EFFECTS OF REDISET ADDITIVE ON THE ENGINEERING PROPERTIES OF WARM ASPHALT BINDERS AND MIXTURES

By

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LIST OF ABBREVIATIONS

AASHTO	American Association of State Highway and Transportation Officials
AC	Asphalt Concrete
ANOVA	Analysis of Variance
APA	Asphalt Pavement Analyzer
ASA	Anti Stripping Agent
ASTM	American Society for Testing and Materials
ASCE	American Society of Civil Engineers
AWD	Asphalt Workability Device
BBD	Box Behnken Design
BBR	Bending Beam Rheometer
BBS	Bitumen Bond Strength
BS	British Standard
Caltrans	California Department of Transportation
CCD	Central Composite Design
CEI	Compaction Energy Index
CEN	European Committee for Standardization
CEN/TS	European Committee for Standardization / Technical Specification
DD	Draft for Development
DF	Degree of Freedom
DMA	Dynamic Mechanical Analyzer
DOT	Department of Transportation
DSR	Dynamic Shear Rheometer
DSC	Differential Scanning Calorimetry
DTG	Derivative Thermogravimetry
DTT	Direct Tensile Test
ER	Energy Ratio
EN	European Standard
FTIR	Fourier Transform Infrared Spectroscopy

GHG	Green House Gas Emissions
HMA	Hot Mix Asphalt
HVS	Heavy Vehicle Simulator
HW	High Natural Wax
HWT	Hamburg Wheel Tracking Test
ITS	Indirect Tensile Strength
JKR	Jabatan Kerja Raya
LCA	Life Cycle Assessment
MEPDG	Mechanistic Empirical Design Guide
MI	Modification Index
MR	Malaysian Ringgit
MSCR	Multiple Stress Creep and Recovery Test
NDIR	Non Dispersive Infrared Detector
NSRP	Non Dimensional Superpave Rutting Parameter
OBC	Optimum Binder Content
OCD	Orthogonal Composite Design
PAV	Pressure Aging Vessel
PG	Performance Grade
PI	Penetration Index
PPE	Personal Protective Equipment
PWD	Public Works Department
RPM	Revolution per Minute
RAP	Reclaimed Asphalt Pavement
RG	Relative G*sin δ
RSM	Response Surface Method
RTFO	Rolling Thin Film Oven
RV	Rotational Viscometer
SBS	Styrene Butadiene Styrene
SFE	Surface Free Energy
SMA	Stone Matrix Asphalt
SPT	Simple Performance Tester
ST	Stiffness Ratio

Superpave	Superior Performing Asphalt Pavement
TDI	Traffic Densification Index
TG	Thermo Gravimetric
TSR	Indirect Tensile Stress Ratio
TSRST	Tensile Stress Restrained Specimen Test
UCPRC	University of California Pavement Research Center
USA	United States of America
USM	Universiti Sains Malaysia
UTM	Universal Testing Machine
VFA	Void in Aggregate Filled with Asphalt Binder
VG	Viscosity Grade
VOC	Volatile Organic Compounds
WMA	Warm Mix Asphalt
ZSV	Zero Shear Viscosity

LIST OF SYMBOLS

$\nabla\eta_S$	Amount of Normalized Viscosity per Unit Percent of WMA Additive
d	Average Diameter of Specimen
h	Average Height of Specimen
$\varepsilon_r(L)$	Average Percent Recovery at Stress Level of L for Total 10 Cycle
η_i	Average Viscosity over the Last 15 Min
G_{mb}	Bulk Specific Gravity
J	Creep Compliance
J_{end}	Creep Compliance at the End of the Test
$J_{15\ min-before-end}$	Creep Compliance at the 15 Minutes before End
ξ	Damage Parameter
G*	Dynamic Modulus
η*	Dynamic Viscosity
Ā	Effective Cross-Sectional Area in Damaged State
E_a	Energy of Activation
ER	Energy Ratio
F	Failure Load
Y_j	Fitted Value of the Response
$[G^*/\sin(\delta)]_R$	G*/Sin δ of Asphalt Binders Incorporating Additive
$[G^*/\sin(\delta)]_c$	G*/Sin δ of Control Asphalt Binder without Additive
PGx-Hy	HMA Fabricated Using PGx Binder and Compacted at Y Temperature
PGx-HyTz	HMA Fabricated Using PGx Binder, Compacted at Y Temperature and Tested at Z Temperature
ITS	Indirect Tensile Strength
ITS_i	ITS of conditioned Samples in Cycle i
ITS_0	ITS of Unaged Samples
Dj	Individual Desirability Function for Response Number J
A_o	Initial Area of the Undamaged Section
Δt	Last 900 Seconds

G”	Loss Modulus
$max f_j$	Maximum Actual (Experimental) Values of the Response
G_{mm}	Maximum Specific Gravity
$min f_j$	Minimum Actual (Experimental) Values of the Response
η_S	Non Dimensional Viscosity Index
J_{nr}	Non Recoverable Creep Compliance
$J_{nr}(L,N)$	Non Recoverable Creep Compliance at the Stress Level of L for Cycle Number N
$J_{nr}(L)$	Non Recoverable Creep Compliance at the Stress Level of L for Total 10 Cycles
N	Number of Cycle of Loading
n	Number of Responses Included in the Optimization
D	Overall Desirability Function (Geometric Mean of the Individual Desirability Functions)
$\varepsilon_r(L,N)$	Percent Recovery of Each Loading Cycle at Stress Level
δ	Phase Angle
Mr_i	Resilient Modulus of Conditioned Samples in Cycle i
Mr_0	Resilient Modulus of Unaged Samples
γ	Shear Strain
ε_{10}	Shear Strain at the End of Creep Loading and Recovery for Each Cycle After 10 Second
ε_L	Shear Strain at the End of Each Cycle for Shear Stress of L
ε_1	Shear Strain at the End of 1 Second Loading for Each Cycle
σ	Shear Stress
L	Shear Stress (100 and 3200 Pa)
G’	Storage Modulus
$J_{nr\ dif}$	Stress Sensitivity
G*(sin δ)	Superpave Fatigue Factor
G*/sin δ	Superpave Rutting Factor
T	Temperature
t	Time
R	Universal Gas Constant

