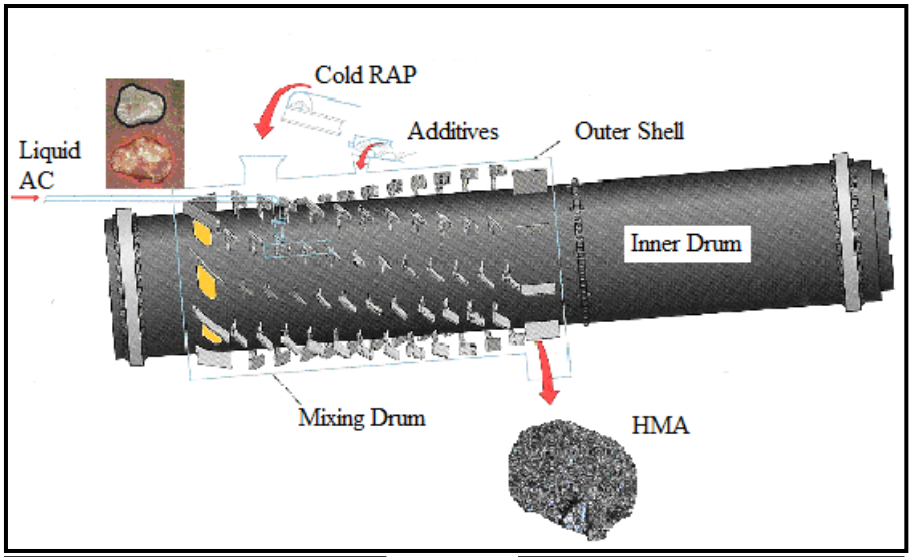
DEVELOPMENT OF A MIX DESIGN METHOD IN THE LABORATORY FOR MIXES WITH RECYCLED ASPHALT PAVEMENT IN A DRUM MIX FACILITY



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Msc Thesis
August 2009

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DEVELOPMENT OF A MIX DESIGN METHOD IN THE LABORATORY FOR MIXES WITH RECYCLED ASPHALT PAVEMENT IN A DRUM MIX FACILITY

by

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A Thesis

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ABSTRACT

The objective of this study was to develop a laboratory mix design procedure of HMA containing high RAP content, which mimics the industrial production process employed in double barrel plants and to compare the mechanical properties using three different mixing methods. Laboratory handling of materials during the mix design process is important for the success of mix design. Handling of the RAP material during the mixing process affects the performance properties of HMA. The laboratory mixing process should simulate the actual industrial production process in order to predict as close as possible the field performance properties of plant produced hot mix asphalt with laboratory made mixes.

To meet the objectives of the study, the research was divided into two phases. Phase one includes the mix design stage according to Dutch RAW 2005 standard, determination of the heating and compaction temperature, determination of mixing time of virgin and RAP materials. RAP material extraction and recovery was done to determine the RAP aggregate gradation and RAP binder rheological properties. An X-ray Fluorescence Spectroscopy (XRF) was done to analyse the effect of high temperature on mineralogical compositions of the virgin aggregate and sand. Phase two of the research included mechanical tests on the asphalt mixtures to evaluate the mixture performance properties.

Three mixing processes were compared during the study. In the standard mixing method the virgin and the RAP materials are heated to 170 ^{o}C similar to batch plants, in the partial warming method the virgin material was heated up to 300 ^{o}C and the RAP was heated to 130 ^{o}C similar to parallel drum plants, in the upgraded mixing method the virgin aggregate was heated to 400 ^{o}C and the RAP was not heated similar to double barrel drum plants. For all mixing methods a base course mix STAC (0/22) with 40 and 50 % RAP content was used according to Dutch RAW 2005 specification.

The resilient modulus tests showed that mixtures prepared by heating the virgin material and the RAP to 170 ^{o}C showed the highest stiffness. The water

sensitivity results showed that all mixes had higher a value of retained tensile strength ratio than the minimum requirement of 80 %. The permanent deformation test results indicated that mixtures prepared by heating the virgin material and the RAP to 170 ^{o}C had a lower creep rate than the two mixing methods. Although, difference in permanent deformation resistance was observed among the mixing methods, all mixes had lower creep rate than the maximum allowable value according Dutch RAW 2005 standard.

The outcome of this research has shown that mechanical properties like stiffness, moisture sensitivity and resistance to permanent deformation are significantly influenced by mixing methods and amount of RAP content. It was also found that heating RAP to a high temperature gives a stiffer mix with less permanent deformation. It is not clear how the higher value of mix stiffness with more aged binder can affect the fatigue life and low temperature performance properties and can cause early pavement distress.

Further study on the blending of the RAP and the virgin binder, the influence of the presence of moisture in the RAP during the mixing process and other performance properties are recommended for the mixing method of cold RAP and superheated aggregate.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVATIONS

DSR	Dynamic Shear Rheometer
EN	European Norm
Eq.	Equation
Fig.	Figure
Gb	Specific gravity of binder
Gmm	Theoretical maximum density
Gsb	Bulk specific gravity
Gse	Effective specific gravity
HMA	Hot Mix Asphalt
ITC	Indirect Tensile Creep
ITS	Indirect Tensile Strength
ITSR	Indirect Tensile Strength Ratio
ITT	Indirect Tensile Test
Log	Logarithm
LVDT	Linear Variable Displacement Transducer
Mr	Resilient Modulus
NEN	Dutch Standardization Institute
PAC	Porous Asphalt Concrete
PAV	Pressure Aging Vessel
Pb	Binder content
Pen	Penetration
Q8	Kuwait Petroleum
RAP	Reclaimed Asphalt Pavements
RAW	Dutch standard specification for civil engineering (RAW Bepallingen)
RTFOT	Rolling Thin Film Oven Test
SMA	Stone Mastic Asphalt
STAC	Stone Asphalt Concrete
Tref	Reference Temperature
TU Delft	Technical University of Delft
VFB	Void Filled with Bitumen
VMA	Void in Mineral Aggregate
XRF	X-ray Fluorescence Spectroscopy

Chapter 1 Introduction

1.1 Background

Economic and Environmental considerations have prompted the recycling of steel, aluminum, plastic and many other materials. One of these recycled materials is hot mix asphalt (HMA). A reclaimed asphalt pavement, which is commonly called RAP, is a hot mix mixture containing aggregates and asphalt cement binder which has been removed and reclaimed from an existing pavement. The concept of recycling of Hot Mix Asphalt (HMA) was documented as far back as 1915, though it didn't gain popularity until the oil crisis of the mid 1970's. Demand for HMA recycling was driven by the increase of cost of the bitumen, coupled with scarcity of the quality of aggregate near the point of utilization. These economic incentives still exist; environmental incentives to recycle are also prominent.

The history of hot mix recycling in the Netherlands also begins in the early 1970's. The global oil crises and other factors like environment, no place for waste disposal and limited source of natural aggregates forced the government to promote the use of Reclaimed Asphalt Pavement (RAP). Two large projects in 1976 and 1980 by Dutch government and a group of contractors were conducted. The purposes of the projects were to use recycling to the highest possible level. In 1980's and 1990's the recycling market became a commercial market because government pushed the market approach with legislations on waste deposits. Since 1990's RAP is recognized as building material and incorporated in Dutch Standard (RAW).

Currently in the Netherlands in all kinds of asphalt mixes except Porous Asphalt (PAC) and Stone Mastic Asphalt (SMA) RAP is used for the production of new asphalt mixes.

1.2 Problem Statement

Most asphalt manufacturing plants in the Netherlands are of the batch plant type and use the system with the so-called parallel drum. In these parallel drum plants the RAP is preheated to a maximum temperature of 130 ^{o}C.

The Double Barrel drier/mixer is another type of asphalt plant which combines the functions of a dryer and a continuous–process mixer in one compact system. In the double barrel asphalt plant the virgin material is superheated to high temperature in the inner drum and the mixing takes place in the outer drum with the cold RAP. During the mixing process, the cold RAP when in contact with the superheated aggregate heated to the required mixing temperature.

Existing laboratory mixing methods with RAP do not have mixing process similar to the double barrel asphalt plant. Such difference in the laboratory mix design process and plant production process can cause considerable difference in performance properties of the laboratory and plant made mixes and the laboratory made mixes can hardly predicate the actual field condition. Therefore, it is important that laboratory mix design procedure should enable to simulate the plant production procedure in order to predict the performance of the mixture in the field. In this research it was tried to develop a laboratory mixing method which mimic the mixing process in the double barrel plant.

1.3 Research Objective

The main objective of this research is to develop a laboratory mix design procedure for HMA containing Reclaimed Asphalt Pavement (RAP) which mimics the industrial production process employed in double barrel asphalt mix plants and to compare the performance of asphalt mixes with RAP using different laboratory mix preparation methods including the standard RAW mixing method.

1.4 Scope of the research

In this research a laboratory mix design procedure will be developed for HMA containing RAP that simulates the process in the double barrel drier/mixer. The research focuses on performing mix design for base course mix (STAC 0/22) with 40 and 50 % RAP content. The following three mixing methods were considered:

- Both the virgin and RAP material are heated together at the same temperature 170 ^{o}C.

- The RAP will be heated to 130 ^{o}C and the Virgin material to higher temperature.
- Virgin aggregate will be superheated to high temperature and mixed with cold RAP.

The study was divided into two phases: Phase one involved the mix design stage according to Dutch RAW 2005 standard, determination of the heating and compaction temperature, determination of mixing time of the virgin and RAP materials and conducting preliminary mix design using the Marshal mix design method. The following tests were conducted in phase one of the study:

- Extraction and recovery for determination of RAP aggregates and binder properties.
- Empirical tests on binders (softening point and penetration).
- Determination of the specific gravity RAP and virgin aggregates.
- X-ray Fluorescence Spectroscopy (XRF) for evaluation of mineralogical composition of aggregate.

Phase two of the research involved utilizing the data from phase one for preparation of specimens for mechanical tests in order to evaluate the mixture performance properties according to Dutch and European standards. These tests include:

- Indirect Tensile Modulus for stiffness evaluation.
- Indirect Tensile test for tensile strength and moisture sensitivity evaluation.
- Cyclic Triaxial test for resistance to permanent deformation evaluation.

1.5 Organization of the report

This report has been divided into seven chapters. The contents of each chapter are described hereafter.

Chapter 1 serves as an introduction, stating the nature of the problem to be addressed, objectives of the research, and scope of work accomplished.

Chapter 2 a literature review provides information on characteristics of RAP, effect of RAP on mix performance properties, mix design methods using RAP, and description of different asphalt plants.

Chapter 3 describes the materials and material properties and testing programs of the study. It also describes various test methods used to evaluate the performance properties of the mixtures.

Chapter 4 describes the mix design procedures, including information on asphalt binder, gradation of both virgin and RAP aggregates materials and mix volumetric properties.

Chapter 5 describes the different mixing process used in the study, including information on mixing temperature, mixing time, sequence of mixing and compaction procedures for the three mixing methods.

Chapter 6 covers analysis of the results from different tests which have been conducted to evaluate the performance properties of the mixtures prepared by different mixing methods: it includes analysis of stiffness, water sensitivity and permanent deformation results.

Chapter 7 presents the conclusions and recommendations that arise from the research.

Chapter 2 Literature Review

This chapter presents the findings of a literature review on the properties of RAP material and performance of asphalt mixes incorporating RAP. It also presents different mix design methods of asphalt mixes with RAP. In addition, it discusses the difference between laboratory vs. plant made mixes and types of asphalt production plants.

2.1 RAP binder Property

2.1.1 RAP binder quantity

When performing a mix design with RAP, it is desirable to know the characteristics, content, properties of the binder and gradation of the aggregate in the RAP. Before determination of RAP aggregate gradation, the binder and the aggregate must be separated. There are a number of methods that have been developed to separate the aggregate from the binder and/ or determine the binder content. These include solvent extraction, nuclear asphalt content gauge and ignition methods. After the extraction process, the binder quantity of the RAP will be determined.

2.1.2 Aged RAP binder property

Aging of asphalt binder causes an increase in viscosity, decrease in penetration and subsequent stiffening of the asphalt mixture. Aged binder in the asphalt mixture result in harder and more brittle behavior at higher service temperatures.

Consideration of the effects of aging on the binder is important during the mix design process involving RAP. When the aged binder in the RAP is combined with the new binder, it will probably influence the resultant binder grade. It was noted that the effect of aged binder from RAP on the performance properties of the virgin binder depends upon the level of RAP used in the asphalt mixture. When the percentage of RAP used in the mixture is low (10 to 20 %) the effect on the asphalt binder properties is minimal (McDaniel et. al, 2000). At low percentages (10 to 20 %), RAP affects the mix volumetric and performance through gradation because RAP also acts like a black rock.

As the content of RAP percentages increased, the aged binder from the RAP blends with the virgin binder in sufficient quantity to significantly affect the mix performance.

2.1.3 Blending of Aged and Virgin Binders

In most RAP mix design methodologies (as well as researchers) total blending is assumed between the binder film on the RAP aggregate and the virgin binder. This hypothesis may or may not be entirely true. If the designer assumes that the materials blend completely when it is actually behaving as a black rock, then the mixture will not be as stiff as initially thought. On the other hand, if the designer assumed that the RAP does not blend with the virgin binder, when it actually blending partially or totally with the virgin binder, then the mixture will be stiffer than expected and a binder rich mix will be the result.

McDaniel et. al (2000) performed research to investigate the degree of binder blending in mixtures for the National Cooperative Research Program's project 9-12 in the United States of America. They investigated three blending conditions: black rock (no blending means no interaction between old and new binder), total blending (100 % blending), and actual practice (blending as it usually occurs in practice). In all cases, the overall gradation and total asphalt binder content were kept constant. Two RAP contents (10 and 40 %) were used as the minimum and maximum percentages of RAP. The mixtures performance parameters where obtained from the Frequency Sweep test, Simple Shear test, and the Repeated Shear at Constant Height test. The Indirect Tensile Creep test (ITC) and Indirect Tensile Strength (ITS) tests were also used to evaluate the HMA performance at low temperature.

