ผลกระทบของการเติมเศษผิวทางแอสฟัลท์และสารเพิ่มชนิดแอดเว่าลงในแอสฟัลท์ผสมร้อนที่อุณหภูมิอุ่น

นายยีเช เพ็นโจ

วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรปริญญาวิศวกรรมศาสตรมหาบัณฑิต

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ปีการศึกษา 2556

EFFECTS OF INCORPORATING RECLAIMED ASPHALT PAVEMENT AND ADVERA ADDITIVE INTO HOT MIX ASPHALT AT WARM TEMPERATURE

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A Thesis Submitted in Partial Fulfillment of the Requirements

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เยเชย์ เพนจอร์ ผลกระทบของการเติมเศษผิวทางแอสฟัลท์และสารเพิ่มชนิดแอดเวร่าลงในแอสฟัลท์ผสมร้อนที่อุณหภูมิอุ่น (EFFECTS OF INCORPORATING RECLAIMED ASPHALT PAVEMENT AND ADVERA ADDITIVE INTO HOT MIX ASPHALT AT WARM TEMPERATURE) อ. ที่ปรึกษาวิทยานิพนธ์หลัก : **บุญชัย แสงเพชรงาม**, 115 หน้า.

งานวิจัยที่ผ่านมาจนถึงปัจจุบันได้ศึกษานำเอาเทคโนโลยีต่างๆมาใช้ในการพัฒนาความยั่งยืนด้านการขนส่งและเพื่อให้เกิดประสิทธิผลต่อลดผลกระทบสิ่งแวดล้อมและต้นทุนให้มากที่สุด เทคโนโลยีที่กล่าวถึงนั้นได้แก่ การนำวัสดุผิวทางแอสฟัลต์เก่ามาใช้ใหม่ (Recycled Asphalt Pavement or RAP) และการใช้สารผสมเพิ่มเติมในแอสฟัลต์ผสมอุ่น (Warm Mix Asphalt) การนำวัสดุผิวทางเก่ามาใช้ใหม่นั้นเป็นวิธีการที่จะช่วยลดปริมาณวัสดุมวลรวมของแอสฟัลต์และปริมาณแอสฟัลต์ที่ใช้ในส่วนผสมอันนำมาซึ่งการลดต้นทุนการผลิตโดยรวม ในส่วนของเทคโนโลยีการใช้สารผสมเพิ่มเติมในแอสฟัลต์ผสมอุ่นนั้นจะดำเนินการผสมวัสดุมวลรวมแอสฟัลต์ และสารผสมเพิ่มเติม ในอุณหภูมิการผสมที่ต่ำกว่าการผสมแบบปกติ จึงนำมาซึ่งการลดการใช้พลังงานและการปลดปล่อยก๊าซคาร์บอนไดออกไซด์

งานวิจัยนี้มีวัตถุประสงค์เพื่อประเมินคุณสมบัติของแอสฟัลต์ผสมอุ่นที่ผสมวัสดุผิวทางเก่าและใช้สารผสมเพิ่มเติมในกลุ่มซีโอไลท์(zeolite)ชนิดแอดเวร่า(Advera) มาผสมลงในวัสดุมวลรวมและแอสฟัลต์ที่อุณหภูมิอุ่น(120-135 °C) คุณลักษณะของแอสฟัลต์จากกระบวนการผสมอุ่นและผสมร้อนจะได้รับการประเมินผลเปรียบเทียบกัน อันประกอบด้วย คุณสมบัติเชิงปริมาตร เสถียรภาพและการไหล การทดสอบความต้านทานแรงดึงแบบอ้อม ความต้านทานความชื้น โดยทดสอบ 3 ปัจจัยคือ ร้อยละของวัสดุผิวทางเก่านำกลับมาใช้ใหม่ (RAP) สารผสมเพิ่มเติม และอุณหภูมิผสมบดอัด ผลลัพธ์จากการทดสอบในห้องปฏิบัติการพบว่าการใช้สารผสมเพิ่มเติม ในกระบวนการผสมอุ่นที่อุณหภูมิ 120°C ของแอสฟัลต์จากวัสดุมวลรวมที่นำกลับมาใช้ใหม่ ได้ให้คุณลักษณะต่างๆจากการทดสอบที่ดีเทียบเท่าตามเกณฑ์ข้อกำหนดของวัสดุแอสฟัลต์ผสมร้อนปกติแบบที่กำหนดโดยกรมทางหลวง

ภาควิชา : วิศวกรรมโยธา ลายมือชื่อนิสิต.....

สาขาวิชา: วิศวกรรมโยธา ลายมือชื่อ อ.ที่ปรึกษาวิทยานิพนธ์หลัก.....

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YESHEY PENJOR: EFFECTS OF INCORPORATING RECLAIMED ASPHALT PAVEMENT AND ADVERA ADDITIVE INTO HOT MIX ASPHALT AT WARM TEMPERATURE. THESIS ADVISOR: ASSISTANT PROFESSOR BOONCHAI SANGPETNGAM, Ph.D.,115 pp

Through numerous research works, technologies have been developed that are sustainable and effective in minimizing the environmental impacts as well as costs. These technologies are recycling of reclaimed asphalt pavement (RAP) and warm mix asphalt (WMA) additives. Recycling of RAP is a critical necessity to save valuable aggregates, and reduce the use of costly asphalt binder. WMA technology allows asphalt mixes to be produced at lower temperatures thereby saving energy and cutting CO2 emission.

The thesis aims to evaluate the benefits of using Advera as WMA additive into HMA containing RAP. Performance of HMA and WMA are evaluated for their volumetric properties, stability and flow, and strength index by varying three factors; percent RAP, Advera WMA and production temperature. The laboratory test results indicate performance of 15% recycled HMA with WMA additives at 135°C is comparable to conventional recycled HMA.

Department : Civil Engineering Student's Signature .....

Field of Study : Civil Engineering Advisor's Signature .....

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GLOSSARY

AASHTO:	American Association of State Highway & Transportation Officials
AC:	Asphalt Content
Agg:	Aggregate
ASTM:	American Society for Testing and Materials
AV:	Air Voids
AVG:	Average
DOH:	Department of Highways, Thailand
FA:	Fresh Aggregate
Gmm:	Maximum Theoretical Specific Gravity
Gsb:	Bulk Specific Gravity
HMA:	Hot Mix Asphalt
NCHRP:	National Cooperative Highway Research Program
OBC:	Optimum Binder Content
RAP:	Reclaimed Asphalt Pavement
VMA:	Voids in Mineral Aggregate
VFA:	Voids Filled with Asphalt
WMA:	Warm Mix Asphalt

CHAPTER I

INTRODUCTION

1.1 Background and Importance of Study

Transportation sector has contributed significantly to the overall health of an economy and many nations have benefited from its services. However this comes at a price. Transport related activities are one of the major contributors of global warming and climate change. Amongst the various modes of transportation, road transport remains by far the largest emitter of air pollutants with its wide range of infrastructures and activities (Greene and Wegener, 1997).

Numerous research works carried out in the transportation industry have successfully developed and used technologies that are sustainable and effective in minimizing the environmental impacts as well as costs. One such innovation is the recycling of asphalt cement in the pavement industry. Reclaimed asphalt pavement (RAP) refers to the recycled hot mix asphalt mixtures containing asphalt and aggregates. Good quality materials are obtained when RAP is properly crushed and separated (FHWA, 2008). Significant amount of RAP started in the mid-1970s due to extremely high asphalt binder prices as the result of the oil embargo (Sondag, Chadbourn and Drescher, 2002). The two primary factors for influencing the use of RAP are economic savings and environmental benefits. The use of RAP reduces the amount of fresh aggregate as well as the fresh binder required in the production of HMA. RAP usage preserves energy, minimizes costs for

acquiring quality fresh aggregate, and saves resources. Further, using RAP reduces the amount of construction wastes and does not deplete nonrenewable natural resources such as fresh aggregate and asphalt binder (Audrey Copeland, 2011).

Another such technology is the Warm Mix Asphalt (WMA) first developed in Europe in the late 1990's that is capable of producing HMA at a lower temperature. The conventional asphalt mixtures were produced at high temperatures ranging from 150°C to 180°C and thus often referred to as Hot Mix Asphalt (HMA). Figure 1.1 shows the typical mixing temperatures for asphalt mixtures. HMA technology requires a lot of energy during the mixing process and at the same time releases unwanted gas i.e. CO2 as by product. Apart from the huge expenditures incurred in HMA industry, it is also responsible for the additional pressure on the already limited natural resources and imposes threat to the natural environment.

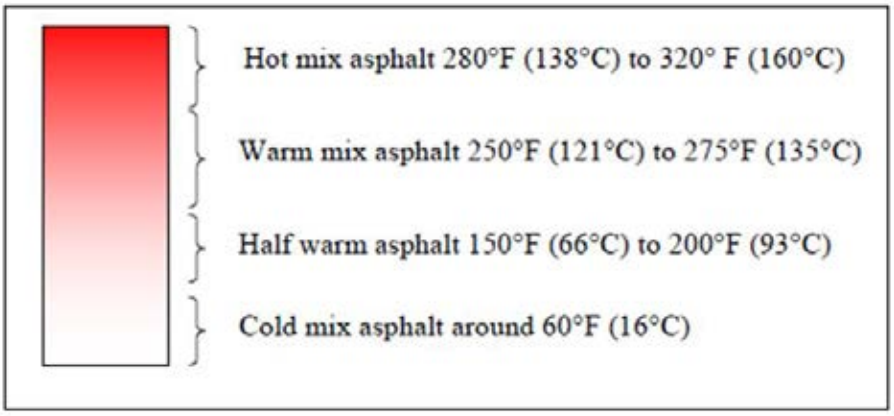

Figure1. 1 Typical Mixing Temperature of Asphalt Mix

Source: Zhanping You et al., 2011

WMA technology helps in producing asphalt mixtures at lower temperatures with the help of certain additives. WMA technology helps in overall reduction in fuel consumption which in turn leads to energy savings and cost reduction. Since WMA are produced at lower temperatures, this technology also helps in minimizing the emissions and thereby help in maintaining air quality standards (Pavement Interactive, 2010).

There are many chemicals and processes available in the market to produce warm mix asphalt which does not drastically change the mixture properties (Gandhi and Amirkhanian, 2007). A reduction of 30°C in the optimum mixing and compaction temperature is expected by incorporating WMA technologies on recycled HMA (Lee et al., 2008).

1.2 Objectives

The primary objective of the study is to investigate the benefits of using Advera as WMA additive for adding reclaimed asphalt particles into hot mixing process. The detailed objectives of this study are:

- To determine the decrease in the level of mixing and compaction temperatures of WMA using Advera® WMA.
- To examine the influence of Advera® WMA on the RAP (Reclaimed Asphalt Pavement) content that can be added to the mix.
- To investigate the characteristics of WMA produced by adding Advera® WMA to RAP in comparison to the conventional HMA (Hot Mix Asphalt) that are mandatory for pavement construction.

1.3 Scope of Study

Materials used in this study include asphalt binder AC 60/70, RAP and Limestone aggregates (Coarse and Fine) with a nominal maximum size of 19mm (3/4''). The source of RAP is from a selected single stockpile but sieving is done prior to its addition to the mix. The WMA technology used is Advera® WMA which is a foaming additive.

The following variables are considered to influence the performance of the mixture/ mixing process:

- Ratio of RAP and Virgin aggregate (Certain Gradation);
- Ratio of Asphalt and Zeolite (Advera);
- Mixing and Compaction Temperature.

In order to evaluate the resultant mixture, Volumetric Test, Marshal Stability and Flow Test and Strength Index Test will be conducted in the laboratory.

1.4 Expectations from the study

- Find out relationship and effects between mixture, mixing process and performance properties of WMA;
- Recommend WMA mix design approach to satisfy requirements;
- Suggest process in WMA production plant and during construction to get quality product that satisfy requirement.

CHAPTER II

LITERATURE REVIEW

2.1 Background.

WMA technology makes use of additives to produce HMA mixtures at lower mixing and compaction temperatures, thereby reducing the energy consumption and greenhouse gases. This has led to a lot of interests in WMA technology over the years. In order to use warm mix asphalt (WMA) technology together with Reclaimed Asphalt Pavement (RAP), a complete understanding of WMA additives, asphalt binder, and the significance of physical properties such as compactability, air voids, rutting potential and fatigue potential is very essential. The primary concern when using RAP in WMA is how well the RAP and new binder mix at the lower temperatures used in WMA.

2.2 WMA Technology

The three main types of WMA technology available today are foaming effect, organic additive and chemical package. Foaming effect is achieved by modifying the production process or by using hydrophilic material which introduces water into the asphalt concrete in the production stage. The water slightly increases the binder volume making it more workable at lower temperature. The organic additives are waxes and fatty acid amide. These additives allow reduction in the binder viscosity when heated above their melting point making the binder more workable at lower temperature. The last

technology makes use of different chemical additives which includes anti-stripping agents and compaction aids. They are designed to improve coating, adhesion and workability of the asphalt mixtures. Examples of common WMA technologies are summarized in Table 1.1(Zhanping You et al., 2011).

Table2. 1Common WMA Technologies

WMA Technology	Company	Recommended Additive/Usage
1. Foaming Additives		
Aspha-min®	Eurovia and MHI	0.3% by total weight of mixture
Advera® WMA	PQ Corporation	0.25% by total weight of mixture
2. Organic Additives		
Sasobit®	Sasol	0.8-3% by weight of asphalt
3. Chemical Additives		
CECABASE RT®	Arkema Group	0.2-0.4% by weight of asphalt
Evotherm®	Meadwestvaco Asphalt Innovations	Generally pumped directly off a tanker truck to the asphalt line using a single pair of heated valves and check valves to allow for recirculation
Rediset WMX®	Akzo Nobel	2% by weight of mixture

Source: Zhanping You et al., 2011

Aspha-min®, a hydrated zeolite, is available in a powder form and contains approximately 20% water. Aspha-min releases water upon

contact with hot mix asphalt making the mix workable at lower temperature (EUROVIA, 2009).

Advera® WMA is an inorganic chemical in powder form containing 18-20% moisture which is chemically and structurally bound. With increased energy, in the form of heat, the water is given off and micro-foaming occurs. Since there is no chemical alteration of the bitumen, no mix design change needed. Also, due to the small amount of material added, any change in gradation or bitumen content is well within the current mix designs. PQ Corporation recommends the addition of 0.25 percent by weight of the mix (A. Smith, 2012).

Sasobit® WMA (wax) is a fine crystalline long chain aliphatic hydrocarbon which is obtained from natural gas using the Fisher Tropsch (FT) process of polymerization. It has a melting point range between 85°- 115°C and is completely dissolves in asphalt temperature above 115°C. It has the ability to reduce viscosity of the binder which helps in reducing the working/mixing temperature (J. Shaw, 2007).

Cecabase RT® is a chemical additive that is efficient in reducing the application temperatures by around 40°C, while maintaining the mechanical properties of the bitumen mix. It is available in liquid form and can be directly added to the asphalt. (Eric Jorda et al., 2008)

2.3 Reclaimed Asphalt Pavement (RAP)

The national cooperative highway research program (NCHRP) established procedures for using RAP by investigating the black rock study,

binder effect study and mixture effect study related to RAP. The black rock study did not show any significant blending between the old and the new binder at lower RAP contents but the blending became significant at higher RAP contents indicating that RAP does not act like a black rock. The binder effects study showed that RAP content up to 20%, depending on the RAP binder stiffness, can be used without making any changes to the virgin asphalt binder grade. Findings from the mixture effect study showed that high RAP content improved asphalt mix properties, fatigue life, increased complex modulus, lowered temperature mixture stiffness, decreased shear deformation and accumulated shear strain. However, increasing the RAP content adversely affects the mixtures resistance to low temperature cracking (NCHRP W30, 2000).

NCHRP also states that the amount of RAP to be used depends on the source from which RAP is milled. Homogeneous source of RAP facilitates higher percentages of RAP to be used in the mix but if the RAP is used from various sources, fewer RAP use is recommended (NCHRP 452, 2001).

Copeland (2011) stated that the main concern of using higher RAP content in asphalt mixtures is its tendency of replacing the virgin binder in the mix, thereby impacting binder properties. The amount of RAP to be used is selected by examining the influence of RAP binder towards the total binder in the mix by weight. U.S. state transportation departments have fixed a minimum percentage of virgin binder content i.e. 70% of the binder content must be virgin binder.

RAP Expert Task Group (2007) mentioned about the maximum practical RAP usage taking into consideration mix design, customer specifications, RAP availability and plant type.

Table2. 2 Maximum Practical RAP Usage

Item	Maximum RAP Content (%)
Base	35
Intermediate	35
Surface	25

Newcomb, D.E. et al., 2007 reported on the two important concerns which make it difficult to accurately measure the bulk specific gravity (Gsb) of RAP aggregate. The ignition method could change aggregate properties and the solvent extraction method did not always remove all of the absorbed asphalt from the aggregate pores. They recommend using the back-calculation method for RAP aggregate Gsb with measured Gmm (Maximum theoretical specific gravity of the RAP mixture) data and using either known asphalt absorption values from similar aggregates or an assumed value of 1.5%.

Al-Qadi, I.L. et al., 2009 reported that selective absorption of binder into RAP aggregate could potentially produce a bond that will be resistant to stripping and also incomplete blending could result in double coating of RAP particle resulting in improved TSR values.

Doyle, J.D. et al., 2011 found that increasing the amount of RAP from 0 to 25% improved the TSR results for 75% of the mixtures studied.

Increasing the amount of RAP from 0 to 50% improved the TSR results for 88% of the mixtures studied.

Rorrer, T. et al., 2009 concluded that the possibility of adding more RAP into the virgin mix would require higher plant operating temperatures. The extracted binder from the mix comprising of a PG 64-22 binder with 30% RAP worked out to be PG 76-22.

Table2. 3 Summary of RAP Vs Temperature

Amount of RAP in HMA	Plant Operating Temperature (^{o}C)
10%	165.5
20%	171.11
30%	176.66
No RAP	148.88-154.44

Source: Rorrer, T.et al., 2009

Zhou, F. et al., 2011 recommended warming up RAP materials overnight at 60°C, which is the most used temperature to dry materials and preheating the RAP at the mixing target temperature for 2 hour, which is often the time for preheating virgin binder.

2.4 Performance Studies of WMA.

Zaumanis, M. (2010) evaluated two WMA technologies; Sasobit and Rediset WMX and found both products to be effective in reducing the compaction temperature to 125^{o}C without significant changes in density, mixture stiffness or resistance to permanent deformations. He also found that

WMA and HMA properties are affected by the curing period. A curing period of two hours was used in the research to evaluate WMA properties.

Hill, B. et al., 2011 studied the effects of three WMA additives; Sasobit (1.5 and 3.0% by binder weight), Advera (0.2 & 0.5% by mixture weight) and Evotherm M1 (0.5% by binder weight) on asphalt binder and mixture properties at three compaction temperatures (150, 125 and 100°C). They found that Advera hardly changed the binder viscosity below 140°C but between140-150°C, 0.2% Advera modified binders exhibited viscosities less than the control binder. Further increasing the Advera content increases binder viscosity making it stiffer. Sasobit modified binders showed significant decrease in the viscosity above 90°C but below this temperature Sasobit makes the binder more viscous. Evotherm WMA did not produce significant change in the binder viscosity. Based on DSR tests, they concluded that WMA technologies will be resistant towards rutting but however mixtures containing Sasobit and Advera will be susceptible to fatigue cracking. Based on TSR test results, WMA produced using Evotherm improved the moisture resistance of the mix while Advera showed more moisture sensitivity when produced at lower temperatures.

Lee, H. & Kim, Y. (2010) found that lab produced WMA mixtures with various additives showed good level of mixing and compaction at lower temperatures (113°C to 126°C). According to their report, WMA mixtures prepared in the lab were similar to HMA mixtures.

Sullivan, K. & Wall, P. (2009) reported that Sasobit® (2%) and Advera® (0.4%) improved the physical properties of a 100% RAP mix design.

Volumetric properties were significantly improved by Advera but dynamic modulus (|E*|) were improved more by Sasobit®. They found that an increase in bulk specific gravity (G_{sb}) resulted in a decrease in air voids, indicating that WMA additives increased the workability of the mixes. Furthermore Sasobit® aided mixtures showed better TSR values than Advera®.

NCHRP 691 (2011) suggested that the compaction temperatures for WMA should exceed the high temperature grade of the extracted RAP binder. The mix design includes short term oven conditioning in order to simulate aging and absorption of binder in the field. According to the report, oven conditioning of 2hrs have been found suitable at 136°C compaction temperature for WMA. The report also suggested that for using RAP in WMA, RAP binder should have a viscosity less than 22,000P (220Pa.s) at field compaction temperature. It was found that the compactability of WMA mixtures was influenced by the temperature, RAP content and WMA process.

Zhao, S. et al., 2011 evaluated the rutting resistance, moisture susceptibility and fatigue resistance of warm-mix asphalt (WMA) mixtures containing high percentages of RAP through laboratory performance tests. They reported that the use of RAP improved the rut resistance of WMA and WMA containing high RAP content showed better resistance to moisture damage. Based on the Energy ratio results, addition of RAP in WMA mixtures showed more resistance to fracture resulting in a longer fatigue life.

