gradation, characterization of mixtures, and the estimation of number of mixtures based on stability, specific gravity of uncompacted mixture (G_{mm}), draindown, and TSR are presented and discussed.

3.3.1 Selection of 12.5 mm NMAS gradation

After the performance of each single sieve, the proportion to produce the blended 12.5 mm NMAS was determined. As indicated in Table 3.4, 72% of 12.5

mm aggregate, 10% of 9.5 mm aggregate, 10% of dust rock, and 8% of Portland cement were combined to produce the 12.5 mm NMAS as shown in Figure 3.33.

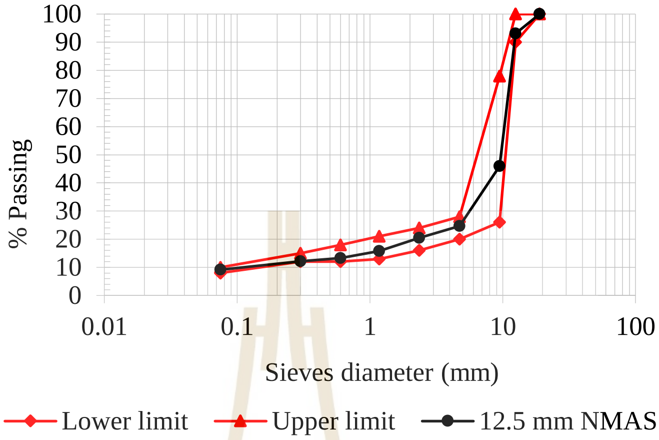


Figure 3.33 The selected gradation of this study

3.3.2 Mixture characteristics

Three types of coconut fiber lengths including 5 - 20, 20 - 40, and 40 - 60 mm-long and various contents including 0%, 0.1 - 0.7% (0.2% increment) were used to mix with AC60/70 incorporated with 12.5 mm NMAS for SMA mixtures. Mixtures containing 0% of coconut fiber were mixed with 5.5 - 7% of AC60/70 (0.5% increment) while those containing 0.1 - 0.7% of coconut fiber were mixed with 6 - 7% of AC60/70 (0.5% increment).

According to the standard, SMA requires at least 6% of asphalt content to mix with 1,200 g blended aggregate. In this study, three samples were tested for Marshall Stability and G_{mm}, 2 samples were tested for draindown test, and 6 samples were tested for TSR (only to those which passed the stability and draindown requirements). Table 3.5 shows the list of sample number using in this study.

Table 3.5 List of sample number using in this study

Coconut fiber mm	%	AC60/70 %	Stability No.	G_{mm} No.	Draindown No.	TSR No.
0	0	5.5	3	3	2	-
		6	3	3		
		6.5	3	3		
		7	3	3		
5 - 20	0.1	6	3	3	2	-
		6.5	3	3		
		7	3	3		
	0.3	6	3	3	2	6
		6.5	3	3		
		7	3	3		
	0.5	6	3	3	2	6
		6.5	3	3		
		7	3	3		
	0.7	6	3	3	2	6
		6.5	3	3		
		7	3	3		
20 - 40	0.1	6	3	3	2	-
		6.5	3	3		
		7	3	3		
	0.3	6	3	3	2	6
		6.5	3	3		
		7	3	3		
	0.5	6	3	3	2	6
		6.5	3	3		
		7	3	3		
	0.7	6	3	3	2	-
		6.5	3	3		
		7	3	3		
40 - 60	0.1	6	3	3	2	-
		6.5	3	3		
		7	3	3		

Table 3.5 List of sample number using in this study (Continued)

Coconut fiber mm	%	AC60/70 %	Stability No.	G_{mm} No.	Draindown No.	TSR No.
	0.3	6	3	3	2	6
		6.5	3	3		
		7	3	3		
	0.5	6	3	3	2	6
		6.5	3	3		
		7	3	3		
	0.7	6	3	3	2	-
		6.5	3	3		
		7	3	3		
Total number of mixture			120	120	26	42

Note that the draindown and TSR were tested at OAC.

3.4 Determination of optimum asphalt content (OAC)

The determination of OAC of each SMA mixtures were obtained based on the process as illustrated in Figure 3.34 below.

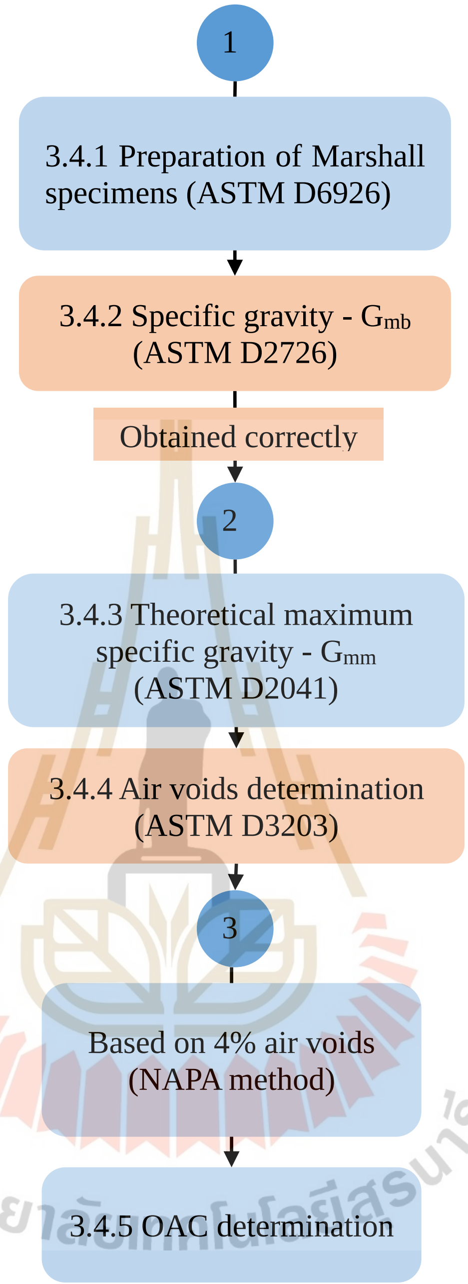


Figure 3.34 The process of the determination of OAC

3.4.1 Preparation of Marshall specimen

The preparation of Marshall stability based on ASTM D6929 was followed to prepare the specimens for Marshall stability test and for other compacted mixtures. The first step is the heating of each material including the blended aggregate and the AC60/70. The blended aggregate (1,200 g) was heated at mixing temperature (170^{o}C) for 24 hours while the AC60/70 was heated below heating temperature (approximately 100^{o}C) for 30 min. The second step is the mixing of mixture which was done into two sup step. The blended aggregated was thoroughly mixed with the coconut fiber content (0, 0.1, 0.3, 0.5, and 0.7% by mass), then suddenly the AC60/70 content (5.5, 6, 6.5, and 7% by mass) was added and the whole mixture was remixed until it was uniform. The next step is the compaction of mixture which was done by the auto compacted machine and 50 blows of the standard hammer were applied on each side of the specimen in order to obtain a specimen of 63.5 ± 3 mm of height and 101 ± 0.5 mm in diameter after the extraction. The procedure of preparation of Marshall specimen is illustrated as shown in Figure 3.35.

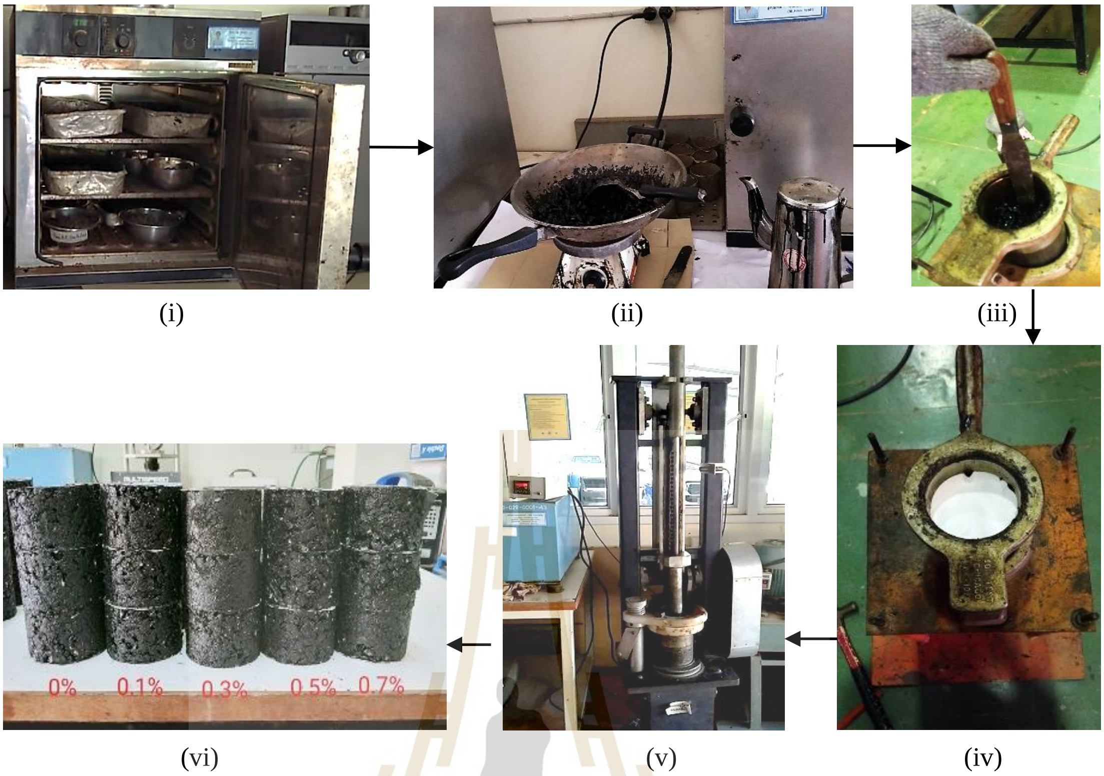


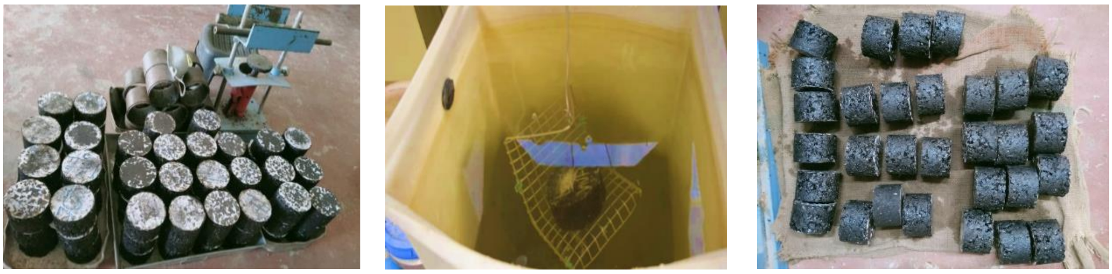
Figure 3.35 Preparation f Marshall specimens

Note: (i) heating, (ii) mixing, (iii) transferring, (iv) placing a paper before transferring and after the 25 rods, (v) compacting, and (vi) specimen after extracting.

3.4.2 Specific gravity of compacted mixture (G_{mb})

The specific gravity of compacted mixture, G_{mb}, was determined immediately on specimens which were extracted after 24 hours. The compacted mixtures were weighted in air (A), in water (B), and in SSD condition (C) as shown in Figure 3.36. These weight were then used to determine the G_{mb} as shown in equation (3.4).

$$G_{mb} = \frac{A}{C-B} \tag{3.4}$$



(A) (B) (C)

Figure 3.36 The specific gravity - G_{mb} test

3.4.3 Theoretical maximum specific gravity

The theoretical maximum specific gravity, G_{mm}, was determined on the uncompacted mixtures itself (ASTM D2041). Mixtures were mixed based on its correspondence asphalt and coconut fiber contents. Apparatus including balance, 2,000 ml glass pycnometer, vacuum pump, water bath, thermometer, and timer were used. To obtain the G_{mm}, samples were firstly mixed and then kept to cool to room temperature overnight as shown in Figure 3.37 (A). Then weight of empty pycnometer as shown in Figure 3.37 (B), weight of pycnometer filled with water to full level as shown in Figure 3.37 (C), weight of pycnometer partially filled with mixture as shown in Figure 3.37 (D), and weight of pycnometer partially filled with mixture and water to full level was cured at 25^{o}C for 10 ∓ 1 min as shown in Figure 3.37 (E) were recorded. After that, the set was vacuumed to take off the air bubbles with pressure of approximately 30 mm Hg for 10 ∓ 1 min as shown in Figure 3.37 (F), and after vacuuming, the set was fully filled with water and then recorded as shown in Figure 3.37 (G). After the test performance, G_{mm} of each mixture was determined as in equation (3.5).

$$G_{mm} = \frac{D-B}{[(D-B)+C)]-G} \tag{3.5}$$

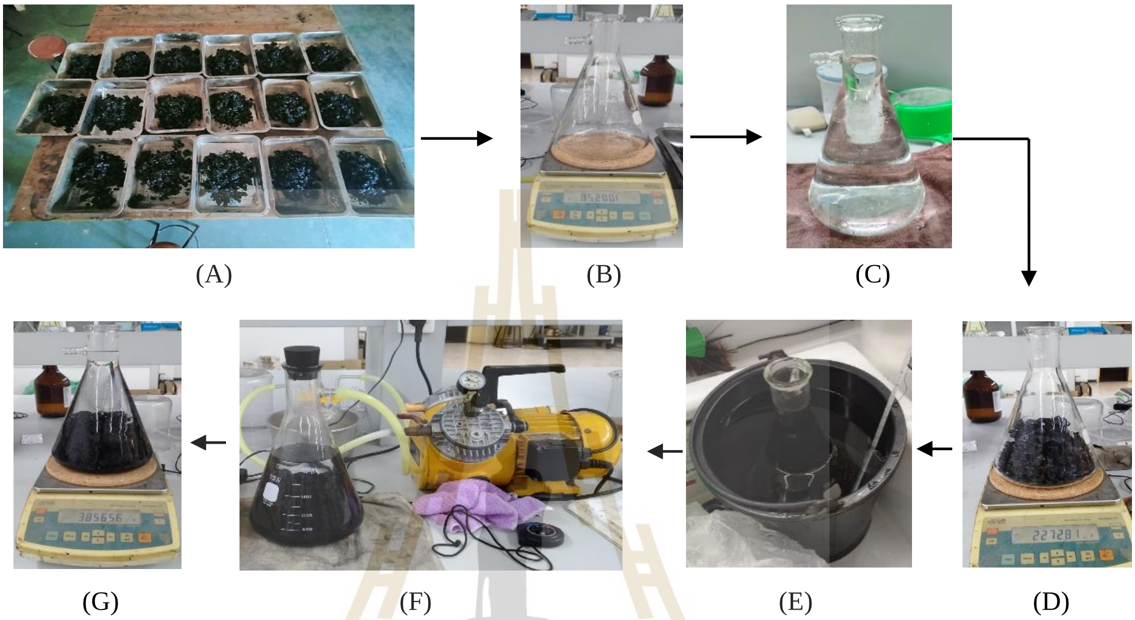


Figure 3.37 The theoretical maximum specific gravity test

3.4.4 Air voids determination

Air voids (AV) of compacted mixtures is defined as the total volume of the small air pockets between the asphalt-coated aggregate particles throughout a compacted mixture (NCHRP, 1999). The air voids of each SMA mixtures was determined as shown in equation (3.6) after the determination of G_{mb} and G_{mb} were obtained correctly.

$$AV\ (\%) = 100\frac{G_{mm} - G_{mb}}{G_{mm}} \tag{3.6}$$

3.4.5 OAC determination

There are two methods including NAPA procedure and AI method used to determine the OAC (NAPA, 1996). In this study, NAPA procedure was followed in order to obtain the OAC of all job mixes. To determine OAC, 3 samples were prepare for each asphalt content (6, 6.5, and 7%). It was proposed by NCHRP (1999) that at the target OAC the air voids shall be 4%. The OAC of all job mixes therefore were chosen to be evaluated depending on 4% air voids. Figure 3.38 shows the determination of OAC of mixture containing 0% coconut fiber. This OAC was then used to project to find VMA, VCA_{mix}, stability; and to determine the draindown, VCA_{drc}, and TSR. The OAC determination of other contents of coconut fiber are presented in Appendix IV.