ΔJ	Variation of Creep Compliance
η	Viscosity
ν_0	Viscosity of Control Binder
ν	Viscosity of Modified Binder
wt_j	Weighting Factor of the Response
PGx-Wy	WMA Fabricated Using PGx Binder and Compacted at Y Temperature
PGx-WyTz	WMA Fabricated Using PGx Binder, Compacted at Y Temperature and Tested at Z Temperature
W^{dry}	Work of Adhesion in Dry Condition
W^{wet}	Work of Adhesion in Wet Condition

KESAN BAHAN TAMBAH REDISET KE ATAS SIFAT KEJURUTERAAN PENGIKAT DAN CAMPURAN ASFALT SUAM

ABSTRAK

Rediset adalah bahan tambah kimia yang berpotensi untuk membolehkan campuran asphalt dihasilkan dan dipadat pada suhu yang lebih rendah berbanding suhu penyediaan campuran turapan asphalt biasa. Tesis ini mendedahkan aspek baru penggunaan Rediset di dalam pengikat dan campuran asfalt. Objektif utama kajian ini adalah untuk mencirikan kesan kandungan Rediset terhadap sifat reologi pengikat asfalt dan campuran asfalt yang didedahkan kepada pelbagai keadaan persekitaran termasuk penuaan, suhu ujian dan keadaan kelembapan. Kesan kandungan Rediset terhadap parameter Superpave dikaji menggunakan kaedah reka bentuk eksperimen satu faktor pada satu masa dan kaedah tindak-balas permukaan. Manakala, kesan kandungan Rediset terhadap sifat reologi bahan pengikat pada suhu tinggi diuji menggunakan reometer ricih dinamik berasaskan pelbagai ujian makmal yang meliputi suhu, terikan, frekuensi, pelbagai tegasan, aliran, rayapan, rayapan pelbagai tegasan dan pemulihan, serta kelikatan ricih sifar. Penetapan kandungan bahan pengikat optimum (OBC) Rediset dan suhu pemadatan. Kaedah pengoptimaan baru dicadangkan untuk penentuan kandungan Rediset, kandungan bahan pengikat dan suhu pemadatan yang bersesuaian. Gabungan kesan pengusiaan dan kelembapan keatas sifat ketegaran campuran asphalt bersuhu sederhana (WMA) dikaji mengunakan ujian modulus kenyal, kekuatan tegangan tak-langsung dan rayapan dinamik. Keputusan ujikaji menunjukkan Rediset menurunkan kelikatan bahan pengikat semasa ujian dijalankan pada suhu tinggi dan meningkatkan ketahanan bahan turapan terhadap keretakan sebagai akibat kelesuan pada suhu pertengahan. Pencampuran Rediset didapati tidak mengubah gred prestasi semua bahan pengikat yang diuji. Di samping itu, menerusi ujian pelbagai aliran dan tegasan, kandungan Rediset yang tinggi meningkatkan kelikatan bahan pengikat terpinda. Walaubagaimanapun, kaedah tindak-balas permukaan (RSM) menunjukkan pengunaan Rediset di dalam campuran bahan turapan bersuhu sederhana tidak mengubah kandungan bahan pengikat optimum yang diperlukan oleh campuran bahan turapan panas (HMA) yang lazim digunakan di Malaysia. Pengunaan Rediset pada kadar yang tinggi menurunkan sedikit kestabilan dan ketegaran campuran asphalt bersuhu suam. Berdasarkan hasil kajian terperinci, kandungan Rediset sebanyak 1% dicadangkan dan kandungan ini bersesuaian untuk pelbagai keadaan bagi mengoptimumkan pengeluaran campuran asphalt jenis ini. Gabungan kesan pengusiaan dan kelembapan bertindak secara bertentangan dengan sifat ketegaran bahan turapan bersuhu suam. Proses penuaan meningkatkan kekuatan tegangan tidak-langsung dan modulus kebingkasan campuran asfalt, manakala kelembapan telah menurunkan kedua-dua nilai tersebut.

EFFECTS OF REDISET ADDITIVE ON THE ENGINEERING PROPERTIES OF WARM ASPHALT BINDERS AND MIXTURES

ABSTRACT

Rediset is a chemical warm additive that has potentials to reduce the compaction and mixing temperatures of asphalt mixtures. This thesis covers new aspects on the use of Rediset in warm asphalt binders and mixtures. The main objective of this study is to characterize the effects of Rediset contents on the rheological properties of asphalt binders and asphalt mixtures subjected to various environmental conditions including aging, test temperature, and moisture conditioning. The effects of Rediset content on Superpave parameters were investigated using one-factor-at-a-time experimental design and response surface method. The effects of Rediset content on high temperature rheological properties of binders were evaluated using the dynamic shear rheometer based on temperature, strain, frequency and stress sweep, flow, creep, multiple stress creep and recovery and zero shear viscosity tests. The optimum binder content (OBC) of warm mix asphalt (WMA) was studied for mixtures prepared with various Rediset contents and compaction temperatures. A new optimization procedure was proposed to select the appropriate Rediset content, binder content and compaction temperature. The combined effects of aging and moisture conditioning on the stiffness properties of WMA were studied using resilient modulus, indirect tensile strength and dynamic creep tests. The test results showed that Rediset decreased the viscosity of binders at very high temperatures and improved the Superpave fatigue resistance at intermediate temperatures. The incorporation of Rediset did not change the

performance grade of all binders tested. In the flow and stress sweep test, higher Rediset content resulted in higher viscosity for modified binders. The OBC results using RSM indicated that the OBC of WMA containing Rediset is similar to the OBC of typical hot mix asphalt (HMA). Using higher Rediset content slightly decreased the stability and stiffness of WMA. The optimization process in the production of WMA proposed 1% Rediset content as the optimum additive content for various scenarios. The combined effects of aging and moisture conditioning on stiffness properties of WMA indicated that aging and moisture conditioning had opposing effects on the stiffness properties of WMA. The aging process increased the indirect tensile strength (ITS) and resilient modulus of the asphalt mixtures, while the moisture conditioning reduced these values.