Zhanping You et al., 2011 studied properties of WMA mixtures using Advera® WMA, Sasobit® and Cecabase RT®. Based on the dynamic modulus test, they found that WMA made with Advera® WMA and Cecabase RT® showed higher rutting potential while WMA produced with Sasobit®

showed similar rutting potential compared to the control HMA. From the tensile strength ratio test, they found that most of the TSR for WMA produced with Advera® WMA, Sasobit® and Cecabase RT® passed the minimum requirement of 0.8 but were significantly lower than HMA.

Kanitpong, K. et al., 2007 evaluated the effects of Sasobit® on two types of asphalt binders (AC 60/70 and polymer modified asphalt with 5% of SBS) using 3% Sasobit dosage. They found that addition of Sasobit® improved the workability of asphalt binder (by reducing viscosity) particularly of PMA binder. It also improved the resistance of asphalt binders to permanent deformation and fatigue, and increased the complex shear modulus of asphalt binders at high pavement temperatures (60°C). The AC 60/70 binder modified with 3% Sasobit showed significant improvement in the compactability of asphalt mixture. The mixtures modified with Sasobit showed greater resistance to densification under simulated traffic indicating potential for higher resistance to permanent deformation under traffic loads. Finally, Sasobit showed neutral effect on the resistance of asphalt mixtures to moisture damage when compacted at relatively high temperatures.

CHAPTER III

RESEARCH METHODOLOGY

The main objective of the study is to investigate the effects of incorporating reclaimed asphalt pavement and Advera WMA additive into hot mix asphalt at warm temperature. The materials to be used in this study include asphalt binder corresponding to Pen 60/70, reclaimed asphalt pavement (RAP), limestone aggregates with nominal maximum size of 19mm (3/4") and Advera® WMA.

3.1 Identifying Relevant Variables

3.1.1 Independent Variables

The following independent variables are considered to have certain influence on the performance of mixture.

- Properties of RAP material (recovered binder and aggregate)
- Properties of virgin binder
- Dosage of Advera additive
- Gradation of WMA mixture
- Amount of RAP in WMA mixture
- Method of RAP addition
- Mixing temperature
- Compaction temperature

However some of the variables mentioned above are kept constant such as:

- Properties of RAP material including recovered binder and aggregate since this study will use RAP from only one source for producing samples.
- Asphalt binder penetration grade 60/70 is treated as virgin binder because it is a typical binder grade that satisfies many construction standards in Thailand.
- Gradation of WMA mixture will be selected from pilot stage experiment.
- Dosage of Advera will be selected from pilot stage experiment considering viscosity of bitumen added Advera.
- Prepared mixtures will be compacted at the same mixing temperatures after curing for 2 hrs.

3.1.2 Dependent Variables

Performance properties of WMA resulting from varying independent variables are treated as dependent variables.

- Volumetric properties
- Marshall Stability and Flow
- Strength Index

3.2 Design of Experiment

This section determines the effective number of samples and case studies that satisfy the research objectives. The experimental design process consists of two stages i.e. pilot stage and operation stage.

3.2.1 Pilot Stage

The purpose of this stage is to select appropriate material for this research and define variable volume and testing condition that needs to be controlled in the experiment. A flow chart showing the summary of the test process and outcome is shown in Figure 3.1.

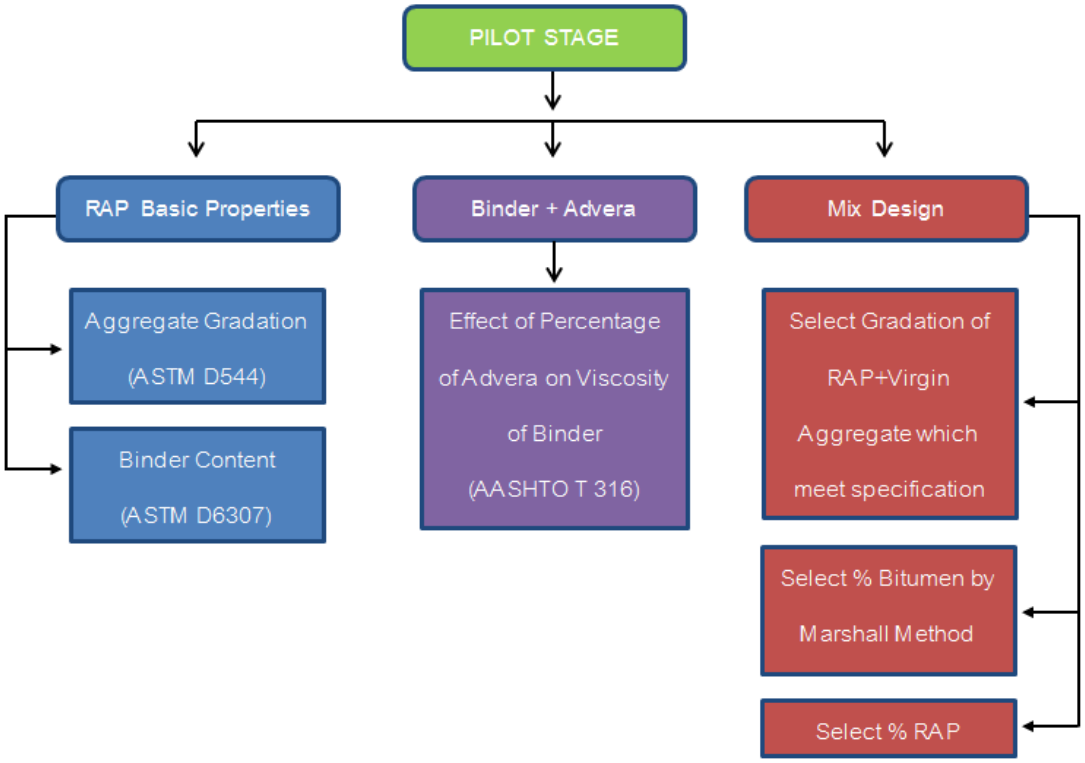

Figure 3. 1Processes and Outcome from Pilot Stage

3.2.1.1 Tests on basic properties of RAP

a) Asphalt/Binder Content (RAP)

The asphalt content of RAP is determined according to ASTM D6307, “Standard Test Method for Asphalt Content of Hot-Mix Asphalt by Ignition Method”. The result is presented in Table 3.1.

Table3. 1 Determination of RAP Binder Content

Sample	M_I (g)	M_L (g)	$(M_I-M_L)/M_I$	CF	Binder Content
1	2220.9	2121.0	4.5%	0.16%	4.7%
2	2218.1	2117.2	4.6%		4.5%
3	2212.7	2111.0	4.6%		4.8%
				AVG	**4.7%**

M_I = total mass of the mixture calibration sample prior to ignition

M_L = total mass of the mixture calibration sample after ignition

CF = Correction factor

b) Gradation Analysis (RAP)

The extracted aggregates obtained from the ignition test are sieved over the standard sieve sizes as per ASTM D5444, “Standard Test Method for Mechanical Size Analysis of Extracted Aggregate”. The gradation of extracted RAP aggregate is shown in Table 3.2. Corrections to gradation are applied to account for the loss of finer particles during the sieve analysis. The percent passing of all sieve sizes are used to plot the gradation curve along with the specifications as per ASTM Standards and obtain master gradation curve for the RAP aggregates as shown in Figure 3.2.

Table3. 2 Gradation Results of RAP Aggregate

Max.aggregate size (mm)			25			Sample						
Sieve	size, d (mm)	d^0.45	P max	ASTM control line low	ASTM control line up	S#1	S#2	S#3	S#4	S#5	S#6	AVG
1.5 in	37.5	5.109	100.0			100.0	100.0	100.0	100.0	100.0	100.0	100.0
1 in	25	4.257	100.0	100	100	100.0	100.0	100.0	100.0	100.0	100.0	100.0
3/4 in	19	3.762	88.4	90	100	100.0	100.0	97.9	100.0	100.0	98.6	99.4
1/2 in	12.5	3.116	73.2			95.9	96.8	89.3	93.7	92.7	90.7	93.2
3/8 in	9.5	2.754	64.7	56	80	91.7	90.9	80.5	85.8	82.8	75.7	84.6
# 4	4.75	2.016	47.4	35	65	79.3	78.3	61.5	63.7	61.9	59.1	67.3
# 8	2.36	1.472	34.6	23	49	59.4	58.9	42.2	43.1	42.8	42.7	48.2
# 16	1.18	1.077	25.3			41.6	41.6	28.9	29.9	29.2	29.6	33.5
# 30	0.6	0.795	18.7			29.2	29.7	21.4	22.6	21.8	21.1	24.3
# 50	0.3	0.582	13.7	5	19	21.2	22.0	16.0	17.6	16.9	15.3	18.2
# 100	0.15	0.426	10.0			15.8	17.0	12.1	13.9	13.4	11.5	14.0
# 200	0.075	0.312	7.3	2	8	12.1	13.2	9.2	10.6	10.7	8.4	10.7
Pan		0	0			0.0	0.0	0.0	0.0	0.0	0.0	0.0

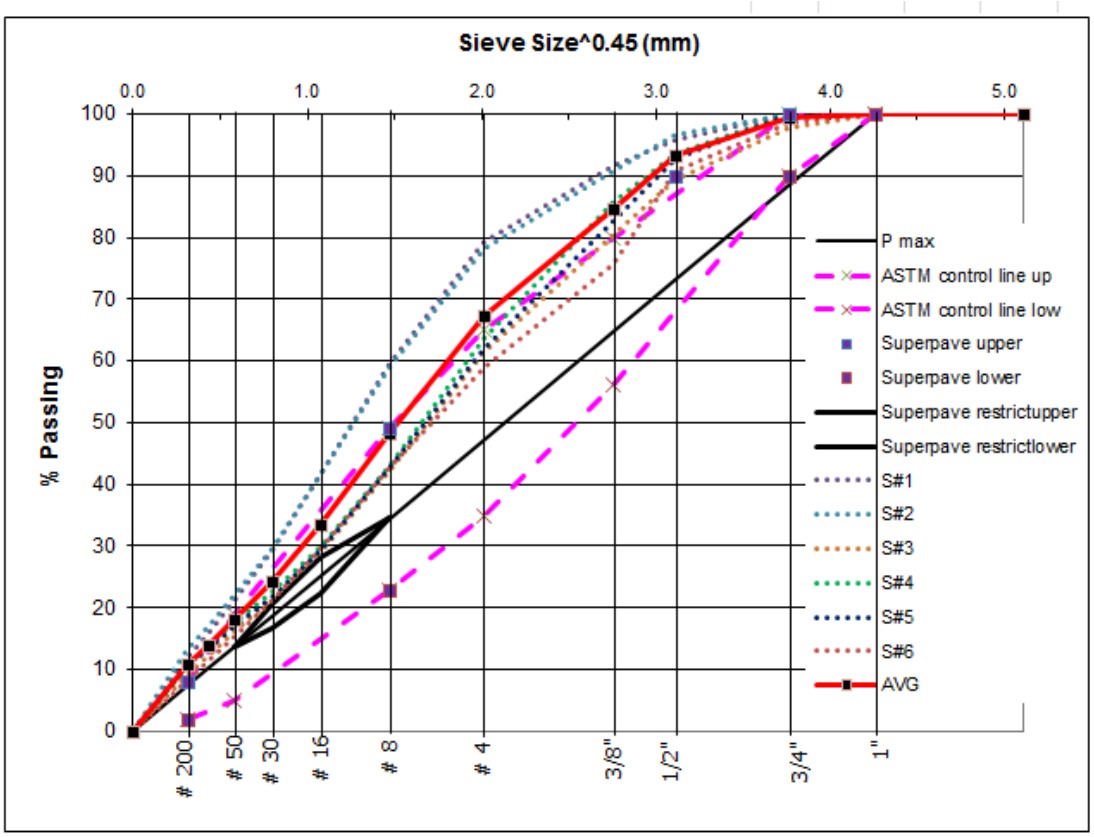

Figure 3. 2 Master Gradation Curve (RAP)

3.2.1.2 Effect of Percentage of Advera on Viscosity

The dosage rate of Advera is selected based on basic properties of bitumen upon adding Advera i.e. viscosity test. These tests are conducted at different temperature and time to simulate properties of binder when being transported from production plant to site, paving and compaction condition. The viscosity test is conducted according to AASHTO T 316," Viscosity Determination of Asphalt Binder Using Rotational Viscometer". Table 3.3 shows the summary of the test conditions and the required samples.

Table3. 3 Summary of Viscosity Test

Treatment	Condition	Tests/rep.	Repetition	Required tests & samples
%Advera (Of mixture wt.)	Temperature: minute			
0%(control) Advera* 0.25% Advera* 0.35% Advera* 0.45%	160°C: 5, 30, 60, 120 140° C: 5, 30, 60, 120 120° C: 5, 30, 60, 120	12	2	24
Advera0.25% Advera0.35% Advera0.45%	160 °C: 5, 30, 60, 120 140° C: 5, 30, 60, 120 120° C: 5, 30, 60, 120	9	2	8
			Σ	32

Note: Advera* is Advera with complete water dismissed by 800°C conditioning.

Viscosity-temperature profile is shown in Figure 3.3. Advera-modified asphalt binder did not reduce the binder viscosity but made it more viscous. Further increasing the Advera content from 0.25% to 0.45% results in

increasing the viscosity of the asphalt binder, making it stiffer throughout the set of test temperatures. P.Q. Corporation which manufactures Advera additive recommends using 0.2 to 0.25% by mixture weight. 0.25% and 0.35% are selected as the Advera content for the WMA mixtures.

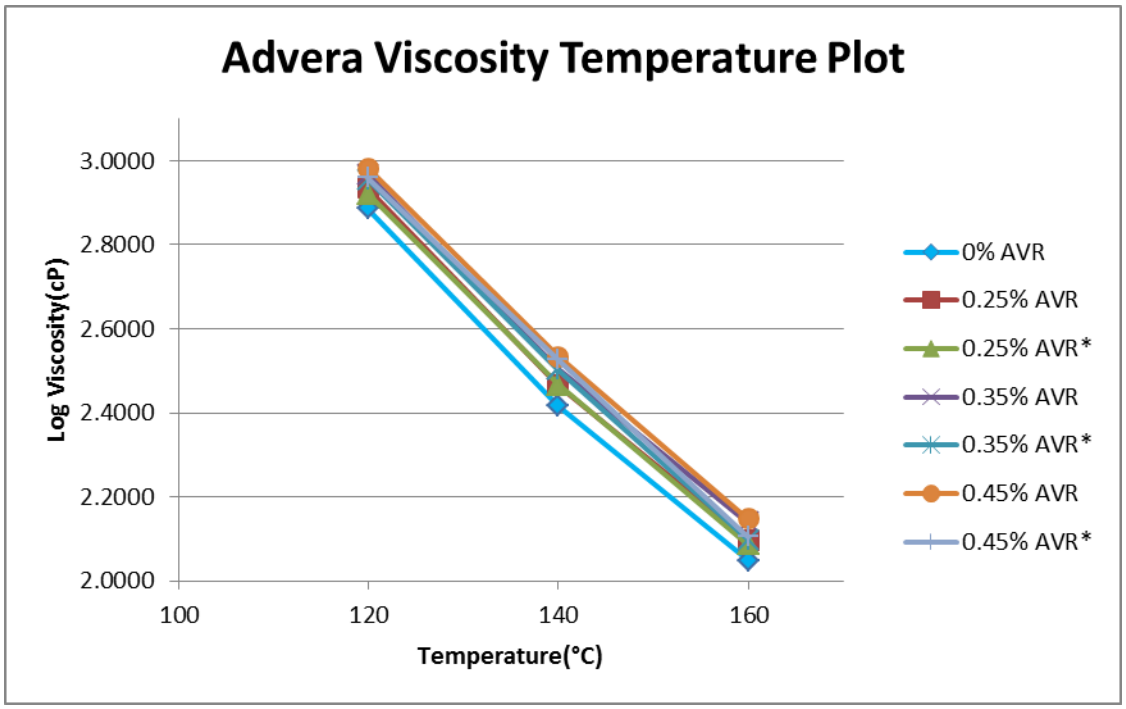

Figure 3. 3 Viscosity-Temperature Plot of Binder+Advera

3.2.1.3 Marshall Mix Design

Mix design of Conventional HMA will be carried out according to ASTM D6926," Standard Practice for Preparation of Bituminous Specimens using Marshall Apparatus" to determine the design gradation and optimum binder content. The standard specification of Marshall Mix Design Method as per DOH requirement is shown in Figure 3.4.

รายการ	Wearing Course	Wearing Course	Binder Course	Base Course	Shoulder
	ขนาด 9.5 มม.	ขนาด 12.5 มม.			
Blows	75	75	75	75	50
Stability N	8006	8006	8006	7117	7117
(Ib)	(1800)	(1800)	(1800)	(1600)	(1600)
Flown 0.25 mm (0.01 in)	8-16	8-16	8-16	8-16	8-16
Percent Air Voids	3-5	3-5	3-6	3-6	3-5
Percent Voids in Mineral Aggregate (VMA) Min	15	14	13	12	14
Stability/Flow Min					
N/0.25 mm	712	712	712	645	645
(Ib/0.01 in)	(160)	(160)	(160)	(145)	(145)
Percent Strength Index Min	75	75	75	75	75

Figure 3. 4 Marshall Mix Design Criteria

Source: DH-S 408/2352

a) Design Gradation

Few gradations based on standard of surface layer material are tested to find the best one that satisfies limitation. Figure 3.5 shows the design gradation that meets the requirements. The gradation resulting from this step is used in the operation stage that uses virgin aggregate and RAP together to control variation due to gradation.

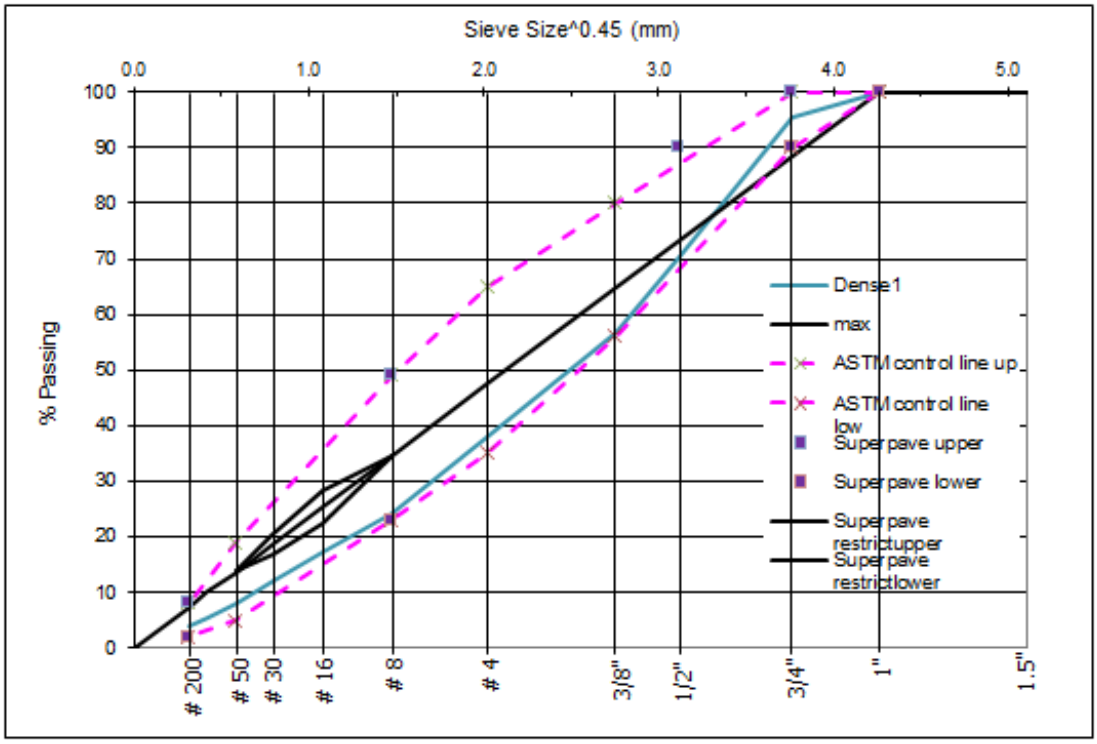

Figure 3. 5 Dense Graded Mix

b) Optimum Binder Content

Trial HMA mixtures with three binder contents i.e. 4%, 5% & 6% with three replicates each are used to determine the optimum binder content for the HMA mixture. Fresh Aggregates are heated for 4 hours and the asphalt binder for 2 hours at 150°C. The heated binder is then added to the heated aggregates in a mixing bowl and mixed for 1 minute. The HMA mixture is cured for 2 hours in the oven at 150°C and then placed in a preheated mould and compacted at 150°C using Marshall Hammer (75 blows on either side). Volumetric properties i.e. maximum theoretical specific gravity (Gmm), bulk specific gravity (Gmb), air void (AV), void in mineral aggregate (VMA) and voids filled with asphalt (VFA), and stability and flow are determined at each binder content as shown in Table 3.4.