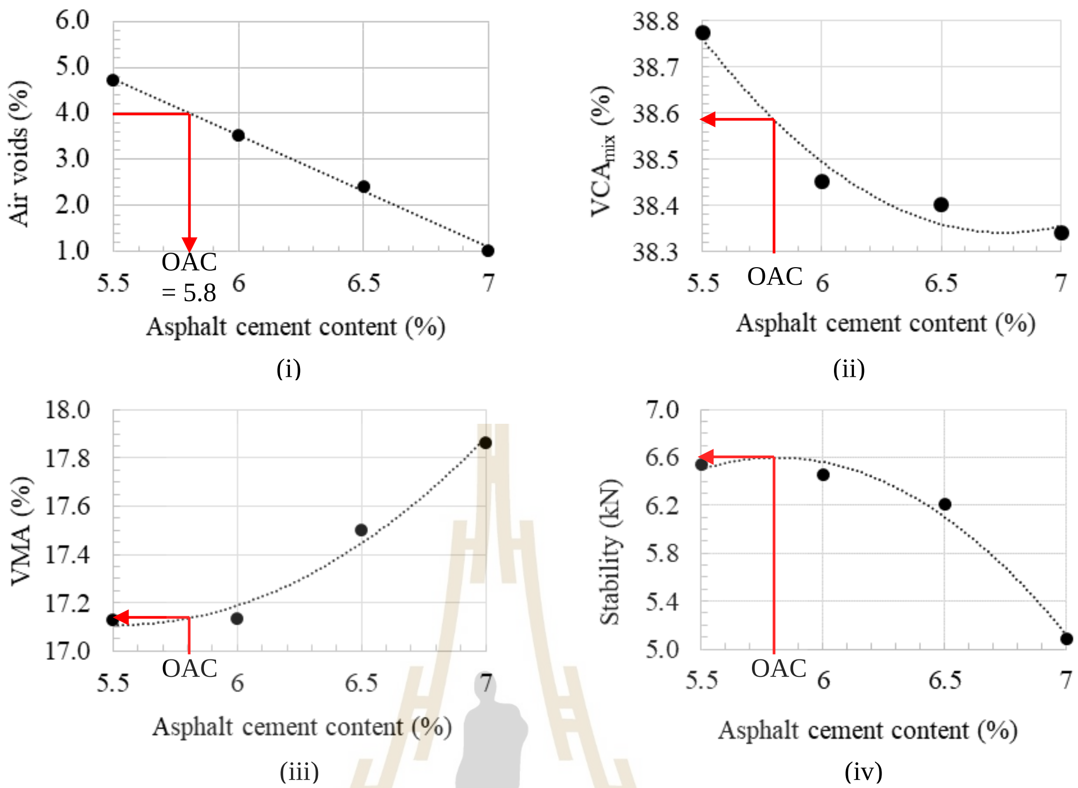


Figure 3.38 An illustration of OAC determination of 0% coconut fiber

3.5 Determination of optimum coconut fiber

The optimum coconut fiber including length in mm and percent were determined based on the requirements of SMA as shown in Table 3.6. Some requirements were already described and discussed above, the rest requirements including stability, VCA_{drc}, VCA_{mix}, draindown, and TSR are presented and given below.

Table 3.6 SMA mixture specifications for Marshall hammer compacted designs

Property	**Requirement**
Air voids (%)	4.0 [1]
VMA (%)	17 min
VCA_{mix} (%)	Less than VCA_{drc}
Stability (N)	6,200 min [2]
TSR (%)	70 min
Draindown at production temperature (%)	0.30 max

Note: [1] For low traffic volume roadways or colder climates, air void contents less than 4.0% can be used, but should not be less than 3.0%. [2] Successful SMA mixtures have been designed with Marshall Stability values below 6,200 N, therefore this requirement can be waived based on experience.

Source: NCHRP (1999)

3.5.1 Voids in mineral aggregate

Voids in mineral aggregate, VMA, was determined as equation (3.7) right after the recording of weight of mixture in air, in water, and in saturated surface dry condition were done.

$$VMA\ (\%) = 100 \times \left(1 - \frac{G_{mb}\,(1 - AC/100)}{G_{sb}}\right) \tag{3.7}$$

where, AC is the percent of AC60/70

G_{sb} is the specific gravity of the blended aggregate which is determined as shown in equation (3.8).

$$G_{sb} = Sum[(G_s \; of \; each \; aggregate \; and \; filler) \times \% \; of \; each \; aggregate \; and \; filler)]$$

$$G_{sb} = [G_s(12.5\,mm) \times \%(12.5\,mm)] + [G_s(9.5\,mm) \times \%(9.5\,mm)]$$

$$+ [G_s(Dust\ rock) \times \%(Dust\ rock)] + [G_s(PC) \times \%(PC)] \tag{3.8}$$

3.5.2 Voids of coarse aggregate in the compacted mixture

Voids of coarse aggregate in the compacted mixture, VCA_{mix}, was determined as shown in equation (3.9).

$$VCA_{mix}(\%) = 100 - \frac{G_{mb} P_{bp}}{G_{CA}} \tag{3.9}$$

But, $P_{bp} = (100 - \%OAC) \times \left(\frac{100 - P_{CA}}{100}\right)$

Where, P_{CA} is the percent aggregate by total aggregate mass retained on 4.75 mm,

G_{CA} is the combined specific gravity of coarse aggregate which can be determine as shown in equation (3.10).

$$G_{CA} = [G_s(12.5\,mm) \times \%(12.5\,mm)] + [G_s(9.5\,mm) \times \%(9.5\,mm)] \tag{3.10}$$

3.5.3 Voids of coarse aggregate in dry rode condition

The voids of coarse aggregate in dry rode condition, VCA_{drc}, was determined according to T19 (AASHTO T19). To obtain the VCA_{DRC} as shown in equation (3.11), three samples were prepared and tested.

$$VCA_{drc}(\%) = 100 \times \frac{G_{CA}\gamma_w - \gamma_s}{G_{CA}\gamma_w} \tag{3.11}$$

where, G_{CA} is the specific gravity of 12.5 and 9.5 mm aggregate

γ_w is the unit weight of water (1,000 kg/m^3)

γ_s is the unit weight of coarse aggregate in dry rod condition (kg/m^3) and it was determined on 12.5 and 9.5 mm

3.5.4 Marshall stability test

Marshall Stability test was performed right after the determination of volumetric properties were done correctly. The compacted specimens were soaked at 60°C water for 24 hours. Then the load was applied on each specimen and the peak load was recorded as the stability (ASTM D6927, NCHRP, 1999). The process to determine the stability of mixtures is shown in Figure 3.39.

(i) (ii) (iii)

Figure 3.39 Marshall Stability test

Note (i) soaking, (ii) compression, and (iii) the specimen before the test and the failed specimens.

3.5.5 Draindown test

Draindown test following by ASTM D6390-11 was used to determine the draindown characteristic of mixtures. Uncompacted samples were prepared for the draindown test. The uncompacted mixture was pour into 1,000 ml glass beaker as shown in Figure 3.40 (i) and then kept for 1 hour in the oven at mixing temperature as shown in Figure 3.40 (ii). After then, mixture was pour out of the glass beaker without shaking force as shown in Figure 3.40 (iii). The remained mixtures sticking inside the glass beaker as shown in Figure 3.41 were used to determine the draindown. In this test, two samples of each OAC were tested and the average values were recorded and used to determine the draindown as shown in equation (3.12).

(i) (ii) (iii)

Figure 3.40 Procedure to determine driandown of all mixtures

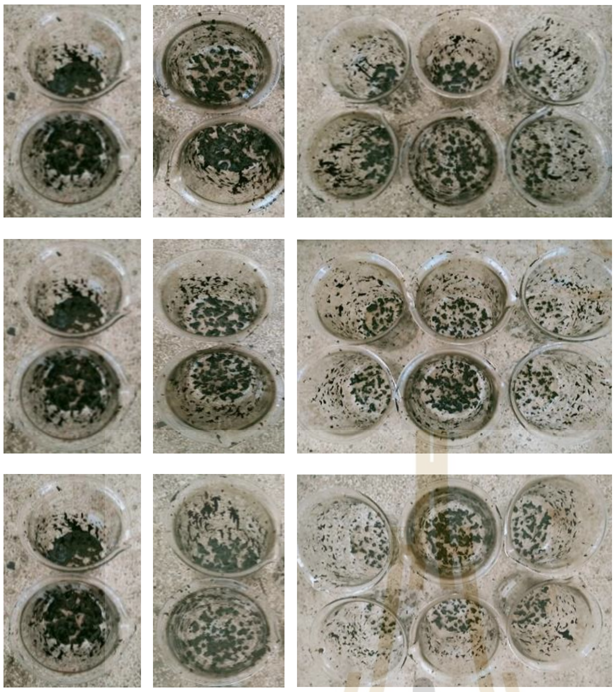
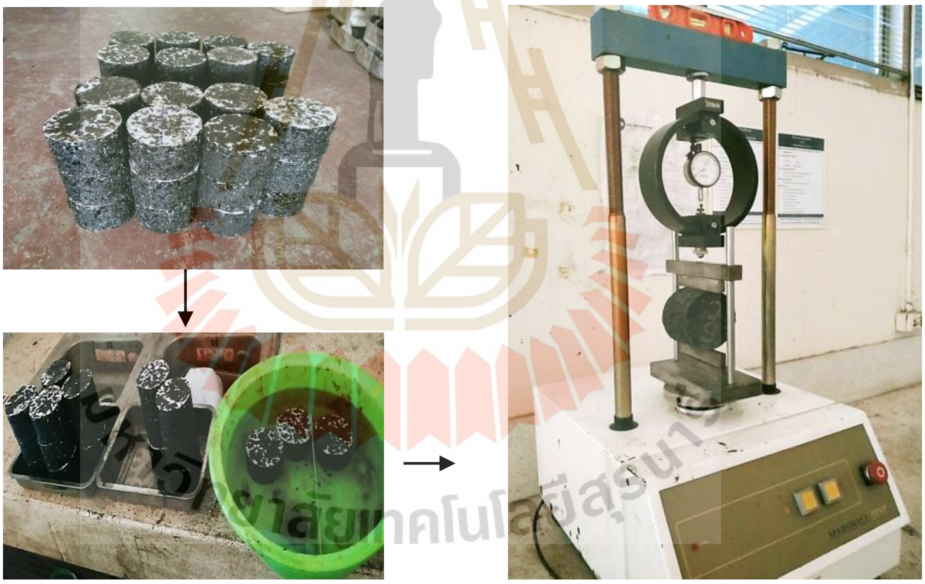


Figure 3.41 Remained mixtures after testing

$$Draindown\ (\%) = 100 \times \frac{\mathrm{Re}\,mained\ mixture}{Initail\ mixture} \tag{3.12}$$

3.5.6 Tensile strength ratio

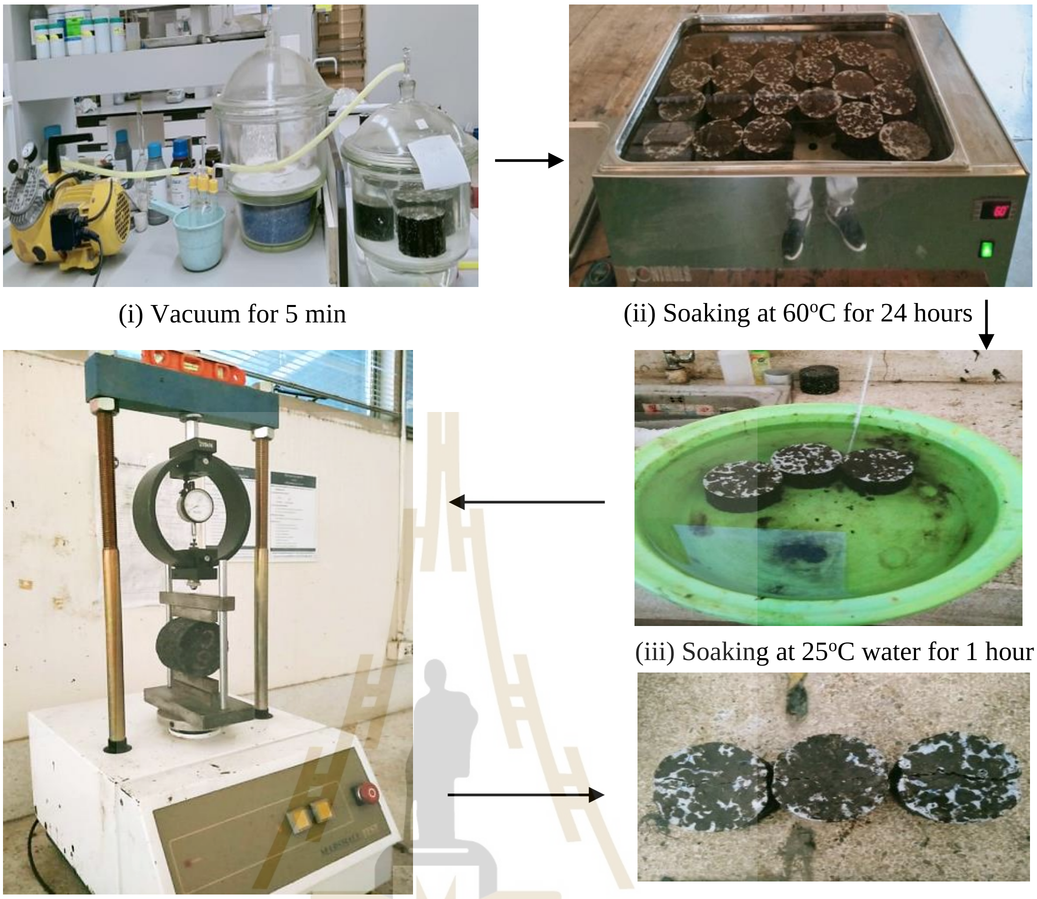
Tensile strength ratio (TSR) was determined by ratio of the tensile strength of water conditioned specimens to the tensile strength of unconditioned specimens. The static indirect tensile strength (ITS) test according to ASTM D6931 and ASTM D4867 were conducted in this study. These both tests were conducted to those mixtures passing stability and draindown requirements only. To be able to obtain TSR of SMA mixtures, 6 samples were prepared and divided into three each of unconditioned ITS (ASTM D6931) and conditioned ITS (ASTM D4867). Samples of unconditional ITS were maintained at least 1 hour but not more than 2 hours at 25°C while samples of conditioned ITS were maintained at 25°C within the vacuum suction (70 kPa or 525 mmHg) such as 5 min in order to get the samples to reach its degree of saturation (volume of water is between 55 and 80 % of the volume of air). After samples reached its degree of saturation, they were maintained 24 hours more at 60°C water bath and then proceed another 1 hour in 25°C water bath. After the above mentioned criteria were met, static ITS tests of each group were subjected as shown in Figure 3.42 - 3.43, respectively. The peak loads were recorded to determine the static ITS (St) and TSR.