CHAPTER 1

INTRODUCTION

1.1 General

Warm mix asphalt (WMA) additives are materials which can be used to reduce the mixing and compaction temperatures of asphalt mixtures. The use of such materials can decrease both fuel consumption and emissions from asphalt plants and hence can be considered as an environmentally sustainable technology. Therefore, WMA technology can be important to policy makers, decision makers, asphalt suppliers and researchers.

Using WMA additives permits longer haul distances, provides more time for compaction of asphalt mixtures, permits operation of asphalt plants in regions with strict air pollution rules, extends the pavement construction season, improves the workability of asphalt mixtures at lower compaction temperatures, improves the aggregate coating by asphalt binders, slows binder aging, reduces wear and tear on asphalt mixture facilities, reduces odor emissions from asphalt plants, and improves working conditions at paving sites (Bennert et al., 2010; Hamzah et al., 2010a; Arega et al., 2011; Kim et al., 2011a; Banerjee et al., 2012; Xiao et al., 2012b).

WMA additives are classified into three groups: chemical additives, foamed asphalt binder technology, and organic additives (Rubio et al., 2012; Capitão et al., 2012). Rediset is a water-free chemical warm additive that can reduce compaction and mixing temperatures of asphalt mixtures by about 35°C (Arega et al., 2011; Banerjee et al., 2012). It is a combination of surfactants and organic additives into which the surfactants can improve the aggregate surfaces wetting potential with binder by active adhesion and the other components that reduces binder viscosity (Prowell et al., 2007). This thesis will cover new aspects of the use of Rediset in WMA studies.

1.2 Problem Statement

According to the detailed literature review conducted on the performance of WMA and especially WMA incorporating Rediset, some specific issues and problems were identified.

Most of researchers are interested to compare the rheological properties of the effects of the manufacturer’s recommended dosage of WMA additives with each other. Bennert et al. (2010), Arega et al. (2011), Xiao et al. (2011a), Benerje et al. (2012), and Xiao et al. (2012b) compared the effects of fixed dosage of Rediset in comparison with those of binders containing Sasobit, Evotherm, and Cecabese. Since strain tolerance of asphalt binders are significantly varied depending on asphalt binder sources and aging conditions (Kim, 2009), it is postulated that the recommended dosage of Rediset by the manufacturer might be inappropriate for the modification of asphalt binders under selected aging conditions. Therefore, it is necessary to evaluate the effects of Rediset content on the various rheological properties of asphalt binders subjected to different aging conditions.

Previous researchers such as Arega et al. (2011) and Xiao et al. (2012b) have only investigated the main effects of WMA additives on the rheological properties of asphalt binders without the quantification of the effects of the additive content and its interaction with other factors such as aging conditions, test temperatures, and binder types. Therefore, the quantification of the effects of Rediset on the rheological properties of asphalt binders using mathematical relationships can be a useful approach to provide a clear interpretation in characterizing the asphalt binder properties.

The rheological properties of asphalt binders play an important role on the performance of asphalt mixtures at high temperatures. WMA are more prone to permanent deformation at high temperature conditions (Capitão et al., 2012). Therefore, characterization of high service temperature properties of asphalt binders containing various Rediset contents under various shear loads can provide useful information in prediction of the real performance of WMA.

In mix design methods, the optimum binder content (OBC) for each material and each preparation method is determined by developing a distinct volumetric and strength behavior model. It is obvious that determining the OBC for a range of materials and methods, in aforementioned procedure, needs a lot of time and materials. The use of experimental design methods based on response surface method (RSM) has ability to decrease the number of samples required for testing and provide a possibility to determine the OBC for selected conditions. From the review of the literatures, it seems that the evaluation of warm mix asphalt behavior incorporating Rediset using RSM can be a new approach for determining the OBC of WMA.

In asphalt mixture performance studies, most researchers investigated the effects of compaction and mixing temperatures of WMA as well as other test parameters like binder type, aggregate source, and aggregate gradation using one-factor-at-a-time procedure (Hurley and Prowell, 2005; Bennert et al., 2010; Bennert et al., 2011; Mo et al., 2012). In this approach, the effects of these parameters cannot be simultaneously analyzed. Consequently, determining the optimum mixing and compaction temperatures and even binder and additive contents are difficult. Therefore, it is necessary to reach a procedure to optimize production process of warm mix asphalt in terms of mixing or compaction temperature, additive content and binder content, simultaneously. To meet this objective, using regional standard specifications, minimization of the cost of raw materials in production of WMA, and minimization of energy consumption are necessary and important.

Evaluation of the moisture damage of asphalt mixtures in field condition shows that pavement usually gains strength for a short time because of aging and then begins to weaken because of stripping (Kim, 2009). WMA are susceptible to moisture damage (Capitão et al., 2012). Although, some limited aspects of the combined effects of aging and moisture conditioning for asphalt mixtures and asphalt binders were studied (Lu and Harvey, 2006; Copeland et al., 2007; Grenfell et al., 2012; Punith et al., 2012), this phenomenon is needed to be studied for WMA incorporating Rediset, as well.

1.3 Objectives

This research was conducted to characterize the effects of Rediset on asphalt binder and asphalt mixture properties based on the problems stated in Section 1.2. The detailed objectives are as follows:

i. To investigate the rheological properties of asphalt binders containing various Rediset content subjected to different aging conditions and test temperatures using one-factor-at-a-time method and response surface method.

ii. To evaluate the high temperature rheological properties of asphalt binders incorporating Rediset under different shear loading conditions.

iii. To study the effects of binder content, compaction temperature, Rediset content on the engineering properties of WMA and subsequently determining the optimum binder contents using response surface method and proposing an optimization method for production process of WMA.

iv. To assess the combined effects of aging and moisture conditioning on the properties of WMA containing Rediset measured in terms of indirect tensile strength, dynamic creep and resilient modulus properties.