Table3. 4 Marshall Mix Design Result

No.	%AC		Weight		specimen height	Bulk S.G.	Max S.G. Gmm (by lab)	Air Void	VMA	VFA	Stability	Flow
	target	actual	Agg.	AC								
	%	%	g	g	mm			%	%	%	KN	(0.25mm)
1	4	4.1	1203.1	50.8	65.8	2.374	2.547	6.8	14.2	52.0	12.4	11.5
2	4	4.0	1201.5	50.1	65.1	2.362	2.547	7.3	14.5	50.1	14.4	11.8
3	4	4.0	1202.2	50.0	66.3	2.352	2.547	7.7	14.9	48.6	11.0	11.0
AVG		4.0				2.362	2.547	7.2	14.5	50.2	12.6	11.4
1	5	5.0	1201.9	63.5	65.1	2.403	2.510	4.3	14.0	69.4	12.5	12.6
2	5	5.0	1199.6	63.1	65.1	2.392	2.510	4.7	14.3	67.3	11.3	12.2
3	5	5.0	1201.4	63.2	65.4	2.375	2.510	5.4	15.0	64.1	12.3	13.0
AVG		5.0				2.390	2.510	4.8	14.4	67.0	12.0	12.6
1	6	6.0	1200.0	76.7	64.3	2.390	2.469	3.2	15.3	79.2	11.7	15.9
2	6	6.0	1201.2	76.7	63.2	2.384	2.469	3.4	15.5	77.9	12.8	15.4
3	6	6.0	1201.8	76.5	65.3	2.404	2.469	2.6	14.8	82.2	11.0	13.0
AVG		6.0				2.393	2.469	3.1	15.2	79.8	11.8	14.8

Data from Table 3.4 are used to plot the Marshall graphical plots as shown in Figure 3.6. The optimum binder content is then determined according to Marshall Mix Design. The asphalt content corresponding to 4%AV from the Marshall graphical plots i.e. 5.4% is the optimum binder content (OBC). Properties such as stability, flow, VFA and VMA at the OBC are evaluated and found to be within the allowable range as shown in Table 3.5.

Table3. 5 HMA Properties at OBC=5.4%

Properties	Value	Min	Max	Unit	Result
Stability @ OBC	11.9	8		KN	PASS
Flow @ OBC	13.5	8	16		PASS
VMA @ OBC	14.7	14		%	PASS
VFA @ OBC	72.5	65	80	%	PASS

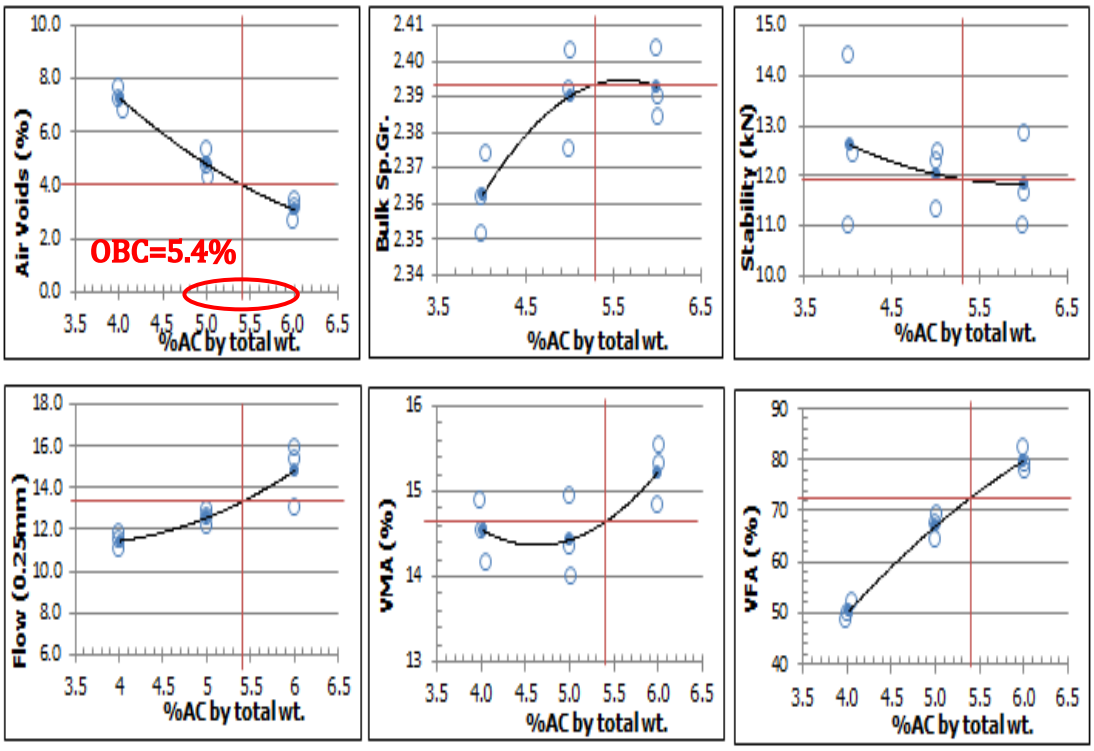

Figure 3. 6 Marshall Graphical Plots

c) Combined Aggregate Blend

The bulk specific gravity of both virgin aggregates and RAP aggregates are determined separately in order to obtain the combined bulk specific gravity (Gsb) of the aggregate blend. The results are shown in Table 3.6.

Table3. 6 Bulk Specific Gravity of Combined Aggregate Blend

	Fresh Aggregate	RAP Aggregate	Combined Aggregate Blend
Gsb	2.695	2.671	
Content	85%	15%	2.691
	70%	30%	2.688

d) Percentage of RAP in the Asphalt Mixture

The amount of RAP to be used depends on the source from which RAP is milled. Homogeneous source of RAP facilitates higher percentages of RAP to be used in the mix compared to a RAP stockpile consisting of material from several projects. The main concern of using higher RAP content is that the pre-existing binder in RAP tends to replaces the virgin binder in the mix thereby affecting the overall binder properties. Various U.S. State transportation departments have fixed a minimum percentage of virgin binder content i.e. 70% of the binder content must be virgin binder. 15% and 30% RAP content have been selected as the amount of RAP to be used in the production of asphalt mixtures.

3.2.2 Operation Stage

Influence of independent variables on WMA performance properties is investigated by varying 2-3 levels per variable.

- %RAP added in WMA (15% and 30%)
- %Advera adding in mixture (0.25% and 0.35%)
- Mixing/Compaction temperature (150°C, 135°C and 120°C)

Figure 3.7 shows a flow chart illustrating test process and outcome from the operation stage. Table 3.7 shows the summary of experiment design.

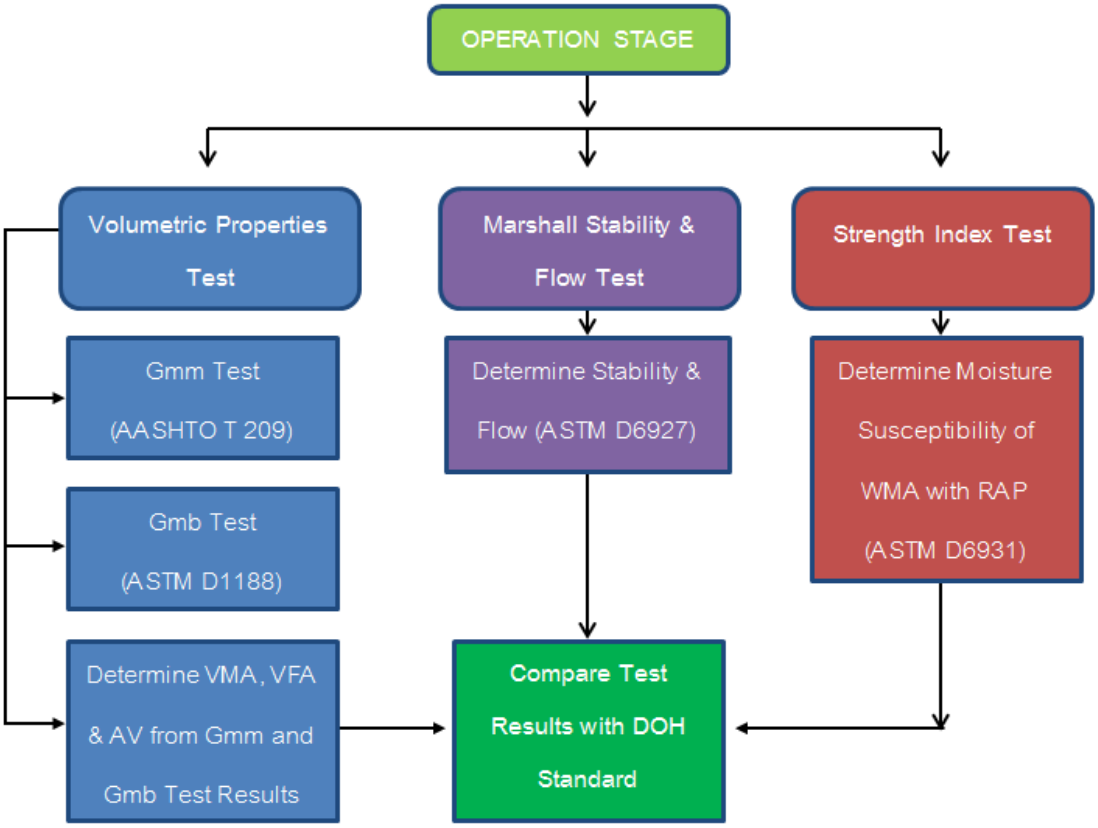

Figure 3. 7 Processes and Outcome from Operation Stage

Table3. 7 Summary of Experiment Design

#	V1	V2	V3
Variable	%RAP	% Advera by mixture weight	Mixing/Compaction Temperature
Conditioned	0% 15% 30%	0%	150°C
Treatment	15% 30%	0.25% 0.35%	150°C 135°C 120°C
N	2	2	3
Note	% of bitumen 60/70 & aggregate added vary by RAP mix design	% Advera affects amount of foams	Mixing/Compaction temp affects binder aging, amount of foams & %binder absorption. All mixes will be mixed & compacted at same temp after curing for 2 hrs

CHAPTER IV

LABORATORY TEST PROCEDURES

4.1 Preparation of Control Sample

a) Conventional Hot Mix Asphalt consisting of virgin aggregate + Pen 60/70 binder

Fresh Aggregates are heated in an oven at 150°C for four hours. The binder (AC 60/70) is heated to 150°C for two hours and mixed with the fresh aggregates in mixing bowl for one minute. The mixture is then cured for two hours at 150°C and compacted at the same temperature.

b) Recycled Hot Mix Asphalt consisting of virgin aggregate + Pen 60/70 binder + given proportion of RAP

Fresh Aggregates are heated in an oven at 150°C for four hours while the RAP (15% and 30%) is covered in can and heated at 110°C for two hours. Fresh aggregates and RAP are mixed together for a minute and binder (heated to 150°C for 2 hours) is added and the mixture is mixed for two minutes. The mixture is then cured for two hours at 150°C and compacted at the same temperature.

4.2 Preparation of WMA Mixture

WMA mixtures with two Advera content (0.25% and 0.35% by Mixture weight) and two RAP content (15% and 30%) are produced at three temperatures i.e. 150°C, 135°C and 120°C. Fresh Aggregates are heated in

an oven at the mixing temperature (150°C, 135°C and 120°C) for four hours while the RAP (covered in can) is heated at 110°C for two hours. Fresh aggregates and RAP are mixed together in a mixing bowl for a minute. The binder, heated to 150°C for 2 hours, is poured into mixing bowl followed by addition of 0.25% & 0.35% Advera by mixture weight and the mixture is mixed for two minutes. The mixture is then cured for two hours at 150°C, 135°C and 120°C and compacted at the three temperatures.

4.3 Volumetric Properties

HMA and WMA samples are produced in the laboratory according to the procedure explained above. Maximum theoretical specific gravity (Gmm) of un-compacted HMA mixtures with and without RAP shall be determined as per AASHTO T209,"Theoretical Maximum Specific Gravity and Density of Hot Mix Asphalt (HMA)". A weighed sample of oven-dry un-compacted asphalt mixture is placed in a tarred vacuum vessel. Water is added to fully immerse the sample and vacuum is applied for 15minutes. Next the entire set up is submerged into a water bath to determine the volume of the sample. Gmm is then calculated by dividing the sample's mass by its volume.

The samples are compacted to 4 percent air void by using Marshall hammer (75 blows) and allowed to cool for 24hours. Bulk specific gravity (Gmb) test is conducted as per ASTM D1188, "Standard Test Method for Bulk Specific Gravity and Density of Compacted Bituminous Mixtures Using Coated Samples". A compacted specimen is weighed dry, wrapped in thin paraffin film and weighed in and out of water. These weights are used to

calculate Gmb. Air voids, voids in mineral aggregate (VMA) and voids filled with asphalt (VFA) are then determined from the Gmm and Gmb values.

4.4 Marshall Stability and Flow

The Marshall stability and flow test provides the performance prediction measure for the Marshall mix design method. The standard followed is ASTM D 6927, “Standard Test Method for Marshall Stability and Flow of Bituminous Mixtures”. The specimens should have a diameter of 100mm and a thickness of 63.5mm. Specimens are immersed in a water bath for 30 minutes at 60±1.0 °C, placed on a Marshall apparatus and subjected to loading. The stability assessment determines the maximum load that can be supported by the test specimen when subjected to a loading rate of 50.8 mm/minute. Load is applied to the specimen till failure, and the maximum load is designated as stability. During the loading, an attached dial gauge measures the specimen's plastic flow (deformation) as a result of the loading (Figure 4.1). The flow value is recorded in 0.25 mm (0.01 inch) increments at the same time when the maximum load is recorded.

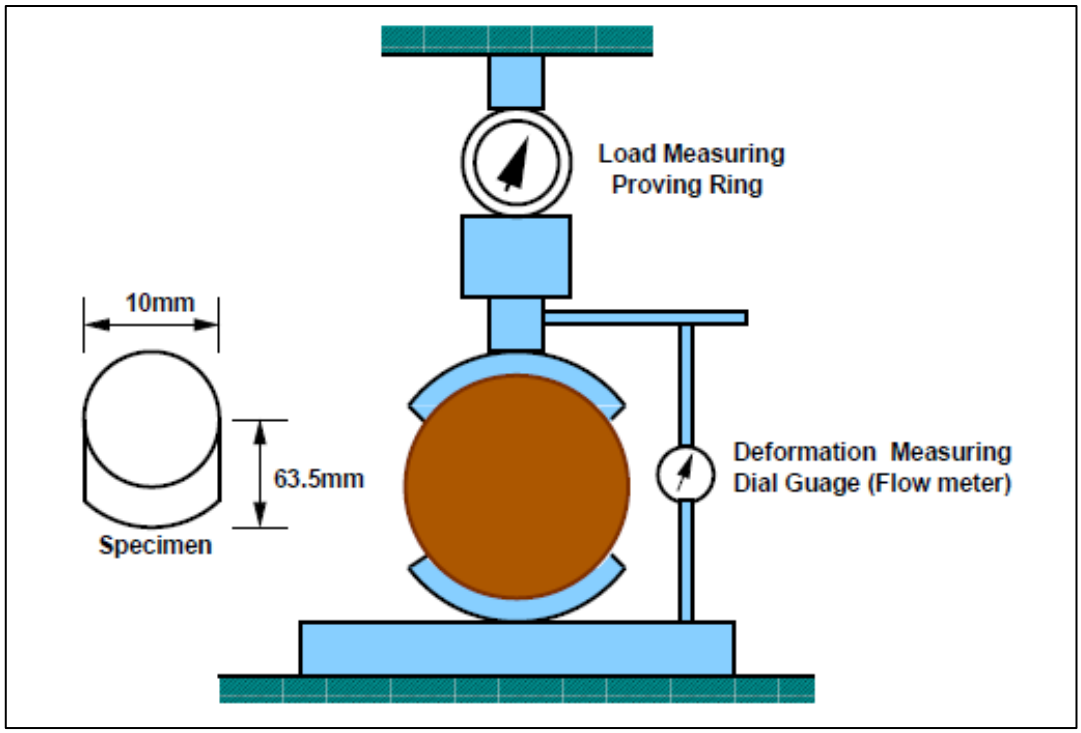

Figure4. 1 Marshall Apparatus

Source: NPTEL, 2006

4.5 Strength Index Test

The strength index test is conducted to evaluate the moisture susceptibility of WMA mixtures following DOH standard DH T-413/2544. Each set of specimens is divided into subsets. One subset is tested in dry condition while the other subset is conditioned. For the conditioned subset, specimens are soaked in sodium chloride solution followed by the application of vacuum for 1 hour. After the vacuum period, specimens are again soaked in sodium chloride solution at 60°C for 4 hours. Specimens are then placed in a 25°C water bath for 1 hour and Marshall stability and flow are determined. For the dry subset, specimens are placed in a 25°C water bath for 1 hour and then

Marshall stability and flow are determined. Strength index is calculated by dividing the measured stability values of conditioned samples by that of the dry samples expressed in percentage.

A summary of the laboratory tests along with the required sample size is presented in Table 4.1.

Table4. 1Laboratory test with 100mm sample size

Test	Condition	Tests /Rep	Repetition	Cases	Required Sample
Volumetric Property	4% air voids + 75 blows	1	3	Conditioned =3 V1xV2xV3xV4=12	45
Marshall Stability and Flow	4% air void+75 blows	1	3	Conditioned=3 V1xV2xV3=12	45
Strength Index	7% air void	2	3	Conditioned=2 V1XV2XV3=1	18
				Σ	**108**

CHAPTER V

EXPERIMENTAL RESULTS AND FINDINGS

5.1 Results

5.1.1 Volumetric Properties

The theoretical maximum specific gravity (Gmm) of all test specimens is measured twice. The Gmm values range between 2.490 – 2.511(0.02 range) which is within the range of ASTM allowance. It is assumed that Advera® WMA did not affect the Gmm of the mix as WMA additives affect the workability of the mix, which in turn increases compactability of a mix with the same Gmm as the mix without the aid of additives. Bulk specific gravity (Gmb) values are measured with three replicates. The Gmb laboratory test results ranges between 2.310 – 2.432 (Figure 5.1). Given the same level of compaction (75blows using Marshall Hammer), WMA with RAP resulted in higher bulk specific gravities.

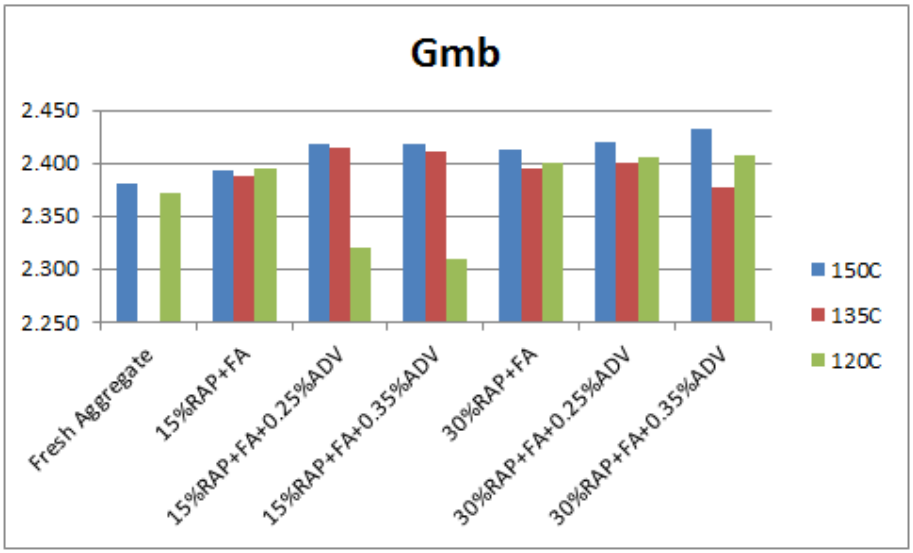

Figure5. 1 Average Results of Bulk Specific Gravity Test

The average air voids for each set of specimen is shown in Figure 5.2. It is found that changing the temperature from 150°C to 120°C results in higher air void due to lower workability. The addition of RAP seems to lower the percent air void. The reason behind this could be that since RAP in Bangkok area has been in service for shorter period, the binder inside RAP has not aged excessively and the other possibility could be that the milling process might have caused the RAP particles to be more rounded in shape. The addition of Advera results in lowering the percent air void however 0.35% Advera seems to have no improvements from 0.25% Advera WMA mixtures.