(i) Soaking samples at 25°C for 30 min

(ii) ITS test

Figure 3.42 ITS test for unconditioned samples



(i) Vacuum for 5 min
(ii) Soaking at 60°C for 24 hours
(iii) Soaking at 25°C water for 1 hour
(iv) ITS test
(v) Failure samples

Figure 3.43 ITS test for conditioned samples

(i) Samples before ITS
(ii) Failure of samples
(iii) Inside the failure

Figure 3.44 Static ITS test for both un- and conditioned samples

Figure 3.45 shows the samples before and after ITS test. The peak load was used to determine the TSR as shown in equation (3.13).

$$TSR\ (\%) = \frac{ITS\ of\ conditioned\ sample}{ITS\ of\ unconditioned\ sample} \tag{3.13}$$

when, $$ITS\ (kPa) = \frac{2000 \times P}{\pi \times h_{average} \times d}$$

where, P is the peak load in N,

$h_{average}$ is the average height of specimen in mm,

d is the diameter of the specimen in mm.

CHAPTER IV

RESULTS AND DISCUSSION

The engineering properties including volumetric properties, Marshall stability, draindown, ITS, and TSR of SMA mixtures mixing with and without coconut fiber are given and discussed.

4.1 Influence of coconut fiber on OAC and volumetric properties

4.1.1 Optimum asphalt content (OAC)

The volumetric properties including AV (air voids), VMA (voids in mineral aggregate), VCA_{mix} (voids of coarse aggregate in compacted mixture), G_{mb} (specific gravity of compacted mixture) of mixtures with various contents and lengths of coconut fiber at OAC are presented in Table 4.1 and shown through Figure 4.1 - 4.4. VCA_{drc} (voids of coarse aggregate in dry rod condition) was also determined as shown in Figure 4.3.

Figure 4.1 shows the results of OAC of each mixture containing various contents and lengths of coconut fiber. The vertical axis represents the percent OAC while the horizontal axis represents the percent coconut fiber content. It is seen that the OAC of SMA mixtures without coconut fiber (OAC = 5.8%) is lower than the SMA mixtures with coconut fiber. It is due to the fact that mixtures containing 0% fiber and AC60/70 of more than 6% tend to have lower air void (mixture sufficiently coated).

Table 4.1 Results of OAC and volumetric properties of each mixture

Coconut fiber		OAC	AV	VMA	VCA_{drc}	VCA_{mix}	G_{mb}	G_{mm}
mm	%	%	%	%	%	%		
0	0	5.80	4.15	17.08	42.61	38.55	2.354	2.456
5 - 20	0.1	6.00	4.11	17.32	42.61	38.72	2.352	2.453
	0.3	6.15	4.05	17.86	42.61	39.12	2.340	2.439
	0.5	6.30	3.96	18.09	42.61	39.29	2.338	2.434
	0.7	6.40	3.96	19.08	42.61	40.01	2.312	2.407
20 - 40	0.1	6.00	4.10	17.95	42.61	39.19	2.334	2.434
	0.3	6.10	4.08	18.41	42.61	39.53	2.324	2.422
	0.5	6.35	3.97	19.56	42.61	40.38	2.297	2.392
	0.7	6.48	4.02	19.90	42.61	40.58	2.290	2.386
40 - 60	0.1	6.02	4.03	18.11	42.61	39.31	2.330	2.427
	0.3	6.12	4.00	18.59	42.61	39.67	2.319	2.416
	0.5	6.35	3.98	19.69	42.61	40.48	2.293	2.388
	0.7	6.50	3.97	20.24	42.61	40.81	2.281	2.375
Specification		6-7	4	≥ 17	$VCA_{drc} > VCA_{mix}$		-	-

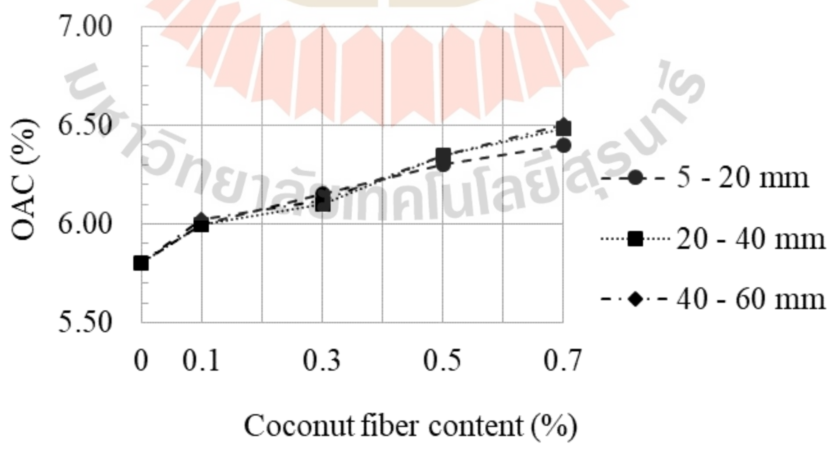


Figure 4.1 OAC of SMA mixtures with different contents and lengths of coconut fiber

It is also seen that the OAC of mixtures increase when coconut fiber content increases. It is due to the fact that in every additional coconut fiber content, mixtures need more asphalt content to provide a suitable coated area. This finding is in the agreement with the study of Panda et al. (2013) and Wo (2011). It is also seen that the OAC of mixtures containing different lengths and contents of coconut fiber share similar increase trends. The OAC of mixtures containing 0.1, 0.3, 0.5, and 0.7% of 5 - 20 mm-long coconut fiber are 6, 6.15, 6.3, and 6.4%, respectively; those of 20 - 40 mm-long coconut fiber are 6, 6.1, 6.35, and 6.48, respectively; and those of 40 - 60 mm-long coconut fiber are 6.02, 6.12, 6.35 and 6.5%, respectively. It is able to conclude that the OAC of mixtures depend on coconut fiber content rather than on coconut fiber length. The finding of such mixtures share similarities with the study of Beena and Bindu (2011). However, the results of OAC in this study are quite lower than those of Beena and Bindu's. The reason is that they used fine aggregate (30% by mass) and filler (11% by mass) higher than those (10% by mass for each type) of this study. The fine aggregate consists of particles passing through 4.75 mm sieve, it is therefore required more asphalt for absorption (NAPA, 1996).

4.1.2 Voids in mineral aggregate (VMA)

Figure 4.2 shows the results of VMA of mixtures containing various contents and lengths of coconut fiber. It is seen that mixtures containing 0% content of coconut fiber consist VMA almost equals to minimum value (17%). It is also seen that VMA of mixtures containing 20 - 40 mm-long and 40 - 60 mm-long coconut fiber has similar increase trends; while, those of 5 - 20 mm-long coconut fiber results the lowest. It is also seen that VMAs increase in every additional coconut fiber content. Additionally, VMA of mixtures rely on both contents and lengths of coconut fiber.

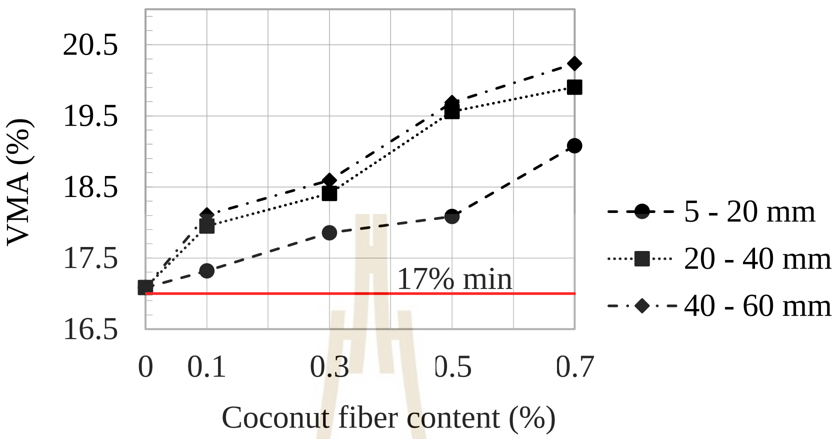


Figure 4.2 VMA of SMA mixtures with different contents and lengths of coconut fiber

4.1.3 Voids of coarse aggregate in compacted mixture (VCA_{mix})

Figure 4.3 presents the results of VCA of SMA (VCA_{mix}) mixtures containing various contents and lengths of coconut fiber. It is seen that increasing in coconut fiber content resulted in increase of VCA_{mix}. This is due to the additional coconut fiber content adding into mixtures.

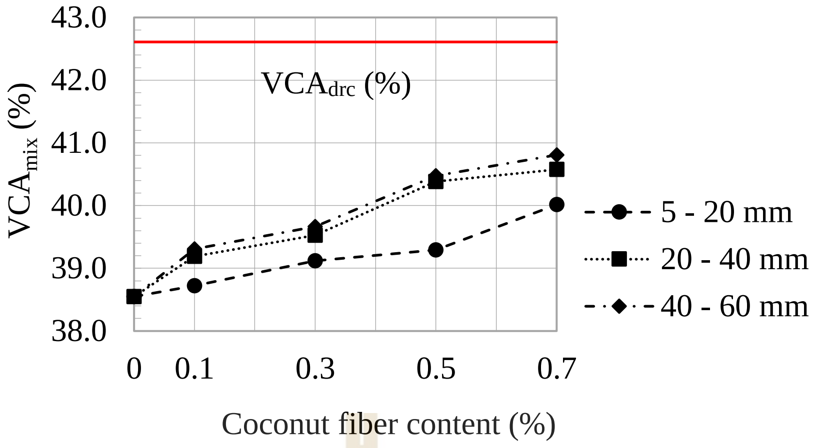


Figure 4.3 VCA_{mix} of SMA mixtures with different contents and lengths of coconut fiber

The VCA_{mix} of 20 - 40 and 40 - 60 mm-long coconut fiber increase in similar trend while the VCA_{mix} of 5 - 20 mm-long results the lowest. It is also seen that the VCA_{mix} of each SMA mixtures are lower than the VCA_{drc}, which indicated that these both properties comply with specifications.

4.1.4 Specific gravity G_{mb}

Figure 4.4 presents the results of G_{mb} of mixtures containing various contents and lengths of coconut fiber. It is observed that mixtures containing 5 - 20 mm-long coconut fiber provide the highest G_{mb} following by those of 20 - 40 mm-long and 40 - 60 mm-long. It is also seen that the G_{mb} of all mixtures decrease due to further coconut fiber addition. This trend is in agreement with other research (Tapkin, 2008; Saeed and Ali, 2008; Beena and Bindu, 2011). The G_{mb} was determined based on the weights of mixture in dry, water, and saturated surface dry condition (SSD). When mixtures contained high coconut fiber content, its weight in water was lower as compared to those mixing with low coconut fiber content. According to the investigation during the test, it could be the reason that the air bubbles were likely trapped to the mixtures containing high coconut fiber content. This therefore could be indicated that the air bubbles are likely to happen to mixtures consisting of high coconut fiber content.

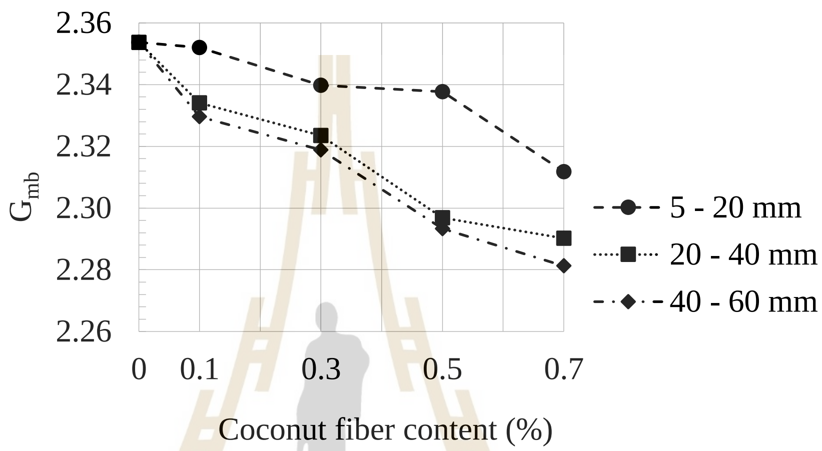


Figure 4.4 G_{mb} of SMA mixtures with different contents and lengths of coconut fiber

4.2 Influence of coconut fiber on stability

The results of Marshall Stability of mixtures mixing in various lengths and contents of coconut fiber are shown in Table 4.2 and Figure 4.5.

Table 4.2 Results of Marshall stability test of SMA mixtures

Coconut fiber		**Marshall stability**
mm	%	kN
0	0	6.46
5 - 20	0.1	6.78
	0.3	7.14
	0.5	6.73
	0.7	6.30
20 - 40	0.1	6.72
	0.3	7.07
	0.5	6.65
	0.7	6.14
40 - 60	0.1	6.68
	0.3	6.99
	0.15	6.37
	0.7	5.68
Specification		≥ 6.2

Figure 4.5 is used to present the Marshall Stability results of SMA mixtures. It is observed that the stability of all lengths of coconut fiber increase up to 0.3% content of coconut fiber, and thereafter decrease. This finding is similar to Beena and Bindu (2011) who stated that SMA mixture is a non-uniform which consists of aggregates, filler, and asphalt. It is therefore the excessive fiber could lead the mixture to have less uniformity so that the weak points may happen inside the mixture. It is also seen that the SMA mixtures without coconut fiber content provides the lowest stability compared to mixtures containing 0.1 - 0.5% but it's higher than 0.7% coconut fiber content. This could be indicated that the presence of coconut fiber significantly brings the improvement of stability (Beena and Bindu, 2011). However, after the fiber content

reaches a certain value, excessive fibers are unable to disperse uniformly in the mixture. Therefore, the coconut fiber content of 0.7% is not recommended. The requirement of stability is required to be at least 6.2 kN (NCHRP, 1999), it is therefore seen that these results are greater than the minimum requirement.