1.4 Scope of Work

The scope of work is limited to a study on the effects of various Rediset contents on the properties of asphalt binders and mixtures. The aggregate type used was crushed granite aggregate based on Malaysian Public Works Department (JKR) gradation for mix type AC14. Since, PG64 asphalt binder is a conventional asphalt binder in construction of the roads in Malaysia and PG76 asphalt binder is a polymer modified binder that has ability to improve the performance of conventional asphalt binders, these binders were selected for fabrication of asphalt mixtures. Asphalt mixtures were mixed and compacted at three temperatures using a gyratory compactor. The asphalt binders were characterized using a rotational viscometer (RV) and a dynamic shear rheometer (DSR), while the properties of asphalt mixtures were analyzed based on the results of volumetric measurements, Marshall test and also using the resilient modulus, dynamic creep and indirect tensile strength tests. This research was carried out in the following four phases:

In the first phase, Superpave performance tests were conducted on the asphalt binders containing Rediset under unaged, short-term aged, and long-term aged conditions at very high, high, and intermediate temperatures. Short- term aging and long-term aging was performed by rolling thin film oven (RTFO) and pressure aging vessel (PAV) according to ASTM D2872 (ASTM, 2006a) and ASTM D6521(ASTM, 2006b), respectively.

The second phase focused on strain sweep, stress sweep, frequency sweep, temperature sweep, flow, creep, multiple stress creep recovery, and zero shear viscosity tests for binders incorporating Rediset at high performance temperatures.

Phase three covered the determination of the OBC of WMA using Marshall tests and volumetric measurements based on central composite experimental design and response surface method. This phase also used the JKR standard specification, cost of raw materials in the production of WMA and energy consumption for determining the optimum mixing temperature, Rediset content and binder content.

In phase four, three aging cycles and two moisture conditioning cycles were used as a combined conditioning process for evaluating the effects of aging and moisture conditioning on the stiffness properties of WMA. Aging was done at a high temperature (85°C) for 3 days while moisture conditioning was conducted by vacuuming the samples in water for 30 minutes, freezing the samples and submerging the same samples in water for 24 hours at 60°C (in chemical environment).

1.5 Significance of the Research

This research evaluates the performance of WMA containing Rediset for Malaysian local materials including asphalt binders, aggregate type, and aggregate gradation. So, the outcomes of this research can promote rational use of this product in the local context.

Rediset decreases fuel consumption and emissions from asphalt plants and can be a green sustainable technology. So, the detailed knowledge from the results of this research can be useful to policy and decision makers to select the appropriate alternatives for a sustainable development.

Although the lower production and paving temperatures of WMA are beneficial, there are other problems associated with its usage. The incomplete drying of the aggregates, poor bitumen coating, less aging of the binder and moisture susceptibility can lead to poor performance (Rubio et al., 2012). Recently, limited rheological properties of some asphalt binders and mixtures containing Rediset have been investigated in comparison with other WMA additives like Sasobit and

Cecabase. Rediset is a combination of the wax and surfactant, while Sasobit and Cecabase are wax and surfactant warm additives, respectively (Prowell et al., 2007; Chowdhury and Button, 2008; Smiljanic et al., 2009; Tsai and Lai, 2010; Zaumanis and Haritonovs, 2010; Bennert, 2012b; Kheradmand et al., 2014; Shi et al., 2013; Zhu et al., 2013; Jamshidi et al., 2013). Therefore, it is necessary to characterize the effects of Rediset content on the engineering properties of asphalt binders and mixtures. The results of this study can provide useful information for future works to upgrade and develop a native warm additive to suit Malaysian conditions.

Test procedures in engineering and scientific experiments are often guided by subjective consideration of practicality and established laboratory protocols (Mason et al., 2003). While these kinds of experiments are viewed economically based on the number of test runs, statistical approaches in design of experiments are used to ensure that experiments are designed by economical criteria (Mason et al., 2003). Introducing and developing methods for finding some basic parameters using statistical experimental design (objective 3 and some part of objective 1), will decrease the use of materials and laboratory efforts.

This study presents a new approach for determining the optimum binder content in warm mix asphalts based on the volumetric and strength behavior of asphalt mixture samples using a specific experimental design (response surface method). Also, developing an optimization procedure in the production process of WMA to reach an optimum mixing temperature, binder content and Rediset content can be important step in building a decision making system for WMA technologists. These ideas will open a new horizon for asphalt material researchers and warm mix additive producers as well as civil engineers in the design and evaluation of asphaltic materials.

In last part of this thesis, the combined effects of aging and moisture damage on the stiffness properties of WMA were characterized. These results can provide an initial informative data for prediction of the behavior of WMA incorporating Rediset in the laboratory conditions.

1.6 Thesis Organization

This thesis is divided into eight chapters and presented as follows:

i. Chapter One introduces WMA and explains the problem statement, objectives, significance of the research, and scope of study.
ii. Chapter Two describes previous studies on the effects of Rediset on the rheological properties of asphalt binders and asphalt mixtures. The effects of Rediset in field studies are shown in this chapter, as well.
iii. Chapter Three explains the materials, sample preparation methods, tests procedures, and data analysis methods for characterization of the asphalt binders and mixtures.
iv. Chapter Four presents the results of the evaluation of the effects of Rediset content on the rheological properties of asphalt binders subjected to various aging conditions and test temperatures.
v. Chapter Five shows the results of shear loads on the high service temperatures properties of asphalt binders incorporating Rediset tested using the DSR machine.

vi. Chapter Six deliberates on the results, discussions, and statistical analysis on the effects of Rediset content, mixing temperature, and binder content on asphalt mixture properties to determine the OBCs and to develop an optimization method in production process of WMA using response surface method.

vii. The combined effects of aging and moisture conditioning on the stiffness properties of asphalt mixtures incorporating Rediset are presented and discussed in chapter Seven.

viii. Chapter Eight presents the conclusions and recommendations for future works.