Based on the results of the study, it was concluded that at a RAP content of 10 %, no significant difference existed between various blends. On the other hand, at a RAP content of 40 %, the black rock case was statistically different from the actual practice and total blending cases. Statistical analysis conducted in the study showed that out of 66 possible comparisons, 11 and 16 cases were inconclusive at a RAP content of 10 and 40 %, respectively. At a RAP content of 10 %, a majority of the cases (70 %) supported the

conclusion that all cases were similar. However, at a RAP content of 40 %, only 42 % of the comparisons supported the conclusion that the total blending (TB) cases are similar to the actual practice (AP) cases. It was suggested by the researchers that it was not likely that total blending occurs in all cases even at low RAP contents.

Stephens et al. (2001) conducted an experimental program to evaluate the effects of blending between RAP and virgin binders in a mixture. Stephens, acquired mixtures from two separate asphalt plants and used gentle heating with mechanical mixing and sieving to separate the mixture into 3 size categories: aggregate pieces larger than 6.36 mm, aggregate lumps larger than 6.36 mm and aggregate pieces and lumps smaller that 6.36 mm. He assumed that the binder recovered from the coarse aggregate particles would be more similar to the stiffness of the virgin binder, the binder recovered from the loose fine aggregate would be more similar to the completely blended RAP and virgin binder stiffness, while the recovered binder from the aggregate lumps would be more similar to the stiffness of the recovered RAP binder. The recovered binder stiffness was determined using DSR for the three mixture particle size categories. It was determined that there was no pattern in the stiffness values. The results showed that degree of binder blending could not be readily found by sorting the material.

Stephens also evaluated the effect of RAP preheating times on the degree of material blending. To validate that RAP does not act as a black rock and has an effect on the overall blend, 11 mixes were prepared with the same gradation, RAP percentage (15 %), and binder content. The difference between the prepared samples were the RAP preheating time before being added to virgin aggregates and binder. A 12th mix was also prepared with virgin aggregates and binder with no RAP binder. The RAP preheating time was varied from zero to 540 minutes. If RAP acts as a black rock, preheating time should not have any effect on the mix properties. In contrast, if long heating times facilitate the blending between aged and virgin binders, an increase in the mix strength should be detected. Figure 2.1 presents the variation of the indirect tensile and unconfined compression strengths with RAP preheating time. As shown in the figure, preheating time had a profound

effect on the mix strength, indicating that blending does occur between aged and virgin binders. In addition, when comparing the mix with no preheating to the mix made with virgin materials only, a one third increase in indirect tensile strength and unconfined compressive strength is immediately observed upon adding the RAP to the virgin materials even without any preheating. Stephens summarized that preheating time had little effect on binder blending as long as the RAP reaches a temperature that at least softens the RAP binder to allow intimate blending.

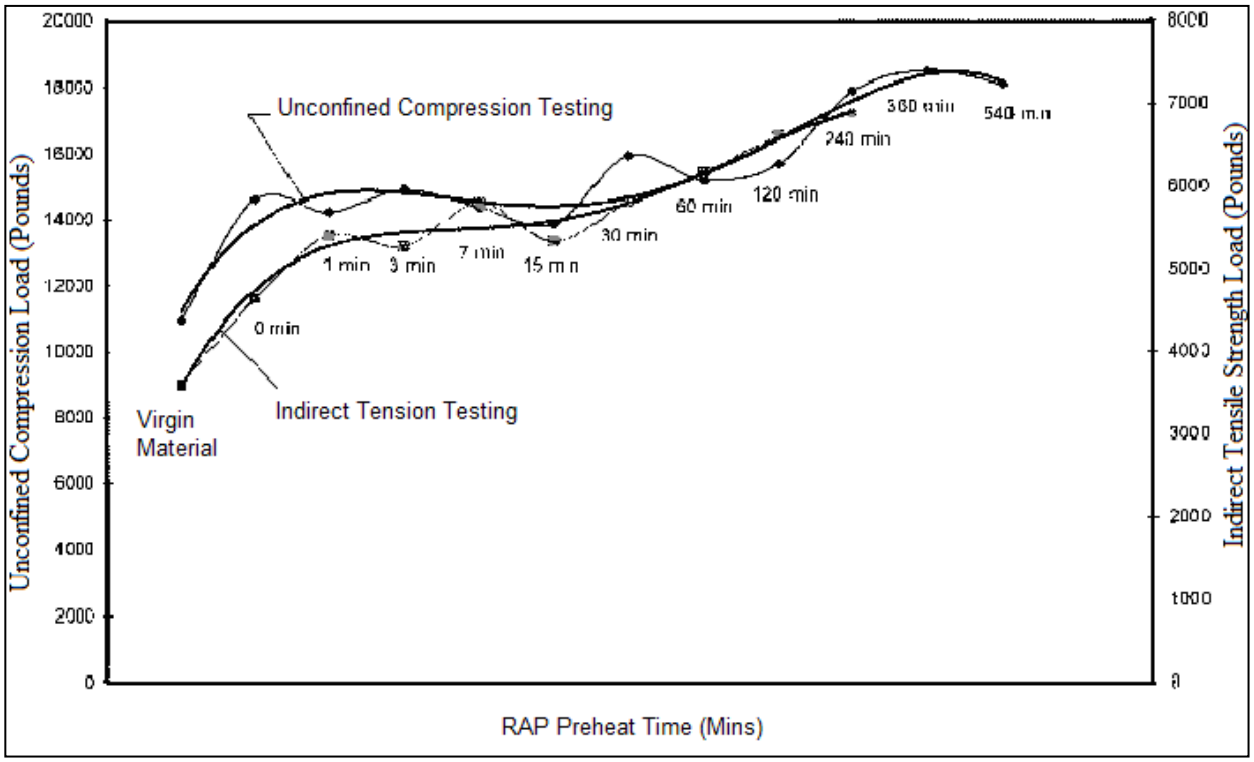

Figure 2.1: Effect of RAP preheating time on unconfined compression and indirect tensile strength (Stephens et al., 2001)

2.2 RAP Aggregate properties

Hardly any research is done into how the reclaimed aggregate from RAP affects mix design and performance. At high RAP content it was evident that aggregate in the RAP may also affect mixture volumetric and performance properties. The design aggregate structure, gradation and content of dust should be taken into account when using aggregate from the RAP. At low RAP percentages, the effects may be minimal.

Gradation of the RAP aggregate is influenced by the milling process. Some researchers compared the gradation taken from core samples and the gradation determined after the pavement has been milled. The results indicate that, the milling process results in a finer aggregate gradation than the cores indicated. The potentially adverse effects of the milling operation can present a problem in meeting fine gradation requirements. Currently, this problem is addressed by placing restrictions on the maximum amount of RAP that may be used in the mixture for blending with virgin aggregate. It has been suggested by Stroup-Gardiner and Wanger (1999) that RAP could be split into a coarse and fine fraction in order to keep the large amount of dust fraction out of the mix, thereby allowing a higher percentage of RAP to be used.

2.3 Asphalt Mix Characteristics containing RAP

Many studies have reported on laboratory and field performance of hot mix asphalt. However, published studies on performance properties of hot mix asphalt incorporating RAP are limited.

Most studies on laboratory produced mixtures concluded that the effect of RAP on mixtures' properties is negligible at low contents of 10 to 20 % (McDaniel et al., 2000 and Li et al., 2008). The low RAP content did not significantly affect the stiffness and strength of the mix at low and high temperature. However the increase in RAP content beyond 20 % increased the mixture stiffness and strength resulting in rutting resistance (McDaniel et al., 2007; Xiao et al., 2007 and Li et al., 2008). Some researchers have found that the higher mixture stiffness was obtained for asphalt mixes with RAP than mixes without RAP (Servas et al., 1987 and Huang et al., 2004). The indirect tensile strength of asphalt mixes with RAP was found to be satisfactory or higher when compared with asphalt mixes without RAP (Little et al., 1980; McDaniel et al., 2000 and Huang et al., 2004). Kandhal et al. (1995) found lower value of indirect tensile strength for mixes containing RAP than mixes without RAP. In general, a recycled mix has a greater resistance to rutting than virgin mix (Servas et al., 1987; Kandhal et al., 1995; Little et al., 1980 and Malpass G.A., 2002).

The fatigue performance of recycled mixes is observed to be lower with respect to the virgin mixes (McDaniel et al., 2000 and X. Shu et al., 2007), although other studies suggest that it could be similar (Little et al., 1980 and Whitcomb et al., 1980). It can be noted from the above discussions that the performance of recycled mixes in fatigue, rutting or stiffness could be better, worse, or similar compared to the corresponding virgin mix.

2.4 Mix Design Concept with RAP

This section provides an overview of the mixture design methods that are being used in HMA incorporating RAP. When the mix design incorporates RAP the mix design process is very much the same regardless the inclusion of the RAP. The differences include the following:

- The RAP aggregate is treated like another stockpile for blending and weighting.
- The RAP aggregate specific gravity must be estimated.
- The weight of the binder and moisture if available in the RAP must be accounted for when batching aggregates.
- The total asphalt content is reduced to compensate for the binder provided by the RAP.
- A change in the virgin binder grade may be needed depending on the amount of RAP, final binder grade, and RAP binder stiffness.

2.4.1 Marshal Mix Design Method

The Marshall Mix design method for HMA containing RAP generally includes the following procedure for recycled asphalt mix design.

1. Determination of RAP aggregate gradation.
2. Determination of RAP bitumen content and bitumen binder viscosity.
3. Blending of RAP and virgin aggregate to obtain a gradation which meets specifications.
4. Approximation of the asphalt demand of the combined aggregates.

5. Estimation of the percent of virgin bitumen in the mix.

6. Selection of the grade of the virgin bitumen.

7. Performing trial mix design using the Marshall method.

2.4.2 Superpave Mix Design Method

The Superpave mix design procedure for HMA containing RAP generally follows the same mix design requirements as mixes without RAP. The process of binder selection is further split into three tiers, depending on the RAP content:

1. Less than 20 % RAP

The binder grade should remain the same as what would be chosen for a mix design using only virgin materials.

2. 20 to 30 % RAP

Using a virgin binder one grade lower for both the high and low temperature.

3. More than 30 % RAP

A blending chart for high and low temperatures should be used to select the grade for the new binder.

2.5 Difference between Laboratory and Plant mixing

Laboratory mix design is a simulation of the actual HMA manufacturing and construction as good as possible. From laboratory mix design prediction (with some certainty) can be made of what type of mix design is best for the particular application in question and how it will perform. It is important to realize however that mix design has its limitations. There are differences between laboratory and field conditions. Table 2.1 summarizes some of those differences. Certainly, a small laboratory setup consisting of several 100 - 150 mm samples, a compaction machine and a couple of testing devices cannot fully mimic actual manufacturing, construction and performance conditions. However, despite limitations, mix design procedures can be a cost effective tool that is useful in making mix design decisions.

Table 2.1: Comparison of Laboratory and field conditions (Hot Mix Asphalt Paving Handbook, 2000)

Laboratory Conditions	**Field Conditions**
Binders	**Binders**
More aging because of heating for various of time in open containers.	Binders stored in closed tanks and minimal aging and hardening occur in storage.
Aging is simulated using the RTFOT or PAV. All of these methods are only rough simulations of actual asphalt binder aging.	Aging is much more complex especially after construction when it is highly dependent upon construction quality and the environment.
After mixing the loose mix is generally aged to allow for asphalt binder absorption and in increase in viscosity.	After mixing the loose mix can be immediately transported to the construction site or can be placed in storage silos for up to a week.
Aggregates	**Aggregates**
Gradation is carefully measured and controlled.	During the manufacturing process aggregate gradation will change slightly as it passes through the cold feed bins, aggregate dryer and drum mixer/pug mill.
Aggregate used is completely dry.	Even after drying, aggregates typically contains between 0.1 - 0.5 % by weight.
Fines are retained during the mixing process.	Some fines are collected in the mix plant bag house.
Oven heating of the aggregate usually results in uniform heating of the coarse and fine aggregate.	In a drum plant there is often a distinct temperature difference between the coarse and fine aggregate.

(Continued from Table 2.1)

Laboratory Conditions	Field Conditions
Mixing Process	**Mixing Process**
The mixing process occurs on essentially unaged asphalt binder for the Marshall method. The Superpave method roughly simulates short-term aging using the RTFOT.	The mixing process can substantially age the asphalt binder. A mixing time of 45 seconds can increase asphalt binder viscosity by up to 4 times.
Compaction	**Compaction**
Compaction uses a laboratory device and a small cylindrical sample of HMA. This combination attempts to simulate the particle orientation achieved by field compaction with rollers.	Particle orientation and compactive effort can vary widely depending upon roller variables and the environment (e.g., temperature, wind speed).
Compaction is relatively quick (< 5 minutes) and thus occurs at an almost constant temperature.	Compaction can take a significant amount of time (30 minutes or more in some cases) and thus occurs over a wide range of mix temperatures.
Compaction occurs against a solid foundation.	Compaction can occur against a range of foundations (solid, soft).

2.6 Types of Asphalt Production Plant

Currently two basic types of HMA plants are in use: batch and drum mix plants. Based on the direction of the flow of the materials and direction of the flame, drum mix plants are further divided into parallel flow and counter-flow drum mixes. The above given types of asphalt plants serve the same ultimate purpose. They, however, differ in operation and flow of materials as described in the following sections.

2.6.1 Batch plants

In a batch type plant, the raw aggregate is batched and heated up to the required temperature. After it has been dried the hot aggregate is screened and batched into separate bins. The hot aggregate is discharged into a mixer, known as pug mill where filler and binder are added. The blend is mixed and discharged into the delivery vehicles or into a weighting and collecting hopper.