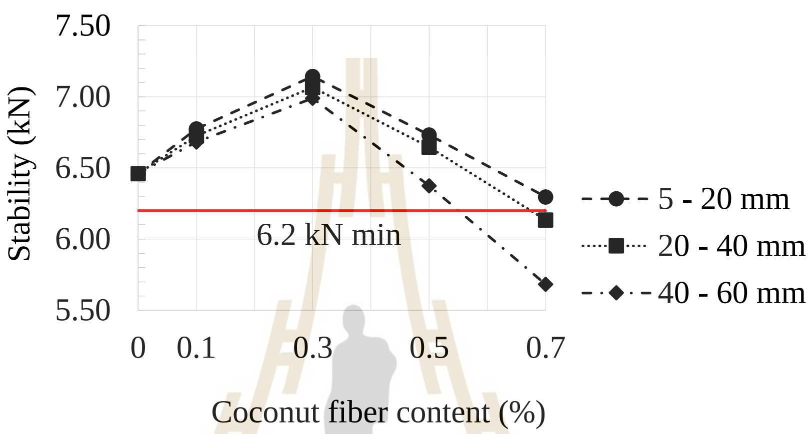


Figure 4.5 Marshall stability of SMA mixtures with different contents and lengths of coconut fiber

It is also seen that the results of stability of 5 - 20 mm-long coconut fiber show the highest value compared to other lengths. This is due to the fact that the shorter length is easy to mix, to compact, and also provides more homogeneity to mixtures. A research work from Bilu et al. (2018), studied on SMA mixtures characteristics using 8 mm-long coconut fiber have found out that the 0.3% of coconut fiber provided the highest stability as compared to the 0.3% of 5 - 20 mm-long coconut fiber in this study. Therefore, it can be indicated that the coconut fiber length of below 20 mm-long should be used to prepare for SMA mixtures in order to obtain the optimum results.

4.3 Influence of coconut fiber on draindown characteristic

The draindown test was conducted right after the results of OAC have already obtained. It means that the OAC of each correspondence mixtures were used as asphalt content for mixtures of the draindown test. The results of this test are shown in Table 4.3 and Figure 4.6. A typical SMA mixtures required draindown value (ASTM D 6390-1) of not greater than 0.3% (NCHRP, 1999).

Table 4.3 Results of draindown test of SMA mixtures

Coconut fiber		Draindown result
mm	%	%
0	0	0.56
5 - 20	0.1	0.37
	0.3	0.25
	0.5	0.23
	0.7	0.21
20 - 40	0.1	0.35
	0.3	0.20
	0.5	0.23
	0.7	0.17
40 - 60	0.1	0.32
	0.3	0.24
	0.5	0.27
	0.7	0.22
Specification		≤ 0.3

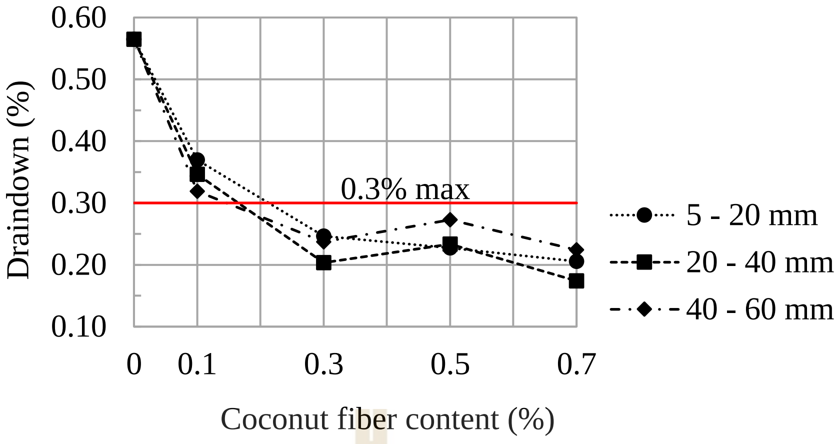


Figure 4.6 Percentage of draindown in SMA mixtures with different contents and lengths of coconut fiber

Figure 4.6 presents the results of draindown of SMA mixtures mixing with various coconut fiber lengths and contents. It is observed that the draindown results at 0 and 0.1% of any lengths of coconut fiber are higher than the maximum value (0.3%). In contrast, the draindown results of mixtures having 0.3, 0.5 and 0.7% of any lengths of coconut fiber are lower than the maximum value. According to specification taken from NCHRP (1999), draindown is specified to be lower than 0.3%. Therefore, it is seen that draindown of 0 and 0.1% of any lengths of coconut fiber are out of the prescript specification. This is due to the fact that the ability to absorb AC60/70 at these contents is lower as compared to other contents. Adding that, it may be due to the fact that the AC60/70 is not viscous enough (its adhesive force is not as strong as modified asphalt) to make these two contents meet the requirement. Modified asphalt such as polymer modified asphalt (PMA) shall be used to make these contents applicable (Panda et al., 2013). The viscosity of AC60/70 in this study was 42.01 cP at 165^{o}C while that of PMA requires at least 300 cP at 165^{o}C (Charoentham and

Ngamdee, 2019). The higher the viscosity value, the greater the adhesive force will be (NAPA, 1996). This could be indicated that the mechanism characteristic of PMA at high temperature is better (more adhesive force) than AC60/70. However, experiments shall be conducted and investigated when these contents are used with the other binder to prepare for SMA mixtures. This finding shares similarity with the study of Beena and Bindu (2011), who stated that the draindown of SMA mixture considerably decreased in every additional coconut fiber content and met the requirement at 0.3%. It is also observed that mixtures having all of coconut fiber lengths, the values of draindown decrease considerably with increase in coconut fiber content. It indicates that draindown is reduced by using coconut fiber and it is effected by content rather than length of coconut fiber adding into mixture.

4.4 Influence of coconut fiber on indirect tensile strength (ITS)

The indirect tensile strength (ITS) test was conducted after the result of VMA, VCA_{drc}, VCA_{mix}, Marshall Stability, and draindown loss of each mixtures are obtained. However, this test was conducted on any mixtures passing the requirements only. According to the illustration of previous Figure 4.1 - 4.5, it can be seen that each requirement is within prescript specifications except Marshall Stability at 0.7% of 20 - 40 mm and 40 - 60 mm-long coconut fiber. Adding that as seen in Figure 4.6, draindown of 0 and 0.1% of all coconut fiber lengths are higher than the maximum requirement. Therefore, the ITS test was conducted to those mixtures as shown in Table 4.4. The results of ITS of mixtures mixing with different coconut fiber lengths and contents for both unconditioned and conditioned samples are given in Table 4.4 and Figure 4.7 - 4.8.

Table 4.4 Results of unconditioned and conditioned ITS test of SMA mixtures

Coconut fiber		Unconditioned ITS	Conditioned ITS
mm	%	kPa	kPa
5 - 20	0.3	737.60	680.83
	0.5	680.85	603.00
	0.7	639.42	503.71
20 - 40	0.3	720.86	651.60
	0.5	676.67	549.49
40 - 60	0.3	705.47	630.47
	0.5	631.13	506.58

As shown in Figure 4. 7- 4.8, it is observed that mixtures containing 5 - 20 mm-long coconut fiber provide the highest unconditioned and conditioned ITS compared to other lengths. It is also observed that mixtures containing 0.3% content of any coconut fiber length provide the highest unconditioned and conditioned ITS compared to other contents. This can be explained that the shorter lengths bring more homogeneity but the longer lengths (at high content) are likely to stick together and perform to be the ball shape which could lead the mixtures to have less bonds between the fiber, binder and the aggregate. This happened when the addition of coconut fiber increased up to 0.5%. Additionally, mixtures mixing with 0.3% of 5 - 20 mm-long coconut fiber result the highest unconditioned and conditioned ITS among other variations.

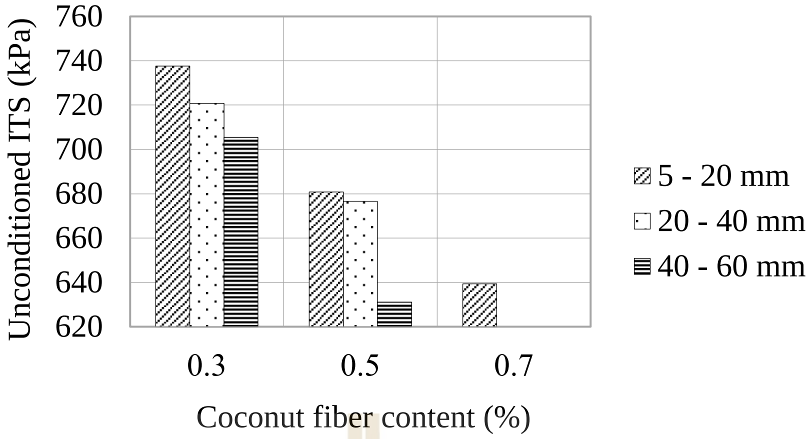


Figure 4.7 ITS of unconditioned SMA mixtures with different contents and lengths of coconut fiber

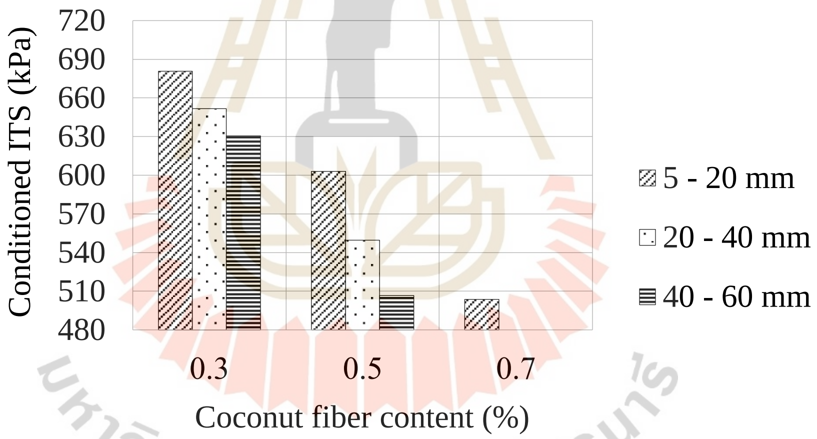


Figure 4.8 ITS of conditioned SMA mixtures with different contents and lengths of coconut fiber

4.5 Influence of coconut fiber on TSR and moisture susceptibility

Tensile strength ratio (TSR) of SMA mixtures is define as the ratio of conditioned to unconditioned ITS. The results of TSR of SMA mixtures mixing with various coconut fiber lengths and contents are given in Table 4.5 and Figure 4.10.

Table 4.5 Results of TSR test of SMA mixtures

Coconut fiber		**TSR**
mm	%	%
5 - 20	0.3	92.30
	0.5	88.57
	0.7	78.78
20 - 40	0.3	90.39
	0.5	81.20
40 - 60	0.3	89.37
	0.5	80.26
Specification		≥ 70%

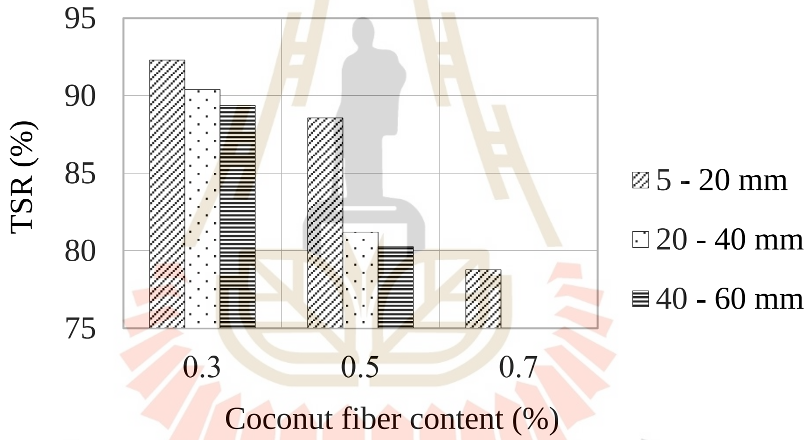


Figure 4.9 TSR of SMA with different contents and lengths of coconut fiber

Based on Figure 4.9, it is seen that the results of TSR at 0.3% content of coconut fiber are greater than those of 0.5% content. It is also seen that the results of TSR of 5 - 20 mm-long coconut fiber present the highest value following by 20 - 40 and 40 - 60 mm-long. This is due to the fact that the conditioned samples which consisted of higher coconut fiber content incorporated with longer length increased the ability of water absorption (during maintained at 60^{o}C for 24 hour). This finding which shares similarity to the study of Mohammadzadeh et al., (2014) and Vale et al., (2013) could indicated that the TSR yields to the optimum value when both conditioned and unconditioned samples consist of optimum amount of coconut fiber (0.3%) with the shorter length. SMA mixtures are required to have TSR at least 70% (NCHRP, 1999), it is therefore indicated that the above TSR results are greater than the prescript requirement.

Moisture susceptibility is defined as the extension of moisture damage (occurs due to the presence of moisture) in asphalt mixes and it is evaluated based on the results of TSR (Tayfur et al., 2007). Therefore, moisture susceptibility is reflected by the TSR. Therefore, it is able to indicate that the addition of only 0.3% content of any lengths of coconut fiber could significantly bring advantage in terms of improving the moisture susceptibility characteristics. This finding is similar to the study of Panda et al., (2013) and Beena and Bindu (2011).

4.6 The optimum coconut fiber

The optimum coconut fiber including contents and lengths are evaluated based requirements of SMA as shown in Table 4.1. As seen in Table 4.2, the VMA, AV, VCA_{mix}, and VCA_{drc} of mixtures are fallen in prescript requirements. Therefore, the optimum coconut fiber including content and length are evaluated based on results of Marshall Stability, draindown, and TSR. It is seen from Figure 4.5 that the mixture containing 0.3% of 5 - 20 mm-long coconut fiber provides the highest stability (7.14 kN) among the others. It is also seen from Figure 4.6 that mixtures reach the requirement of draindown at 0.3% content of all coconut fiber lengths. Moreover, it is observed from Figure 4.9 that mixture containing 0.3% of 5 - 20 mm-long coconut fiber provides the highest TSR (92.3%) compared to the others. Therefore, the optimum coconut fiber content is 0.3% (the same as Kumar and Ravitheja, 2019; Shravan, 2013; Panda et al., 2013; Beena and Bindu, 2011) for each coconut fiber length and the optimum coconut fiber length is 5 - 20 mm-long. The detailed results of chapter 4 are given in Appendix IV.

CHAPTER V

CONCLUSIONS AND SUGGESTIONS

In this chapter, the conclusions on various properties including volumetric properties, Marshall stability characteristics, draindown characteristics, ITS characteristics, TSR or moisture susceptibility, and optimum coconut fiber effected toward SMA mixtures are given and discussed. The suggestions for further study are also provided.

5.1 Conclusions

The following conclusions based on laboratory investigation on the properties of 12.5 mm NMAS SMA mixtures containing various coconut fiber length and content are made.