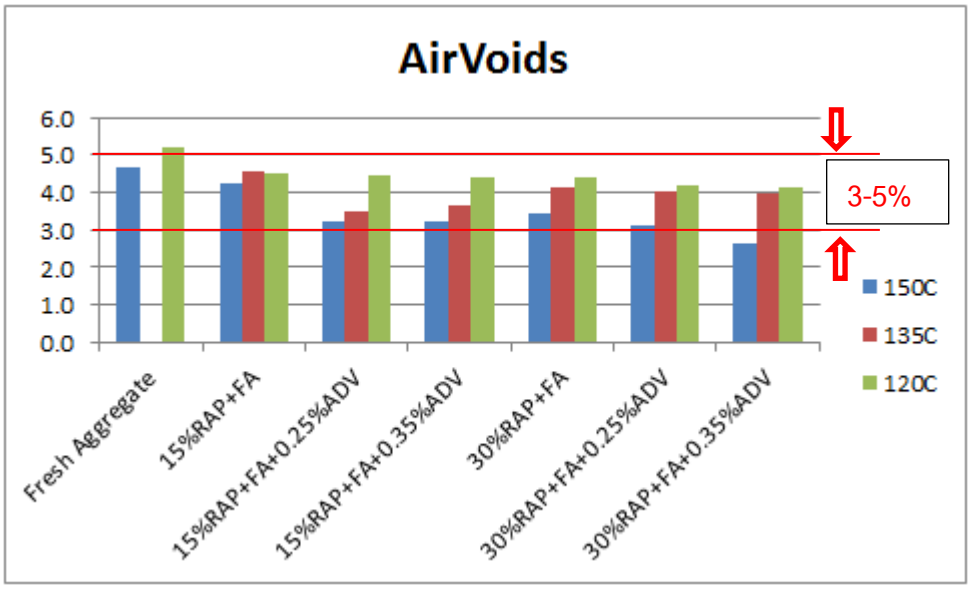

Figure5. 2 Average Results of Air Void

The average voids in mineral aggregate (VMA) for each set of specimen is presented in Figure 5.3. It is evident from the figure that Advera results in lowering the percent VMA and similar trend is observed with the addition of RAP as well. This is due to the lower percent air voids obtained with RAP and Advera as mentioned earlier.

The average values of voids filled with asphalt (VFA) is shown in Figure 5.4. Similar trend is observed with the addition of RAP and Advera as both resulted in higher percent VFA owing to lower percent air voids.

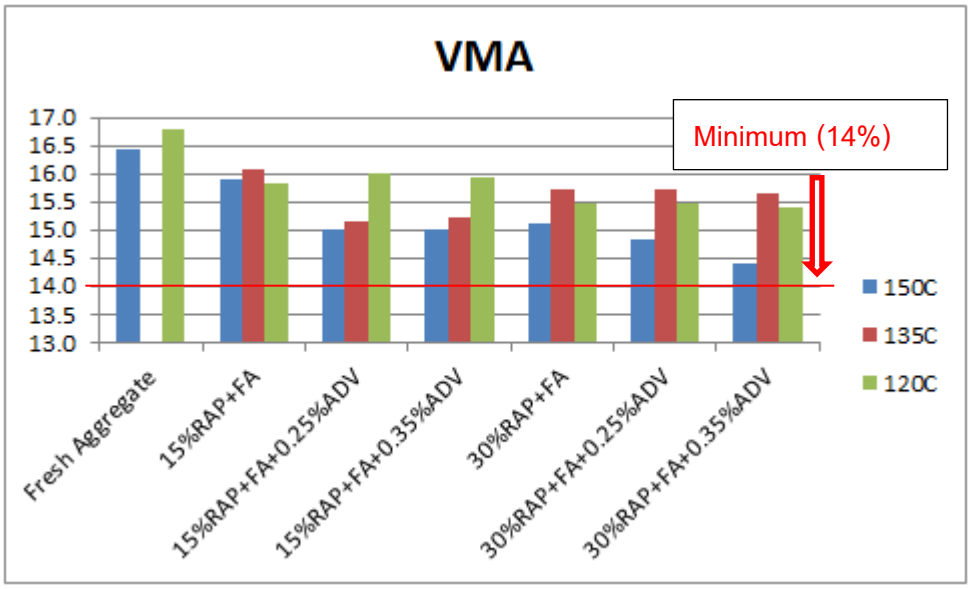

Figure5. 3 Average Results of Voids in Mineral Aggregate

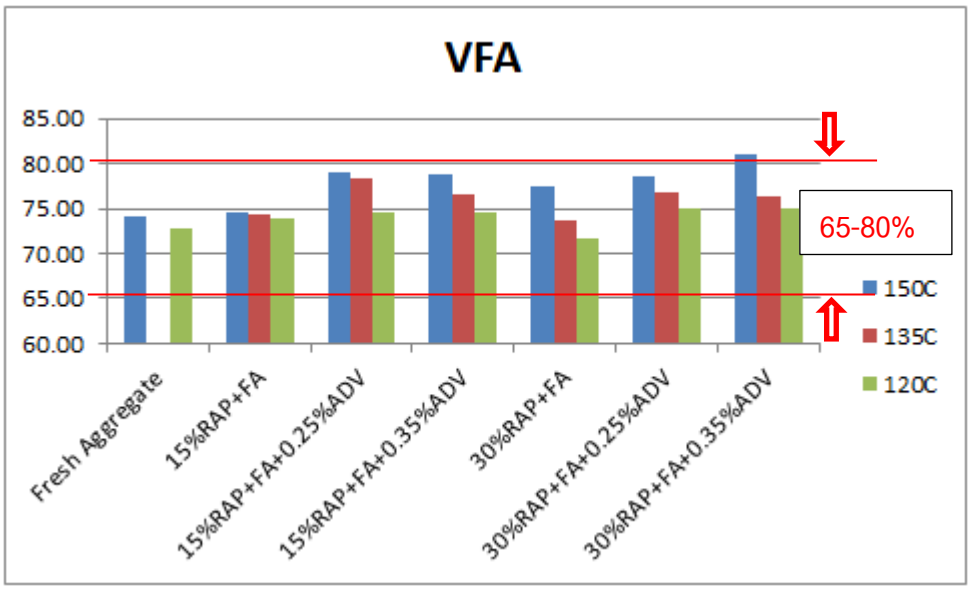

Figure5. 4 Average Results of Voids Filled with Asphalt

5.1.2 Marshall Stability and Flow

Marshall stability and flow test were conducted for all the set of specimens. The average stability test results are shown in Figure 5.5. There is an improvement in stability for mixtures prepared with 0.25%Advera and 15%RAP but in the case of 30%RAP mix, adding Advera tends to reduce stability at 135°C and 120°C.

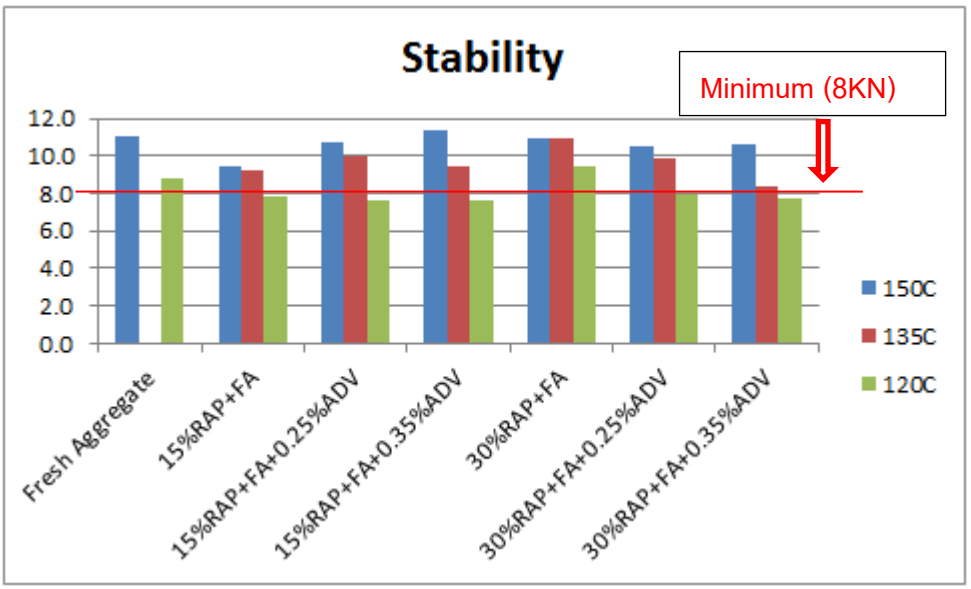

Figure5. 5 Average Results of Stability Test

The average flow results are presented in Figure 5.6. It is found that addition of RAP increases flow. In the case of mix produced with 15%RAP, adding Advera results in increasing the flow but with further increasing the Advera content from 0.25% to 0.35% tends to decrease the flow value. For 30%RAP, adding Advera tends to lower the flow values.

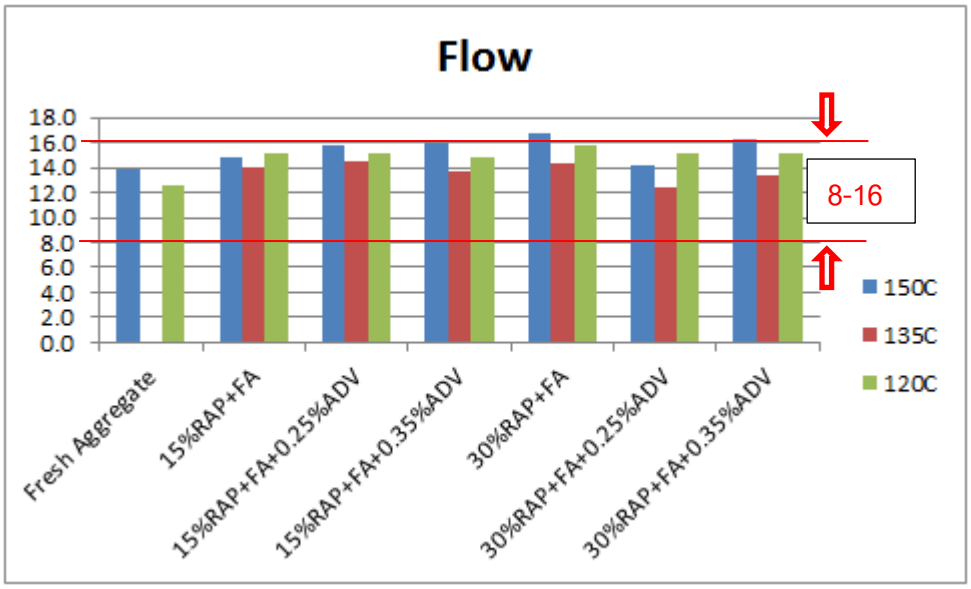

Figure5. 6 Average Results of Flow Test

5.2 Effect of Mixing/Compaction Temperature

The effect of mixing/compaction temperature is evaluated for the control and WMA mixtures with RAP with the aid of correlation using SPSS software. Table 5.1 to 5.6 shows the correlation for the various cases and Table 5.7 presents the overall correlation. The effect of mixing/compaction temperature on the mixture properties at 95% significance level is indicated with a star. It is observed that mixing/compaction temperature significantly affects the AV, VMA, VFA and stability. Changing the mixing/compaction temperature from 150°C to 120°C resulted in higher AV and VMA due to lower workability while VFA and stability decreased at low mixing/compaction temperatures.

Table5. 1 Effect of Mixing/Compaction Temperature_HMA with 15%RAP

		Mixing/Compaction Temperature	AV	VMA	VFA	Stability	Flow
Mixing/Compaction Temperature	Pearson Correlation	1	-.731*	0.132	0.083	0.478	-0.064
	Sig. (2-tailed)		0.011	0.7	0.807	0.137	0.852

Table5. 2 Effect of Mixing/Compaction Temperature_HMA with 30%RAP

		Mixing/Compaction Temperature	AV	VMA	VFA	Stability	Flow
Mixing/Compaction Temperature	Pearson Correlation	1	-.786*	-0.484	.826*	.610*	0.437
	Sig. (2-tailed)		0.004	0.131	0.002	0.046	0.179

Table5. 3 Effect of Mixing/Compaction Temperature_WMA (0.25%Advera) + 15%RAP

		Mixing/Compaction Temperature	AV	VMA	VFA	Stability	Flow
Mixing/Compaction Temperature	Pearson Correlation	1	-.888*	-.861*	.615	.929*	.252
	Sig. (2-tailed)		.001	.003	.078	.000	.513

Table5. 4 Effect of Mixing/Compaction Temperature_WMA (0.25%Advera) + 30%RAP

		Mixing/Compaction Temperature	AV	VMA	VFA	Stability	Flow
Mixing/Compaction Temperature	Pearson Correlation	1	-.843*	-.593	.554	.786*	-.252
	Sig. (2-tailed)		.004	.093	.122	.012	.514

Table5. 5 Effect of Mixing/Compaction Temperature_WMA (0.35%Advera) + 15%RAP

		Mixing/Compaction Temperature	AV	VMA	VFA	Stability	Flow
Mixing/Compaction Temperature	Pearson Correlation	1	-.866*	-.824*	.567	.793*	.321
	Sig. (2-tailed)		.003	.006	.112	.011	.399

Table5. 6 Effect of Mixing/Compaction Temperature_WMA (0.35%Advera) +30%RAP

		Mixing/Compaction Temperature	AV	VMA	VFA	Stability	Flow
Mixing/Compaction Temperature	Pearson Correlation	1	-.897*	-.746*	.694*	.757	.259
	Sig. (2-tailed)		.001	.021	.038	.018	.501

Table5. 7 Overall Effect of Mixing/Compaction Temperature

		Mixing/Compaction Temperature	AV	VMA	VFA	Stability	Flow
Mixing/Compaction Temperature	Pearson Correlation	1	-.596*	-.405*	.414*	.680*	0.224
	Sig. (2-tailed)		0	0.001	0.001	0	0.076

5.3 Effect of RAP Addition

The effect of RAP addition is evaluated at each of the three mixing/compaction test temperatures (150°C, 135°C and 120°C) by running correlation using SPSS software. Table 5.8 to 5.10 shows the correlation for the various cases and Table 5.11 presents the overall correlation. The influence of RAP addition on the mixture properties at 95% significance level is indicated with a star. The addition of RAP showed increase in the flow but brought a decrease in air void and VMA.

Table5. 8 Effect of RAP addition at 150°C

		RAP content	AV	VMA	VFA	Stability	Flow
RAP content	Pearson Correlation	1	-.854*	-.900*	0.44	0.052	.671*
	Sig. (2-tailed)		0	0	0.133	0.866	0.012

Table5. 9 Effect of RAP addition at 135°C

		RAP content	AV	VMA	VFA	Stability	Flow
RAP content	Pearson Correlation	1	-.954*	-.938*	-0.157	0.653	0.115
	Sig. (2-tailed)		0.003	0.006	0.766	0.16	0.828

Table5. 10 Effect of RAP addition at 120°C

		RAP content	AV	VMA	VFA	Stability	Flow
RAP content	Pearson Correlation	1	-0.859*	-0.931*	-0.119	0.351	0.922*
	Sig. (2-tailed)		0.003	0	0.76	0.355	0

Table5. 11 Overall Effect of RAP Addition

		RAP content	AV	VMA	VFA	Stability	Flow
RAP content	Pearson Correlation	1	-0.723*	-0.86*	0.151	0.262	0.595*
	Sig. (2-tailed)		0	0	0.443	0.178	0.001

5.4 Effect of Advera WMA

The influence of Advera on mixture property is evaluated for WMA with 15%RAP & 30%RAP at three mixing/compaction temperatures (150°C, 135°C and 120°C) by running correlation using SPSS software. Table 5.12 to 5.17 shows the correlation for the various cases and Table 5.18 presents the overall correlation. The effect of Advera on mixture properties at 95% significance level is indicated with a star. Overall addition of Advera resulted in decreasing the air void, VFA and VMA.

Table5. 12 Effect of Advera_WMA with 15%RAP at 150°C

		Advera content	STABILITY	FLOW	AV	VMA	VFA
Advera content	Pearson Correlation	1	0.557	0.443	-.904*	-.970*	-0.261
	Sig. (2-tailed)		0.075	0.172	0	0	0.439

Table5. 13 Effect of Advera_WMA with 15%RAP at 135°C

		Advera content	STABILITY	FLOW	AV	VMA	VFA
Advera content	Pearson Correlation	1	0.18	-0.109	-.804*	-.952*	-0.348
	Sig. (2-tailed)		0.643	0.78	0.009	0	0.359

Table5. 14 Effect of Advera_WMA with 15%RAP at 120°C

		Advera content	STABILITY	FLOW	AV	VMA	VFA
Advera content	Pearson Correlation	1	-0.156	-0.165	-0.51	-.963*	-0.386
	Sig. (2-tailed)		0.689	0.672	0.16	0	0.304

Table5. 15 Effect of Advera_WMA with 30%RAP at 150°C

		Advera content	STABILITY	FLOW	AV	VMA	VFA
Advera content	Pearson Correlation	1	-0.154	-0.395	-0.393	-.943*	-0.382
	Sig. (2-tailed)		0.651	0.229	0.231	0	0.246

Table5. 16 Effect of Advera_WMA with 30%RAP at 135°C

		Advera content	STABILITY	FLOW	AV	VMA	VFA
Advera content	Pearson Correlation	1	-.786*	-0.334	-0.426	-.959*	-0.327
	Sig. (2-tailed)		0.012	0.38	0.253	0	0.39

Table5. 17 Effect of Advera_WMA with 30%RAP at 120°C

		Advera content	STABILITY	FLOW	AV	VMA	VFA
Advera content	Pearson Correlation	1	-.789*	-0.374	-.736*	-.967*	-0.283
	Sig. (2-tailed)		0.012	0.322	0.024	0	0.461

Table5. 18 Overall Effect of Advera

		Advera content	STABILITY	FLOW	AV	VMA	VFA
Advera content	Pearson Correlation	1	-0.153	-0.055	-.352*	-.950*	-.335*
	Sig. (2-tailed)		0.226	0.666	0.004	0	0.007

5.5 Comparison of Test Data with Standard HMA

T test is carried out to determine whether the performance property of WMA is significantly different from HMA at 95% significance level by varying 3 factors; %RAP, %Advera and Mixing/Compaction temperature.

5.5.1 Air Voids (AV)

Statistical test showed that the air voids of WMA mix produced with RAP at 150°C are not significant except for mix with 15%RAP and WMA (0.35%Advera) with 30% RAP as shown in Table 5.19. However at lower mixing/compaction temperatures, air voids of most of the WMA mix with RAP were significant indicating that the values are within the allowable range of 3-5% as presented in Table 5.20 and 5.21. The air voids of WMA mixture with

different RAP content are also presented graphically using a box plot (Figure 5.7 and 5.8).