Chapters Four and Five cover the first and second objectives of the research, while Chapters Six and Seven cover objectives three and four, respectively.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter collected, summarized and discussed the effects of Rediset on the rheological properties of asphalt binders, laboratory performance of asphalt mixtures, field behavior of constructed road sections, energy consumption, air pollution, physicochemical properties of asphalt binders, and behavior of asphalt mortars based on the studies reported in journal papers, technical reports, theses, and conference proceedings. The rheological effects of Rediset were scrutinized in four aspects: i. very high temperature properties in terms of viscosity of asphalt binder and workability of asphalt mixtures, ii. high temperature properties in terms of rutting resistance of asphalt mixtures and binders, iii. intermediate temperature in terms of fatigue performance, and iv. low temperature cracking properties. The new detailed information reported in graphs, tables, and texts of available scientific literatures related to Rediset were checked, summarized, and discussed. Other topics such as the mechanism of performance of Rediset, moisture susceptibility, mix design issues, volumetric properties, storage stability, and some economic aspects were investigated, as well. Figure 2.1 shows the structure of this literature review chapter.

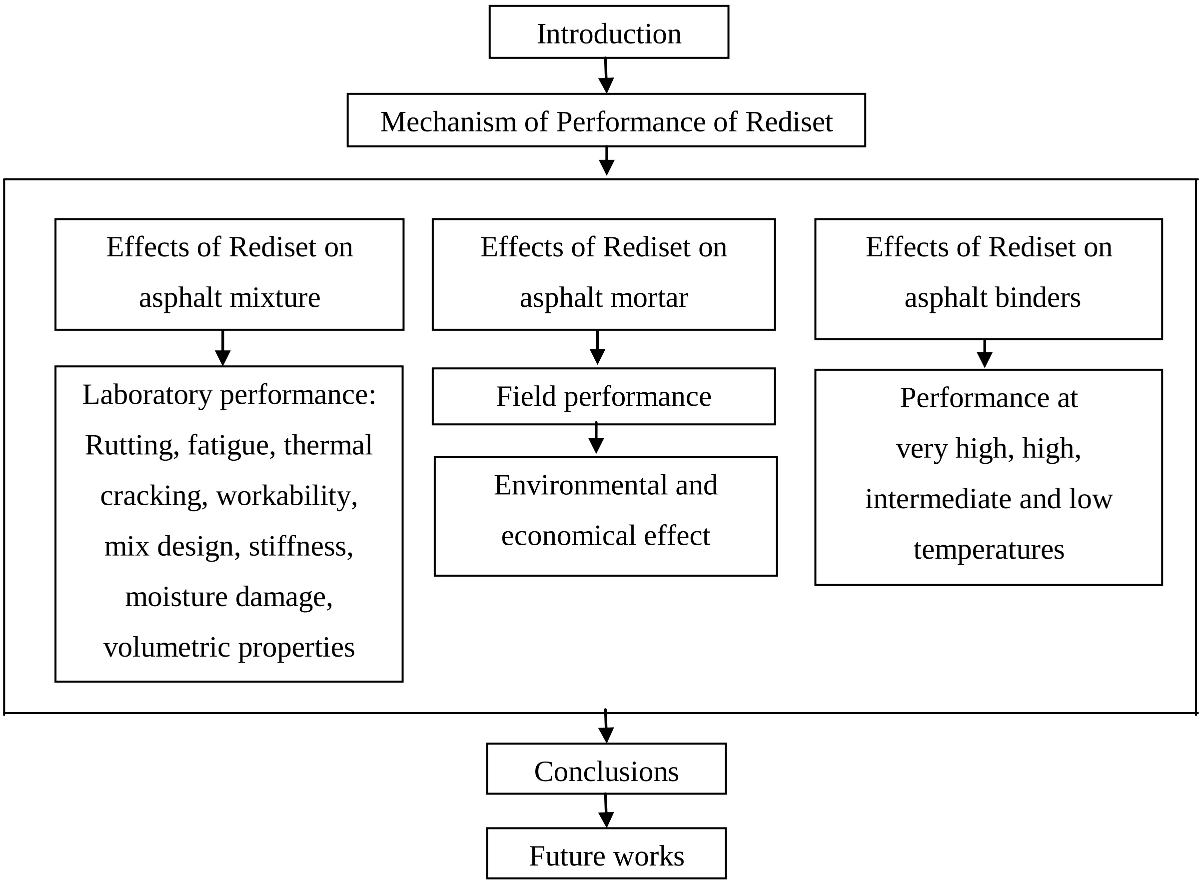

Figure 2.1: Flow Chart of Literature Review

2.2 Rediset

In 2007, Rediset was introduced in the United States (Bonaquist, 2011) to reduce some deficiencies of existing WMA additives (Hainin et al., 2013). Rediset is currently marketed as a warm mix additive with adhesion promoting properties (Bonaquist, 2011). It is a chemical (water-free) WMA additive from AkzoNobel, Netherlands (Arega et al., 2011), Sweden (Smiljanić et al., 2009; Syroezhko et al., 2011; Mo et al., 2012), and United States (Isebäck, 2012). In solid form, it is described by the name of Rediset WMX, while in liquid form, it is described by the name of Rediset LQ (AkzoNobel, 2013). Plate 2.1 shows the typical solid and liquid forms of Rediset.