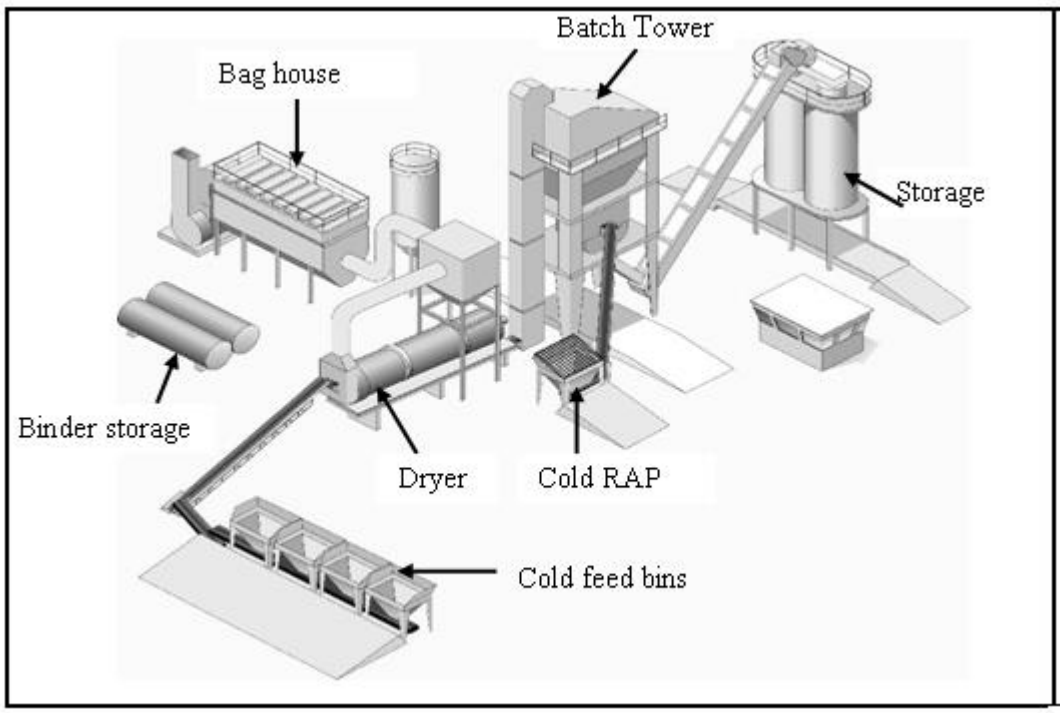

Figure 2.2: Major components of batch plants (Hot Mix Asphalt Paving Handbook, 2000)

2.6.2 Drum mix plants

In drum mix plants mostly the mixing is done in the same drum that is used to dry and heat the aggregate. Such type of plants does not resize the material or use a screen deck, hot bins, and a pug mill. Drum mix plants have higher production rates and ability to use higher percentages of RAP than batch plants. When RAP is introduced into a drum mix plant, it is heated both by aggregate heat transfer and by the exhaust gases of the burner. This dual heating action allows the drum mix plant to run at higher RAP percentages than unmodified batch mix plants. RAP is usually introduced by a conveyer near the centre of the drum mixer (except for the double barrel style plant).

In a parallel flow drum mix plant (Figure 2.3), the aggregate flow is in the direction of the exhaust gas or away from the burner. Whereas, in counter flow drum mix (Figure 2.4) the aggregate flow is against the direction of the exhaust gases or towards the burner.

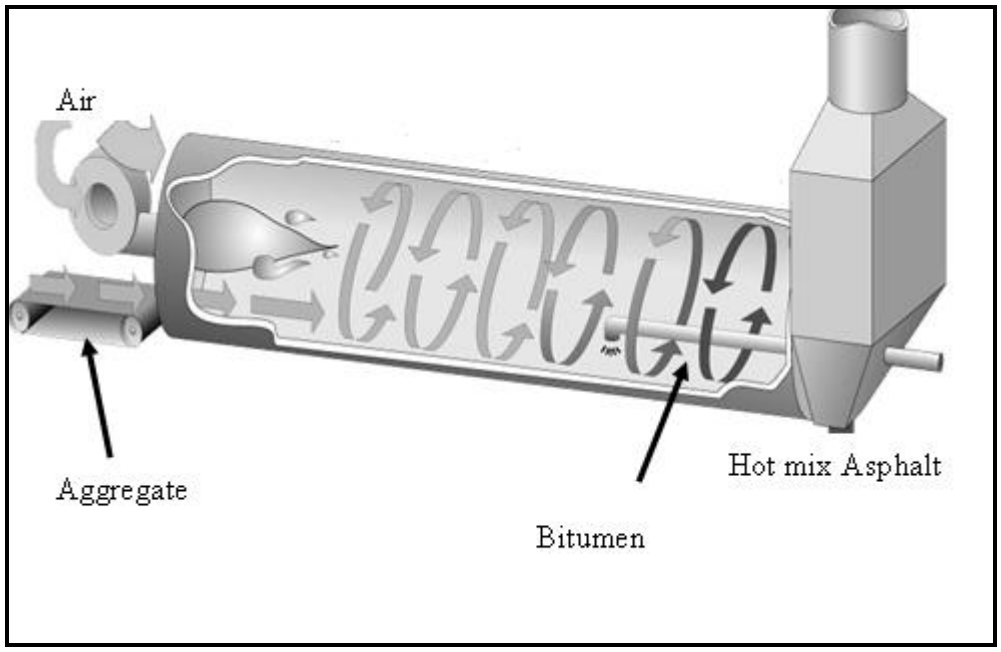

Figure 2.3: Parallel drum asphalt mixer (Hot Mix Asphalt Paving Handbook, 2000)

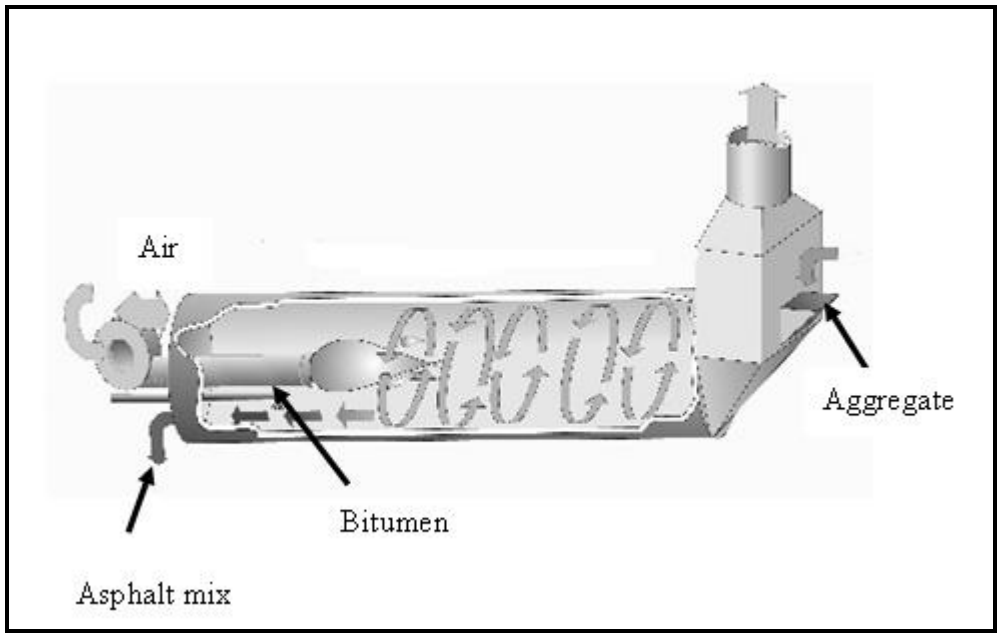

Figure 2.4: Counter Flow drum mixer (Hot Mix Asphalt Paving Handbook, 2000)

Another type of drum mix plant is a double barrel or double drum mixer (Figure 2.5), which consists of basically two drums. The aggregate is discharged into the stationary outer drum where it is mixed with the asphalt binder, RAP and filler material by paddles attached to the outside of the inner drum. Double drum mixing plants result in lower emissions and have better heat transfer ability. The double drum mixers use the entire drum length for drying. Others systems have to utilize one end of the drum as the mixing chamber, making the drying portion shorter. They then have to use higher temperatures to compensate for the shortened drying chamber. Double drums longer drying times enables to dry more efficiently.

In double drum mixer, the RAP material enters directly into the mixing chamber and does not contact with the hot gas stream of the dryer. This is an important advantage minimizing emissions.

Another difference of double drum mixers from other types of drum mix plants, oxidation in the mixing chamber is minimized. As the RAP heats in the mixing chamber by contact with the hot aggregate, moisture in the RAP is driven off as steam. The steam atmosphere in the mixing chamber allows

very little free oxygen and gas movement, which helps to minimize oxidation during mixing.

After the drum mixer portion, all types of drum mix plants are identical in operation. Since these plants operate in a continuous manner, the asphalt mixture must be transported and stored. The mixture is transported from the mixing portion of the drum mixer by a bucket elevator into a silo.

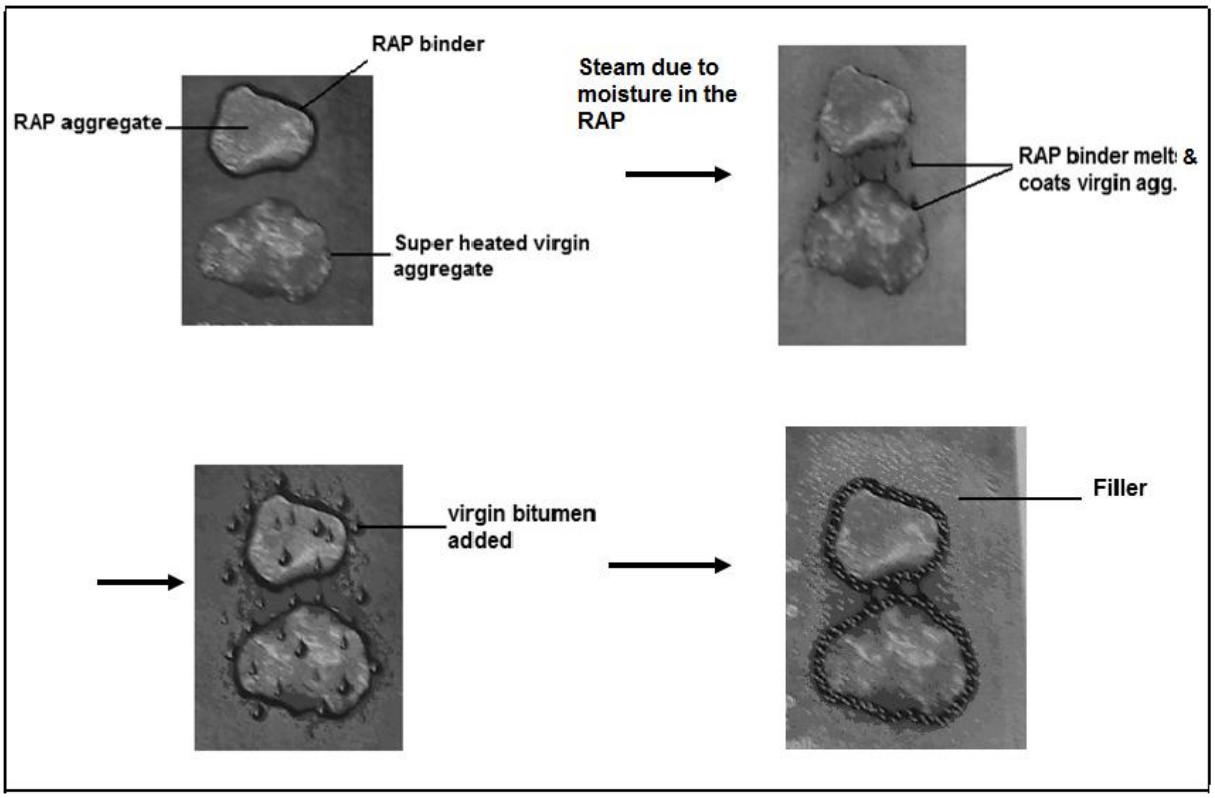

Figure 2.5: Mixing sequence in double drum mix plants

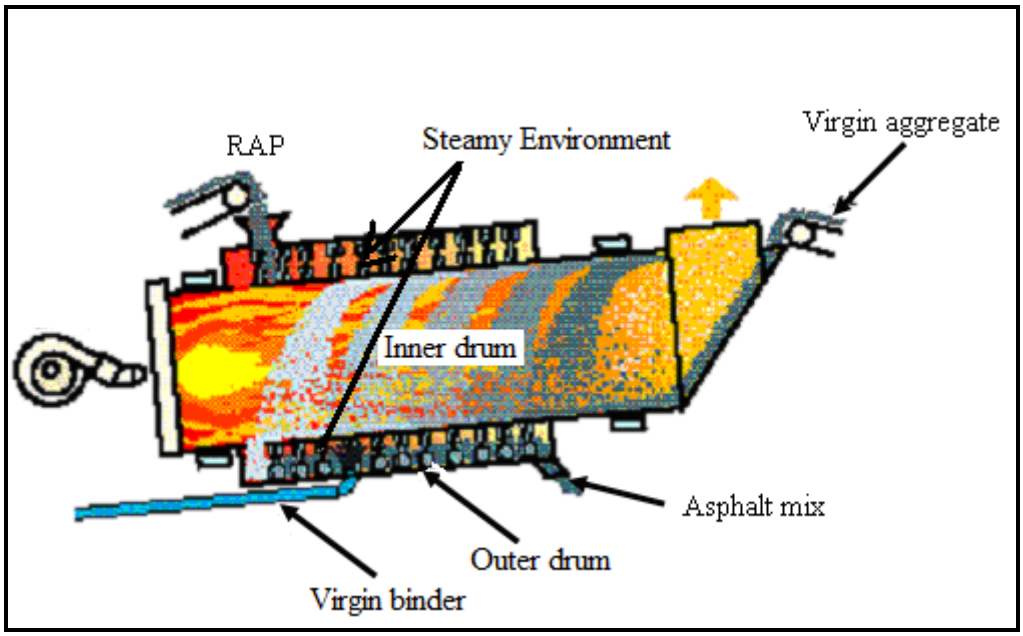

Figure 2.6: Double drum plant (Astec, INC)

From the aforementioned different types of asphalt mix plants, it can be learned that the double drum mix plant operates different from other drum mixers and the normally used batch plants with or without parallel drum for RAP in the Netherlands.