Table5. 19 Statistical Tests of Air Voids at 150°C

RAP (%)	Advera (%)	t score		Significance Value		Result of t test
		μ > = 3	μ < = 5	μ > = 3	μ < = 5	
15	0	21.909	-14.606	0.000	0.000	Significant
15	0.25	1.941	-14.700	0.096	0.002	Not Significant
15	0.35	1.151	-8.713	0.184	0.006	Not Significant
30	0	1.929	-7.257	0.063	0.001	Not Significant
30	0.25	.918	-12.847	0.228	0.003	Not Significant
30	0.35	-3.051	-19.692	0.046	0.001	Significant

Table5. 20 Statistical Tests of Air Voids at 135°C

RAP (%)	Advera (%)	t score		Significance Value		Result of t test
		μ > = 3	μ < = 5	μ > = 3	μ < = 5	
15	0	46.000	-14.000	0.000	0.003	Significant
15	0.25	7.000	-7.206	0.045	0.009	Significant
15	0.35	2.714	-5.857	0.057	0.014	Not Significant
30	0	35.000	-25.000	0.000	0.001	Significant
30	0.25	5.096	-4.768	0.018	0.021	Significant
30	0.35	14.500	-15.500	0.002	0.002	Significant

Table5. 21 Statistical Test of Air Voids at 120°C

RAP (%)	Advera (%)	t score		Significance Value		Result of t test
		μ < = 3	μ > = 5	μ < = 3	μ > = 5	
15	0	23.00	-7.00	0.001	0.010	Significant
15	0.25	22	-8	0.001	0.008	Significant
15	0.35	15.497	-7.181	0.002	0.010	Significant
30	0	20.5	-9.5	0.001	0.006	Significant
30	0.25	20.785	-13.856	0.001	0.003	Significant
30	0.35	17	-13	0.002	0.003	Significant

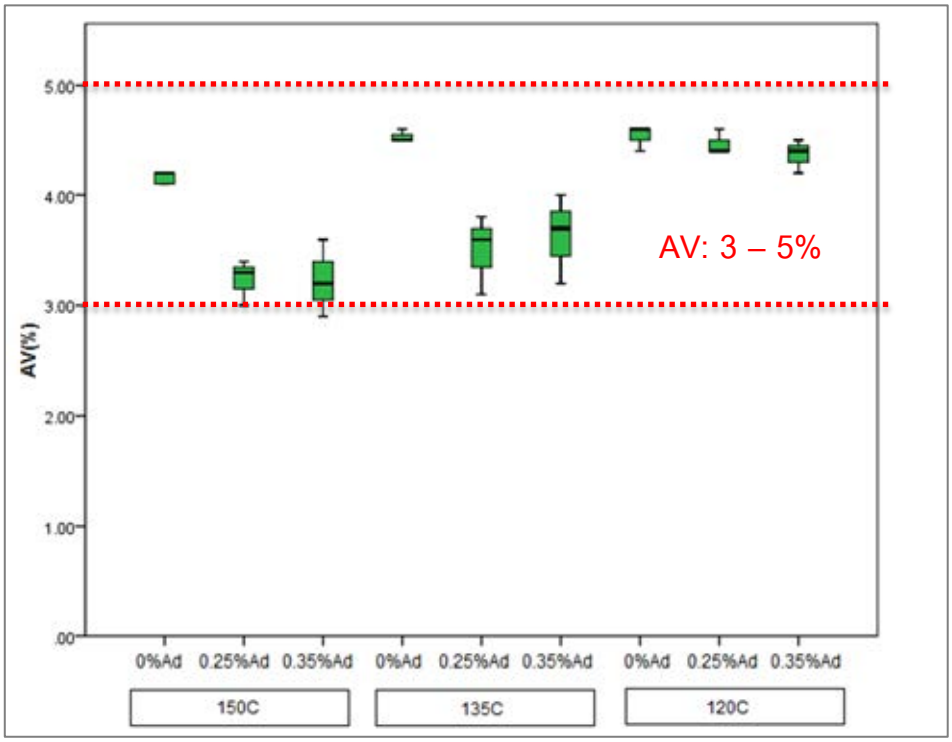

Figure5. 7 Air Voids of WMA Mixtures with 15% RAP

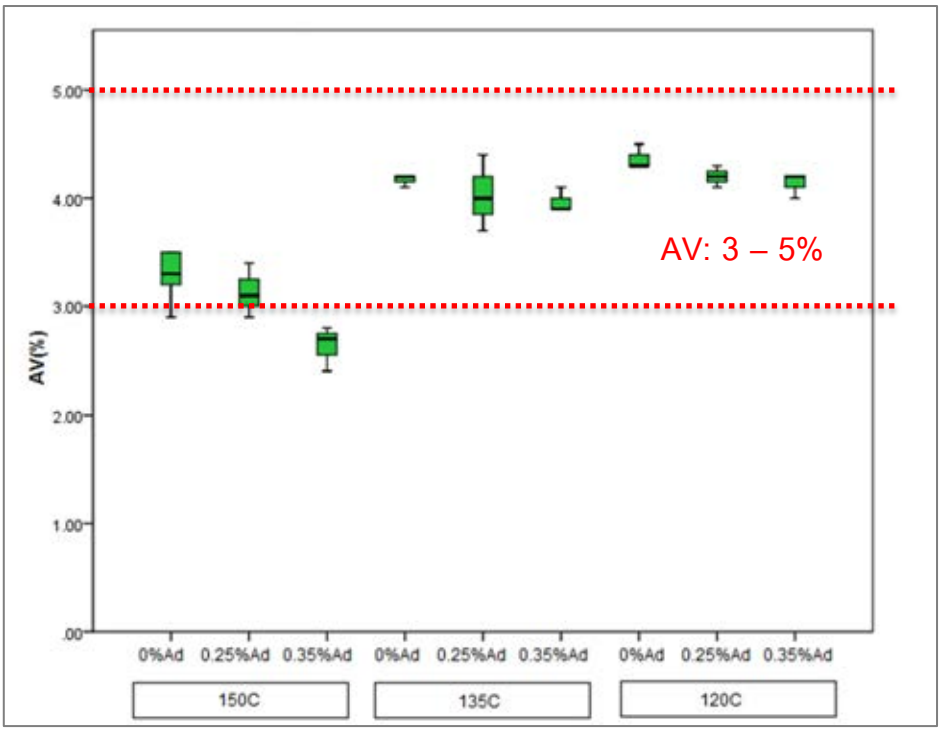

Figure5. 8 Air Voids of WMA Mixtures with 30% RAP

5.5.2 Voids in Mineral Aggregate (VMA)

Statistical test showed that the VMA values for all mixtures are significant indicating that all values are greater than minimum limit of 14%. The t test results are shown in Table 5.22 to 5.24. The VMA values of WMA mixture with different RAP content are presented graphically using a box plot (Figure 5.9 and 5.10.

Table5. 22 Statistical Tests of VMA at 150°C

RAP (%)	Advera (%)	t score	Significance Value	Result of t test
		μ < = 14	μ < = 14	
15	0	34.689	0.000	Significant
15	0.25	10.00	0.005	Significant
15	0.35	7.667	0.042	Significant
30	0	11.418	0.0005	Significant
30	0.25	7.211	0.010	Significant
30	0.35	3.606	0.035	Significant

Table5. 23 Statistical Tests of VMA at 135°C

RAP (%)	Advera (%)	t score	Significance Value	Result of t test
		μ < = 14	μ < = 14	
15	0	62.00	0.000	Significant
15	0.25	9.00	0.035	Significant
15	0.35	14.00	0.023	Significant
30	0	26.00	0.001	Significant
30	0.25	10.333	0.031	Significant
30	0.35	25.00	0.001	Significant

Table5. 24 Statistical Tests of VMA at 120°C

RAP (%)	Advera (%)	t score	Significance Value	Result of t test
		μ < = 14	μ < = 14	
15	0	27.5	0.001	Significant
15	0.25	34.641	0.001	Significant
15	0.35	16.086	0.002	Significant
30	0	22	0.001	Significant
30	0.25	21.5	0.001	Significant
30	0.35	160.635	0.000	Significant

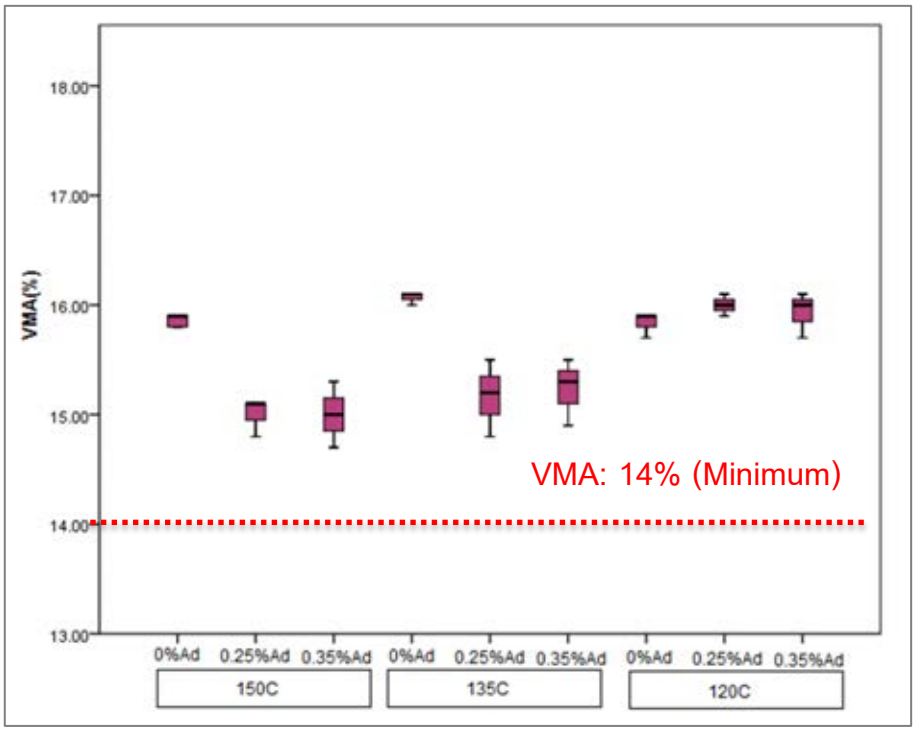

Figure5. 9 Voids in Mineral Aggregate of WMA Mixtures with 15%RAP

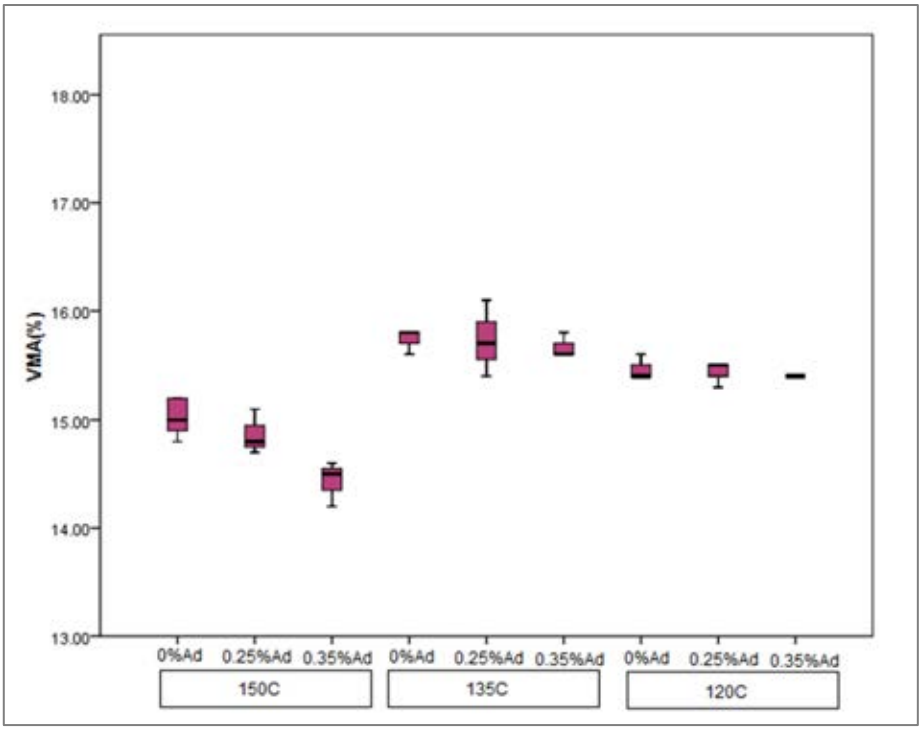

Figure5. 10 Voids in Mineral Aggregate of WMA Mixtures with 30%RAP

5.5.3 Stability

A minimum of 8KN is the standard requirement for asphalt mixtures. From the t test, it is found that stability values of most of the WMA mix are not significant at 150°C and 120°C but however stability values of WMA at 135°C showed better results especially WMA mix (0.25%Advera) with 15%RAP (Table 5.25 to 5.27). The stability values of WMA mixture with different RAP content are presented graphically using a box plot (Figure 5.11 and 5.12).

Table5. 25 Statistical Tests of Stability at 150°C

RAP (%)	Advera (%)	t score	Significance Value	Result of t test
		$\mu <= 8$	$\mu <= 8$	
15	0	2.335	0.145	Not Significant
15	0.25	14.450	0.044	Significant
15	0.35	7.840	0.081	Not Significant
30	0	27.178	0.0014	Significant
30	0.25	8.979	0.071	Not Significant
30	0.35	37.735	0.017	Significant

Table5. 26 Statistical Tests of Stability at 135°C

RAP (%)	Advera (%)	t score	Significance Value	Result of t test
		$\mu <= 8$	$\mu <= 8$	
15	0	11.00	0.049	Significant
15	0.25	33.00	0.019	Significant
15	0.35	4.20	0.149	Not Significant
30	0	21.00	0.030	Significant
30	0.25	7.00	0.090	Not Significant
30	0.35	4.20	0.149	Not Significant

Table5. 27 Statistical Tests of Stability at 120°C

RAP (%)	Advera (%)	t score	Significance Value	Result of t test
		μ < = 8	μ < = 8	
15	0	3.000	0.205	Not Significant
15	0.25	-1.263	0.426	Not Significant
15	0.35	0.667	0.626	Not Significant
30	0	9.820	0.010	Significant
30	0.25	3.000	0.205	Not Significant
30	0.35	11.800	0.054	Not Significant

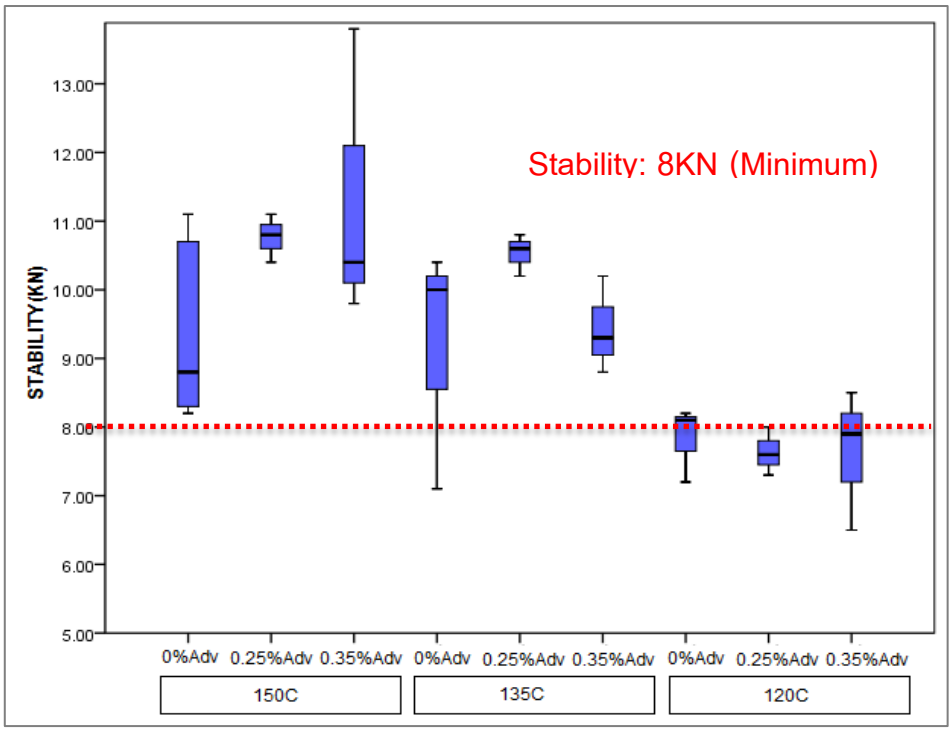

Figure5. 11 Stability of WMA Mixtures with 15%RAP

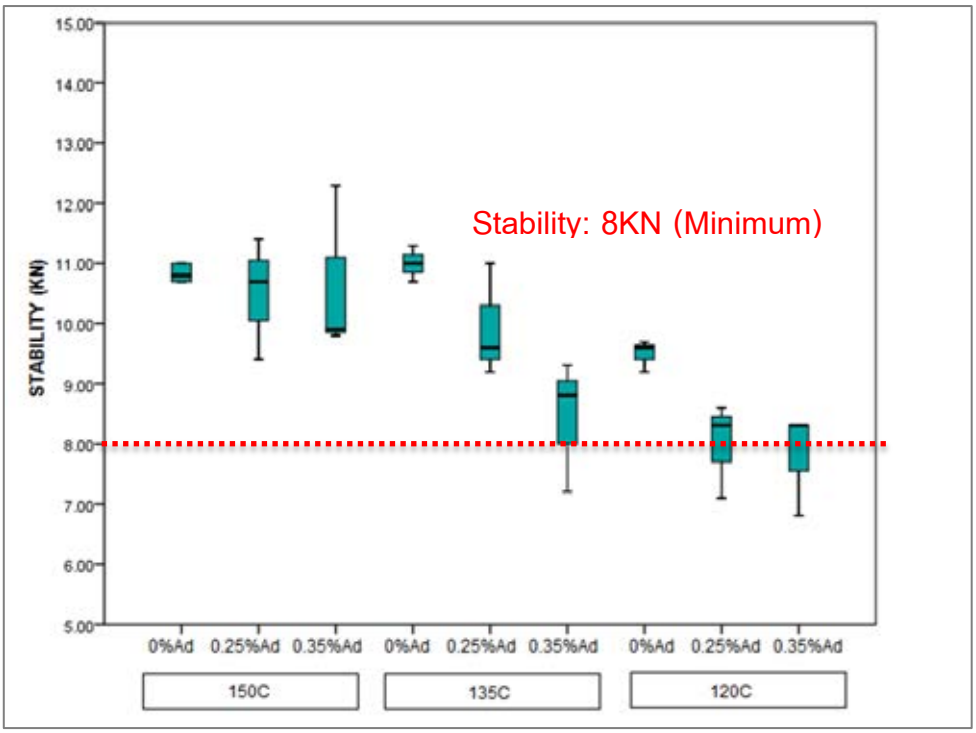

Figure5. 12 Stability of WMA Mixtures with 30%RAP

5.5.4 Flow

Statistical test showed that the flow values of WMA mix produced with RAP at 135°C are better compared to the mix produced at 150°C and 120°C. The test results are shown in Table 5.28 to 5.30. The standard requires flow in the range 8-16. The flow values of WMA mixture with different RAP content are also presented graphically using a box plot (Figure 5.13 and 5.14).

Table5. 28 Statistical Tests of Flow at 150°C

RAP (%)	Advera (%)	t score		Significance value		Result of t test
		μ > = 8	μ < = 16	μ > = 8	μ < = 16	
15	0	48.006	-11.078	0.000	0.0008	Significant
15	0.25	15.667	-0.756	0.021	0.2643	Not Significant
15	0.35	11	-1.308	0.029	0.2078	Not Significant
30	0	62.5	2.500	0.0000	0.0648	Not Significant
30	0.25	21.667	-5.000	0.015	0.0628	Not Significant
30	0.35	147	-13.000	0.002	0.0244	Significant

Table5. 29 Statistical Tests of Flow at 135°C

RAP (%)	Advera (%)	t score		Significance Value		Result of t test
		μ > = 8	μ < = 16	μ > = 8	μ < = 16	
15	0	13.75	-17.386	0.023	0.002	Significant
15	0.25	54.638	-11.926	0.000	0.003	Significant
15	0.35	16.667	-10.000	0.019	0.032	Significant
30	0	19.571	-3.286	0.016	0.094	Not Significant
30	0.25	15.8	-16.200	0.020	0.020	Significant
30	0.35	7.182	-7.364	0.044	0.043	Significant

Table5. 30 Statistical Tests of Flow at 120°C

RAP (%)	Advera (%)	t score		Significance Value		Result of t test
		μ > = 8	μ < = 16	μ > = 8	μ < = 16	
15	0	135	-25.000	0.003	0.013	Significant
15	0.25	30.2	-1.800	0.011	0.161	Not Significant
15	0.35	28.6	-3.400	0.011	0.091	Not Significant
30	0	153	-7.000	0.002	0.045	Significant
30	0.25	41.667	-11.667	0.008	0.027	Significant
30	0.35	49.667	-3.667	0.007	0.085	Not Significant

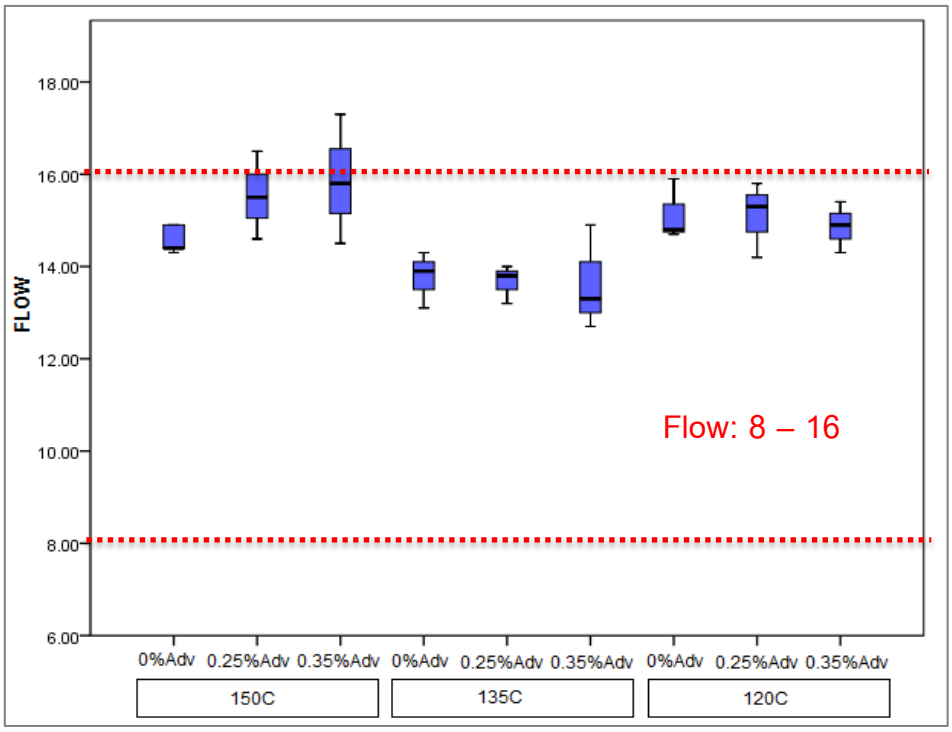

Figure5. 13 Flow of WMA Mixtures with 15%RAP

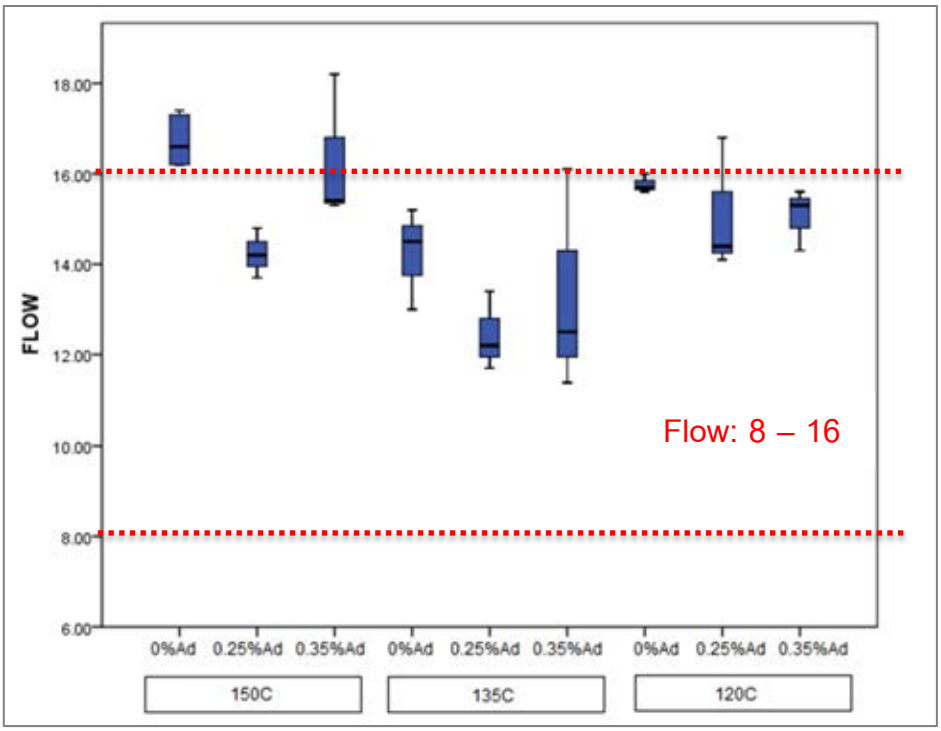

Figure5. 14 Flow of WMA Mixtures with 30%RAP

5.6 Strength Index Test

Based on the findings from the Marshall Design, three mixtures are selected for testing the strength Index of asphalt mixtures. For each mix, three unconditioned and three conditioned specimens were tested. A summary of the results are presented in Table 5.31. All the mixtures tested showed improvement in stability (i.e. greater than or equal to 8KN). Based on the strength index test, all mixtures showed strength index value above 80% (standard requirement) suggesting comparable moisture resistance as the conventional HMA.