5.1.1 Engineering properties of SMA mixtures

Using the coconut fiber in SMA mixture resulted in significant increase in the engineering properties of SMA mixtures as follows:

1) Increasing the coconut fiber content in SMA mixture resulted in an increase in all volumetric properties except the G_{mm} which decreased due to further additional coconut fiber content. The volumetric properties of SMA mixtures with coconut fiber were improved compared to without fiber. This finding is in the agreement with Panda et al. (2013), Wo (2011), Beena and Bindu (2011), Tapkin (2008), and Saeed and Ali (2008).

2) The presence of coconut fiber provided the reducing of draindown in SMA mixtures which is in the agreement with the results of Beena and Bindu (2011).

3) Marshall stability, ITS, and TSR of SMA mixtures with coconut fiber were improved as compared to without coconut fiber. This finding is in the agreement with the finding of Vale et al. (2013) and Beena and Bindu (2011).

5.1.2 The influence of coconut fiber on properties of SMA mixtures

The influence of coconut fiber content and length on properties of SMA mixtures are:

1) Volumetric properties of SMA mixtures were effected by contents and lengths of coconut fiber. These properties were improved when the coconut fiber length decreased, and also improved when the coconut fiber was lower than 0.3%. This finding is similar to the study of Beena and Bindu (2011), Tapkin (2008), and Saeed and Ali (2008).

2) Marshall stability, ITS, and TSR of SMA mixtures were effected by both coconut fiber content and length. These properties considerably increased when the additional coconut fiber content increased up to 0.3%, and thereafter decreased. This finding is in the agreement with Panda et al. (2013), and Beena and Bindu (2011). Moreover these properties also significantly increased when the shorter length of coconut fiber was used.

3) The draindown was not depended on coconut fiber length but this property was depended on coconut fiber content adding into SMA mixtures. The draindown considerably reduced in every additional coconut fiber content. This finding shares similar conclusion as Panda et al. (2013) and Beena and Bindu (2011).

5.1.3 The optimum coconut fiber

In this study, three variations of coconut fiber length including 5 - 20, 20 - 40, and 40 - 60 mm-long with various contents of 0, 0.1, 0.3, 0.5, and 0.7% were used to prepare for 12.5 mm NMAS SMA mixtures. Based on the results, 0.3 and 0.5% of each coconut fiber length could pass the requirements. And among these both contents, the 0.3% content provided the highest stability and TSR as compared to other contents of the same coconut fiber length. Adding that the best overall results in terms of stability and TSR obtained when the 0.3% coconut fiber content and the 5 - 20 mm-long coconut fiber combined. Therefore, the optimum coconut fiber content and length for 12.5 mm NMAS SMA mix were 0.3% and 5 - 20 mm-long, respectively. This finding is similar to the finding of Kumar and Ravitheja (2019), Bilu et al. (2018), Shravan (2013), Panda et al. (2013), and Beena and Bindu (2011). These both optimum content and length could help the SMA mixtures to increase 10.52% stability and reduce 55.35% draindown as compared to without coconut fiber. Moreover, it could provide 1.91 and 2.93% TSR higher than 0.3% of 20 - 40 and 40 - 60 mm-long coconut fiber, respectively. Additionally, the best overall results based on stability and TSR were found on 12.5 mm NMAS SMA mix containing 0.3% of 5 - 20 mm-long coconut fiber.

5.2 Suggestions for further work

Suggestions are made on the following aspects:

1) Based on the results of this research study, the engineers shall be considered on the variation of coconut fiber length and content when this fiber is used in SMA mixtures.

2) For further study, fatigue and rutting tests shall be considered in order to deeply investigate the influence of coconut fiber content and length on SMA mixtures characteristic. The variation of other properties of coconut fiber e.g. resilience, strength, and age should also be considered.

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APPENDIX

APPENDIX I

PROPERTIES OF AC60/70

Table I.1 The results of penetration

Trial No.	Initial reading	Final reading	Penetration	Difference
1	0	6.78	67.80	0.20
	0	6.80	68.00	0.00
	0	6.65	66.50	1.50
2	0	6.70	67.00	0.00
	0	6.45	64.50	2.50
	0	6.55	65.50	1.50
3	0	6.75	67.50	0.50
	0	6.80	68.00	0.00
	0	6.55	65.50	2.50
		Penetration	66.70	Accepted
		Specification	60 - 70	
Condition:				
	Container	55 x 35 mm		
	Time	5 sec		
	Load	100 g		
	Temperature	25°C		
	Sample	1.5 hours cool to room temp and 1.5 hours maintain in 25°C water bath		
	Difference	Not greater than 4		

Table I.2 The results of softening point

Trial No.	Ring 1	Ring2	Unit	softening point	Difference	Specification
1	46.5	47	°C	46.75	0.5	Min 46°C
2	47	47.5	°C	47.25	0.5	
3	48.5	49	°C	48.75	0.5	
	Softening point		°C	47.58		Accepted
Condition:	Differences not greater than 1°C					

Table I.3 The results of flash and fire point

Method	Cleveland Open Cup			
Trial No.	Unit	Flash point	Fire point	Specification
1	°C	325.00	362.78	Min 220°C (Flash point)
2	°C	330	360	
	Average	327.50	361.39	

Table I.4 The results of ductility

Trial No.	Unit	Reading	Specification
1	cm	> 100	Min 100
2	cm	> 100	
3	cm	> 100	

Table I.5 Results of specific gravity and density

Trial No.	A	B	C	D	Gs	Density
1	28.30	54.50	48.05	55.52	1.0545	1051.29
2	29	54.7	48.50	55.56	1.0461	1043.00
			Average		1.0503	1047.15
			Specification		1.02 - 1.06	1020 - 1060

Note:

A = Mass of empty pycnometer (include stopper), g

B = Mass of pycnometer filled with water (include stopper), g

C = Mass of pycnometer partially filled with asphalt (include stopper), g

D = Mass of pycnometer plus asphalt plus water (include stopper), g

Table I.6 The results of viscosity

Trial	Temp.			Reading (cP)				Speed	Viscosity
No.	^{o}C	1 min	2 min	3 min	4 min	5 min	6 min	rpm	Pa.s
1	100	4600	4230	3820	3770	3620	3500	5	3.92
	135	235	220	215	215	212	210	20	0.22
	165	90	81	78	75	75	75.5	110	0.08
	175	49	42	41	40.5	40	39.5	110	0.04
2	100	4800	4280	3900	3720	3600	3510	5	3.97
	135	560	445	425	415	405	400	20	0.44
	165	120	112	108	107	107	107	110	0.11
	175	90	80	78	77	76.5	75.9	110	0.08

Condition:

Spindle No. 21

Torque 10 to 60% of full capacity

APPENDIX II

PROPERTIES OF AGGREGATES AND FILLER

Table II.1 The results of single sieve of 1/2" aggregate

Sample weight		3060.06 g					
Sample type		1/2" (12.5 mm)					
Method		Dried					
Sieve		A	B	C	D	E	Passing
mm	inch	g	g	g	g	%	%
19	3/4	437.78	437.78	0.00	0.00	0.00	100.00
12.5	1/2	451.08	789.74	338.66	338.66	11.07	88.93
9.5	3/8	458.68	2403.62	1944.94	2283.60	74.63	25.37
4.75	No. 4	451.89	1136.43	684.54	2968.14	97.00	3.00
2.36	No. 8	405.81	432.31	26.50	2994.64	97.86	2.14
1.18	No. 16	430.21	438.65	8.44	3003.08	98.14	1.86
0.6	No. 30	323.96	326.72	2.76	3005.84	98.23	1.77
0.3	No. 60	299.88	304.03	4.15	3009.99	98.36	1.64
0.075	No. 200	275.23	289.18	13.95	3023.94	98.82	1.18
Pan		254.56	284.64	30.08	3054.02	99.80	0.20

Table II.1 The results of single sieve of 3/8" aggregate (continued)

Sample weight		1267.59 g					
Sample type		3/8" (9.5 mm)					
Method		Dried					
Sieve		A	B	C	D	E	Passing
mm	inch	g	g	g	g	%	%
19	3/4	437.77	437.77	0.00	0.00	0.00	100.00
12.5	1/2	451.08	451.08	0.00	0.00	0.00	100.00
9.5	3/8	458.03	465.01	6.98	6.98	0.55	99.45
4.75	No. 4	451.67	871.87	420.20	427.18	33.70	66.30
2.36	No. 8	405.46	992.01	586.55	1013.73	79.97	20.03
1.18	No. 16	429.89	588.60	158.71	1172.44	92.49	7.51
0.6	No. 30	323.56	349.76	26.20	1198.64	94.56	5.44
0.3	No. 60	299.69	307.72	8.03	1206.67	95.19	4.81
0.075	No. 200	275.35	299.80	24.45	1231.12	97.12	2.88
Pan		254.36	289.29	34.93	1266.05	99.88	0.12

Table II.1 The results of single sieve of dust rock (Continued)

Sample weight		Before wash = 1849.44 g	After wash = 1576.23 g				
Sample type		Dust rock					
Method		Wet		Passing 0.075 mm after wash = 273.21 g			
Sieve		A	B	C	D	E	Passing
mm	inch	g	g	g	g	%	%
19	3/4	437.77	437.77	0.00	0.00	0.00	100.00
12.5	1/2	451.08	451.08	0.00	0.00	0.00	100.00
9.5	3/8	455.06	455.06	0.00	0.00	0.00	100.00
4.75	No. 4	451.80	503.13	51.33	51.33	2.78	97.22
2.36	No. 8	405.58	652.80	247.22	298.55	16.14	83.86
1.18	No. 16	429.87	829.17	399.30	697.85	37.73	62.27
0.6	No. 30	323.27	650.01	326.74	1024.59	55.40	44.60
0.3	No. 60	299.84	572.16	272.32	1296.91	70.12	29.88
0.075	No. 200	275.33	545.86	270.53	1567.44	84.75	15.25
Pan		254.72	262.24	280.73	1848.17	99.9313	0.0687

Table II.1 The results of single sieve of Portland cement (Continued)

Sample weight		Before wash = 1189.67 g	Passing 0.075 mm = 1082.41 g				
Sample type		Portland cement					
Method		Wet					
Sieve		A	B	C	D	E	Passing
mm	inch	g	g	g	g	%	%
19	3/4	437.77	437.77	0.00	0.00	0.00	100.00
12.5	1/2	451.08	451.08	0.00	0.00	0.00	100.00
9.5	3/8	455.06	455.06	0.00	0.00	0.00	100.00
4.75	No. 4	451.80	451.80	0.00	0.00	0.00	100.00
2.36	No. 8	405.58	405.58	0.00	0.00	0.00	100.00
1.18	No. 16	426.63	426.63	0.00	0.00	0.00	100.00
0.6	No. 30	323.60	324.56	0.96	0.96	0.08	99.92
0.3	No. 60	299.66	300.03	0.37	1.33	0.11	99.89
0.075	No. 200	275.31	379.47	104.16	105.49	8.87	91.13
Pan		254.51	255.44	1083.34	1188.83	99.929	0.071

Note: A = Weight of sieve, g
B = Weight of sieve and retained aggregate, g
C = Weight of retained aggregate, g
D = Cumulative retained aggregate, g
E = Cumulative retained aggregate, %

Table II.2 The proposed blended aggregate

Sieve	Passing (%)					Tolerant limit (%)		
mm	1/2"	3/8"	DC	PC	Combined	Lower	Middle	Upper
19	72.00	10.00	10.00	8.00	100.0	100	100	100
12.5	64.03	10.00	10.00	8.00	92.03	90	95	100
9.5	18.27	9.94	10.00	8.00	46.21	26	52	78
4.75	2.16	6.63	9.72	8.00	26.52	20	24	28
2.36	1.54	2.00	8.39	8.00	19.93	16	20	24
1.18	1.34	0.75	6.23	8.00	16.32	13	17	21
0.6	1.28	0.54	4.46	7.99	14.27	12	15	18
0.3	1.18	0.48	2.99	7.99	12.64	12	13.50	15
0.075	0.85	0.29	1.52	7.29	9.95	8	9	10
Pan	0.14	0.01	0.01	0.01	0.17	Less than 3		
%	72	10	10	8	100			
Weight, g	864	120	120	96	1200 g			

Note: 1/2" = 12.5 mm
3/8" = 9.5 mm)
DC = Dust rock
PC = Portland cement

Table II.3 The results of combined sieve (Trial No. 1)

Trial No. Weight Type		1 1268.10 g Mix									
Sieve		**A**	**B**	**C**	**D**	**E**	**Passing**	**Tolerant Limit (%)**		**F**	**G**
mm	inch	g	g	g	g	%	%	Lower	Upper	%	%
19	3/4	435.74	435.74	0	0	0	100	100	100	0	± 4
12.5	1/2	451.08	529.94	78.86	78.86	6.22	93.78	90	100	1.75	
9.5	3/8	458.69	972.23	513.54	592.40	46.72	53.28	26	78	7.07	
4.75	No.4	451.61	747.55	295.94	888.34	70.05	29.95	20	28	3.43	± 3
2.36	No.8	405.65	516.28	110.63	998.97	78.78	21.22	16	24	1.30	
1.18	No.16	429.87	494.45	64.58	1063.55	83.87	16.13	13	21	-0.19	
0.6	No.30	323.47	353.76	30.29	1093.84	86.26	13.74	12	18	-0.53	
0.3	No.60	299.72	323.86	24.14	1117.98	88.16	11.84	12	15	-0.80	
0.075	No.200	275.23	302.44	27.21	1145.19	90.31	9.69	8	10	-0.26	± 2
Pan		254.42	377.31	122.89	1268.08	100.00	0.00	Less than 3		-0.17	

Table II.3 The results of combined sieve (Trial No. 2)

Trial No. Weight Type		2 3083.90 g Mix									
Sieve		**A**	**B**	**C**	**D**	**E**	**Passing**	**Tolerant Limit (%)**		**F**	**G**
mm	inch	g	g	g	g	%	%	Lower	Upper	%	%
19	3/4	435.74	435.74	0.00	0.00	0.00	100	100	100	0.00	± 4
12.5	1/2	450.60	727.57	276.97	276.97	8.98	91.02	90	100	-1.01	
9.5	3/8	458.20	1956.15	1497.95	1774.92	57.55	42.45	26	78	-3.77	
4.75	No.4	451.53	897.36	445.83	2220.75	72.01	27.99	20	28	1.47	± 3
2.36	No.8	405.21	634.92	229.71	2450.46	79.46	20.54	16	24	0.61	
1.18	No.16	429.65	576.02	146.37	2596.83	84.21	15.79	13	21	-0.52	
0.6	No.30	323.15	408.92	85.77	2682.60	86.99	13.01	12	18	-1.26	
0.3	No.60	299.83	350.85	51.02	2733.62	88.64	11.36	12	15	-1.28	
0.075	No.200	275.06	346.45	71.39	2805.01	90.96	9.04	8	10	-0.91	± 2
Pan		254.72	532.05	277.33	3082.34	99.95	0.05	Less than 3		-0.12	

Table II.3 The results of combined sieve (Trial No. 3)