Therefore, the current laboratory mix design method not only differ when compared to the mixing process in parallel drum mix plants, but also does not simulate the mixing process in the double drum mixer.

Chapter 3 Test methods, testing program and materials

This chapter provides detailed information on the test methods and procedures. In addition, it provides information on the materials used during the research and their properties.

From the literature review, it was found that different types of asphalt plants are used in production of HMA with RAP. The existing laboratory mix design procedures are quite different from the mixing methods employed in the parallel and double drum mixers. The development of laboratory mix design procedure requires identifying the properties of both virgin and RAP materials and simulating the actual plant mixing processes. In order to compare the effect of different laboratory mixing methods on the mixture performance properties mechanical tests (resilient modulus, water sensitivity and permanent deformation) were conducted. The summary and detail description of the test methods, the testing program and materials used in this study will be presented in the following sections.

3.1 Test Methods

Different tests were done in order to identify the properties of the virgin and RAP materials. Performance tests also conducted in order to investigate the effect of different mixing methods on mechanical properties of the asphalt mixture. The following test methods were implemented during the research:

- Extraction and Recovery of binder and aggregate from RAP to identify the rheological properties of the binders and gradation of RAP aggregate.
- Empirical rheological testing program for both recovered RAP and virgin binders.
- X-ray Fluorescence Spectroscopy (XRF) to analyze the effect of high temperature on the mineralogical compositions of the aggregates and sands.

- Cyclic Indirect Tensile Test (ITT) to determine the resilient modulus values at different temperatures.
- Indirect Tensile Strength test to indicate the strength level and moisture sensitivity of the mixture.
- Triaxial cyclic compression test with confinement to investigate the effect of mixing methods on permanent deformation resistance of the asphalt mixture.

3.1.1 Empirical Rheological testing program

Two types of empirical rheological tests were done on the virgin and recovered binders. The penetration tests for both recovered and virgin binders were done according to EN1426 “Bitumen and bituminous binders– Determination of needle penetration” at 25 ^{o}C. The softening point was determined for both recovered and virgin binder according to EN 1427 “Bitumen and bituminous binders – Determination of softening point by Ring and Ball method”.

3.1.2 Extraction of RAP binder and aggregate

The determination of the asphalt content, rheological properties and aggregate properties are important in the mix design process of HMA with RAP. In this study, the solvent extraction method was used to separate RAP binder and aggregate for further testing. During the extraction process approximately 2 kg oven dried sample of RAP mixture was put in the extraction apparatus and the binder was dissolved from the mixture by using Dichloromethane (Methylene Chloride) solvent. During the extraction process, the binder was separated from aggregates in the RAP. The extraction apparatus was fitted with different sieve sizes so that during the washing process the aggregate and sand fractions retained at each sieve size for further gradation. The solution of the binder with solvent, insoluble filler and dust were separated in the centrifuge apparatus. The insoluble materials separated from the binder solvent solution retained in the filter ring in the bowl. The washing process was continued approximately for 20 minutes until the solvent that comes from the sieves becomes colorless. Then the solution

of the binder and the solvent collected for further recovering process. After the extraction process the aggregate, sands, filler and dust were dried and weighted to determine the particle size distribution of the materials in the RAP. The extraction was done according to EN 12697-1 “Test methods for hit mix asphalt - Part 1: Soluble binder content”. Figure 3.1 shows the centrifugal extraction apparatus used in this study.

Figure 3.1: InfraTest extraction apparatus

3.1.3 Recovery of the binder

The purpose of the binder recovery process was to separate the binder from the dichloromethane solvent for further binder testing. The bitumen was recovered with a rotary evaporator distillation apparatus. The apparatus incorporates a rotating evaporating flask, which can be operated under vacuum. It has an oil bath capable of maintaining temperatures of up to

150 ^{o}C. During the distillation process cold water passes through the condenser so that the evaporated solvent is collected in the receiving flask. The distillation process continues until the evaporation of solvent is completed. The recovery of the binder from the solvent was performed according to EN 12697-3 “Test methods for hot mix asphalt - Part 3: Bitumen recovery: Rotary evaporator”. Figure 3.2 shows the rotary evaporator apparatus used in this study.

Figure 3.2: rotary evaporator binder recovery apparatus

3.1.4 Determination of Specific gravity of particles

The specific gravity of the fine and course materials were determined using an ultrapycnometer device. The device measured the true volume of the solid materials by employing ‘Archimedes’ principle of gas displacement. In the test helium gas was used as displacing fluid due to its small atomic dimension it can enter a pore dimension of 2 X 10 $^{-10}$ m, which enables to determine to the maximum accuracy. During the testing a known amount of material was put to the device.

3.1.5 Determination of Bulk density of the specimen

The bulk density of the compacted specimens was determined according to EN 12697-6 “Test methods for hot mix asphalt – Part 6: Determination of the bulk density of bituminous specimens”. The mass of the specimen was determined by measuring the dry mass of the specimen in air and the volume of the specimen determined by measuring the mass of the specimen under water and the mass of saturated surface dry specimen. The bulk density of the specimen was computed using eq. 3.1.

$$\rho_{bulk} = \left(\frac{m_{dry}}{m_{surface\,dry} - m_{under\,water}} \right) * \rho_{water} \qquad \text{(Eq. 3.1)}$$

3.1.6 Theoretical Maximum density of the specimen

The maximum density of the specimen is the mass per volume of the mix without air voids. The determination of the maximum density is important for determination of the void content of the asphalt mix. In this study, the maximum densities of the specimens were determined according to EN-12697-5 “Test methods for hot mix asphalt – Part 5: Determination of the maximum density”.

3.1.7 X-ray Fluorescence Spectroscopy (XRF)

To investigate the effect of a high temperature on the mineralogical composition of the virgin aggregate an X- ray Fluorescence Spectroscopy (XRF) instrument was used. The instrument works by exposing the sample to be measured to a beam of X-rays. The atoms of the sample absorb energy from the X-rays are become temporarily excited and then emit secondary X-rays. Each chemical element emits x-rays at a unique energy. By measuring the intensity and characteristic energy of the emitted X-rays, an XRF analyser can provide qualitative and quantitative analysis regarding the composition of the material being tested.

3.1.8 Pre-treatment of specimens before testing

During the testing program, specimens were pre-treated in such a way that their geometric shape should be consistent and in accordance of the

standards. Therefore, specimens were sawed and polished to the required dimensions. Table 3.1 shows the specimen pre-treatment types done before commencing the tests. Figure 3.3 shows the specimen cutting machine used and Figure 3.4 shows specimens before and after cutting.

Type of test	Specimen shape	Treatment type	Height of specimen (mm)	
			Before treatment	After treatment
Resilient modulus	Cylindrical	Sawing	77	50
Indirect tensile strength	Cylindrical	Sawing	77	50
Permanent deformation	Cylindrical	Sawing and polishing	100	80

Table 3.1: Types of specimens pretreatments

Figure 3.3: Specimen cutting process

Figure 3.4: Specimens after and before cutting

3.1.9 Cyclic Indirect Tensile Resilient Modulus Test

The cyclic indirect tension test is used for measuring the stiffness (resilient modulus - Mr) of a mix. In this test, 5 pulses haversine loading with 3000 ms pulse repetition period and a rest period was applied. The total recoverable diametrical strain was measured from an axis perpendicular to the applied load. Before application of test loading pulses, preconditioning loading pulses were applied to make sure that the loading strip was seated properly to the specimen before the test was performed. The natures of the preconditioning loading pulses were similar to the testing load pulses. The amplitude of the load for the test was less than 10 % of the estimated tensile strength to prevent damage to the specimen. In this research the 5 pulse indirect tensile modulus test was performed according EN 12697-26 “Test methods for hot mix asphalt – Part 26: Stiffness”.

The testing was conducted in a temperature controlled chamber for maintaining constant temperature during the test. Cylinder shaped specimens with 100 mm diameter and 50 mm thickness were used. During the testing, the loading was applied along the vertical diameter of the specimen and the

resulting deformations along the horizontal diameters were measured. Figure 3.5 shows the test setup.

Figure 3.5: Cyclic Indirect tension test setup

The resilient modulus was calculated using the following formula:

$$M_r = \frac{F(0.27+\upsilon)}{l.\Delta d} \qquad \text{(Eq. 3.2)}$$

Where,

F = maximum applied load [N]

υ = Poisson's ratio

l = thickness of the specimen [mm]

Δd = total recoverable (resilient) horizontal deformation [mm]

Mr = resilient modulus [MPa]

With this test setup the determination of Poisson's Ratio was not possible. Poisson's ratio values determined in previous researchers in Road and Railway Engineering group, TU Delft were assumed for different

temperatures during the testing. Table 3.2 shows the values of Poisson's ratio used.

Temperature (^{o}C)	Poisson's Ratio
5	0.22
10	0.24
15	0.27
23	0.32
35	0.4

Table 3.2: Typical values of Poisson's ratio

The tests were conducted at five temperatures (5, 10, 15, 23 and 35 ^{o}C) and with six different frequencies (16, 12, 8, 4, 2 and 1 Hz) at each temperature. The stiffness values obtained using eq. 3.2 were used to construct stiffness master curve using superposition principle. The frequency of the haversine loading pulse was defined by the reciprocal value of the pulse width (f = 1/T).

3.1.10 Indirect Tensile Strength Retained (ITSR)

Moisture susceptibility testing is used to evaluate asphalt the mix potential for stripping. Stripping is defined as loss of bond between binder and aggregate in the presence of water. Moisture susceptibility testing was performed in accordance with EN 12697-12 "Test methods for hot mix asphalt – Part 12: Determination of the water sensitivity of bituminous specimens". The test was done in a cylindrical specimen with 100 mm in diameter and 50 mm thickness. The test specimen was brought to the specified test temperature and placed in the compression testing machine between the loading strips, and loaded diametrically along the direction of the cylinder axis with a constant speed of displacement 50 mm/minute until it breaks. The indirect tensile strength is the maximum tensile stress calculated from the peak load applied at break and the dimensions of the specimen. For each test specimens the indirect tensile strength (ITS) was calculated according to the following formula:

$$ITS = \frac{2P}{\pi DH} \qquad \text{Eq. (3.3)}$$

Where:

ITS indirect tensile strength, expressed in [MPa]

P peak load, expressed in [N]

D diameter of the specimen, expressed in [mm]

H height of the specimen, expressed in [mm]

For each test condition a set of 6 cylindrical test specimens were divided into two equally sized subsets (unconditioned and conditioned). Unconditioned set of specimens were maintained dry at room temperature (25 ^{o}C) while the conditioned subset were saturated and stored in water at elevated conditioning temperature of 40 ^{o}C for a period of 68 hr. Both sets of specimens were conditioned to test temperature of 15 ^{o}C for 4 hours in a temperature controlled chamber for maintaining constant temperature prior to testing. Then the indirect tensile strength for each subset was determined. The ratio of the indirect tensile strength of the wet (conditioned) subset compared to that of the dry (unconditioned) subset was determined and expressed in percentage.

$$ITSR = \left(\frac{ITSwet}{ITSdry} \right) * 100 \qquad \text{Eq. (3.4)}$$

Where:

ITS_{wet} indirect tensile strength of wet specimen [MPa]

ITS_{dry} indirect tensile strength of dry specimen [MPa]

ITSR indirect tensile strength ratio [%]

3.1.11 Permanent deformation (Cyclic Triaxial) Testing program

The resistance to permanent deformation test was done using triaxial cyclic compression test setup. The test was done on cylindrical specimens with a diameter of 100 mm and a thickness 80 mm at 40 ^{o}C. During testing specimens were subjected to a static confining pressure, on which a cyclic axial pressure was superimposed. The test load was generated by means of a servo-hydraulic pneumatic actuator and distributed over the specimen by a circular loading plate. To minimize the friction between the loading platens and the test specimen, a latex rubber membrane was applied. The load was applied vertically through the sample and the vertical deformation of the specimen was measured with two axial LVDTs mounted on the specimen and one actuator LVDT. Specimens were covered with a rubber foil to protect a direct contact between the confining water and specimen. Before applications of the actual test loads, specimens were pre-loaded with static loads for 120 seconds. After pre- loading the confining stress was applied for 10 seconds after that the cyclic axial load was applied. Each test was done in three replicates. The permanent deformation test was done according to EN 12697-25 “Test methods for hot mix asphalt – Part 25: Cyclic compression Test method B”. The control and input parameters used in this testing program are summarized in the following Table 3.3.

Control Parameter	Type	Value
Loading pulse	Mechanism	Triaxial Cyclic compression test
	Number of pulses	Variable
	Wave shape	Haversine
	Pulse width	400 ms
	Pulse rest period	600 ms
Pre-loading	Duration	120 s
	Pre loading stress	9 kPa
Loading	Confining stress	50 kPa
	Confining hold time	10 s
	Cyclic vertical stress	400 kPa
Measurement type	Load	Compressive force
	Displacement	Axial displacement
Specimen sizes	Thickness	80 mm
	Diameter	100 mm
Boundary Condition		Friction reduction applied at both ends.
Testing temperature		40 ^{o}C
Failure type		Permanent deformation
Test termination		10000 load cycles
Number of test replicates		3

Table 3.3: Control input parameters for triaxial cyclic compression test

Figure 3.6: Cyclic Triaxial test setup

3.2 Materials

In this section the properties of the materials used in this study are presented. The RAP materials were obtained from GEBR VAN DER LEE b.v., Lelystad. The samples were evaluated in terms of homogeneity, aggregate gradation and aggregate specific gravity. The virgin aggregate, sand and filler used in the study were also acquired from GEBR VAN DER LEE b.v. Recovered binder properties, virgin aggregate and asphalt binder used in the study are presented and explained.