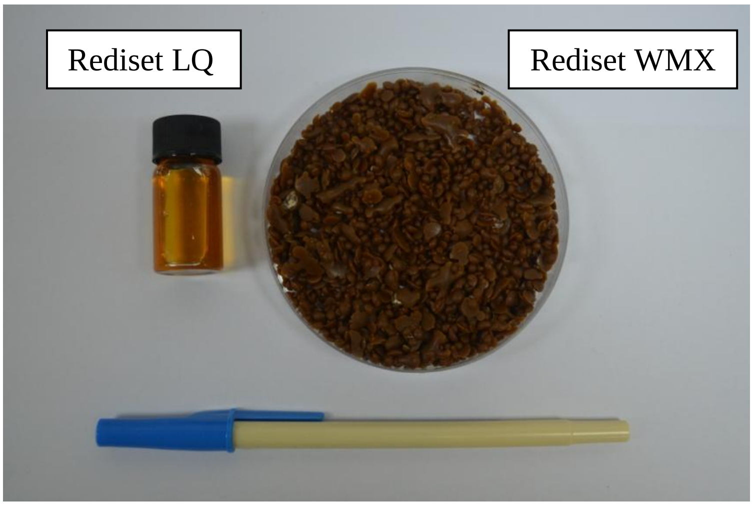

Plate 2.1: Rediset in Solid and Liquid Forms

In scientific literatures, different percentages of Rediset WMX were reported for modification of asphalt binders. Table 2.1 summarized the recommended dosages of Rediset WMX and its predicted effects on the temperature reduction. From Table 2.1, it can be seen that 1 to 3% of Rediset WMX contents were used for modification of WMA to provide a temperature reduction between 17°C and 35°C. Table 2.2 gives useful information regarding the use of Rediset WMX (AkzoNobel, 2013). According to Leng et al. (2013), Rediset LQ reduces mixing and paving temperatures of WMA by 15°C to 30°C. This additive is added at the rate of 0.5 to 1% into the asphalt binder (Leng et al., 2013). Since, there is a limited study on the effects of Rediset LQ on the performance of asphalt binder and mixtures, this literature survey will cover the effects of Rediset WMX for use in WMA and generally referred to as Rediset.

Table 2.1: Recommended Dosage of Rediset WMX and Its Effects on the Construction Temperature of WMA

No.	Recommended dosage	Reduction in construction temperatures	References
1	1.5%	-	(Xiao et al., 2012b)
2	1.5-2%	35°C	(Arega et al., 2011)
3	1-2%	54°F (30 ºC)	(Tsai and Lai, 2010)
4	2%	-	(Arega and Bhasin, 2012)
5	-	20-30ºC	(Smiljanić et al., 2009)
6	1-3%	20-35°C	(Trujillo, 2011)
7	1.5-2.5%	-	(Bonaquist, 2011)
8	1.25-2%	-	(Vallabhu, 2012)
9	-	35°C	(Banerjee et al., 2012)
10	1-3%	-	(Sengoz et al., 2013)
11	2%	60°F (33ºC)	(Sampath, 2010)
12	-	17-28°C (Frequently observed) >28 (Observed)	(Al-Qadi et al., 2012b)
13	1.5-2%	60°F (33ºC)	(Chowdhury and Button, 2008)

Table 2.2: Recommended Dosage of Rediset WMX by AkzoNobel (AkzoNobel, 2013)

Selected conditions	Rediset (%)
Compaction aid	0.5-1.0
WMA for conventional binder (30°C reduction)	1.0-1.5
WMA for polymer modified binder and stone mastic asphalt (SMA) (30°C reduction)	1.5-2
Improving the workability and for hand-laid mixtures	2-3

Rediset is a poly functional additive based on fatty amine surfactants and oly ethylenes (Smiljanic et al., 2011). According to Xiao et al. (2011b) and Xiao et al. (2012a), Rediset is a combination of fatty polyamines, polymer, and non-ionic components. This additive contains a long chain aliphatic hydrocarbon structure and an $–NH_3^+$ group which chemically reacts with aggregate surfaces (Syroezhko et al., 2011). According to Smiljanic et al. (2009), chemical structure of Rediset is based on the alkildiamine and hydrocarbon waxes. Table 3.2 shows some chemical and physical properties of Rediset.

Table 2.3: Physical and Chemical Properties of Rediset WMX

Properties	Value/description	References
Physical state	Solid	(Xiao et al. 2011b; Xiao et al. 2012a; Xiao et al. 2012b)
Color	Brown	
Odor	Amine like	
Solubility in water	Insoluble in cold water	
Bulk density	0.55 g/cc	(AkzoNobel, 2013)
Bulk density	4.6 lbs./gal	
Flash point	>150°C	
Melting point	85°C	(Arega and Bhasin, 2012)
Melting point	80-90°C	(Trujillo, 2011)

Rediset dissolves easily in hot asphalt binder without the need for a high shear mixer device (Trujillo, 2011). According to Arega and Bhasin (2012), this additive melts at about 85°C and completely blends with the asphalt binder (Arega and Bhasin, 2012). Although, conventional mixing temperatures of hot mix asphalt are proposed by suppliers for blending the warm additives with the asphalt binder

(Arega et al., 2011), in laboratory studies, various mixing temperatures and different mixing methods as well as various times of blending were used for preparing Rediset-modified asphalt binder as shown in Table 2.4.

Table 2.4: Methods for Preparing Rediset-Modified Asphalt Binder

No.	Number of binder type	Type of mixer	Blending temperature	Blending duration	Rediset content	Reference
1	8	Medium-shear radial flow impeller at 300 rpm	Hot binder	5 minutes	1.5	(Xiao et al., 2012b)
2	4	Digital overhead mixer equipped with a four-Blade propeller		30 minutes	2%	(Arega et al., 2011)
3	1	Low shear mixer	196°C	1 hour	1 and 2%	(Bennert et al., 2010)
4	1	Low shear mixer	196°C	1 hour	1 and 2%	(Bennert et al., 2011)
5	8	Medium-shear radial flow impeller at 300 rpm		5 minutes	1.5%	(Xiao et al., 2013b)
6	2	Digital overhead mixer equipped with a four blade propeller		30 minuts	2%	(Arega et al., 2013)
7	1	Mechanical stirrer at 6000 rpm	150°C	10 minutes		(Abdullah et al., 2012)
8	1	High shear mixer at 2000 rpm	150-160°C	10 minutes	1, 2, 3, and 4%	(Hainin et al., 2013)
9	1	High shear mixer at 2000-2500 rpm	120 to 130ºC	10 minutes	1, 2%	(van de Ven et al., 2012)
10	1	-	155 to 160ºC	30 minutes	3%	(Syroezhko et al., 2011)
11	1	High shear mixer		10 minutes	1.5%	(Doyle et al., 2013)
12	2	Low shear mixer	149°C		2%	(Alavi et al., 2012)

Rediset can be added into the asphalt binder or can be added into the mixture during the mixing procedure (Chowdhury and Button, 2008; van de Ven et al., 2012). If this additive is directly blended with asphalt binder at the refinery, the existing asphalt plant does not need any modifications (Chowdhury and Button, 2008). According to Bonquist (2011), Rediset can be added into the asphalt binder in the asphalt plant supply tank or into the mixture in the asphalt plant drum.