Trial No. Weight Type		3 3500 g Mix									
Sieve		**A**	**B**	**C**	**D**	**E**	**Passing**	**Tolerant Limit (%)**		**F**	**G**
mm	**inch**	**g**	**g**	**g**	**g**	**%**	**%**	**Lower**	**Upper**	**%**	**%**
19	3/4	435.54	435.54	0.00	0.00	0.00	100.00	100	100	0.00	± 4
12.5	1/2	450.63	691.58	240.95	240.95	6.88	93.12	90	100	1.08	
9.5	3/8	458.22	2106.56	1648.34	1889.29	53.98	46.02	26	78	-0.19	
4.75	No.4	451.55	1198.32	746.77	2636.06	75.32	24.68	20	28	-1.83	± 3
2.36	No.8	405.05	554.59	149.54	2785.60	79.59	20.41	16	24	0.48	
1.18	No.16	428.50	589.01	160.51	2946.11	84.17	15.83	13	21	-0.49	
0.6	No.30	323.50	412.42	88.92	3035.03	86.72	13.28	12	18	-0.99	
0.3	No.60	299.70	338.21	38.51	3073.54	87.82	12.18	12	15	-0.45	
0.075	No.200	275.56	381.78	106.22	3179.76	90.85	9.15	8	10	-0.80	± 2
Pan		254.34	565.08	310.74	3490.50	99.73	0.27	Less than 3		0.10	

Note: A = Weight of sieve, g
B = Weight of sieve and retained aggregate, g
C = Weight of retained aggregate, g
D = Cumulative retained aggregate, g
E = Cumulative retained aggregate, %
F = Difference of passing between Table II.2 and Table II.3
G = Allowable range of the difference

Table II.4 The result of G_s and water absorption of 1/2" aggregate

Aggregate	1/2" (12.5 mm)				
Trial No.	A	B	C	G_s	AW
1	1989.18	2009.02	1250.86	2.62	1.00
2	1971.35	2006.05	1255.14	2.63	1.76
3	2049.50	2078.05	1300.09	2.63	1.39
4	2086.32	2097.92	1327.05	2.71	0.56
Average				2.65	1.18

Table II.4 The result of G_s and water absorption of 3/8" aggregate (Continued)

Aggregate	3/8" (9.5 mm)				
Trial No.	A	B	C	G_s	AW
1	1990.51	2015.09	1268.38	2.67	1.23
2	1953.96	1982.07	1235.80	2.62	1.44
3	1995.95	2020.48	1269.80	2.66	1.23
4	1974.38	1994.94	1257.69	2.68	1.04
Average				2.66	1.24

Note A = Weight of aggregate after oven dry, g
B = Weight of aggregate in saturated surface dry, g
C = Weigh of aggregate in water, g
AW = Water absorption, %

Table II.4 The result of G_s and water absorption of dust rock (Continued)

Aggregate	Dust rock						
Trial No.	A	B	C	D	E	G_s	AW (%)
1	306.62	655.04	845.53	544.69	242.91	2.64	1.60
2	323.26	655.04	857.10	753.98	435.95	2.67	1.64
3	301.06	655.04	842.12	744.50	445.98	2.64	0.85
4	316.96	655.04	852.44	847.26	532.85	2.65	0.81
Average						2.65	1.23

Note A = Weight of aggregate after saturated surface dry, g
B = Weight of pycnometer filled with water to full level, g
C = Weight of pynometer filled with aggregate and water to full level, g
D = Weight of aggregate plus container after oven dry, g
E = Weight of container, g
AW = Water absorption, %

Table II.4 The results of G_s and water absorption of Portland cement (Continued)

Aggregate	Portland cement				
Trial No.	A	C	D	E	G_s
1	148.00	249.03	436.23	362.12	2.96
2	147.77	278.40	457.95	362.12	2.97
3	147.89	268.09	450.30	362.12	2.97
Average					2.97

Note A = Weight of empty pycnometer, g
B = Weight of pycnometer partially filled with Portland cement, g
C = Weight of pycnometer filled with Portland cement and kerosene to full, g
D = Weight of pycnometer filled with kerosene to full level, g

Table II.5 The results of Los Angeles of 1/2" and 3/8" aggregates

Trial No.	Aggregate	Grade	A	B	C	D	LA	Average
1	1/2"	B	19	12.5	2502.30	3551.94	29.03	28.22
	(12.5 mm)		12.5	9.5	2502.40			
2			19	12.5	2502.20	3631.80	27.41	
			12.5	9.5	2501.30			
1	3/8"	D	4.75	2.36	5001.70	3595.28	28.12	28.08
2	(9.5 mm)				5002.50	3599.35	28.05	

Note A = Weight of aggregate passing sieve (mm), g
B = Weight of aggregate retained on sieve (mm), g
C = Initial weight of aggregate before rotating in abrasion machine, g
D = Weight of aggregate after rotating and also retained on 1.17 mm sieve, g
LA = Los Angles abrasion, %

Table II.6 The results of flakiness and elongation of 1/2" (12.5 mm) aggregate

Size	Trial No.	Gauge size		Sieves size		Sample weight	Passing flakiness gauge	Retained on elongation gauge	Not passing flakiness and elongation gauge
				Passing	Retained				
mm		mm		mm	mm	g	g	g	g
12.5	1	20	14	19	12.5	801.48	90.11	0.00	711.37
		14	10	12.5	9.5	993.61	58.44	87.05	935.17
		10	6.3	9.5	4.75	347.94	11.77	105.03	336.17
		Sum				2143.03	160.32	192.08	1982.71
		FI (%) =		7.48		ET (%) =	8.96	Combined (%) =	16.44
	2	20	14	19	12.5	721.48	50.47	0	671.01
		14	10	12.5	9.5	612.24	71.65	82.55	540.59
		10	6.3	9.5	4.75	305.42	20.06	79.89	285.36
		Sum				1639.14	142.18	162.44	1496.96
		FI (%) =		8.67		ET (%) =	9.91	Combined (%) =	18.58
Average		8.08				9.44		17.51	
Specification		10				10		20	

Table II.6 The results of flakiness and elongation of 3/8" (9.5 mm) aggregate (Continued)

Size	Trial No.	Gauge size		Sieves size		Sample weight	Passing flakiness gauge	Retained on elongation gauge	Not passing flakiness and elongation gauge
				Passing	Retained				
mm		mm		mm	mm	g	g	g	g
9.5	1	20	14	19	12.5	0	0	0	0
		14	10	12.5	9.5	0	0	0	0
		10	6.3	9.5	4.75	327.34	30.23	26.33	297.11
		Sum				327.34	30.23	26.33	297.11
		FI (%) =		9.27		ET (%) =	8.04	Combined (%) =	17.28
	2	20	14	19	12.5	0	0	0	0
		14	10	12.5	9.5	0	0	0	0
		10	6.3	9.5	4.75	527.34	51.23	46.33	476.11
		Sum				527.34	51.23	46.33	476.11
		FI (%) =		9.71		ET (%) =	8.79	Combined (%) =	18.50
Average		9.47				8.41		17.89	
Specification		10				10		20	

APPENDIX III

PROPERTIES OF COCONUT FIBER

Table III.1 The results of flash and fire point

Trial No.	Coconut fiber g	Temperature Increase ^{o}C/min	Flash point ^{o}C	Fire point ^{o}C
1	50.24	10	> 200	> 250
2	50.50	10	> 200	> 250
3	50.46	10	> 200	> 250

Table III.2 The results of water absorption

Trial No.	A g	B g	C g	D g	Water absorption %
1	106.26	114.18	7.92	8.02	1.26
2	238.86	250.58	11.72	11.86	1.19
3	240.54	270.46	29.92	30.34	1.40
		Average			1.29

Note A = Weight of container, g
B = Weight of dried coconut fiber and container, g
C = Weight of dried coconut fiber, g
D = Weight of coconut fiber after soaking overnight, g

Table III.3 The results of tensile strength

Length (tested) mm	Trial No.	Diameter mm	Max load N	Tensile strength N/mm^2	Average N/mm^2
40 - 60, (50)	1	0.2	15.21	121.10	136.52
	2	0.3	38.42	135.95	
	3	0.4	70.48	140.29	
	4	0.5	116.75	148.73	
20 - 40, (30)	1	0.2	14.8	117.83	133.16
	2	0.3	36.79	130.18	
	3	0.4	72.61	144.53	
	4	0.5	109.98	140.10	
5 - 20, (10)	1	0.2	15.07	119.98	134.98
	2	0.3	40.02	141.61	
	3	0.4	68.94	137.22	
	4	0.5	110.75	141.08	
Condition	Machine	INSTRON			
	Capacity	5 kN			
	Speed	0.5 mm/min			

Table III.4 The results of PH

Trial No.	Coconut fiber g	Distilled water ml	PH	Temperature °C
1	8.20	200	5.72	27.1
2	8.16	200	5.73	26.9
3	8.25	300	5.65	27.2
4	8.20	400	5.57	26.8
5	8.22	400	5.58	27.2
Average			5.65	27.04

APPENDIX IV

TEST RESULTS OF SMA MIXTURES

Table IV.1 The determination of OAC of SMA mixtures containing 0.1% of 5 - 20 mm-long coconut fiber

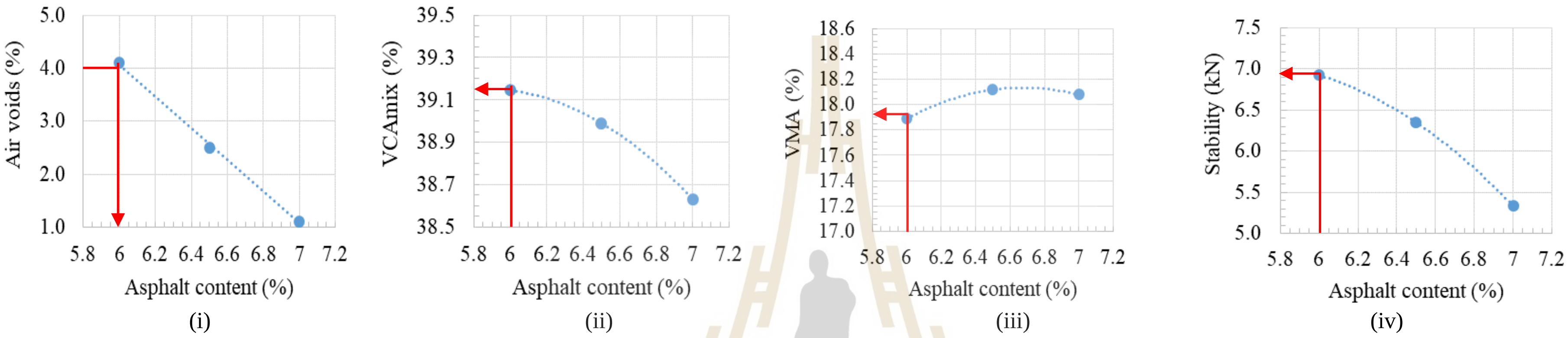


Table IV.1 The determination of OAC of SMA mixtures containing 0.3% of 5 - 20 mm-long coconut fiber (Continued)

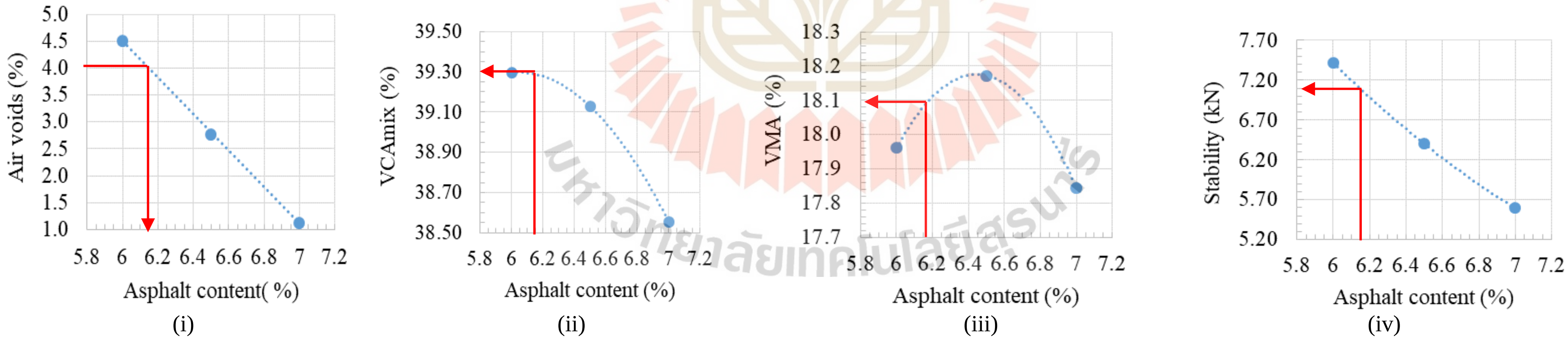
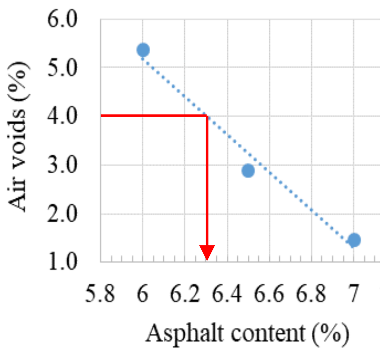


Table IV.1 The determination of OAC of SMA mixtures containing 0.5% of 5 - 20 mm-long coconut fiber (Continued)



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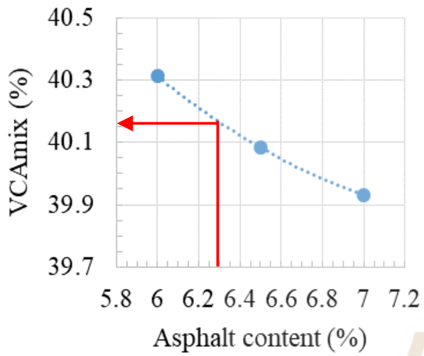

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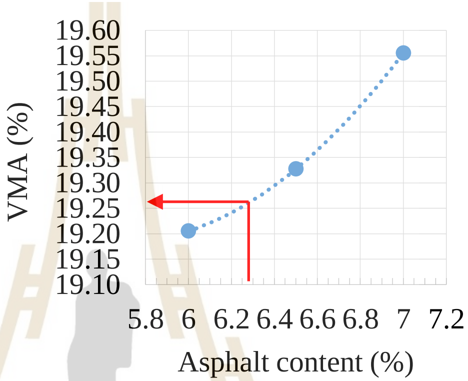

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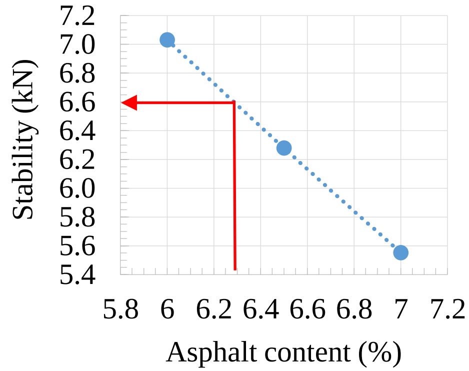