3.2.1 RAP binder content and aggregate gradations

RAP samples were obtained from (GEBR VAN DER LEE b.v.) asphalt plant stockpiles in Lelystad. The RAP stockpiles have sizes ranging between 0 – 20 mm. The required amount of the RAP material was obtained from the

middle height of the stockpile after removing the first 150 mm top layer in order to reduce the effects of particle segregation. The RAP binder properties and the gradation of the RAP aggregate were determined after extraction and recovery processes. Five samples were taken for the determination of the RAP properties. The moisture content of the RAP was also determined during the testing. Results of the moisture content are given Table 3.4.

Sample	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Average	Standard Deviation
MC (%)	3.0	2.7	3.0	3.2	3.2	3.0	0.20

Table 3.4: Moisture content of the RAP

The binder content of each RAP sample was determined with EN 12697-1 “Test methods for hit mix asphalt - Part 1: Soluble binder content by solvent extraction method”. Five samples were used for the determination of the binder content. The results of this testing are given in Table 3.5.

	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Average	Standard Deviation
Pb (%) m/m “in”	4.1	4.1	3.9	4.3	4.4	4.18	0.19

Table 3.5: RAP binder content percentage by weight after extraction

The determination of the RAP aggregate gradation was done according EN 933-1”Determination of particle size distribution Sieving method”. The individual particle size fractions of the aggregates separated using a range of sieve sizes and the relative percentages of each size fraction determined after extraction process. The RAP aggregate gradations will be used in the design of the asphalt mixture containing RAP. Results of the RAP gradations are given in Table 3.6.

Sieve Size (mm)	Cumulative Percentage Retained						Standard Deviation (%)
	Sample 1 (%)	Sample 2 (%)	Sample 3 (%)	Sample 4 (%)	Sample 5 (%)	Average (%)	
C22.4	3.2	0.0	1.5	1.1	3.0	1.8	1.3
C16	10.7	5.2	11.2	6.2	11.1	8.9	2.9
C11.2	18.9	16.8	21.7	15.8	19.1	18.5	2.3
C 8	28.3	27.9	29.6	25.0	29.4	28.1	1.9
C 5.6	35.4	34.8	39.6	35.3	35.0	36.0	2.0
2	50.6	50.2	52.0	50.0	50.6	50.7	0.8
0.5	60.3	59.8	62.0	60.2	60.6	60.6	0.8
0.18	82.4	82.0	83.0	81.6	82.9	82.4	0.6
0.063	92.3	92.3	92.7	92.0	92.6	92.4	0.3

Table 3.6: Gradation of RAP aggregate (after extraction)

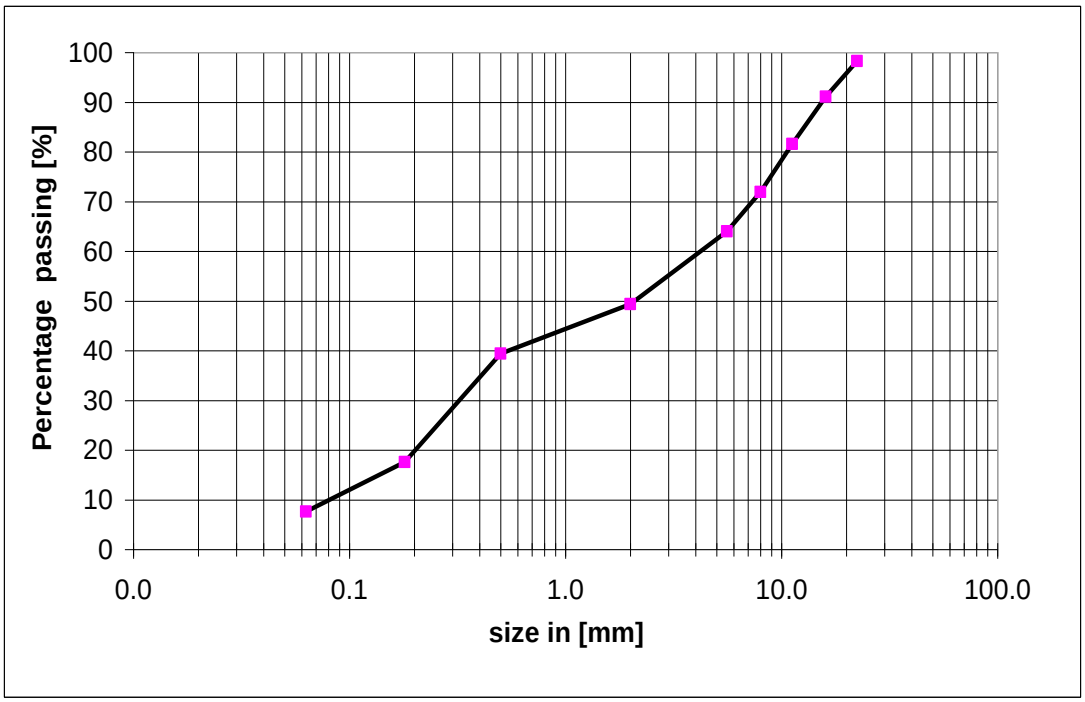

Figure 3.7: Gradation curve of RAP aggregate (after extraction)

3.2.2 RAP binder penetration and softening point

The empirical tests i.e. the penetration and softening point were done to determine the binder viscosity characteristics on a recovered RAP binder. The penetration test was done according to EN1426 “Bitumen and bituminous binders - Determination of needle penetration” at 25 ^{o}C. The softening point was determined for both recovered and virgin binder according to EN 1427 “Bitumen and bituminous binders - Determination of softening point by Ring and Ball method. The results are summarized in Tables 3.7 and 3.8.

Penetration (0.1 mm)	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Average
Pen.1 (0.1 mm)	29.0	29.0	29.0	29.0	29.0	29.0
Pen.2 (0.1 mm)	29.0	29.0	29.0	29.0	29.0	29.0
Pen.3 (0.1 mm)	29.0	29.0	29.0	29.0	29.0	29.0
Avg. Pen.(0.1 mm)	29.0	29.0	29.0	29.0	29.0	29.0

Table 3.7: RAP binder penetration at 25 ^{o}C

Ring and Ball Temperature (^{0}C)	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Average
Left Ball (^{0}C)	58.6	58.6	58.6	58.6	58.6	
Right Ball (^{0}C)	58.3	58.3	58.3	58.3	58.3	
Average	58.5	58.5	58.5	58.5	58.5	58.5

Table 3.8: Ring and Ball temperature of RAP binder in ^{o}C

3.2.3 RAP aggregate specific gravity

The maximum specific gravity of the RAP mixture without air voids determined by using ultrapycnometer density measuring device.

Theoretical max. spec. gravity of RAP mixture (Gmm)	2.495

Table 3.9: Specific gravity of RAP aggregate

3.2.4 Virgin material properties

In this section, the properties of the virgin material used in this research will be presented. First, the physical properties of the virgin aggregates, sand, and filler are presented followed by the empirical rheological properties of the virgin asphalt binders.

The virgin aggregate used in this study consisted entirely of crushed Norwegian granite from GEBR VAN DER LEE b.v., Lelystad. The required amount of the aggregates in each fraction was obtained from different stockpiles. The sampled aggregates were transported to the laboratory of Road and Railways section, TU Delft. The samples were oven dried to a constant mass and sieved into the following individual size fractions; 22 mm, 16 mm, 11.2 mm, 8 mm, 5.6 mm, 2 mm and 0.063 mm. Aggregate size fractions separated during the sieving operation were then stored in individual containers until used for further physical property testing or recombined by mass batching in order to satisfy a specified gradation for asphalt mixture sample fabrication. This method of blending is time and labour intensive, but it allows for strict control and exact replication of an asphalt mixture's aggregate gradation. Table 3.10 shows the specific gravity of each aggregate fraction.

Fraction [mm]	2/5.6	5.6/8	8/11.2	11.2/16	16/22.4
Bulk specific gravity	2.799	2.755	3.140	2.748	2.782

Table 3.10: Bulk specific gravity of Norwegian granite

From Table 3.10 it can be seen that the bulk specific gravity value of the 8/11.2 fraction is about 15 % higher than the rest of the fraction. The test was repeated three times and the result of the bulk specific gravity of this fraction found still 15 % higher than the other fractions.

The sand and filler material was also obtained from GEBR VAN DER LEE b.v., Lelystad. The type of sand used in this study was a river sand fraction in the range from 0.063 - 2 mm. The sampled sand was transported to the laboratory of Road and Railways Engineering section, TU Delft where it was oven dried to a constant mass for further use.

Wigras 40 k filler with size less than 0.063 mm was used. The specific gravity of the sand and filler are shown in Table 3.11.

	Bulk specific gravity	Fraction [mm]
River sand	2.655	0.063 - 2
Filler (Wigras 40 k)	2.641	< 0.063

Table 3.11: River sand specific gravity

Penetration grade virgin binder 70/100 was used in this study. The binder was a product of Q8 (Kuwait Petroleum B.V.). The properties of the virgin binder are shown in Table 3.12.

Binder Grade	Penetration [0.1 mm]	Softening Point in ^{0}C	Penetration Index	Specific gravity
70/100	89	45.8	-0.91	1.028

Table 3.12: Virgin asphalt binder properties

Chapter 4 Mix Design

4.1 Introduction

This chapter describes the methodology followed in the mix design process of asphalt mixtures containing 40 and 50 % RAP content. A base course mix STAC 0/22 (Stone Asphalt Concrete) with 40 and 50 % RAP was designed based on Dutch, RAW 2005 Standard specification. This section also contains information about the aggregate gradation of the mix and volumetric properties. The first step of the mix design procedure was the determination of the grading of the mixture based on the specification requirement, then the demand of the new virgin binder was determined based on the percentage of the RAP, the amount of RAP binder and total binder requirement of the mix based on the specification. The last step was the determination of the mixing temperature and mixing time for different mixing methods and checking the volumetric properties according to standard specification.

4.2 Determination of combined aggregate gradation

Once the RAP aggregate gradation has been determined, the next step was the blending of the RAP aggregate with the virgin aggregates to meet the overall mixture gradation requirements. The blending was done for two percentages of RAP (40 and 50 %). The blending process was done by treating the RAP aggregate as stockpile aggregate. Using an Excel spreadsheet the amount on new virgin material to be added was determined for each percentage of RAP material so that the gradation of the blended mixture will meet the RAW 2005 specification for base course mix (STAC 0/22). In addition, the final blend selected must meet the required volumetric properties (i.e. VMA, VFB and air void). Table 4.1 shows RAW 2005 gradation requirements for base course mix - STAC (0/22).

Sieve opening (mm)	Cumulative % retained in each sieve		
	Target	Min.	Max.
22.4	1.2	0	6
16.0	13.5		
11.2	20	15	40
8.0	40.2		
5.6	47.9		
2.0	57	54.0	60.0
0.063	94.0	92.0	94.0
< 0.063	6.0		

Table 4.1: Gradation requirement for STAC (0/22) (RAW 2005)

Based on the RAP aggregate gradation, the amount and size of virgin material to be added in both mix types i.e. STAC (0/22) with 40 and 50 % RAP was determined. Table 4.2 shows the RAP gradation.

Sieve (mm)	C22.4	C16	C11.2	C8	C5.6	2.0	0.5	0.18	0.063
Retained (%)	1.76	8.87	18.45	28.06	36.02	50.66	60.58	82.38	92.37

Table 4.2: RAP aggregate gradation (after extraction)

The final gradation of the mixture with 40 and 50 % RAP content are summarized in Tables 4.3 and 4.4, the plot of gradation curve also presents in Figure 4.1.

Sieve (mm)	% retained in each sieve		
	50 % RAP (% m/m)	Virgin material (% m/m)	Total (% m/m)
> C22.4	0.88		0.88
C22.4 - C16	3.56	9.06	12.62
C16 - C11.2	4.79	1.71	6.50
C11.2 - C8	4.80	15.40	20.20
C8 - C5.6	3.98	3.72	7.70
C5.6 - C2	7.32	1.78	9.10
River Sand (0/2)	20.86	16.14	37.00
< 0.063	3.81	2.19	6.00
Total (%)	50.00	50.00	100.00

Table 4.3: Gradation of STAC (0/22) with 50 % RAP

Sieve (mm)	% retained in each sieve		
	40 % RAP (% m/m)	Virgin material (% m/m)	Total (% m/m)
> C22.4	0.70		0.70
C22.4 - C16	2.84	9.96	12.80
C16 - C11.2	3.83	2.67	6.50
C11.2 - C8	3.84	16.36	20.20
C8 - C5.6	3.19	4.51	7.70
C5.6 - C2	5.86	3.24	9.10
River Sand (0/2)	16.69	20.31	37.00
< 0.063	3.05	2.95	6.00
Total (%)	40.00	60.00	100.00

Table 4.4: Gradation of STAC (0/22) with 40 % RAP

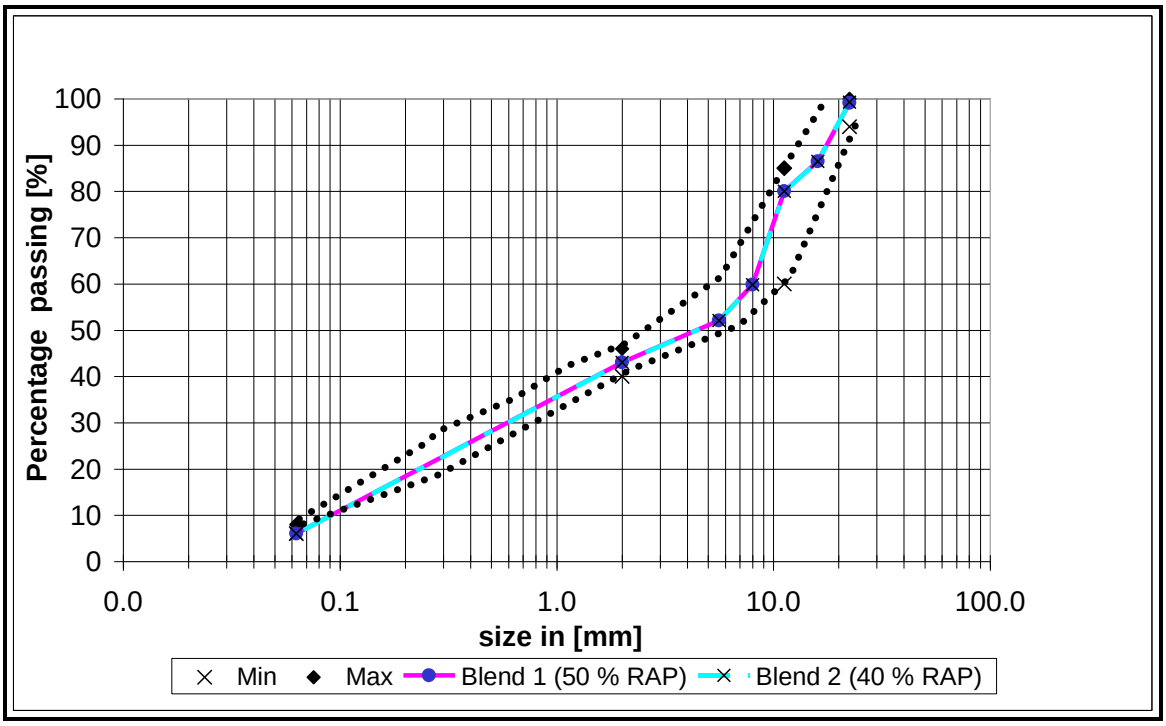

Figure 4.1: Final Gradation of the blended aggregate (Virgin & RAP)

4.3 Determination of new binder to be added

The selection of the new binder type depends on factors like; properties of the RAP binder, amount of RAP and the specification requirement of the final mixture (which depends on climate condition and traffic classes). As it was explained in the previous chapter the properties of the RAP binder was determined after the extraction and recovery process. Table 4.5 shows the percentage of binder, penetration and ring and ball temperature of the RAP binder.