Table5. 31 Strength Index Test Results

Detail	Mixing/Compaction Temperature	Stability (KN)		Strength Index
		Soaked	Un-soaked	
Fresh Aggregate	150°C	8.5	9.2	91.3%
		8.0	9.1	
		8.1	8.5	
15%RAP+FA	150°C	9.5	9.8	95.0%
		9.7	10.2	
		9.4	10.2	
15%RAP+FA+0.25%ADV	135°C	10.1	10.5	95.0%
		9.9	10.3	
		9.8	10.6	

CHAPTER VI

CONCLUSIONS

This study is an evaluation of laboratory production of RAP blended asphalt mixture at warm mixing temperature using foam-releasing chemical additive. The materials used in this study are asphalt binder Pen 60/70, Reclaimed Asphalt Pavement (RAP), fresh Limestone aggregates (Coarse and Fine) with a nominal maximum size of 19mm (3/4'') and Advera® WMA additive. Advera is a zeolite substance, an inorganic chemical in powder form containing 18-20% moisture which is chemically and structurally bound. With increased energy, in the form of heat, water is released creating small-sized bubbles enhancing the workability of the asphalt mix. Asphalt mixtures are produced as per Marshall mix design (ASTM D 6927, "Standard Test Method for Marshall Stability and Flow of Bituminous Mixtures). The mix design result yields 5.4% optimum binder content based on the dense-graded distribution of virgin aggregate which satisfies Marshall requirements.

One of the purposes is to investigate the influences of amount of Advera added and the RAP content in the warm mixed production, they are considered as variables in the composition of mixture samples in the study. By using the optimum binder content and aggregate gradation obtained from the mix design stage, Advera is added at the rate of 0.25% and 0.35% by mixture weight. RAP is added in substitution of virgin aggregate at the rate of 15% and 30%. Also three mixing/compacting temperatures (150°C, 135°C and 120°C) are considered in the sample preparation for studying warm temperature.

Laboratory tests are conducted on asphalt mixture samples containing RAP and Advera® WMA at three mixing/compaction temperatures (150°C, 135°C and 120°C). Fundamental properties such as air void (AV), voids in mineral aggregate (VMA), voids filled with asphalt (VFA), stability & flow, and strength index are evaluated to determine the effects of mixing/compaction temperature, RAP and Advera on the mixture properties. The findings from the study are summarized as follows:

- Based on rotational viscosity test conducted on Advera modified binder with 0.25%, 0.35% and 0.45% Advera at 120°C, 140°C and 160°C for duration of 2 hours, Advera-modified asphalt binder did not reduce the binder viscosity but made it more viscous. Further increase in the Advera content, increases the viscosity of the asphalt binder, making it stiffer throughout the set of test temperatures. 0.25% Advera showed 12% increase in the viscosity compared to the unmodified binder while 0.35% and 0.45% Advera showed 20.5% and 18.4% increase in the viscosities respectively. However, the addition of Advera into the asphalt mixture resulted in lowering the percent AV indicating Advera allows better compaction of the asphalt mixtures due to improved workability. However 0.35% Advera seems to have no improvements on AV, VMA, VFA, stability and flow from 0.25% Advera. Overall, addition of Advera resulted in decreasing the AV, VMA and VFA.

- The effect of warm mixing/compacting temperature is significant on the AV, VMA, VFA and stability. Changing the mixing/compacting temperature from 150°C to 120°C resulted in higher AV and VMA due

to lower workability at low mixing and compacting temperature while VFA and stability decreased at low mixing/compaction temperatures. The addition of Advera helps in reducing the AV at lower mixing and compaction temperature due to improved workability. However these findings are dependent on the percent RAP and Advera additive.

- The addition of RAP into the asphalt mixture significantly affected the AV, VMA and flow properties. In this study, adding higher RAP content tends to increase the flow but brought a decrease in AV and VMA. These outcomes are different from the previous research works which found that addition of RAP made the binder stiffer due to excessive aging of the RAP binder. One possible reason could be that RAP used in this study was obtained from milling wearing course of asphalt pavement in Bangkok area that has been in service for shorter duration and the binder inside has not aged excessively, thereby making the RAP binder more workable. Another reason might be that the milling process may have caused the RAP particles to be more rounded shape which resulted in better densification of the asphalt mixture due to improved workability.

- Volumetric properties (AV, VMA and VFA) and flow test data of most of the asphalt mixtures produced with Advera in this study were within the allowable range specified by DOH standard. There is an improvement in stability for mixtures prepared with 0.25%Advera and 15%RAP but in the case of 30%RAP mix, adding Advera tends to reduce stability at 135°C and 120°C. Statistical test indicates that asphalt mixtures

containing RAP are comparable to conventional HMA mixtures. Based on the strength index test conducted as per DOH specifications to determine the moisture susceptibility of asphalt mixtures, recycled HMA produced with Advera exhibited similar or better resistance to moisture susceptibility compared to the control HMA.

From this research, it has been found that Advera helps in improving workability at the warm mixing/compacting temperature of asphalt mixtures considerably. The WMA mixtures produced at 135°C and 120°C are comparable to the control HMA at 150°C indicating reduction in the mixing/compaction temperature by 15 to 30°C. Advera is found to be effective in HMA containing RAP but the use of RAP significantly affects the mixture properties limiting its dosage. Statistical tests show that WMA mixtures produced with 15%RAP are comparable to HMA rather than WMA mixtures produced with 30%RAP content.

REFERENCES

Al-Qadi, I.L., Carpenter, S.H., Robert, G., Ozer, H., Aurangzeb, Q., Elseifi, M., and Trepanier, J. Determination of Usable Residual Asphalt Binder in RAP. Report No. FHWA-ICT-09-031, Illinois Department of Transportation, Urbana, 2009.

Audrey Copeland. Reclaimed Asphalt Pavement in Asphalt Mixtures: Sate of the Practice. Report No.FHWA-HRT-11-021, Federal Highway Administration, Mclean, 2011.

Daniel, J. and Mogawer, W. Determining the Effective PG Grade of Binder in RAP Mixes. Report No.NETCR78 Project No.04-4, New England Transportation Consortium, Fall River, 2010.

Doyle, J.D., Mejias-Santiago, M., Brown, E.R., and Howard, I.L. Performance of High RAP- WMA Surface Mixtures. Journal of the Association of Asphalt Paving Technologists, 80(2011): 419-457.

E. Jorda, J.P.Gillet, J..A.Gonzalez, and G. BARRETO. Sustainable development and resources savings in the road industry using workability additives and surfactants from renewable sources. ARKEMA GROUP, France, 2008.

Federal Highway Administration.FHWA-RD-97-148:User Guidelines for Waste and Byproduct Materials in Pavement Construction. Washington D.C.: FHWA Archived Publication, 2008.

Gandhi, T.S and Amirkhanian, S.N. Laboratory Simulation of Warm Mix Asphalt (WMA) Binder Aging Characteristics: Proceedings of International Conference of maintenance and Rehabilitation of Pavements and Technological Control: A Preliminary Analysis. Utah, 2007.

Greene and Wegener. Sustainable Transport. Journal of Transport Geography 5(1997):177-90.

Hill, B., Hakimzadeh, S., and Buttlar, W. An Investigation of the Effects of Three Warm Mix Asphalt Additives on Asphalt binder and Mixture properties. Proceedings of the Second International Warm-Mix Conference. St. Louis, 2011.

John Shaw. TWG-Warm Mix Asphalt. Hunt Valley, MD, 2007

Kanitpong, K., Sonthong, S., Nam, K., Martono, W., and Bahia, H. Laboratory Study on Warm Mix Asphalt Additives. Transportation Research Board 86th Annual Meeting. Washington, D.C., 2007.

Lee, H. and Kim, Y. Performance Measures of Warm Asphalt Mixtures for Safe and Reliable Freight Transportation. Report No. MATC-UI 124, Public Policy Center, University of Iowa, Iowa City, 2009.

Lee, S., Amirkhanian, S.N., Park, N.M. and Kim, K.W. Characterization of Warm Mix Asphalt Binders Containing Artificially Long-term Aged Binders. Construction and Building Materials 23 (December 2008): 2371-2379.

Michael S. Sondag, Bruce A. Chadbourn and Andrew Drescher. Investigation of Recycled Asphalt Pavement (RAP) Mixtures. Final Report 1998-2002, Minnesota, Minnesota Department of Transportation, 2002.

National Cooperative highway Research Program. Recommended Use of Reclaimed Asphalt Pavement in the Superpave Mix Design Method. Report No. 30(D9-12), Transportation Research Board, Washington, D.C., 2000.

National Cooperative highway Research Program. NCHRP 452: Recommended Use of Reclaimed Asphalt Pavement in the Superpave

Mix Design Method: Technician's Manual. Washington, D.C.: National Academy Press, 2001.

National Cooperative highway Research Program. NCHRP Report691:Mix Design Practices for Warm Mix Asphalt. Washington, D.C.: National Academy Press, 2011.

Newcomb, D.E., Brown, E.R., and Epps, J.A. Designing HMA Mixtures with High RAP Content: A Practical Guide. Report No. Quality Improvement Series 124, National Asphalt Pavement Association, Lanham, 2007.

Rorrer, T., Appea, A. and Clark, T. Case Studies on Processes Involved in The Production And Placement of High RAP Asphalt Concrete Mixes in 2007 on Selected Routes in Virginia. Transportation Research Board 88th Annual Meeting. Washington, D.C., 2009.

Smith, A. Production, Testing and Compaction Details. Advera WMA, P.Q.Corporation, PA,USA, 2012.

Sullivan, K. and Wall, P. The Effects of Warm Mix Asphalt Additives on Recycled Asphalt Pavement. Report No. MQPRBM0903, Worcester Polytechnic Institute, Worcester, 2009.

Zhao, S., Huang, B., Shu, X., Jia, X. and Woods, M. Laboratory Performance Evaluation of Warm Mix Asphalt containing High Percentages of RAP. Transportation Research Board 91st Annual Meeting. Washington, D.C., 2012.

Zhanping Y.,Goh, S.W., and Dai, Q. Laboratory Evaluation of Warm Mix Asphalt. Report No. RC- 1556, Michigan Technological University, Houghton, 2011.

Zhou, F., Hu, S., Das, G. and Scullion, T. High RAP Mixes Design Methodology with Balanced Performance. Report No. 0-6092-2, Texas Transportation Institute, College Station, 2011.

Zumanis, M. Warm Mix Asphalt Investigation. Master's Thesis, Department of Civil Engineering, Technical University of Denmark, 2010.

Appendices

Appendix A

Determination of Correction Factor (CF) for the Ignition Oven Method

The asphalt binder content results may be affected by the type of aggregate in the mixture and the ignition furnace. Accordingly, to optimize accuracy, a correction factor (CF) must be established by three calibration specimens for each mix type. The test procedure follows ASTM D6307, “Standard Test Method for Asphalt Content of Hot-Mix Asphalt by Ignition Method”.

- Three calibrations samples at 4.5%, 5.0% and 5.5% binder content are prepared in the laboratory following the conventional hot mix asphalt design.
- The mass of the sample tray(s) and catch pan are recorded to the nearest 0.1g.
- Calibration samples are distributed evenly in the sample tray(s).
- Mass of the sample, sample tray(s) and catch pan to the nearest 0.1g is recorded to determine the mass of the sample (M_I).
- Calibration samples are heated in the ignition oven at 540±5°C until the change in mass of the sample during three consecutive 1 minute intervals does not exceed 0.01% of the sample mass (M_I).
- The mass of the sample after ignition (M_L) is recorded to the nearest 0.1g.
- The correction factor (CF) is calculated as follows:

$$CF = \left(\frac{M_I - M_L}{M_I} X\ 100\right) - P \qquad (Eq. 1)$$

M_I = total mass of the mixture calibration sample prior to ignition

M_L = total mass of the mixture calibration sample after ignition

CF = Correction factor

- The above procedure is repeated for two additional calibration samples. The average correction factor is calculated by averaging the three CF values.

Table A-1 Determination of Correction Factor (CF)

Sample	M_I(g)	M_L(g)	$(M_I-M_L)/M_I$	P	CF
1	2010.9	1911.8	4.93%	5%	0.07%
2	2009	1918.6	4.5%	4.5%	0.00%
3	2068.4	1962.9	5.1%	5.5%	0.40%
				AVERAGE	0.16%

Appendix B

Bulk Specific Gravity Test Results

Table B-1 Bulk Specific Gravity of Virgin Aggregate (Coarse)

Details	Mass of oven dry sample in air[A] (g)	Mass of SSD sample in air[B] (g)	Mass of SSD sample in water[C] (g)	G_{sb}=A/(B-C)	Absorption = [(B-A)/A]*100
Retained on #8 sieve size	905.6	909.0	574.0	2.703	0.375
	906.9	909.9	575.8	2.714	0.331
			Average	2.709	0.353
			Standard Deviation	0.008	0.032

Table B-2 Bulk Specific Gravity of Virgin Aggregate (Fine)

Details	Mass of oven dry sample in air[A] (g)	Mass of pycnometer filled with water[B] (g)	Mass of pycnometer with SSD sample and water[C] (g)	Mass of SSD sample[S] (g)	G_{sb}=A/(B+S-C)	Absorption = [(S-A)/A]*100
Passing #8 sieve size	247.1	625.7	782.2	250.0	2.643	1.174
	246.2	624.9	781.2	248.9	2.659	1.097
			Average		2.651	1.135
			Standard Deviation		0.011	0.054

Table B-3 Bulk Specific Gravity of Virgin Aggregates (Fine + Coarse)

Type	Percent Retained	Gsb
Coarse Aggregate	75.7	2.709
Fine Aggregate	24.3	2.651
Average Bulk Specific Gravity of Virgin Aggregate		2.695

Table B-4 Bulk Specific Gravity of RAP Aggregate (Coarse)

Details	Mass of oven dry sample in air[A] (g)	Mass of SSD sample in air[B] (g)	Mass of SSD sample in water[C] (g)	G_{sb}=A/(B-C)	Absorption = [(B-A)/A]*100
Retained on 3/8" sieve size	235.12	237.54	149.97	2.685	1.029
	236.19	238.73	150.07	2.664	1.075
			Average	2.674	1.052
			Standard Deviation	0.015	0.033

Table B-5 Bulk Specific Gravity of RAP Aggregate (Fine)

Details	Mass of oven dry sample in air[A] (g)	Mass of pycnometer filled with water[B] (g)	Mass of pycnometer with SSD sample and water[C] (g)	Mass of SSD sample[S] (g)	G_{sb}=A/(B+S-C)	Absorption = [(S-A)/A]*100
Retained on #30 sieve size	271.4	651.3	829.7	282.3	2.612	4.016
	238.7	660.3	819.4	247	2.716	3.477
			Average		2.664	3.747
			Standard Deviation		0.073	0.381

Table B-6 Bulk Specific Gravity of RAP Aggregate (Fine + Coarse)

Type	Percent Retained	Gsb
Coarse Aggregate	63.3	2.674
Fine Aggregate	36.7	2.664
Average Bulk Specific Gravity of Virgin Aggregate		2.671

Table B-7 Bulk Specific Gravity of Combined Aggregate Blend (RAP+Virgin)

	Fresh Aggregate	RAP Aggregate	Combined Aggregate Blend
Gsb	2.695	2.671	
Content	85%	15%	2.691
	70%	30%	2.688

Appendix C

Maximum Theoretical Specific Gravity (Gmm) Test Results

Table C-1 Maximum Theoretical Specific Gravity of Fresh Aggregate @ 150°C

Sample	Mass of dry sample in air [A]	Mass of Bowl under water [B]	Mass of bowl + sample under water [C]	Gmm
1	1250.5	622.1	1370.3	2.490
2	1250.4	622.1	1373.6	2.506
		Average		2.498
		Standard Deviation		0.012

Table C-2 Maximum Theoretical Specific Gravity of 15% RAP +FA @150°C

Sample	Mass of dry sample in air [A]	Mass of Bowl under water [B]	Mass of bowl + sample under water [C]	Gmm
1	1239.3	488.8	1232.2	2.499
2	1246.2	488.8	1236.0	2.498
3	1248.1	630.9	1379.5	2.499
		Average		2.499
		Standard Deviation		0.001

Table C-3 Maximum Theoretical Specific Gravity of 30% RAP +FA @150°C

Sample	Mass of dry sample in air [A]	Mass of Bowl under water [B]	Mass of bowl + sample under water [C]	Gmm
1	1231.4	634.50	1372.50	2.496
2	1239.1	634.50	1378.1	2.501
3	1243.8	634.50	1380.1	2.497
		Average		2.498
		Standard Deviation		0.003

Table C-4 Maximum Theoretical Specific Gravity of 15% RAP +FA @135°C

Sample	Mass of dry sample in air [A]	Mass of Bowl under water [B]	Mass of bowl + sample under water [C]	Gmm
1	1241.9	610.6	1355.1	2.497
2	1240.5	610.6	1356.5	2.508
		Average		2.502
		Standard Deviation		0.008

Table C-5 Maximum Theoretical Specific Gravity of 30% RAP +FA @135°C

Sample	Mass of dry sample in air [A]	Mass of Bowl under water [B]	Mass of bowl + sample under water [C]	Gmm
1	1230.7	624.70	1362.9	2.499
2	1228.2	624.70	1361.3	2.498
		Average		2.499
		Standard Deviation		0.000

Table C-6 Maximum Theoretical Specific Gravity of Fresh Aggregate @ 120°C

Sample	Mass of dry sample in air [A]	Mass of Bowl under water [B]	Mass of bowl + sample under water [C]	Gmm
1	1267.6	622.1	1383.2	2.503
2	1266.3	622.1	1381.9	2.500
		Average		2.501
		Standard Deviation		0.002

Table C-7 Maximum Theoretical Specific Gravity of 15% RAP +FA @120°C

Sample	Mass of dry sample in air [A]	Mass of Bowl under water [B]	Mass of bowl + sample under water [C]	Gmm
1	1256.6	610.5	1366.4	2.510
2	1254.2	610.5	1364.6	2.508
		Average		2.509
		Standard Deviation		0.001

Table C-8 Maximum Theoretical Specific Gravity of 30% RAP +FA @120°C

Sample	Mass of dry sample in air [A]	Mass of Bowl under water [B]	Mass of bowl + sample under water [C]	Gmm
1	1250.1	610.5	1363.2	2.513
1	1249.5	610.5	1362.0	2.509
		Average		2.511
		Standard Deviation		0.003