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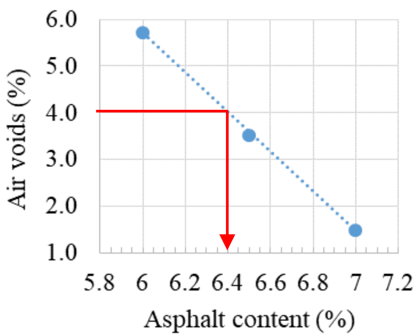
Table IV.1 The determination of OAC of SMA mixtures containing 0.7% of 5 - 20 mm-long coconut fiber (Continued)



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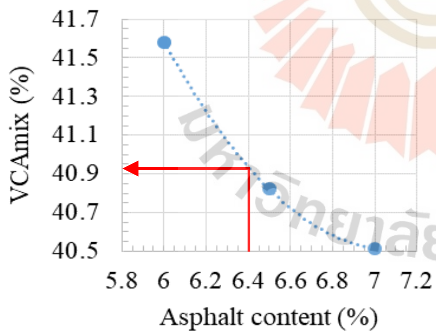

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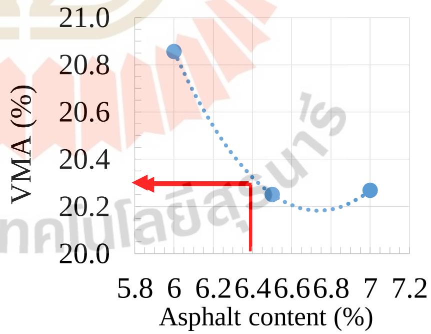

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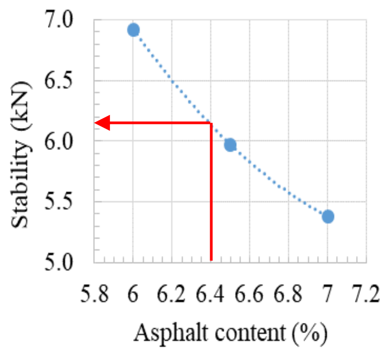

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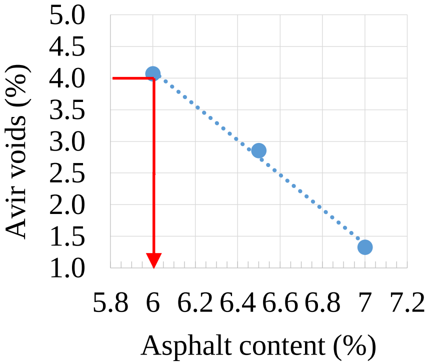
Table IV.1 The determination of OAC of SMA mixtures containing 0.1% of 20 - 40 mm-long coconut fiber (Continued)



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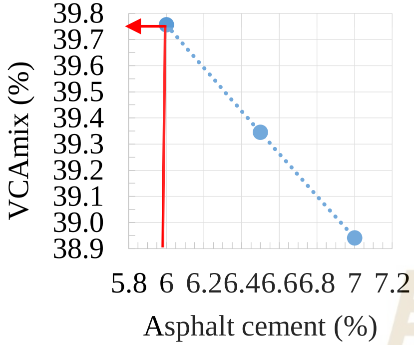

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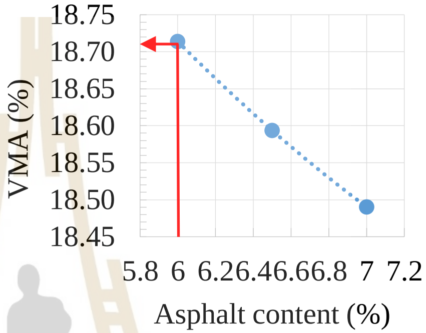

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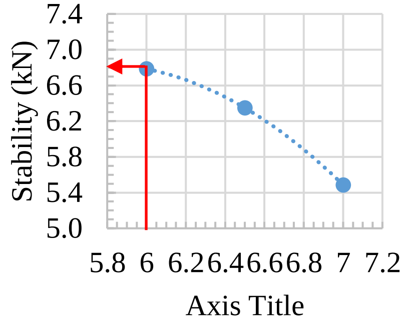

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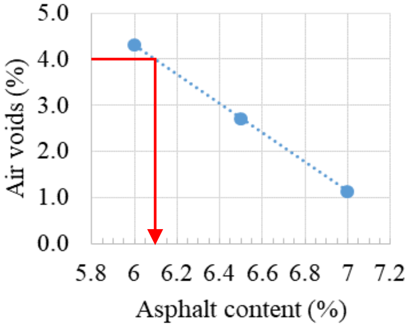
Table IV.1 The determination of OAC of SMA mixtures containing 0.3% of 20 - 40 mm-long coconut fiber (Continued)



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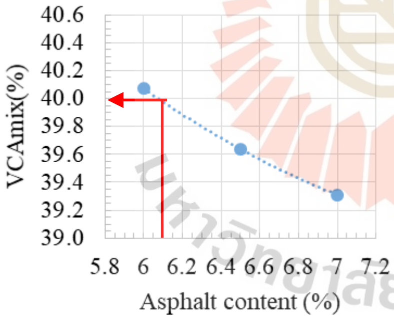

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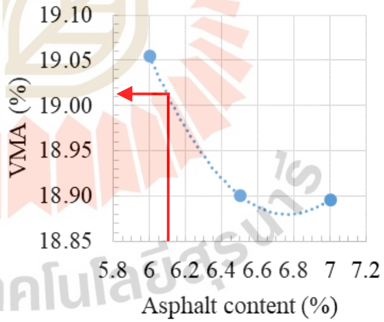

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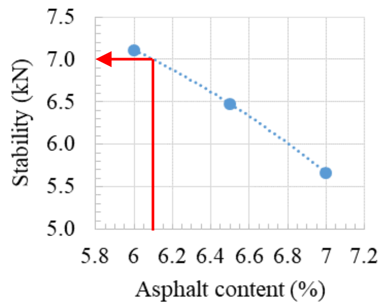

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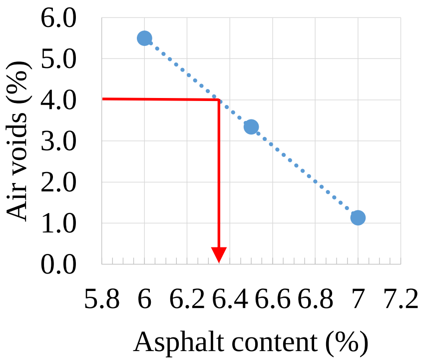
Table IV.1 The determination of OAC of SMA mixtures containing 0.5% of 20 - 40 mm-long coconut fiber (Continued)



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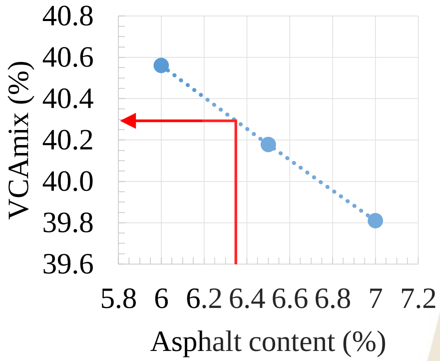

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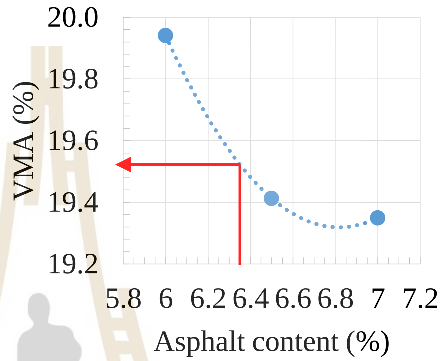

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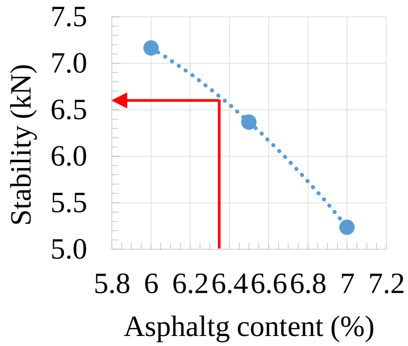

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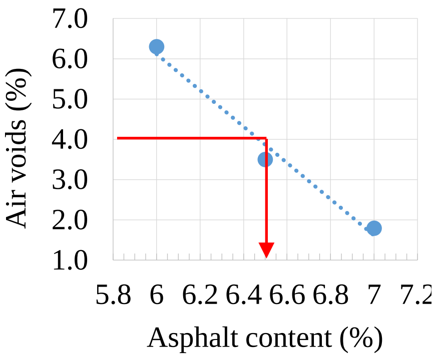
Table IV.1 The determination of OAC of SMA mixtures containing 0.7% of 20 - 40 mm-long coconut fiber (Continued)



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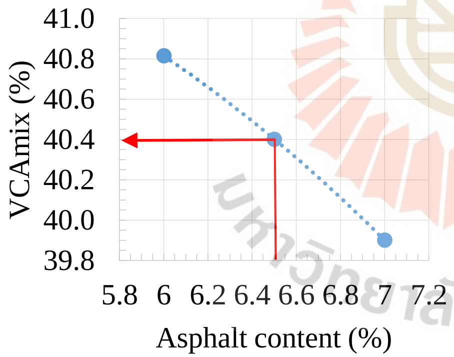

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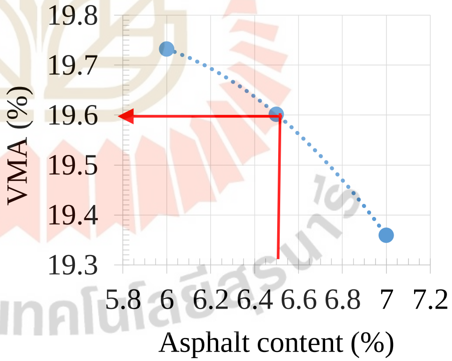

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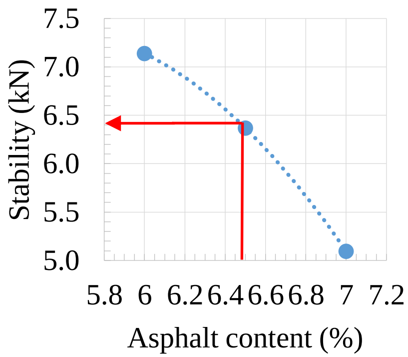

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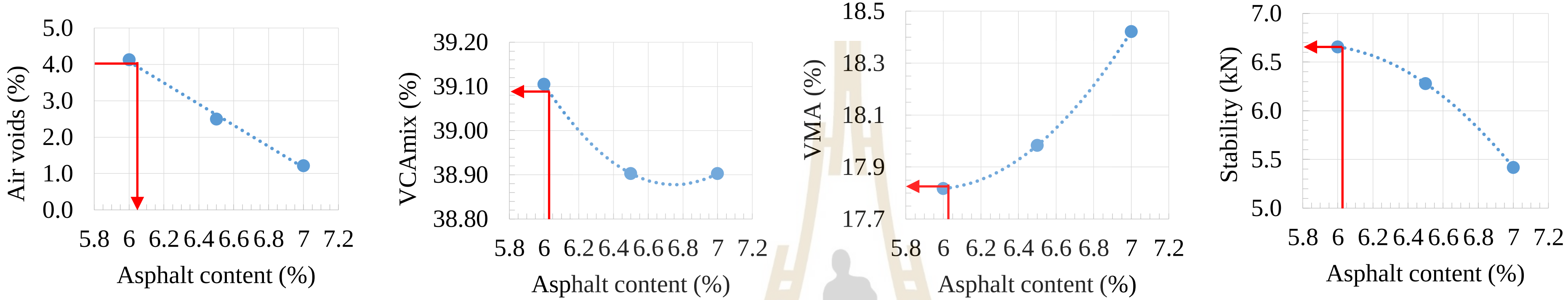
Table IV.1 The determination of OAC of SMA mixtures containing 0.1% of 40 - 60 mm-long coconut fiber (Continued)



(i) (ii) (iii) (iv)

Table IV.1 The determination of OAC of SMA mixtures containing 0.3% of 40 - 60 mm-long coconut fiber (Continued)

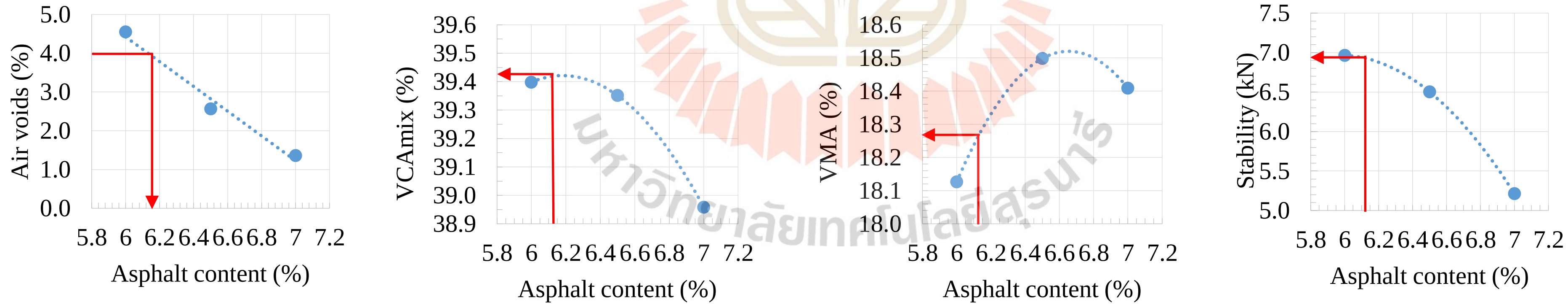


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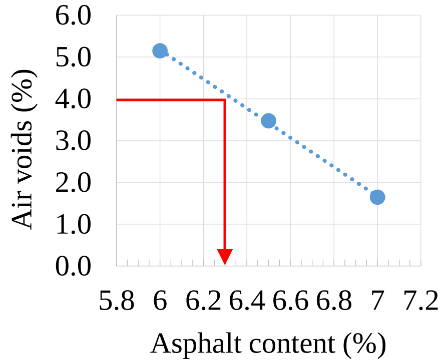
Table IV.1 The determination of OAC of SMA mixtures containing 0.5% of 40 - 60 mm-long coconut fiber (Continued)



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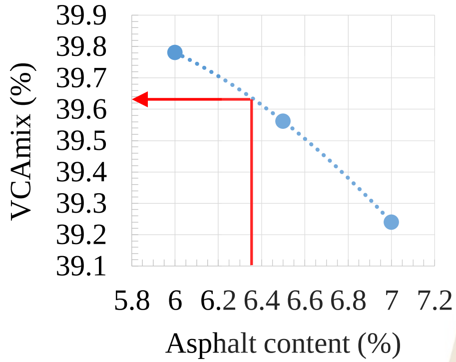