Binder content (Pb) % “in”	4.2
Penetration (0.1 mm) at 25 ^{o}C	29
Ring and ball temperature in ^{o}C	58.5

Table 4.5: Properties of RAP binder

Table 4.6 presents the binder content and penetration requirement for a base course mix according to Dutch RAW 2005 standard.

Type of Asphalt Mix- STAC (0/22)	Requirement
Binder content - Pb (%) "on"	4.0 – 5.0
Penetration (0.1 mm) at 25 ^{o}C	40 - 60

Table 4.6: Binder properties requirement for STAC (0/22) (RAW 2005)

The combined penetration and softening point of the virgin and the RAP binder was determine using eq. 4.1, as described in the European Standard (EN 13108-1). In this study, new softer binder 70/100 penetration grade was selected. Table 4.7 shows the combined penetration of the total blended binder (virgin and RAP) obtained using eq. 4.1. From Table 4.7 it was observed that the penetration of the blended binder met the RAW 2005 binder grade requirement (Table 4.6).

$$a.\log pen_{RAP} + b.\log pen_{NEW} = (a+b).\log pen_{mix} \quad \text{(Eq. 4.1)}$$

Where a= % of RAP

b= % of Virgin material

a+b=1

No.	% of RAP	% of Virgin material	Pen. of RAP binder. [0.1 mm]	Pen. of New binder [0.1 mm]	Pen. mix. [0.1 mm]
1	50	50	29	89	50.8
2	40	60	29	89	56.83

Table 4.7: Blended binder properties

Once the grade of the virgin binder was selected the next step was the determination of amount of the new virgin binder to be added. This depends on the binder content of the RAP and the total binder requirement of the asphalt mix according to the specification. Table 4.8 shows the percentage of

new binder added for 40 and 50 % RAP, in order to have total binder content of 4.5 % (m/m “on”) (Table 4.6).

RAP Content (%)	RAP binder content (P_{bRAP}) (% m/m) “in” 4.2 %	New binder to Added ($P_{b\ NEW}$) (%) (m/m “in”)	Total Binder (%)(m/m “in”)
40 %	0.40*4.2=1.7	2.6	4.3
50 %	0.5*4.2=2.1	2.2	4.3

Table 4.8: Binder content

4.4 Determination of the specific gravity

In the Mix design the volume of asphalt binder and aggregates necessary to produce a mixture with the desired properties are determined. However, since weight measurements are much easier, the measured weighted then converted to volume by using specific gravities. So proper determination of specific gravity of the virgin and RAP aggregate is important in the mix design. The following section describes the methods applied in determination of specific gravity of each components of the mixture.

4.4.1 Bulk specific gravity of aggregate (G_{sb})

The aggregate consists of separate fractions of coarse and fine aggregates, RAP and mineral filler all having different specific gravities. The total bulk specific gravity for the blend is calculated using the following formula:

$$G_{sb} = \frac{(P_1 + P_2 + P_3 + P_4)}{\left(\frac{P_1}{G_1} + \frac{P_2}{G_2} + \frac{P_3}{G_3} + \frac{P_4}{G_4}\right)} \qquad \text{(Eq. 4.2)}$$

Where,

$G_{sb} =$ Combined bulk specific gravity of the aggregate blend including RAP aggregate.

$P_1, P_2, P_3 and P_4 =$ Percentage of different aggregate types the mix.

$G_1, G_2, G_3 =$ Bulk specific gravity of the aggregate types in the mix.

The use of the above formula for the determination of the combined bulk specific gravity requires the determination of the specific gravities of each components of the mix i.e. course aggregate fractions, sand, filler and RAP aggregates. The bulk specific gravity of the virgin aggregate is determined in an ultrapycnometer test as discussed in chapter 3.

For the determination of the bulk specific gravity of the RAP aggregate it is necessary to know the maximum theoretical specific gravity of the RAP mixture and absorption of RAP aggregate. Table 4.9 shows the specific gravity of different fractions of aggregate, sand, filler, binder and RAP used in the mix.

Aggregate fractions – Bulk Specific gravity					
Fraction [mm]	2/5.6	5.6/8	8/11.2	11.2/16	16/22.4
Bulk specific gravity	2.799	2.755	3.140	2.748	2.782
River Sand (0/2)					
Fraction [mm]	0/2				
Bulk specific gravity	2.655				
Filler – Wigras 60 k					
Fraction [mm]	< 0.063				
Specific gravity	2.641				
New virgin binder (Specific gravity)	1.028				
RAP binder (Specific gravity)	1.035				
Maximum spec. gravity of RAP (Gmm)	2.495				

Table 4.9: Specific gravity of components

The procedure for the determination of the bulk specific gravity of the RAP aggregate will be described in detail in the following section. The bulk specific gravity of the RAP aggregate was determined based on the maximum theoretical specific gravity of the RAP mixture and the absorption of the RAP aggregate. The bulk specific gravity of the RAP aggregate will be determined using the following formula:

$$G_{sb(RAP)} = \frac{G_{se(RAP)}}{\frac{P_{ba(RAP)} * G_{se(RAP)}}{100 * G_{b(RAP)}} + 1} \quad \text{(Eq. 4. 3)}$$

Where:

$G_{sb(RAP)}$ = Bulk specific gravity of RAP aggregate

$P_{ba(RAP)}$ = Absorption of RAP aggregate = 0.3 %

$G_{b(RAP)}$ = RAP binder specific gravity = 1.035

$G_{se(RAP)}$ = Effective specific gravity of RAP aggregate determined by,

$$\frac{100 - P_{b(RAP)}}{\frac{100}{G_{mm(RAP)}} - \frac{P_{b(RAP)}}{G_{b(RAP)}}} \quad \text{(Eq. 4. 4)}$$

$P_{b(RAP)}$ = RAP binder content in = 4.2 %

In Table 4.10 a summary of input parameters is given of the inputs and results obtained from eq. 4.3 and 4.4.

Gmm (theoretical max. spec. gravity) of RAP	2.495
RAP binder content $P_{b(RAP)}$	4.2
Absorption of RAP aggregate (P_{ba})	0.3 %
Specific gravity of RAP binder $Gb_{(RAP)}$	1.035
Effective specific gravity of RAP agg. (Gse)	2.659
Bulk specific gravity of RAP agg. (G_{sb})	2.651

Table 4.10: Summary of specific gravity computation

In Table 4.11 the total combined bulk specific gravity of the aggregate, sand, filler and RAP aggregate computed using eq. 4.2 is given.

	50 % RAP		40 % RAP	
Sieve (mm)	Retained percentage (% m/m)	Bulk spec. gravity	Retained percentage (% m/m)	Bulk spec. gravity
C22.4 - C16	9.06	2.782	9.96	2.782
C16 - C11.2	1.71	2.748	2.67	2.748
C11.2 - C8	15.40	3.140	16.36	3.140
C8 - C5.6	3.72	2.755	4.51	2.755
C5.6 - C2	1.78	2.799	3.24	2.799
River Sand 0/2	16.14	2.655	20.31	2.655
Filler < 0.063	2.19	2.641	2.95	2.641
RAP aggregate	50.00	2.651	40.00	2.651
TOTAL	100.00		100.00	
Combined bulk Spec. gravity		2.737		2.747

Table 4.11: Combined bulk specific gravity of the components

4.4.2 Maximum specific gravity of the compacted mixture (G_{mm})

The maximum specific gravity of the asphalt mix (G_{mm}) is needed to calculate the percentage of air voids in the mix. The maximum density of the specimen is the mass per volume of the mix without air voids. In this study the maximum specific gravity of the asphalt mix (Gmm) was determined using EN 12697-5 “Determination of the maximum density of hot mix asphalt using Mathematical Procedure”. The maximum specific gravity of the asphalt mixture was computed using the following relationship:

$$G_{mm} = \frac{100}{\left(\frac{P_{agg.}}{G_{sb.}} + \frac{P_b}{G_b}\right)} \qquad \text{(Eq. 4.5)}$$

Where:

G_{mm} = Maximum specific gravity of the compacted mixture

$P_{agg.} and P_b =$ Percent of aggregate and binder in the mix.

$G_{sb} and G_b =$ Bulk specific gravities of the aggregate and binder

Table 4.12 summarizes the results of the maximum specific gravity of the asphalt mix with 40 % and 50 % RAP.

STAC (0/22)	Maximum specifc gravity (Gmm)
50 % RAP	2.555
40 % RAP	2563

Table 4.12: Maximum specific gravity values of mixes with 40 and 50 % RAP

The volumetric properties for all specimens are summarized and presented in Appendix A. It can be observed that, the air void contents are not constant enough for all of the specimens. The RAP material used in this research was not separated in different fractions. Separating the RAP material into different size groups reduces the variability in a RAP mixture's aggregated gradation and consequently minimizes the variation in volumetric properties. During specimen fabrication process, the RAP was typically treated as one material source in mixture design; this procedure is currently used in the GEBR VAN DER LEE b.v.

Chapter 5 Mixing Process and Specimen fabrication

This chapter contains information about the mixing process, mixing and compaction temperatures and specimen fabrication methods used in this study. The use of correct and strictly controlled mixing and compaction temperatures is important in the mix design process. The handling of RAP during the mixing process has an important effect on mix performance properties. If the RAP material is overheated during mixing time, the stiffness of the RAP binder will increase and also asphalt plant emissions increase. If the RAP material is not heated at a high enough temperature, it may not blend completely with the virgin materials.

The mixing process in the asphalt plants depends on the type of plant used. The sequence of mixing, the heating temperature of the RAP material with the virgin aggregate differs for a batch and drum-mix plant (parallel-flow, counter-flow and double barrel). The degree of mixing and the transfer of heat from the virgin aggregate to the RAP are functions of many variables such as: the amount of RAP to be added, the point of introduction of the RAP, the temperature of the RAP and the virgin aggregate, and the amount of mixing time available. Therefore, it is important to understand the actual mixing process in the plants to develop a mix design method in the laboratory, which can simulate the actual plant production process as good as possible.

In this study, a laboratory mix design procedure was developed that mimics the mixing process in the double barrel asphalt plant. In addition, comparisons of other types of mixing processes with the double barrel were done to see the effect of different mixing methods on the performance properties. The following three mixing processes were used in this study:

- Mixing RAP and virgin aggregate at the same temperature, standard mixing method (SM).
- Mixing RAP at 130 ^{o}C with virgin aggregate at high temperature, to simulate the mixing methods that take place in the parallel drum mixer where the RAP is more heated in a separate drum before mixing with the virgin aggregates (PW).

- Mixing cold RAP (with moisture) with superheated virgin aggregate; this mixing method simulates the actual mixing process of double barrel drum mixer (UPG).

A detailed description of the above mixing procedures (mixing time, heating temperature and sequence of mixing) is given in the following sections.

5.1 Mixing RAP and virgin aggregate at the same temperature

The virgin and the RAP materials are heated together at the same temperature. Heating the virgin material and the RAP together at the same temperature is a standard mixing method described in EN 12697 “Test methods for hot mix asphalt - Part 35: Laboratory mixing”. The following procedure was used in this mixing process for the fabrication of mixtures:

- The virgin aggregate, sand, filler and RAP materials were batched by weight to meet the gradation requirements.
- The virgin aggregates, sand and filler were heated in the oven at temperature of 170 ^{o}C overnight. The heating temperature of the virgin materials was selected 10 ^{o}C higher than target mixing temperature.
- The RAP was heated in the oven at temperature of 170 ^{o}C for 3 hours and placed in a relatively thin layer with pan covered with aluminium foil. The RAP was agitated periodically to avoid non-uniform heating.
- To assure uniform mixing all mixing equipments were also placed in the oven at 150 ^{o}C prior to mixing.
- The virgin binder was heated to the mixing temperature of 160 ^{o}C for duration of 3 hour in a closed bitumen heater prior to mixing. At this mixing temperature the binder is sufficient enough to flow and coat the stones. The temperature of the binder should be regularly monitored by using immersible thermometer in order to avoid binder overheating.
- The heated virgin aggregates and batched RAP samples were added to a heated mixing bowel and mixed for 1 minute.