Appendix D

Bulk Specific Gravity (Gmb) of Compacted Specimens

Table D-1 Bulk Specific Gravity_Fresh Aggregate @ 150°C

Sample wt. after compaction	oven Dried Weight (Sample)	oven dried + plastic	oven dried sample + plastic submerged	Gmb
1250.2	1250.2	1252.1	721.3	2.378
1252.8	1252.8	1254.9	723.7	2.383
1245.7	1245.7	1245.7	722.8	2.382
		Average		2.381
		Standard Deviation		0.003

Table D-2 Bulk Specific Gravity_15%RAP+FA @ 150°C

Sample wt. after compaction	oven Dried Weight (Sample)	oven dried + plastic	oven dried sample + plastic submerged	Gmb
1233.4	1233.21	1234.8	715.3	2.393
1241.9	1241.69	1243.2	720.8	2.395
1244.1	1243.86	1245.3	721.83	2.394
1238.3	1238.13	1239.9	718.4	2.396
1238.6	1238.46	1239.7	717.8	2.388
		Average		2.393
		Standard Deviation		0.003

Table D-3 Bulk Specific Gravity_15%RAP+FA+0.25%Advera @ 150°C

sample	dry mass in air(g)	dry & wrapped mass in air(g)	wrapped mass under water(g)	Gmb
1	1247.6	1249.1	730.4	2.425
2	1244.2	1245.8	726.4	2.416
3	1239.5	1241.3	722.9	2.414
			Average	2.418
			Standard Deviation	0.006

Table D-4 Bulk Specific Gravity_15%RAP+FA+0.35%Advera @ 150°C

N.o	dry mass in air(g)	dry & wrapped mass in air(g)	wrapped mass under water(g)	Gmb
1	1237.2	1238.8	724.5	2.427
2	1232.1	1233.6	720.3	2.420
3	1236.1	1237.5	720.5	2.409
			Average	2.419
			Standard Deviation	0.009

Table D-5 Bulk Specific Gravity_30%RAP+FA @ 150°C

No.	Dry Weight (Sample)	sample + moisture	sample + moisture + plastic	sample + moisture + plastic submerged	Weight (Plastic)	Gmb
1	1222.63	1223.11	1224.93	712.8	2.30	2.416
2	1228.59	1229.20	1230.56	711.8	1.97	2.392
3	1235.34	1235.63	1237.83	721.9	2.49	2.425
4	1234.78	1234.88	1236.76	721.08	1.98	2.419
5	1233.43	1234.06	1234.57	719.75	1.14	2.410
				Average		2.415
				Standard Deviation		0.005

Table D-6 Bulk Specific Gravity_30%RAP+FA+0.25%Advera @ 150°C

No.	dry mass in air(g)	dry & wrapped mass in air(g)	wrapped mass under water(g)	Gmb
1	1232.0	1233.4	720.7	2.421
2	1225.4	1227.1	716.9	2.424
3	1227.1	1228.7	715.5	2.412
			Average	2.419
			Standard Deviation	0.006

Table D-7 Bulk Specific Gravity_30%RAP+FA+0.35%Advera @ 150°C

No.	dry mass in air(g)	dry & wrapped mass in air(g)	wrapped mass under water(g)	Gmb
1	1237.5	1239.1	724.7	2.427
2	1218.4	1219.8	714.5	2.430
3	1224.7	1226.1	720.0	2.439
			Average	2.432
			Standard Deviation	0.006

Table D-8 Bulk Specific Gravity_15%RAP+FA @ 135°C

Sample wt. after compaction	oven Dried Weight (Sample)	oven dried + plastic	oven dried sample + plastic submerged	Gmb
1247.1	1247	1248.7	722.3	2.389
1247.5	1247.5	1249.4	721.9	2.387
1242.2	1242.2	1243.8	719.7	2.389
		Average		2.389
		Standard Deviation		0.001

Table D-9 Bulk Specific Gravity_15%RAP+FA+0.25%Advera @ 135°C

No.	Sample wt. after compaction	oven Dried Weight (Sample)	oven dried wt. + plastic	oven dried sample + plastic submerged	Gmb
1	1222	1222	1223.7	715	2.425
2	1249.5	1249.4	1251.1	727.3	2.407
3	1249.6	1249.6	1251.4	728.5	2.413
			Average		2.415
			Standard Deviation		0.009

Table D-10 Bulk Specific Gravity_15%RAP+FA+0.35%Advera @ 135°C

No.	Sample wt. after compaction	oven Dried Weight (Sample)	oven dried wt. + plastic	oven dried sample + plastic submerged	Gmb
1	1251.5	1251.5	1253.5	727.1	2.403
2	1248.8	1248.8	1250.8	729.6	2.422
3	1252.8	1252.8	1254.6	729.7	2.410
			Average		2.411
			Standard Deviation		0.010

Table D-11 Bulk Specific Gravity_30%RAP+FA @ 135°C

Sample wt. after compaction	oven Dried Weight (Sample)	oven dried + plastic	oven dried sample + plastic submerged	Gmb
1233.3	1233.3	1237.5	711.4	2.394
1240.4	1240.4	1243.7	717.6	2.397
1241	1241	1242.9	719.2	2.392
		Average		2.395
		Standard Deviation		0.002

Table D-12 Bulk Specific Gravity_30%RAP+FA+0.25%Advera @ 135°C

No.	Sample wt. after compaction	oven Dried Wt. (Sample)	oven dried wt. + plastic	oven dried sample + plastic submerged	Gmb
1	1241.3	1241.3	1242.8	725.3	2.418
2	1239.4	1239.4	1241.1	718.8	2.395
3	1243.3	1243.3	1245	719.6	2.388
			Average		2.400
			Standard Deviation		0.016

Table D-13 Bulk Specific Gravity_30%RAP+FA+0.35%Advera @ 135°C

No.	Sample wt. after compaction	oven Dried Wt. (Sample)	oven dried wt. + plastic	oven dried sample + plastic submerged	Gmb
1	1241.0	1241	1242.9	715.6	2.377
2	1242.7	1242.7	1244.4	714.9	2.368
3	1247.7	1247.7	1249.5	721.2	2.384
			Average		2.377
			Standard Deviation		0.008

Table D-14 Bulk Specific Gravity_Fresh Aggregate @ 120°C

Sample wt. after compaction	oven Dried Weight (Sample)	oven dried + plastic	oven dried sample + plastic submerged	Gmb
1256	1256	1257.5	725.5	2.379
1256.1	1256.1	1258	722.4	2.367
1259	1259	1260.9	724.3	2.368
		Average		2.371
		Standard Deviation		0.006

Table D-15 Bulk Specific Gravity_15%RAP+FA @ 120°C

sample wt. after compaction	oven Dried Weight (Sample)	oven dried + plastic	oven dried sample + plastic submerged	Gmb
1247.8	1247.8	1249.8	723.3	2.394
1248.3	1248.3	1250.3	724.8	2.399
1242.6	1242.6	1244.4	720.3	2.392
		Average		2.395
		Standard Deviation		0.004

Table D-16 Bulk Specific Gravity_15%RAP+FA+0.25%Advera @ 120°C

No.	sample wt. after compaction	oven Dried Weight (Sample)	oven dried wt. + plastic	oven dried sample + plastic submerged	Gmb
1	1246.7	1246.7	1248.8	720.9	2.388
2	1249.1	1249.1	1251.5	722.8	2.393
3	1247.9	1247.9	1250.2	722.1	2.392
			Average		2.391
			Standard Deviation		0.003

Table D-17 Bulk Specific Gravity_15%RAP+FA+0.35%Advera @ 120°C

No.	sample wt. after compaction	oven Dried Weight (Sample)	oven dried wt. + plastic	oven dried sample + plastic submerged	Gmb
1	1242.1	1242.1	1244.3	718.9	2.392
2	1253.4	1253.4	1255.6	726.8	2.398
3	1252.8	1252.8	1254.3	725.7	2.389
			Average		2.393
			Standard Deviation		0.005

Table D-18 Bulk Specific Gravity_30%RAP+FA @ 120°C

sample wt. after compaction	oven Dried Weight (Sample)	oven dried + plastic	oven dried sample + plastic submerged	Gmb
1233.9	1233.9	1235.7	717.3	2.402
1241	1241	1243.2	719.7	2.397
1241.4	1241.4	1243.5	721.5	2.404
		Average		2.401
		Standard Deviation		0.003

Table D-19 Bulk Specific Gravity_30%RAP+FA+0.25%Advera @ 120°C

No.	sample wt. after compaction	oven Dried Wt. (Sample)	oven dried wt. + plastic	oven dried sample + plastic submerged	Gmb
1	1244.5	1244.5	1247.8	721.9	2.408
2	1247	1246.9	1250.2	722.7	2.406
3	1237.9	1237.9	1240.6	718	2.403
			Average		2.406
			Standard Deviation		0.003

Table D-20 Bulk Specific Gravity_30%RAP+FA+0.35%Advera @ 120°C

No.	sample wt. after compaction	oven Dried Wt. (Sample)	oven dried wt. + plastic	oven dried sample + plastic submerged	Gmb
1	1241.8	1241.7	1244.9	720	2.407
2	1242.1	1242	1245	721.2	2.410
3	1250	1249.9	1253	724.9	2.406
			Average		2.407
			Standard Deviation		0.002

Appendix E

HMA Design Data by Marshall Method

Table E-1 HMA Design Data by Marshall Method_FA@150°C

No.	%AC		Weight				Total Mixture Weight		Specimen height	Bulk S.G.	Max S.G.	Air Void (%)	VMA (%)	VFA (%)	Peak load (KN)	Deform. At peak load (mm)	Corr. Ratio	Stability		Flow
	target	actual	Fresh Agg		RAP													measured	corrected	
	%	%	Agg.	AC	Agg.	AC	Agg	AC		Gmb	Gmm (by lab)							kN	kN	(0.25mm)
			g	g	g	g	g	g	mm											
1	5.4	5.5	1200.8	69.5	0.0	0.0	1200.8	69.5	63.5	2.378	2.498	4.8	16.6	71.0	11.53	3.6	0.98	11.5	11.3	14.6
2	5.4	5.4	1200.8	68.5	0.0	0.0	1200.8	68.5	63.3	2.383	2.498	4.6	16.3	79.4	10.84	3.2	0.99	10.8	10.7	12.7
3	5.4	5.4	1199.1	68.8	0.0	0.0	1199.1	68.8	63.5	2.382	2.498	4.6	16.4	71.8	11.30	3.6	0.98	11.3	11.1	14.3
AVG.		5.4								2.381	2.498	4.7	16.4	74.1				11.2	11.0	13.9

Table E-2 HMA Design Data by Marshall Method_15%RAP+FA@150°C

No.	%AC		Weight				Total Mixture Weight		Specimen height	Bulk S.G.	Max S.G.	Air Void (%)	VMA (%)	VFA (%)	Peak load (KN)	Deform. At peak load (mm)	Corr. Ratio	Stability		Flow
	target	actual	Fresh Agg		RAP					Gmb	Gmm (by lab)							measured	corrected	(0.25mm)
	%	%	Agg.	AC	Agg.	AC	Agg	AC										kN	kN	
			g	g	g	g	g	g	mm											
1	5.4	5.4	1018.9	59.6	181.3	8.9	1200.2	68.5	63.7	2.393	2.499	4.2	15.9	73.6	11.34	3.6	0.98	11.3	11.1	14.3
2	5.4	5.4	1018.8	59.5	181.3	8.9	1200.1	68.4	64.1	2.395	2.499	4.1	15.8	79.4	11.08	3.6	0.97	11.1	10.7	14.4
3	5.4	5.4	1018.7	60.0	181.3	8.9	1200.0	68.9	63.3	2.394	2.499	4.2	15.9	73.6	8.87	4.1	0.99	8.9	8.8	16.3
4	5.4	5.4	1018.8	59.7	181.3	8.9	1200.1	68.6	64.9	2.396	2.499	4.1	15.8	74.1	8.65	3.7	0.95	8.6	8.2	14.9
5	5.4	5.4	1018.9	60.0	181.3	8.9	1200.2	68.9	64.6	2.388	2.499	4.4	16.1	72.7	8.65	3.6	0.96	8.6	8.3	14.4
AVG.		5.4								2.393	2.499	4.2	15.9	74.7				9.7	9.4	14.9

Table E-3 HMA Design Data by Marshall Method_15%RAP+FA+0.25%Advera @150°C

No.	%AC		Weight				Total Mixture Weight		specimen height	Bulk S.G. Gmb	Max S.G. Gmm	Air Void	VMA	VFA	Peak Load	Deform. at peak	Corr. Ratio	Stability		Flow (0.25mm)
	target	actual	Virgin		RAP Agg													measured	corrected	
	%	%	Agg.(g)	AC(g)	Agg.(g)	AC(g)	Agg.(g)	AC(g)	mm		(by lab)	%	%	%	kN	mm		kN	kN	
1	5.4	5.4	1023.4	60.0	181.2	8.9	1204.6	68.9	63.0	2.425	2.499	3.0	14.8	79.7	11.08	3.76	1.00	11.1	11.1	15.0
2	5.4	5.4	1021.5	59.6	181.5	8.9	1203.0	68.5	63.4	2.416	2.499	3.3	15.1	79.4	10.52	4.14	0.99	10.5	10.4	16.5
3	5.4	5.4	1021.4	59.7	181.1	8.9	1202.5	68.6	64.0	2.414	2.499	3.4	15.1	77.5	11.10	3.89	0.97	11.1	10.8	15.5
AVG.		**5.4**										**3.2**	**15.0**	**78.9**				**10.9**	**10.8**	**15.7**

Table E-4 HMA Design Data by Marshall Method_15%RAP+FA+0.35%Advera @150°C

No.	%AC		Weight				Total Mixture Weight		specimen height	Bulk S.G. Gmb	Max S.G. Gmm	Air Void	VMA	VFA	Peak Load	Deform. at peak	Corr. Ratio	Stability		Flow (0.25mm)
	target	actual	Virgin		RAP Agg													measured	corrected	
	%	%	Agg.(g)	AC(g)	Agg.(g)	AC(g)	Agg.(g)	AC(g)	mm		(by lab)	%	%	%	kN	mm		kN	kN	
1	5.4	5.4	1016.9	59.8	178.2	8.9	1195.1	68.7	63.3	2.427	2.499	2.9	14.7	80.3	13.98	3.94	0.99	14.0	13.8	15.8
2	5.4	5.5	1015.0	60.0	178.4	8.9	1193.4	68.9	63.4	2.420	2.499	3.2	15.0	79.4	10.49	4.32	0.99	10.5	10.4	17.3
3	5.4	5.4	1018.7	59.7	178.2	8.9	1196.9	68.6	63.9	2.409	2.499	3.6	15.3	76.5	10.15	3.63	0.97	10.2	9.8	14.5
AVG.		**5.4**										**3.2**	**15.0**	**78.7**				**11.5**	**11.4**	**15.9**

Table E-5 HMA Design Data by Marshall Method_30%RAP+FA@150°C

No.	%AC		Combined Weight				Total Mixture Weight		Specimen height	Bulk S.G.	Max S.G.	Air Void (%)	VMA (%)	VFA (%)	Peak load (KN)	Deform. At peak load (mm)	Corr. Ratio	Stability		Flow
	target	actual	Fresh Agg		RAP													measured	corrected	
	%	%	Agg.	AC	Agg.	AC	Agg	AC		Gmb	Gmm (by lab)							kN	kN	(0.25mm)
			g	g	g	g	g	g	mm											
1	5.4	5.4	837.7	50.6	362.7	17.9	1200.4	68.5	63.8	2.416	2.498	3.3	15.0	78.1	11.23	4.04	0.98	11.2	11.0	16.2
2	5.4	5.4	839.1	51.0	362.4	17.9	1201.5	68.9	63.9	2.392	2.498	4.2	15.8	73.3	11.10	4.32	0.97	11.1	10.8	17.3
3	5.4	5.6	838.3	52.9	362.6	17.9	1200.9	70.8	63.6	2.425	2.498	2.9	14.8	80.4	9.86	4.14	0.98	9.9	9.7	16.6
4	5.4	5.4	839.8	50.6	362.7	17.9	1202.5	68.5	63.0	2.419	2.498	3.2	14.9	78.7	12.36	4.35	1	12.4	12.4	17.4
5	5.4	5.4	841.0	50.6	362.4	17.9	1203.4	68.5	63.4	2.410	2.498	3.5	15.2	76.8	10.77	4.05	0.99	10.8	10.7	16.2
AVG.		5.4								2.412	2.498	3.4	15.1	77.5				11.1	10.9	16.7

Table E-6 HMA Design Data by Marshall Method_30%RAP+FA+0.25%Advera @150°C

No.	%AC		Combined Weight				Total Mixture Wt.		specimen	Bulk S.G.	Max S.G.	Air	VMA	VFA	Peak	Deform.	Corr.	Stability		Flow
	target	actual	Virgin		Rap		Agg.	AC	height	Gmb	Gmm	Void			Load	at peak	Ratio	measured	corrected	(0.25mm)
	%	%	Agg.(g)	AC(g)	Agg.(g)	AC(g)	g	g	mm		(by lab)	%	%	%	kN	mm		kN	kN	
1	5.4	5.4	837.8	50.5	362.5	17.9	1200.3	68.4	63.7	2.421	2.498	3.1	14.8	79.3	11.66	3.71	0.98	11.7	11.4	14.8
2	5.4	5.4	836.8	50.7	362.7	17.9	1199.5	68.6	63.3	2.424	2.498	2.9	14.7	79.4	9.49	3.42	0.99	9.5	9.4	13.7
3	5.4	5.4	838.4	50.5	362.5	17.9	1200.9	68.4	63.0	2.412	2.498	3.4	15.1	77.3	10.74	3.55	1.00	10.7	10.7	14.2
AVG.		**5.4**										**3.1**	**14.8**	**78.7**				**10.6**	**10.5**	**14.2**

Table E-7 HMA Design Data by Marshall Method_30%RAP+FA+0.35%Advera @150°C

No.	%AC		Combined Weight				Total Mixture Wt.		specimen	Bulk S.G.	Max S.G.	Air	VMA	VFA	Peak	Deform.	Corr.	Stability		Flow
	target	actual	Virgin		Rap		Agg.	AC	height	Gmb	Gmm	Void			Load	at peak	Ratio	measured	corrected	(0.25mm)
	%	%	Agg.(g)	AC(g)	Agg.(g)	AC(g)	g	g	mm		(by lab)	%	%	%	kN	mm		kN	kN	
1	5.4	5.4	836.4	50.5	362.7	17.9	1199.1	68.4	63.8	2.427	2.498	2.8	14.6	80.5	10.00	3.81	0.98	10.0	9.8	15.3
2	5.4	5.4	838.6	50.6	362.5	17.9	1201.1	68.5	63.6	2.430	2.498	2.7	14.5	79.4	10.10	3.85	0.98	10.1	9.9	15.4
3	5.4	5.4	837.0	50.6	362.6	17.9	1199.6	68.5	61.2	2.439	2.498	2.4	14.2	83.3	11.84	4.56	1.04	11.8	12.3	18.2
AVG.		**5.4**										**2.6**	**14.4**	**81.1**				**10.6**	**10.7**	**16.3**

Table E-8 HMA Design Data by Marshall Method_15%RAP+FA@135°C

No.	%AC		Weight				Total Mixture Weight		Specimen height	Bulk S.G.	Max S.G.	Air Void (%)	VMA (%)	VFA (%)	Peak load (KN)	Deform. At peak load (mm)	Corr. Ratio	Stability		Flow
	target	actual	Fresh Agg		RAP													measured	corrected	
	%	%	Agg.	AC	Agg.	AC	Agg	AC		Gmb	Gmm (by lab)							kN	kN	(0.25mm)
			g	g	g	g	g	g	mm											
1	5.4	5.5	1018.6	60.6	181.1	8.9	1199.7	69.5	66.9	2.389	2.502	4.5	16.1	71.9	7.77	3.56	0.91	7.8	7.1	14.3
2	5.4	5.4	1019.4	59.6	181.4	8.9	1200.8	68.5	64.3	2.387	2.502	4.6	16.1	79.4	10.90	3.64	0.97	10.9	10.6	14.6
3	5.4	5.4	1019.3	59.9	181.4	8.9	1200.7	68.8	64.5	2.389	2.502	4.5	16.0	71.8	10.30	3.63	0.96	10.3	9.9	14.5
AVG.		5.4								2.389	2.502	4.5	16.1	74.4				9.7	9.2	14.5

Table E-9 HMA Design Data by Marshall Method_15%RAP+FA+0.25%Advera @135°C

No.	%AC		Weight				Total Mixture Weight		specimen height	Bulk S.G. Gmb	Max S.G. Gmm	Air Void	VMA	VFA	Peak Load	Deform. at peak	Corr. Ratio	Stability		Flow (0.25mm)
	target	actual	Virgin		RAP Agg													measured	corrected	
	%	%	Agg.(g)	AC(g)	Agg.(g)	AC(g)	Agg.(g)	AC(g)	mm		(by lab)	%	%	%	kN	mm		kN	kN	
1	5.4	5.4	1019.3	60.1	181.4	8.9	1200.7	69.0	62.7	2.425	2.502	3.1	14.8	79.0	10.62	3.50	1.00	10.6	10.6	14.0
2	5.4	5.5	1016.8	60.6	181.3	8.9	1198.1	69.5	64.4	2.407	2.502	3.8	15.5	79.4	10.60	3.45	0.96	10.6	10.2	13.8
3	5.4	5.4	1019.3	59.8	181.4	8.9	1200.7	68.7	64.3	2.413	2.502	3.6	15.2	76.4	11.29	3.30	0.96	11.3	10.8	13.2
AVG.		**5.4**										3.5	15.2	78.3				**10.8**	**10.5**	**13.7**