Rediset is a patented additive that differs from other chemical additives (like Evotherm and Cecabase) because it can act like an anti stripping agent and can improve the moisture susceptibility of the asphalt mixtures (Banerjee et al., 2012). Rediset usually does not need other anti stripping agent for use in mixture because this product provides anti-stripping properties (Chowdhury and Button, 2008).

The producer of this additive claims that this material performs beyond a typical warm additive. It acts as anti striping agent, anti oxidant agent, easy compactor additive, as well as warm mix additive (AkzoNobel, 2013).

2.3 Mechanism of Temperature Reduction

According to the scientific literatures, three mechanisms are used for reducing the production temperature of WMA as follows (Hanz et al., 2010a):

i. Reducing the viscosity of asphalt binders by adding organic additives such as wax (first mechanism)

ii. Foaming the asphalt binder through the use of hydrophilic additives (zeolite) or using injected water in vaporization process (second mechanism)

iii. Regulating and decreasing the frictional forces at the interface of the aggregate and asphalt binder at high temperature ranges, for instance between 85-140°C with the use of chemical additives (third mechanism) (Al-Qadi et al., 2012a).

Rediset is a multifunctional WMA additive (van de Ven et al., 2012) that reduces mixing and compaction temperature of WMA based on first and third mechanisms. Rediset is a combination of the surfactant (surface active agent) and organic additives (rheology modifier) (Prowell et al., 2007; Chowdhury and Button, 2008; Tsai and Lai, 2010; Zaumanis and Haritonovs, 2010; Bennert, 2012b; Kheradmand et al., 2014; Shi et al., 2013; Zhu et al., 2013). The surfactant part of this product (similar to chemical additives) decreases the surface tension of asphalt binder (Banerjee et al., 2012; Vallabhu, 2012), reduces the interfacial frictions between thin film of asphalt binder and aggregate (Arega and Bhasin 2012; Capitão et al. 2012) and improves the wettability of aggregate by asphalt binder (Banerjee et al., 2012), while the organic part reduces the viscosity of asphalt binder and provides lubricating effect for easier coating and compaction (Tsai and Lai, 2010; Kheradmand et al., 2014). Chemical additives are not similar to organic additives. They act at the microscopic interface of the asphalt binders and aggregates, while the organic additive change some asphalt binder properties such as viscosity. Emulsification agents, surfactants, and polymers are chemical additives that improve coating, workability, and compaction properties of asphalt mixtures (Al-Qadi et al., 2012a).

Rediset promotes active and passive adhesion between aggregate and asphalt binder (Syroezhko et al., 2011). It chemically modifies the asphalt binder to encourage active adhesion. Active adhesion improves coating and wetting of aggregates by binder at high temperatures (Prowell et al., 2007; Zaumanis and Haritonovs, 2010), while passive adhesion is related to the improvement of the asphalt binder resistance to displacement by water (Castaño et al., 2004).

Surfactants have been widely used in the asphalt industries. Surfactants are materials that reduce surface or interfacial tension between a liquid and a solid or between two liquids. Surfactants are used in detergents, wetting agents, emulsifiers, foaming agents, dispersants, and anti striping agents. Table 2.5 presents the use of some surfactants in asphalt studies. These materials are classified into four groups: cationic, anionic, amphoteric and nonionic surfactant (Rosen and Kunjappu, 2012). Rediset is a cationic surfactant (Prowell et al., 2007; Zaumanis and Haritonovs, 2010; Bennert, 2012b). According to Syroezhko et al. (2011), the tail of this surfactant can be a long chain aliphatic hydrocarbon, while its head can be a $–NH_3^+$. The head of this additive can exhibit cationic property. Plate 2.2, shows a schematic form of this additive as well as its interaction with a siliceous aggregate. Silica atoms can bond with cationic surfactant, while calcium ions can bond with both anionic and cationic surfactants (Lesueur et al., 2012). Therefore, surfactants can act as a bridge between the asphalt binder and the aggregate surface, promote adhesion, and improve moisture susceptibility of asphalt mixtures (Capitão et al., 2012). The surface active compounds enable coating of damp aggregate which could be encountered with lower drying temperatures (Bennert, 2012b).

Table 2.5: Surfactant in Asphalt Binders and Mixtures Researches

No.	Type of surfactant	Function	Percentage	Commercial name	Reference
1	Amine surfactant	Asphaltene dispersant	0.75		(Ahmed et al., 2012)
2	Amine surfactant	Adhesive agent	0.75		
3	Combination of rheology modifier and surfactant	WMA additive and adhesive agent	1.5		
4	Surfactant of amino nature	Anti-stripping agents	0.4		(DelRio-Prat et al., 2011)
5	Mix of surfactants	Anti-stripping agent	0.3		
6	Mix of surfactants, waxes, polymers, etc.	Anti-stripping agent	3		
7	Surfactant phosphoric nature	Anti-stripping agent	0.3		
8	Mix of surfactant, wax and polymers in a prills form	Chemical WMA additive	3		(Sanchez-Alonso et al., 2013)
9	Mix of surfactants in liquid form	Chemical WMA additive	0.3		
10	surfactant of amino nature in viscous liquid state	Chemical WMA additive	0.4		
11	A synthetic amides in a liquid form	WMA additive	-	Gemul XT14	(Motta et al., 2012)
12	Metal ion surfactants	Anti-stripping agent	-		(Iskender et al., 2012)
13	Surfactant used in nano composites with base asphalt	Dispersing additive	-		(Fang et al., 2013)