- The required amount of heated virgin binder was added to the virgin aggregate – RAP mixture.
- The virgin binder, virgin aggregate – RAP mixture was mixed with a mechanical mixer for 1.5 minutes.
- After mixing operation, the mixture was artificially aged at the compaction temperature of 150 ^{o}C for half an hour.
- After half an hour the mixture was compacted using gyratory compactor according to Dutch RAW 2005 standard and EN 126971 - 31 “Test methods for hot mix asphalt - Part 31: Specimen preparation by gyratory compactor”.

5.2 Mixing RAP at 130 ^{o}C with hot virgin aggregate

This mixing method simulates the mixing process of parallel drum mixer, where the virgin aggregate and the RAP heated in separate drums before mixing. In such asphalt plants, the RAP is heated to a temperature of 130 ^{o}C in order to minimize the hardening of the RAP binder and to reduce plant emission. The laboratory simulation of this mixing process requires the determination of the heating temperature of the new virgin aggregate combined with the heated RAP at 130 ^{o}C. The required final mixing temperature can be determined in this way. The following section describes the procedures utilised in this mixing process.

5.2.1 Determination of virgin aggregate heating temperature

The temperature to which the virgin aggregate is need to be heated for the necessary heat transfer is determined based on the initial heating temperature of the RAP, the discharge temperature of the final asphalt mix and the amount of RAP material used. During the heating time of the RAP, the moisture in the RAP evaporates and the effect of moisture in heating temperature of the virgin aggregate was minimal. The heating temperature of the virgin aggregate was determined based on different laboratory trials. Table 5.1 shows the heating temperature of the RAP and virgin aggregate used in this study.

RAP (%)	RAP temperature (^{o}C)	Virgin aggregate temperature (^{o}C)
50	130	300
40	130	270

Table 5.1: Virgin aggregate and RAP heating temperature to get the right mixture temperature

5.2.2 Mixing of virgin aggregate, RAP and new binder

After determination of the heating temperature of the virgin aggregate, the next step was the determination of the heating temperature and time of other components of the mixture. The following steps were followed during the mixing process:

- The virgin aggregate, sand, filler and RAP materials were batched by weight to meet the gradation requirements.
- The virgin aggregates, sand and filler were heated in the oven at temperature of 270 and 300 ^{o}C for 40 and 50 % RAP respectively for overnight.
- The RAP was heated in the oven at temperature of 130 ^{o}C for 3 hours placed in a relatively thin layer with pan covered with aluminium foil. The RAP was agitated periodically to avoid non-uniform heating.
- To assure uniform mixing all mixing equipments were also placed in the oven at 150 ^{o}C prior to mixing.
- The virgin binder was heated to the mixing temperature of 160 ^{o}C for duration of 3 hour in a closed bitumen heater prior to mixing. At this mixing temperature the binder is sufficient enough to flow and coat the stones. The temperature of the binder should be regularly monitored by using immersible thermometer in order to avoid binder overheating.
- The heated virgin aggregates and batched RAP samples were added to a heated mixing bowel and mixed for 1 minute.

- The required amount of heated virgin binder was added to the virgin aggregate – RAP mixture.
- The virgin binder, virgin aggregate – RAP mixture was mixed with a mechanical mixer for 1.5 minutes.
- After mixing operation, the mixture was artificially aged at the compaction temperature of 150 ^{o}C for half an hour.
- After half an hour the mixture was compacted using gyratory compactor according to Dutch RAW 2005 standard and EN 126971-31 “Test methods for hot mix asphalt - Part 31: Specimen preparation by gyratory compactor”.

5.3 Mixing cold RAP with superheated virgin aggregate

This mixing method simulates the mixing process that takes place in double barrel drum-mix plants. In the double barrel system the mixing takes place in the outer drum, the inner drum is used for virgin aggregate heating. The sequence of mixing in a double barrel system is as follows; first the virgin aggregate is heated to a high temperature in the inner drum, after the aggregate enters into the outer drum (mixing unit) cold (with moisture) RAP at ambient temperature is added and the blending of the RAP with superheated virgin aggregate takes place. The heat transfer from the hot virgin aggregate to the RAP at ambient-temperature takes place by direct contact between the superheated virgin aggregate and the RAP. Further heating occurs through contact with the inner drum and by radiation of heat from the inner drum into the outer shell. Once the RAP material is entered in the outer shell, mineral filler and new binder are introduced in the mixing area (outer shell) (refer Fig. 2.5).

The laboratory simulation of this mixing process requires the determination of heating temperature of the virgin aggregate (depends on percentage of the RAP, moisture content of the RAP and the required mix discharge temperature), heating time, mixing time (both dry and wet mixing) and mixing sequence. In this mixing method the mixing was done in an airtight temperature insulation box (Figure 5.1) to minimize the heat loss to the

surrounding and oxidation during the mixing process. During the dry mixing phase (virgin aggregate-RAP) the moisture in the cold RAP will evaporate and steamy environment will be developed in the mixing unit. The detail description of the above parameters considered in the mix design process will be described in the following section. Figure 5.2 shows the sequence of the mixing process.

Figure 5.1: Temperature insulation and airtight mixing unit

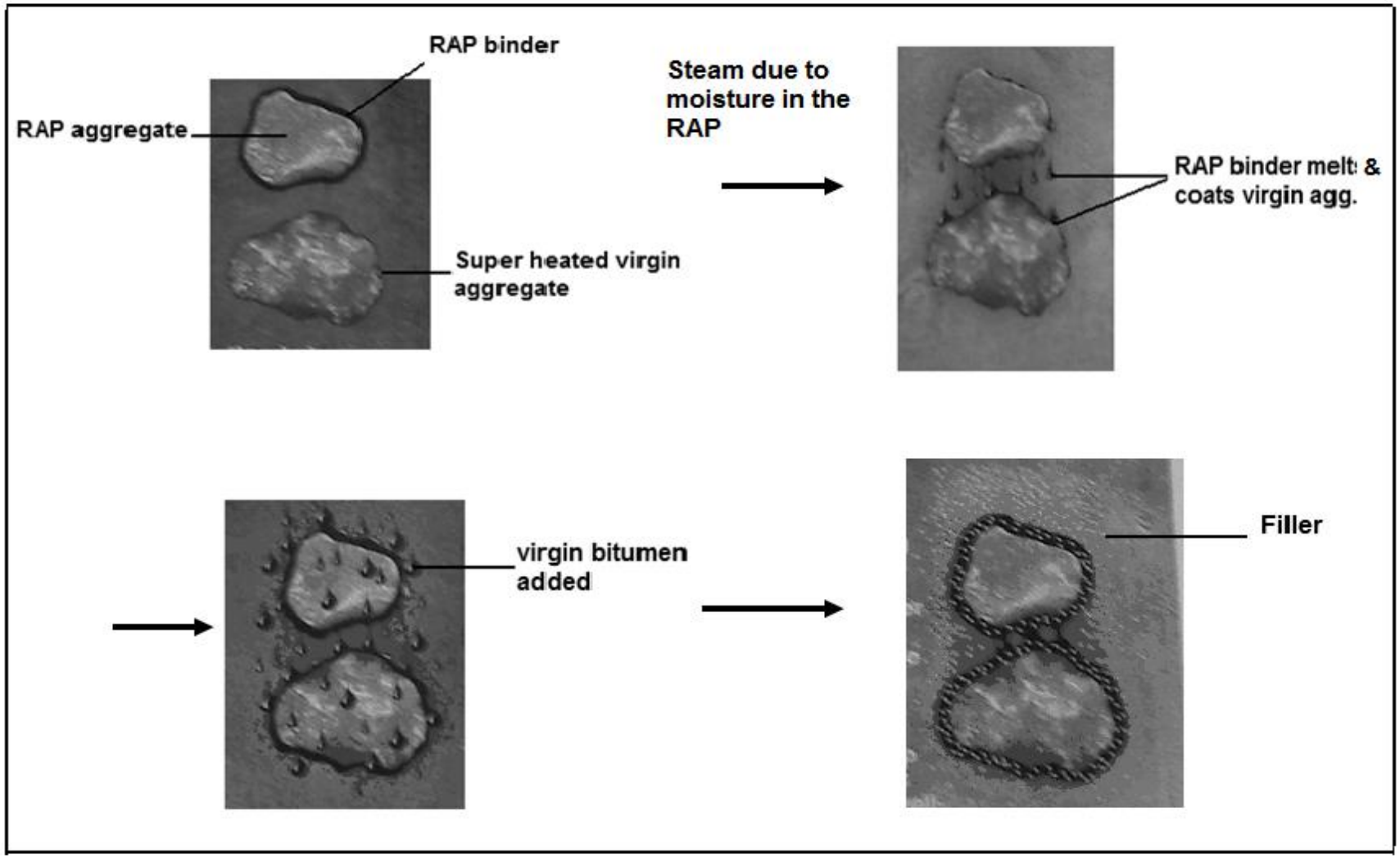

Figure 5.2: Sequence of Mixing in UPG method

5.3.1 Determination of virgin aggregate heating temperature

The three primary variables that determine the temperature to which the virgin aggregate must be heated to accomplish the necessary heat transfer are the moisture content of the RAP, the discharge temperature of the final mix and the amount of RAP material used. The detail description of these factors will be presented in the following sections.

- **Moisture Content of the RAP**

During the mixing process 4 % moisture was added in the RAP in order to simulate the actual moisture condition in the RAP stockpile. The selection of 4 % moisture content was based on the previous moisture content determination done on the RAP stockpile. The required amount of moisture content was added by measuring 4 % of the dry weight of the RAP. In order to measure the moisture content accurately prior to mixing, the RAP material was dried by spreading it on the floor at room temperature for several days. Removing of moisture in the RAP by heating is not advisable, during the heating vaporisation of some light hydrocarbons may occur which can alter the behaviour of the binder in the RAP.

- **Discharge temperature of the mix**

The target discharge temperature, which is the temperature of the combined mixture, was selected based on the combined RAP and virgin binder grade. In practice the discharge temperature also depends on the transportation distance between the mix production and the compaction and the climatic conditions at the site during compaction. In this study a compaction temperature of 150 ^{o}C was selected, based on the combined penetration of the RAP binder and the virgin binder. Therefore, the virgin aggregate must be heated high enough to accomplish the heat transfer necessary for removing the moisture from the RAP and heating the RAP material to target discharge temperature.

- **Amount of RAP**

The amount of the RAP in the mix is one of the most important factors that determine the temperature to which the virgin aggregate must be heated to accomplish the heat transfer. As the amount of the RAP percentage increases, the virgin aggregate temperature must be increased.

Based on the above three factors, the heating temperature of the virgin aggregate as obtained by trial and error different heating temperatures. Table 5.2 shows the heating temperature of virgin aggregate used in this study.

RAP (%)	RAP Moisture Content (%)	RAP Temperature (^oC)	Target Discharge Temperature (^oC)	Virgin Aggregate Temperature (^oC)
50	4	23	150	400
40	4	23	150	380

Table 5.2: Heating temperature of virgin aggregate

5.3.2 Mixing of virgin aggregate, RAP and new binder

In this mixing method only virgin aggregate was heated and cold RAP without heating was mixed. In order to simulate the actual mixing process in double drum mixer it was tried to build an insulated and airtight mixing chamber where all the mixing equipments were placed. The insulated airtight mixing chamber helps; to minimize the incoming oxygen from the outside during the mixing process, it minimizes the heat loss from the superheated virgin aggregate to the surrounding and it helps to create steamy environment during the mixing process. All the mixing processes were done in an enclosed environment. The following steps were followed during the mixing process:

- The virgin aggregate, sand, filler and RAP materials were batched by weight to meet the gradation requirements.
- The virgin aggregates and sand were heated in the oven at temperature of 380 and 400 ^oC for 40 and 50 % RAP respectively for overnight.

- To assure uniform mixing all mixing equipments were also placed in the oven at 150 ^{o}C prior to mixing.
- The virgin binder was heated to the mixing temperature of 160 ^{o}C for duration of 3 hour in a closed bitumen heater prior to mixing. At this mixing temperature the binder is sufficient enough to flow and coat the stones. The temperature of the binder regularly monitored by using immersible thermometer in order to avoid binder overheating.
- The required amount of moisture content was added by measuring 4 % of the dry weight of RAP and mixed by hand.
- The mixing bucket and the mixer were brought to the airtight temperature insulation box.
- The superheated virgin aggregate and cold RAP with 4 % moisture were added to a heated mixing bowel in closed airtight temperature insulation box and mixed for 1 minute.
- The required amount of virgin binder was added, followed by the addition of filler material and the mixing continues for 1.5 minutes in closed airtight temperature insulation box.
- After mixing operation, the mixture was artificially aged at the compaction temperature of 150 ^{o}C for half an hour.
- After half an hour the mixture was compacted using gyratory compactor according to Dutch RAW 2005 standard and EN 126971 - 31 “Test methods for hot mix asphalt - Part 31: Specimen preparation by gyratory compactor”.

During the mixing process, the moisture in the RAP driven off as steam. It was also tried to measure the pressure developed due to the steam in the mixing chamber, but it was not able to detect the development of the pressure using the gauges. The intention of measuring the pressure developed during the laboratory mixing process was to compare to the actual pressure developed in the double drum mixer. Figure 5.3 shows the steam generated during mixing process.