Table E-10 HMA Design Data by Marshall Method_15%RAP+FA+0.35%Advera @135°C

No.	%AC		Weight				Total Mixture Weight		specimen height	Bulk S.G. Gmb	Max S.G. Gmm	Air Void	VMA	VFA	Peak Load	Deform. at peak	Corr. Ratio	Stability		Flow (0.25mm)
	target	actual	Virgin		RAP Agg													measured	corrected	
	%	%	Agg.(g)	AC(g)	Agg.(g)	AC(g)	Agg.(g)	AC(g)	mm		(by lab)	%	%	%	kN	mm		kN	kN	
1	5.4	5.4	1021.8	59.6	181.4	8.9	1203.2	68.5	64.3	2.403	2.502	4.0	15.5	74.4	9.08	3.72	0.97	9.1	8.8	14.9
2	5.4	5.4	1020.4	59.7	181.3	8.9	1201.7	68.6	64.5	2.422	2.502	3.2	14.9	79.4	10.60	3.18	0.96	10.6	10.2	12.7
3	5.4	5.4	1019.1	59.6	181.3	8.9	1200.4	68.5	64.6	2.410	2.502	3.7	15.3	75.8	9.66	3.32	0.96	9.7	9.3	13.3
AVG.		**5.4**										3.6	15.2	76.5				**9.8**	**9.4**	**13.6**

Table E-11 HMA Design Data by Marshall Method_30%RAP+FA@135°C

No.	%AC		Combined Weight				Total Mixture Weight		Specimen height	Bulk S.G.	Max S.G.	Air Void (%)	VMA (%)	VFA (%)	Peak load (KN)	Deform. At peak load (mm)	Corr. Ratio	Stability		Flow
	target	actual	Fresh Agg		RAP													measured	corrected	
	%	%	Agg.	AC	Agg.	AC	Agg	AC		Gmb	Gmm (by lab)							kN	kN	(0.25mm)
			g	g	g	g	g	g	mm											
1	5.4	5.5	836.2	51.7	362.5	17.9	1198.7	69.6	64.2	2.394	2.499	4.2	15.8	73.6	11.02	3.26	0.97	11.0	10.7	13.0
2	5.4	5.4	840.8	50.7	362.6	17.9	1203.4	68.6	64.4	2.397	2.499	4.1	15.6	74.0	11.41	3.81	0.96	11.4	11.0	15.2
3	5.4	5.4	838.0	50.6	362.6	17.9	1200.6	68.5	64.5	2.392	2.499	4.2	15.8	73.1	11.78	3.63	0.96	11.8	11.3	14.5
AVG.		5.4								2.395	2.499	4.2	15.7	73.6				11.4	11.0	14.3

Table E-12 HMA Design Data by Marshall Method_30%RAP+FA+0.25%Advera @135°C

No.	%AC		Combined Weight				otal Mixture W		specimen	Bulk S.G.	Max S.G.	Air	VMA	VFA	Peak	Deform.	Corr.	Stability		Flow
	target	actual	Virgin		Rap		Agg.	AC	height	Gmb	Gmm	Void			Load	at peak	Ratio	measured	corrected	(0.25mm)
	%	%	Agg.(g)	AC(g)	Agg.(g)	AC(g)	g	g	mm		(by lab)	%	%	%	kN	mm		kN	kN	
1	5.4	5.4	836.3	50.8	362.8	17.9	1199.1	68.7	63.9	2.407	2.499	3.8	15.4	75.0	11.29	3.35	0.97	11.3	11.0	13.4
2	5.4	5.5	839.2	51.6	362.6	17.9	1201.8	69.5	64.3	2.389	2.499	4.5	16.1	79.4	9.44	3.05	0.97	9.4	9.2	12.2
3	5.4	5.4	838.4	50.7	362.6	17.9	1201.0	68.6	64.4	2.398	2.499	4.2	15.7	73.1	10.00	2.94	0.96	10.0	9.6	11.7
AVG.		**5.4**										**4.2**	**15.7**	**75.9**				**10.2**	**9.9**	**12.5**

Table E-13 HMA Design Data by Marshall Method_30%RAP+FA+0.35%Advera @135°C

No.	%AC		Combined Weight				otal Mixture W		specimen	Bulk S.G.	Max S.G.	Air	VMA	VFA	Peak	Deform.	Corr.	Stability		Flow
	target	actual	Virgin		Rap		Agg.	AC	height	Gmb	Gmm	Void			Load	at peak	Ratio	measured	corrected	(0.25mm)
	%	%	Agg.(g)	AC(g)	Agg.(g)	AC(g)	g	g	mm		(by lab)	%	%	%	kN	mm		kN	kN	
1	5.4	5.4	838.6	51.0	362.8	17.9	1201.4	68.9	65.0	2.397	2.499	4.2	15.8	73.2	9.23	2.84	0.95	9.2	8.8	11.4
2	5.4	5.4	840.1	50.6	362.5	17.9	1202.6	68.5	66.0	2.400	2.499	4.2	15.6	79.4	7.73	3.12	0.93	7.7	7.2	12.5
3	5.4	5.4	838.7	50.8	362.6	17.9	1201.3	68.7	63.3	2.402	2.499	4.1	15.6	73.8	9.40	4.04	0.99	9.4	9.3	16.1
AVG.		**5.4**										**4.2**	**15.7**	**75.5**				**8.8**	**8.4**	**13.3**

Table E-14 HMA Design Data by Marshall Method_FA@120°C

No.	%AC		Total Mixture Weight		Specimen height	Bulk S.G.	Max S.G.	Air Void (%)	VMA (%)	VFA (%)	Peak load (KN)	Deform. At peak load (mm)	Corr. Ratio	Stability		Flow
	target	actual				Gmb	Gmm (by lab)							measured	corrected	(0.25mm)
	%	%	Agg	AC										kN	kN	
			g	g	mm											
1	5.4	5.4	1200.2	68.4	65.3	2.379	2.501	4.9	16.5	70.2	9.18	3.2	0.94	9.2	8.6	12.6
2	5.4	5.4	1200.5	68.3	65.5	2.367	2.501	5.4	16.9	79.4	8.74	3.2	0.94	8.7	8.2	12.7
3	5.4	5.5	1200.4	69.4	65.0	2.368	2.501	5.3	16.9	68.6	10.02	3.1	0.95	10.0	9.5	12.6
AVG.		**5.4**				**2.371**	**2.501**	**5.2**	**16.8**	**72.7**				**9.3**	**8.8**	**12.6**

Table E-15 HMA Design Data by Marshall Method_15%RAP+FA@120°C

No.	%AC		Weight				Total Mixture Weight		Specimen height	Bulk S.G.	Max S.G.	Air Void (%)	VMA (%)	VFA (%)	Peak load (KN)	Deform. At peak load (mm)	Corr. Ratio	Stability		Flow
	target	actual	Fresh Agg		RAP													measured	corrected	
	%	%	Agg.	AC	Agg.	AC	Agg	AC		Gmb	Gmm (by lab)							kN	kN	(0.25mm)
			g	g	g	g	g	g	mm											
1	5.4	5.4	1017.9	59.7	181.3	8.9	1199.2	68.6	66.7	2.394	2.509	4.6	15.9	71.1	7.80	4.0	0.92	7.8	7.2	15.9
2	5.4	5.4	1019.6	59.6	181.3	8.9	1200.9	68.5	64.4	2.399	2.509	4.4	15.7	79.4	8.53	3.7	0.96	8.5	8.2	14.7
3	5.4	5.4	1017.7	59.6	181.3	8.9	1199.0	68.5	64.3	2.392	2.509	4.6	15.9	70.9	8.30	3.7	0.97	8.3	8.1	14.8
AVG.		**5.4**								**2.395**	**2.509**	**4.5**	**15.8**	**73.8**				**8.2**	**7.8**	**15.1**

Table E-16 HMA Design Data by Marshall Method_15%RAP+FA+0.25%Advera @120°C

No.	%AC		Weight				Total Mixture Weight		specimen height	Bulk S.G. Gmb	Max S.G. Gmm	Air Void	VMA	VFA	Peak Load	Deform. at peak	Corr. Ratio	Stability		Flow (0.25mm)
	target	actual	Virgin		RAP Agg													measured	corrected	
	%	%	Agg.(g)	AC(g)	Agg.(g)	AC(g)	Agg.(g)	AC(g)	mm		(by lab)	%	%	%	kN	mm		kN	kN	
1	5.4	5.4	1018.7	59.6	181.2	8.9	1199.9	68.5	66.6	2.388	2.502	4.6	16.1	71.5	7.92	3.55	0.92	7.9	7.3	14.2
2	5.4	5.4	1016.7	59.9	181.3	8.9	1198.0	68.8	66.3	2.393	2.502	4.4	15.9	79.4	8.23	3.96	0.92	8.2	7.6	15.8
3	5.4	5.5	1016.8	61.0	181.2	8.9	1198.0	69.9	66.1	2.392	2.502	4.4	16.0	72.4	8.55	3.82	0.93	8.6	8.0	15.3
AVG.		**5.4**										**4.5**	**16.0**	**74.5**				**8.2**	**7.6**	**15.1**

Table E-17 HMA Design Data by Marshall Method_15%RAP+FA+0.35%Advera @120°C

No.	%AC		Weight				Total Mixture Weight		specimen height	Bulk S.G. Gmb	Max S.G. Gmm	Air Void	VMA	VFA	Peak Load	Deform. at peak	Corr. Ratio	Stability		Flow (0.25mm)
	target	actual	Virgin		RAP Agg													measured	corrected	
	%	%	Agg.(g)	AC(g)	Agg.(g)	AC(g)	Agg.(g)	AC(g)	mm		(by lab)	%	%	%	kN	mm		kN	kN	
1	5.4	5.5	1018.9	60.4	181.3	8.9	1200.2	69.3	66.0	2.392	2.502	4.4	16.0	72.4	8.47	3.56	0.93	8.5	7.9	14.3
2	5.4	5.4	1020.6	60.2	181.2	8.9	1201.8	69.1	66.8	2.398	2.502	4.2	15.7	79.4	9.31	3.86	0.91	9.3	8.5	15.4
3	5.4	5.4	1019.8	60.1	181.3	8.9	1201.1	69.0	67.5	2.389	2.502	4.5	16.1	71.7	7.21	3.72	0.90	7.2	6.5	14.9
AVG.		**5.4**										**4.4**	**15.9**	**74.5**				**8.3**	**7.6**	**14.9**

Table E-18 HMA Design Data by Marshall Method_30%RAP+FA@120°C

No.	%AC		Combined Weight				Total Mixture Weight		Specimen height	Bulk S.G.	Max S.G.	Air Void (%)	VMA (%)	VFA (%)	Peak load (KN)	Deform. At peak load (mm)	Corr. Ratio	Stability		Flow
	target	actual	Fresh Agg		RAP													measured	corrected	
	%	%	Agg.	AC	Agg.	AC	Agg	AC		Gmb	Gmm (by lab)							kN	kN	(0.25mm)
			g	g	g	g	g	g	mm											
1	5.4	5.4	838.9	50.5	362.7	17.9	1201.6	68.4	64.0	2.402	2.511	4.3	15.4	71.9	9.50	3.90	0.97	9.5	9.2	15.6
2	5.4	5.4	838.0	50.6	362.7	17.9	1200.7	68.5	64.1	2.397	2.511	4.5	15.6	70.9	9.95	3.93	0.97	10.0	9.7	15.7
3	5.4	5.4	836.7	50.5	362.7	17.9	1199.4	68.4	64.2	2.404	2.511	4.3	15.4	72.2	9.87	4.00	0.97	9.9	9.6	16.0
AVG.		**5.4**								**2.401**	**2.511**	**4.4**	**15.5**	**71.7**				**9.8**	**9.5**	**15.8**

Table E-19 HMA Design Data by Marshall Method_30%RAP+FA+0.25%Advera @120°C

No.	%AC		Combined Weight				Total Mixture W		specimen	Bulk S.G.	Max S.G.	Air	VMA	VFA	Peak	Deform.	Corr.	Stability		Flow
	target	actual	Virgin		Rap		Agg.	AC	height	Gmb	Gmm	Void			Load	at peak	Ratio	measured	corrected	(0.25mm)
	%	%	Agg.(g)	AC(g)	Agg.(g)	AC(g)	g	g	mm		(by lab)	%	%	%	kN	mm		kN	kN	
1	5.4	5.4	838.3	50.6	362.8	17.9	1201.1	68.5	67.0	2.408	2.511	4.1	15.3	73.4	7.79	3.60	0.91	7.8	7.1	14.4
2	5.4	5.5	838.0	51.7	362.8	17.9	1200.8	69.6	66.5	2.406	2.511	4.2	15.5	79.4	9.33	3.52	0.92	9.3	8.6	14.1
3	5.4	5.4	840.1	50.7	362.7	17.9	1202.8	68.6	67.5	2.403	2.511	4.3	15.5	72.3	9.20	4.19	0.90	9.2	8.3	16.8
AVG.		**5.4**										**4.2**	**15.5**	**75.0**				**8.8**	**8.0**	**15.1**

Table E-20 HMA Design Data by Marshall Method_30%RAP+FA+0.35%Advera @120°C

No.	%AC		Combined Weight				Total Mixture W		specimen	Bulk S.G.	Max S.G.	Air	VMA	VFA	Peak	Deform.	Corr.	Stability		Flow
	target	actual	Virgin		Rap		Agg.	AC	height	Gmb	Gmm	Void			Load	at peak	Ratio	measured	corrected	(0.25mm)
	%	%	Agg.(g)	AC(g)	Agg.(g)	AC(g)	g	g	mm		(by lab)	%	%	%	kN	mm		kN	kN	
1	5.4	5.4	836.3	51.0	362.6	17.9	1198.9	68.9	67.2	2.407	2.511	4.2	15.4	73.1	9.09	3.91	0.91	9.1	8.3	15.6
2	5.4	5.5	840.4	52.0	362.6	17.9	1203.0	69.9	67.2	2.410	2.511	4.0	15.4	79.4	7.44	3.59	0.91	7.4	6.8	14.3
3	5.4	5.4	838.3	50.7	362.7	17.9	1201.0	68.6	67.6	2.406	2.511	4.2	15.4	72.9	9.24	3.83	0.9	9.2	8.3	15.3
AVG.		**5.4**										**4.1**	**15.4**	**75.1**				**8.6**	**7.8**	**15.1**

Appendix F

Strength Index Test Result

Table F-1 Fresh Aggregate @ 150°C

			Soaked Sample			Unsoaked Sample		
Specimen Code			1	2	3	4	5	6
% AC by Mass of Agg.		(a)	NA			NA		
% AC by Mass of Mix		(b)	5.40			5.40		
% Eff. AC by Mass of Mix		(c) = b-x(100-b)/1	5.12			5.12		
Specimen Height	mm.	(d)	58.7	58.7	58.7	58.7	58.7	58.7
DENSITY								
Mass in Air	gm.	(e)	1148.0	1147.5	1150.2	1149.9	1151.1	1148.6
Mass Sat. Surface Dry	gm.	(f)	1151.0	1149.3	1152.8	1152.2	1152.7	1150.1
Mass in Water	gm.	(g)	676.1	677.8	679.3	677.2	677.7	678.2
Bulk Volume	ml.	(h) = f-g	474.9	471.5	473.5	475.0	475.0	471.9
Bulk Density	gm./ml.	(i) = e/h	2.417	2.434	2.429	2.421	2.423	2.434
Average Density			2.427			2.426		
VOIDS ANALYSIS								
Volume AC	% Tot (j) = c * i /Gac		12.2			12.2		
Volume Agg.	% Tot (k) = (100-b)*i/Gag		85.2			85.2		
VMA	%	(l) = 100-k	14.8			14.8		
Air Voids	%	(m) = l-j	2.6			2.7		
VFB	%	(n) = 100*j/l	82.2			82.0		
STABILITY								
Meas	lbs		7440	6980	7060	8100	7950	7490
Adjust	lbs		8480	7960	8050	9230	9060	8540
Average Stability			8163			8943		
FLOW								
Meas	1/100"		12	15	14	14	16	15
Average Flows			14			15		

trength Index (%) $\frac{\text{Soaked Stability} * 100}{\text{Unsoaked Stability}} = \frac{8163}{8943} \times 100 =$ 91.3 %

Table F-2 15%RAP+FA @ 150°C

			Soaked Sample			Unsoaked Sample		
Specimen Code			1	2	3	4	5	6
% AC by Mass of Agg.		(a)	NA			NA		
% AC by Mass of Mix		(b)	5.40			5.40		
% Eff. AC by Mass of Mix		(c) = b-x(100-b)/100	5.02			5.02		
Specimen Height	mm.	(d)	57.1	58.7	58.7	57.1	58.7	58.7
DENSITY								
Mass in Air	gm.	(e)	1139.8	1147.6	1147.6	1144.2	1145.8	1147.8
Mass Sat. Surface Dry	gm.	(f)	1141.6	1149.2	1148.7	1145.0	1147.6	1150.0
Mass in Water	gm.	(g)	673.6	677.8	677.1	677.0	677.0	676.8
Bulk Volume	ml.	(h) = f-g	468.0	471.4	471.6	468.0	470.6	473.2
Bulk Density	gm./ml.	(i) = e/h	2.435	2.434	2.433	2.445	2.435	2.426
Average Density			2.434			2.435		
VOIDS ANALYSIS								
Volume AC	% Total (j) = c * i /Gac		12.0			12.0		
Volume Agg.	% Total (k) = (100-b)*i/Gag		85.6			85.6		
VMA	%	(l) = 100-k	14.4			14.4		
Air Voids	%	(m) = l-j	2.4			2.4		
VFB	%	(n) = 100*j/l	83.1			83.3		
STABILITY								
Meas	lbs		8000	8510	8280	8200	8920	8970
Adjust	lbs		9520	9700	9440	9760	10170	10230
Average Stability			9553			10053		
FLOW								
Meas	1/100"		13	13	14	15	12	16
Average Flows			13			14		

Strength Index (%) $= \frac{\text{Soaked Stability} * 100}{\text{Unsoaked Stability}} = \frac{9553}{10053} \times 100 =$ 95.0 %

Table F-3 15%RAP+FA+0.25%Advera @ 135°C

			Soaked Sample			Unsoaked Sample		
Specimen Code			7	9	10	8	11	12
% AC by Mass of Agg.		(a)	NA			NA		
% AC by Mass of Mix		(b)	5.40			5.40		
% Eff. AC by Mass of Mix		(c) = b-x(100-b)/100	5.02			5.02		
Specimen Height	mm.	(d)	57.1	58.7	57.1	58.7	58.7	58.7
DENSITY								
Mass in Air	gm.	(e)	1146.3	1145.6	1143.6	1149.9	1148.7	1150.2
Mass Sat. Surface Dry	gm.	(f)	1148.3	1146.9	1144.6	1151.3	1149.8	1152.0
Mass in Water	gm.	(g)	679.0	673.0	674.4	678.9	677.0	678.3
Bulk Volume	ml.	(h) = f-g	469.3	473.9	470.2	472.4	472.8	473.7
Bulk Density	gm./ml.	(i) = e/h	2.443	2.417	2.432	2.434	2.430	2.428
Average Density			2.431			2.431		
VOIDS ANALYSIS								
Volume AC	% Total (j) = c * i /Gac		12.0			12.0		
Volume Agg.	% Total (k) = (100-b)*i/Gag		85.4			85.4		
VMA	%	(l) = 100-k	14.6			14.6		
Air Voids	%	(m) = l-j	2.6			2.6		
VFB	%	(n) = 100*j/l	82.2			82.2		
STABILITY								
Meas	lbs		8490	8660	8200	9180	9020	9250
Adjust	lbs		10100	9870	9760	10470	10280	10550
Average Stability			9910			10433		
FLOW								
Meas	1/100"		13	13	14	14	16	14
Average Flows			13			15		

Strength Index (%) $= \frac{\text{Soaked Stability} * 100}{\text{Unsoaked Stability}} = \frac{9910}{10433} \times 100 =$ 95.0 %

Biography

Yeshey Penjor was born on April 23, 1984 in Bhutan. He graduated in bachelors in civil engineering from Vasavi College of Engineering, affiliated to Osmania University, Hyderabad, AndraPradesh, India in the year 2007 with a scholarship grant from the Royal Government of Bhutan. In 2008 he got employed in the Ministry of Works and Human Settlements in Bhutan. In 2011, he got the opportunity to study masters in civil engineering (transportation) with a scholarship from Thailand International Cooperation Agency (TICA) scholarship under the Ministry of Foreign Affairs, Thailand.