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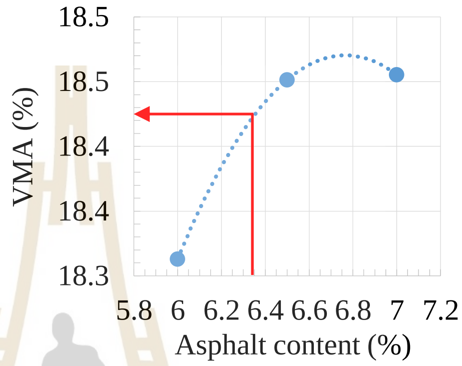

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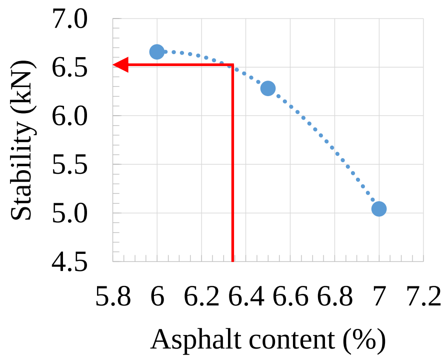

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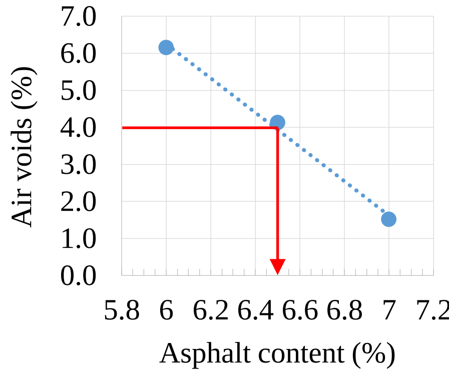
Table IV.1 The determination of OAC of SMA mixtures containing 0.7% of 40 - 60 mm-long coconut fiber (Continued)



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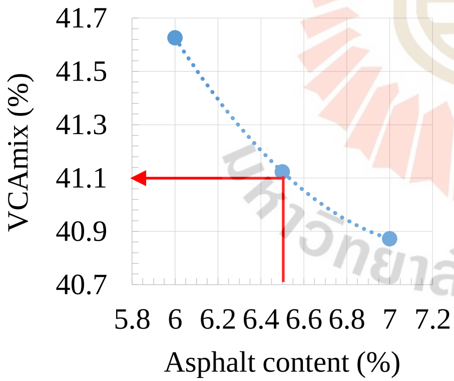

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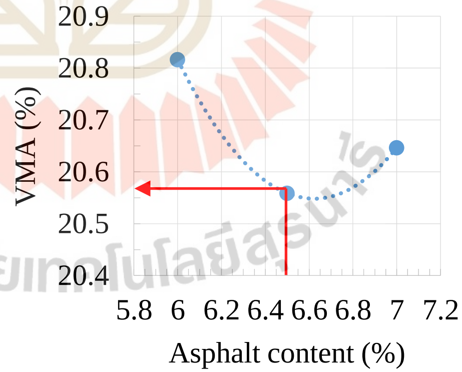

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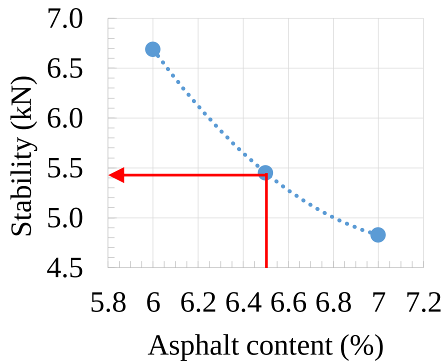

(iv)

Table IV.2 Volumetric properties and stability of mixtures at OAC

0 mm	%OAC	VMA,%	Stability, kN	Air Void, %	VCA_{drc}, %	G_{mb}	G_{mm}	VCA_{mix}, %
0%	5.80	17.18	6.56	4.26	42.61	2.351	2.456	38.62
	5.80	16.95	6.28	3.99	42.61	2.358	2.456	38.45
	5.80	17.13	6.54	4.20	42.61	2.352	2.456	38.58
Average	5.80	17.08	6.46	4.15	42.61	2.354	2.456	38.55
5 - 20 mm	%OAC	VMA,%	Stability, kN	Air Void, %	VCA_{drc}, %	G_{mb}	G_{mm}	VCA_{mix}, %
0.1%	6.00	17.34	6.92	4.13	42.61	2.351	2.453	38.74
	6.00	17.27	6.79	4.05	42.61	2.353	2.453	38.69
	6.00	17.34	6.61	4.13	42.61	2.351	2.453	38.74
Average	6.00	17.32	6.78	4.11	42.61	2.352	2.453	38.72
0.3%	6.12	17.94	6.92	4.15	42.61	2.337	2.439	39.18
	6.12	17.66	7.33	3.82	42.61	2.345	2.439	38.98
	6.12	17.97	7.18	4.18	42.61	2.337	2.439	39.20
Average	6.12	17.86	7.14	4.05	42.61	2.340	2.439	39.12
0.5%	6.30	17.98	6.72	3.84	42.61	2.341	2.434	39.21
	6.30	18.12	6.82	4.00	42.61	2.337	2.434	39.31
	6.30	18.16	6.66	4.05	42.61	2.336	2.434	39.35
Average	6.30	18.09	6.73	3.96	42.61	2.338	2.434	39.29
0.7%	6.40	19.00	6.41	3.87	42.61	2.314	2.407	39.95
	6.40	18.95	6.28	3.81	42.61	2.316	2.407	39.92
	6.40	19.29	6.20	4.22	42.61	2.306	2.407	40.17
Average	6.40	19.08	6.30	3.96	42.61	2.312	2.407	40.01

Table IV.2 Volumetric properties and stability of mixtures at OAC (Continued)

20 - 40 mm	%OAC	VMA,%	Stability, kN	Air Void, %	VCA_{drc}, %	G_{mb}	G_{mm}	VCA_{mix}, %
0.1%	6.00	17.87	6.72	4.01	42.61	2.336	2.434	39.13
	6.00	18.05	6.66	4.22	42.61	2.331	2.434	39.26
	6.00	17.93	6.79	4.08	42.61	2.335	2.434	39.18
Average	6.00	17.95	6.72	4.10	42.61	2.334	2.434	39.19
0.3%	6.10	18.39	7.13	4.06	42.61	2.324	2.422	39.51
	6.10	18.59	6.90	4.30	42.61	2.318	2.422	39.67
	6.10	18.24	7.18	3.89	42.61	2.328	2.422	39.41
Average	6.10	18.41	7.07	4.08	42.61	2.324	2.422	39.53
0.5%	6.35	19.51	6.54	3.91	42.61	2.298	2.392	40.34
	6.35	19.30	6.79	3.67	42.61	2.304	2.392	40.19
	6.35	19.87	6.61	4.35	42.61	2.288	2.392	40.61
Average	6.35	19.56	6.65	3.97	42.61	2.297	2.392	40.38
0.7%	6.48	19.79	6.02	3.88	42.61	2.293	2.386	40.49
	6.48	19.84	6.15	3.93	42.61	2.292	2.386	40.52
	6.48	20.09	6.23	4.23	42.61	2.285	2.386	40.71
Average	6.48	19.90	6.14	4.02	42.61	2.290	2.386	40.58

Table IV.2 Volumetric properties and stability of mixtures at OAC (Continued)

40 - 60 mm	%OAC	VMA,%	Stability, kN	Air Void, %	VCA_{drc}, %	G_{mb}	G_{mm}	VCA_{mix}, %
0.1%	6.00	17.90	6.59	3.79	42.61	2.335	2.427	39.16
	6.00	18.33	6.79	4.29	42.61	2.323	2.427	39.47
	6.00	18.09	6.66	4.01	42.61	2.330	2.427	39.30
Average	6.00	18.11	6.68	4.03	42.61	2.330	2.427	39.31
0.3%	6.12	18.39	7.15	3.55	42.61	2.325	2.410	39.52
	6.12	18.74	6.77	4.29	42.61	2.315	2.418	39.78
	6.12	18.64	7.05	4.17	42.61	2.317	2.418	39.70
Average	6.12	18.59	6.99	4.00	42.61	2.319	2.416	39.67
0.5%	6.35	19.73	6.28	4.04	42.61	2.292	2.388	40.51
	6.35	19.85	6.41	4.18	42.61	2.289	2.388	40.60
	6.35	19.47	6.43	3.73	42.61	2.299	2.388	40.32
Average	6.35	19.69	6.37	3.98	42.61	2.293	2.388	40.48
0.7%	6.50	20.15	5.64	3.86	42.61	2.284	2.375	40.74
	6.50	20.62	5.90	4.43	42.61	2.270	2.375	41.09
	6.50	19.93	5.51	3.60	42.61	2.290	2.375	40.58
Average	6.50	20.24	5.68	3.97	42.61	2.281	2.375	40.81

Table IV.3 Results of draindown test at OAC

Coconut fiber		OAC	A	B	C	Draindown	Average
mm	%	%	g	g	g	%	%
0	0	5.8	401.00	1669.96	408.48	0.59	0.56
			397.54	1667.99	404.40	0.54	
5 - 20	0.1	6.00	400	1670.19	404.89	0.38	0.37
			405.5	1672.34	409.99	0.35	
	0.3	6.15	399.87	1676.09	402.67	0.22	0.25
			396.55	1670.32	400.03	0.27	
	0.5	6.30	407.35	1688.58	410.54	0.25	0.23
			400.43	1677.77	403.03	0.20	
	0.7	6.40	394.59	1678.26	396.99	0.19	0.21
			417.71	1702.60	420.59	0.22	
20 - 40	0.1	6.00	402.24	1670.04	406.99	0.37	0.35
			410.43	1675.25	414.45	0.32	
	0.3	6.10	397.38	1671.16	400.05	0.21	0.20
			414.93	1694.03	417.45	0.20	
	0.5	6.35	417.93	1702.23	420.88	0.23	0.23
			416.83	1700.77	419.87	0.24	
	0.7	6.48	394.10	1680.13	396.64	0.20	0.17
			394.55	1685.84	396.49	0.15	
40 - 60	0.1	6.02	418.29	1689.45	422.15	0.30	0.32
			401.16	1685.84	405.45	0.33	
	0.3	6.12	420.59	1697.45	423.50	0.23	0.24
			395.26	1674.84	398.41	0.25	
	0.5	6.35	398.86	1676.57	402.16	0.26	0.27
			401.43	1680.42	405.10	0.29	
	0.7	6.50	398.33	1684.74	401.54	0.25	0.22
			398.38	1682.98	400.93	0.20	

Note: A = Weight of glass beaker, g
B = Weight of glass beaker filled with mixture, g
C = Weight of glass beaker after removal of mixture, g

Table IV.4 Conditioned and unconditioned ITS of mixtures at OAC

Dried conditioned ITS						
Coconut fiber		OAC	Weight of sample	Volume	Density	ITS
mm	%	%	g	cm3	g/cm3	kPa
5 - 20	0.3	6.15	1281.02	2070.34	0.62	728.90
			1277.08	2086.51	0.61	748.19
			1275.90	2086.51	0.61	735.72
			Average			737.60
	0.5	6.30	1281.26	2102.69	0.61	680.57
			1281.08	2082.02	0.62	673.99
			1280.22	2102.69	0.61	687.99
			Average			680.85
	0.7	6.40	1284.76	2135.04	0.60	621.51
			1283.10	2135.04	0.60	638.57
			1286.36	2118.86	0.61	658.18
			Average			639.42
20 - 40	0.3	6.10	1282.46	2070.34	0.62	733.93
			1277.46	2070.34	0.62	713.82
			1280.96	2049.99	0.62	714.83
			Average			720.86
	0.5	6.35	1274.82	2102.69	0.61	695.41
			1270.34	2118.86	0.60	663.09
			1275.58	2082.02	0.61	671.50
			Average			676.67
40 - 60	0.3	6.12	1269.22	2049.99	0.62	737.56
			1273.82	2070.34	0.62	691.20
			1275.72	2118.86	0.60	687.65
			Average			705.47
	0.5	6.35	1275.34	2118.86	0.60	618.88
			1278.08	2102.69	0.61	643.44
			1277.90	2102.69	0.61	631.07
			Average			631.13

Table IV.4 Conditioned and unconditioned ITS of mixtures at OAC (Continued)

Wet conditioned ITS						
Coconut fiber		OAC	Weight of sample	Volume	Density	ITS
mm	%	%	g	cm3	g/cm3	kPa
5 - 20	0.3	6.15	1275.28	2070.34	0.62	673.61
			1271.86	2049.99	0.62	704.72
			1275.26	2066.01	0.62	664.17
			Average			680.83
	0.5	6.30	1280.22	2102.69	0.61	581.57
			1280.50	2086.51	0.61	633.47
			1281.28	2102.69	0.61	593.95
			Average			603.00
	0.7	6.40	1292.18	2135.04	0.61	536.20
			1285.58	2135.04	0.60	487.46
			1286.44	2135.04	0.60	487.46
			Average			503.71
20 - 40	0.3	6.10	1271.90	2102.69	0.60	623.65
			1277.02	2049.99	0.62	679.47
			1270.28	2049.99	0.62	651.68
			Average			651.60
	0.5	6.35	1276.42	2118.86	0.60	537.84
			1281.08	2098.04	0.61	542.97
			1280.08	2098.04	0.61	567.65
			Average			549.49
40 - 60	0.3	6.12	1277.52	2070.34	0.62	643.44
			1269.52	2049.99	0.62	623.90
			1274.78	2066.01	0.62	624.07
			Average			630.47
	0.5	6.35	1274.94	2114.06	0.60	514.36
			1278.46	2135.04	0.60	521.58
			1274.72	2151.21	0.59	483.79
			Average			506.58

Table IV.5 TSR of mixtures at OAC

Coconut fiber		OAC	IDT Dry	IDT Wet	TSR
mm	%	%	kPa	kPa	%
5 - 20	0.3	6.15	737.60	680.83	92.30
	0.5	6.30	680.85	603.00	88.57
	0.7	6.40	639.42	503.71	78.78
20 - 40	0.3	6.10	720.86	651.60	90.39
	0.5	6.35	676.67	549.49	81.20
40 - 60	0.3	6.12	705.47	630.47	89.37
	0.5	6.35	631.13	506.58	80.26

BIOGRAPHY

Ms. Chandy Chin was born on 6th December, 1994 at Sihanouk Ville Province, Cambodia. Her mother is Mrs. Soeurng Som (housework) and her father is Mr. Bros Pel (passed away). She has three siblings; they are Mrs. Chinda Chin, Mrs. Sreydoung Chin, and Mr. Oudormlynet Chin. She started her primary education at Hun Sen Primary School; secondary education at Hun Sen Secondary School; and obtained her high school diploma at Hun Sen High School. She then received her B. Eng. degree in Water Resources Engineering and Rural Infrastructure (GRU) from Institute of Technology of Cambodia (ITC), Cambodia in 2018. After her graduation, she then pursued to Master degree in Civil, Transportation and Geo-Resources Engineering at Suranaree University of Technology (SUT), Thailand in 2018.