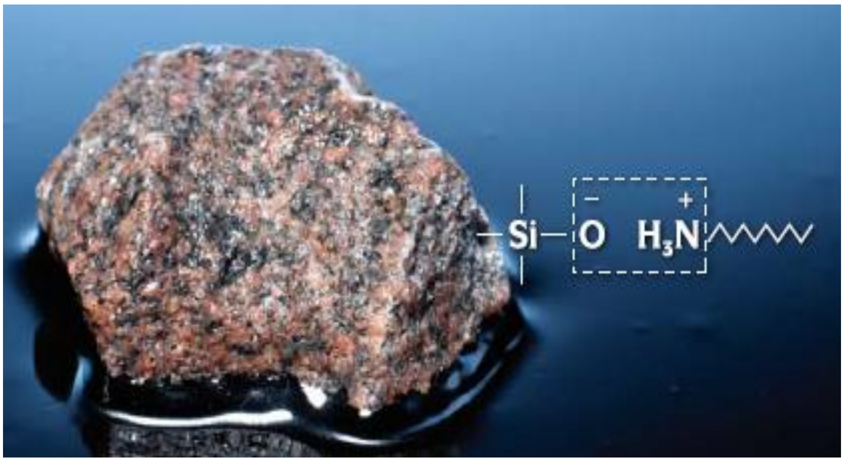

Plate 2.2: Interaction of Rediset with a Siliceous Aggregate (AkzoNobel, 2013)

2.4 Asphalt Binder Properties

2.4.1 Construction Temperatures

Asphalt binder properties at a range of mixing and compaction temperatures can be evaluated using rotational viscosity, dynamic viscosity, kinematics viscosity, and lubricity tests. Rotational viscosity can be used to determine the flow characteristics of asphalt binder at the hot mixing facility (Xiao et al., 2011b; Xiao et al., 2012b). In previous warm mix asphalt studies (Akisetty et al., 2009; Lee et al., 2009, Silva et al., 2010; Arega et al., 2011; Shang et al., 2011; Xiao et al., 2012a; Xiao et al., 2012b), rotational viscosity has been extensively used to evaluate the warm asphalt binder's behavior in both unaged and short-term aged conditions.

The use of Rediset decreases the rotational viscosity of asphalt binders (Xiao et al., 2011b; Sengoz and Oylumluoglu, 2013). It implies that lowering viscosity can be one of the mechanisms that Rediset uses for reducing the mixing and compaction temperatures. The degree of change of the rotational viscosity depends on the binder type, binder source, test temperature, aging state, and Rediset content (Sampath, 2010; Arega et al., 2011; Xiao et al., 2011b; Mo et al., 2012; Xiao et al., 2012b). Some researchers showed that binders with Rediset have lower viscosity than other WMA additives like Evotherm, Cecabase, Aspha-min, and Sasoflex regardless of test temperature and binder type (Xiao et al., 2011b; Xiao et al., 2012b). In addition, van de Ven et al (2012) reported that the effects of Rediset on the viscosity become less when temperature increases from 100ºC to 150ºC. In another study, Xiao et al. (2011b) reported that the viscosity of Rediset-modified binder does not obviously change when the storage duration increases.

Rediset has positive effects on kinematic and dynamic viscosity, as well. According to Zaumanis and Haritonovos (2010) and Shi et al. (2013), Rediset decreases kinematic viscosity of asphalt binder at 135°C. Also, van de Ven et al. (2012) showed that Rediset has strong influence on the dynamic viscosity at 110°C for a hard asphalt binder using the result of DSR with a cone and plate device.

Although the positive effects of Rediset on the viscosity has been mostly reported, Arega et al. (2011) observed a negative effect of 2% Rediset on the rotational viscosity for a PG76-22 asphalt binder containing high amount of natural wax under unaged condition at 135°C. This case was not observed for the same binder in short-term ageing condition as well as other selected asphalt binders in both unaged and short-term aged conditions.

The results of rotational viscosity tests can be used to determine the activation energy of asphalt binders. Activation energy can be related to the asphalt binder thermal susceptibility. Mo et al. (2012) showed that addition of Rediset has positive effects on the reduction of activation energy and thermal susceptibility of asphalt binders. They showed that increasing Rediset content results in less susceptibility of the material to temperature, where asphalt binders with low activation energy are less susceptible to temperature. Equation (2.1) shows the relationship between viscosity and activation energy based on the Arrhenius-like Equation (Mo et al., 2012):

$$\eta = Ae^{(Ea/RT)} \tag{2.1}$$

where,

η = Viscosity (Pa.s)

A = Regression parameter

R = Universal gas constant (8.314 JK^{-1} mol^{-1})

T = Temperature (°K)

E_a = Activation energy kJ/mol

In some studies, the rotational viscosity test results were used to determine mixing and compaction temperatures of WMA using the Asphalt Institute recommendations based on the temperature–viscosity graph. Sengoz and Oylumluoglu (2013) showed that using Rediset decreases the mixing and compaction temperature of WMA by 8°C and 6°C, respectively. It seems that this method does not have the ability to predict mixing and compaction temperatures, appropriately. Since surfactant-based WMA additives are using other types of mechanisms for reducing mixing and compaction temperatures, other laboratory tests such as lubricity tests were considered for evaluation of asphalt binder properties at very high temperatures (Hanz et al., 2010b). Generally, the concepts of thin-film rheology are used in lubricity test (Bennert et al., 2010). Benert et al. (2010) showed that the shear rate of asphalt binder with various amounts of Rediset is higher than neat binder at peak point of torque on DSR plates in lubricity test. It implies that internal friction in the particles of asphalt mixture containing Rediset can be lower than asphalt mixture without warm additive. Lower internal friction provides a successful condition for production of WMA.

2.4.2 High Temperatures

According to the literatures discussed in this section, high temperature properties of asphalt binders blended with Rediset is evaluated by different parameters such as dynamic modulus (G*), phase angle (δ), dynamic viscosity (η*), Superpave rutting factor (G*/sin δ), high failure temperature, high temperature Superpave performance grade (PG), creep compliance, creep angle, and also softening point under unaged or short-term aging condition. Some of these parameters were determined at specific temperatures (at high performance grade temperature or at a reference temperature such as 60°C), a range of temperatures (temperature sweep tests), or in a specific loading condition (frequency sweep tests, strain sweep tests, flow tests, and creep and recovery tests). These parameters can be used to predict the resistance of asphalt mixtures to permanent deformation. The effects of Rediset on the properties of asphalt binders at high temperature are:

i. Positive effects: Shi et al. (2013) reported that addition of 2% Rediset increases dynamic viscosity of asphalt binders tested at 60°C by approximately 21.8% and 38.9%. Research conducted by Doyle et al. (2013) showed that incorporating 1.5% Rediset increases G*/sin δ of asphalt binder