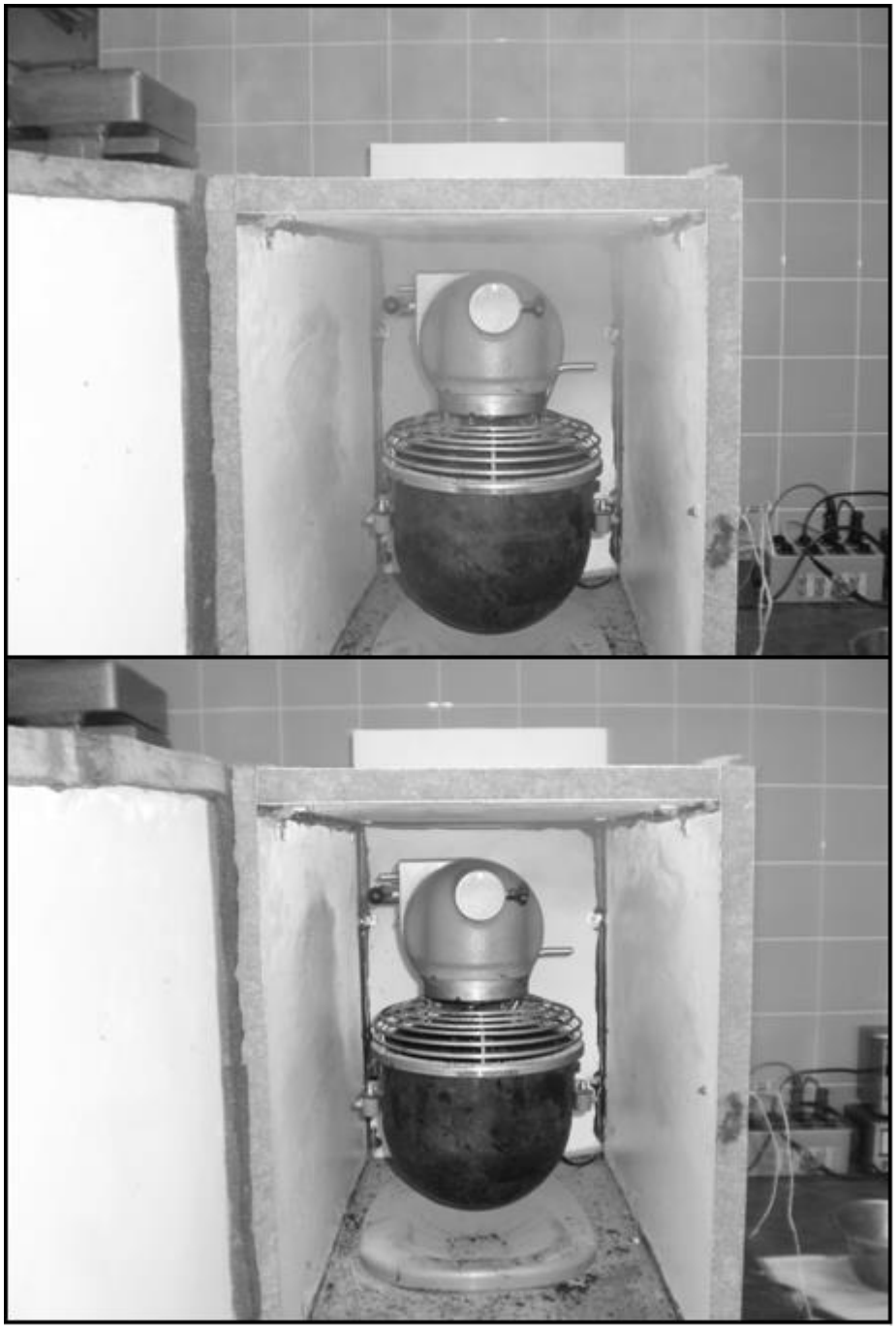

Figure 5.3: Mixing process with steam (top) and without steam (bottom)

5.4 Specimen Compaction Procedure

Laboratory test specimens were prepared for different mechanical tests used in this study. Each test has specific requirements in terms of the specimen height. The mixtures were compacted using the Gyratory Compactor. The compaction was done according to the Dutch standard, RAW 2005 specification. During the compaction 1.25 degree angle of compaction was used, 30 gyrations per minute were used and 600 kPa of compaction pressure was applied in the specimen. The compaction cylindrical moulds were heated to the compaction temperature of 150 ^{o}C for 3 hours prior to charging them with the loose mixes. After compaction the specimens were demolded after cooling for about 15 minutes.

The compaction was done based on the requirement of the height, resulting target air void content of 5 %. Different sizes of cylindrical specimens were produced using the Gyratory Compactor (Figure 5.4). For the Indirect Tensile Strength and Resilient Modulus test, 100 mm in diameter by 70 mm thickness specimens were compacted and for Permanent deformation test, 100 mm in diameter by 100 mm thickness specimens were prepared.

The prepared specimens were further treated by sawing and polishing in order to obtain the actual test specimens with the dimensions and surface characteristics that allow better instrumentation and minimize testing variability. Air void content was determined on the cut and polished specimens to ensure that the level of air voids was still within the targeted range.

Figure 5.4: Servopac Gyratory compactor

Chapter 6 Results and Analysis

This section discusses the results and analysis of data obtained from this study. The data analysis will compare mixture performance test results for the three mixing methods with 40 and 50 % RAP contents. The following test results will be discussed:

- Resilient modulus results from ITT test
- Indirect tensile strength test results
- Permanent deformation test results

Table 6.1 summarizes the three mixing methods and their coding used in the subsequent sections of the chapter.

Mixing Method	RAP (%)	Abbreviation
Mixing of RAP and virgin aggregate at same temperature (Standard Mixing - SM)	40	SM 40
	50	SM 50
Mixing of RAP at 130 ^{o}C with hot virgin aggregate (Partial Warming Mixing - PW)	40	PW 40
	50	PW 50
Mixing cold RAP with superheat virgin aggregate (Upgraded Mixing Method - UPG)	40	UPG 40
	50	UPG 50

Table 6.1: Mixing methods with abbreviation

6.1 Resilient Modulus

This section contains the results of the resilient modulus (Mr) tests for the three mixing methods with 40 and 50 % of RAP contents. The objectives of conducting the resilient modulus tests are:

- To determine the resilient modulus of the asphalt mixes.
- To examine the effect of mixing method on the resilient modulus.
- To examine the effect of RAP amount on the resilient modulus.
- To describe the material behaviour over a wide range of temperature and loading time by constructing a master curve.

The resilient modulus tests were performed for six test series (three mixing method and two RAP content), each test condition was repeated 3 times. The tests were done at five different temperatures (5, 10, 15, 23 and 35 ^{o}C) and with six different frequencies (16, 12, 8, 4, 2 and 1 Hz). Cylindrical specimens with 100 mm in diameter and 50 mm in thickness were used during the testing. The resilient modulus value for each test condition was determined by using eq.3.2 (Chapter 3). For each selected test temperature and loading frequency, five loading pulses were considered. The average peak load and the recoverable horizontal deformation of the five-pulse loading were used in the computation. The resilient modulus values for each mixing method and RAP content at different test temperatures and frequencies are shown in Appendix B. A summary of the resilient modulus test results (average of three test replicates) with corresponding air void contents are shown in Table 6.2, 6.3 and 6.4.

Mixing Method	Temp. (°C)	Sample ID	Air Voids (%)	Resilient Modulus (MPa) at different frequencies (Hz)					
				1	2	4	8	12	16
Standard Mixing Method (SM) 40 % RAP	5	SM 40 %	4.53	19089	20410	21679	23436	23686	23822
		Stdev	0.10	1595	1605	1886	2069	2074	824
		CV (%)	2.16	8.4	7.9	8.7	8.8	8.8	3.5
	10	SM 40 %	4.53	15257	16558	18292	19825	20347	20819
		Stdev	0.10	158	270	350	346	449	1116
		CV (%)	2.16	1.0	1.6	1.9	1.7	2.2	5.4
	15	SM 40 %	4.53	8906	10263	11856	13797	14713	14644
		Stdev	0.10	298	419	445	78	217	891
		CV (%)	2.16	3.3	4.1	3.8	0.6	1.5	6.1
	23	SM 40 %	4.53	3091	3703	4731	6050	6958	7361
		Stdev	0.10	201	282	215	234	139	94
		CV (%)	2.16	6.5	7.6	4.6	3.9	2.0	1.3
	35	SM 40 %	4.53	1038	1306	1561	2231	2538	2840
		Stdev	0.10	119	131	245	143	118	109
		CV (%)	2.16	11.4	10.1	15.7	6.4	4.6	3.9
Standard Mixing (SM) 50 % RAP	5	SM 50 %	4.61	19672	20991	22105	23667	23884	24099
		Stdev	0.18	286	313	306	373	297	685
		CV (%)	3.93	1.5	1.5	1.4	1.6	1.2	2.8
	10	SM 50 %	4.61	14361	15752	17220	18803	18818	18156
		Stdev	0.18	412	386	493	404	1192	933
		CV (%)	3.93	2.9	2.5	2.9	2.1	6.3	5.1
	15	SM 50 %	4.61	9818	11081	12624	14791	15643	15522
		Stdev	0.18	210	373	178	174	505	1705
		CV (%)	3.93	2.1	3.4	1.4	1.2	3.2	11.0
	23	SM 50 %	4.61	3165	3838	4901	6283	7164	7507
		Stdev	0.18	169	202	220	244	191	141
		CV (%)	3.93	5.3	5.3	4.5	3.9	2.7	1.9
	35	SM 50 %	4.61	925	1175	1555	2074	2373	2602
		Stdev	0.18	135	174	201	257	265	364
		CV (%)	3.93	14.6	14.9	12.9	12.4	11.2	14.0

Table 6.2: Resilient modulus and air void, Standard Mixing (SM)

Stdev: standard deviation of three test repetitions

CV : coefficient of variation of three test repetitions

Mixing Method	Temp. (°C)	Sample ID	Air Voids (%)	Resilient Modulus (MPa) at different frequencies (Hz)					
				1	2	4	8	12	16
Partial Warming Mixing 40 % RAP	5	PW 40 %	4.69	17218	18467	19543	20629	21026	20117
		Stdev	0.43	621	607	676	682	101	1852
		CV (%)	9.24	3.6	3.3	3.5	3.3	0.5	9.2
	10	PW 40 %	4.69	13638	14760	16131	17618	18008	17529
		Stdev	0.43	707	720	835	1148	1153	1369
		CV (%)	9.24	5.2	4.9	5.2	6.5	6.4	7.8
	15	PW 40 %	4.69	8883	10133	11721	13727	14717	15453
		Stdev	0.43	400	358	152	40	342	492
		CV (%)	9.24	4.5	3.5	1.3	0.3	2.3	3.2
	23	PW 40 %	4.69	2571	3150	4070	5269	6139	6607
		Stdev	0.43	125	141	152	217	298	225
		CV (%)	9.24	4.9	4.5	3.7	4.1	4.8	3.4
	35	PW 40 %	4.69	723	917	1196	1657	1932	2118
		Stdev	0.43	15	25	26	9	29	24
		CV (%)	9.24	2.1	2.7	2.2	0.6	1.5	1.1
Partial Warming Mixing 50 % RAP	5	PW 50 %	4.61	18898	20090	21249	21984	21937	20539
		Stdev	0.10	708	710	796	1062	1482	2771
		CV (%)	2.26	3.7	3.5	3.7	4.8	6.8	13.5
	10	PW 50 %	4.61	14560	15892	17174	18579	19038	19725
		Stdev	0.10	608	574	493	376	426	602
		CV (%)	2.26	4.2	3.6	2.9	2.0	2.2	3.1
	15	PW 50 %	4.61	10811	11936	13291	15719	16674	17311
		Stdev	0.10	753	714	660	735	581	653
		CV (%)	2.26	7.0	6.0	5.0	4.7	3.5	3.8
	23	PW 50 %	4.61	3391	4091	5118	6466	7303	7602
		Stdev	0.10	651	758	821	974	869	715
		CV (%)	2.26	19.2	18.5	16.0	15.1	11.9	9.4
	35	PW 50 %	4.61	1132	1427	1823	2387	2746	3011
		Stdev	0.10	231	291	322	483	586	636
		CV (%)	2.26	20.4	20.4	17.7	20.2	21.3	21.1

Table 6.3: Resilient modulus and air void, Partial Warming Mixing (PW)

Stdev: standard deviation of three test repetitions

CV : coefficient of variation of three test repetitions

Mixing Method	Temp (°C)	Sample ID	Air Voids (%)	Resilient Modulus (MPa) at different frequencies (Hz)					
				1	2	4	8	12	16
Upgraded Mixing Method (UPG) 40 % RAP	5	UPG40 %	4.86	15743	16872	17820	19081	19585	19762
		Stdev	0.17	1450	1413	1551	1995	1669	2167
		CV (%)	3.52	9.2	8.4	8.7	10.5	8.5	11.0
	10	UPG40 %	4.86	11067	12284	13638	15219	15857	16235
		Stdev	0.17	1808	1895	1917	2031	1949	1571
		CV (%)	3.52	16.3	15.4	14.1	13.3	12.3	9.7
	15	UPG40 %	4.86	6733	7890	9543	11155	12006	11670
		Stdev	0.17	1317	1175	1298	1251	1082	1983
		CV (%)	3.52	19.6	14.9	13.6	11.2	9.0	17.0
	23	UPG40 %	4.86	1705	2115	2803	3734	4356	4784
		Stdev	0.17	376	464	564	703	758	821
		CV (%)	3.52	22.0	21.9	20.1	18.8	17.4	17.2
	35	UPG40 %	4.86	499	631	854	1178	1446	1529
		Stdev	0.17	107	129	169	229	250	251
		CV (%)	3.52	21.5	20.5	19.8	19.4	17.3	16.4
Upgraded Mixing Method (UPG) 50 % RAP	5	UPG50 %	4.95	17772	19170	20452	21528	22132	22076
		Stdev	0.20	516	667	492	1073	807	723
		CV (%)	4.05	2.9	3.5	2.4	5.0	3.6	3.3
	10	UPG50 %	4.95	15223	16609	17966	19797	19776	20028
		Stdev	0.20	2861	3013	2823	2748	2523	2528
		CV (%)	4.05	18.8	18.1	15.7	13.9	12.8	12.6
	15	UPG50 %	4.95	8759	9963	11812	13668	14601	14361
		Stdev	0.20	439	389	513	438	403	742
		CV (%)	4.05	5.0	3.9	4.3	3.2	2.8	5.2
	23	UPG50 %	4.95	2331	2885	3829	4960	5724	6322
		Stdev	0.20	259	297	334	422	423	388
		CV (%)	4.05	11.1	10.3	8.7	8.5	7.4	6.1
	35	UPG50 %	4.95	695	895	1182	1618	1902	2074
		Stdev	0.20	91	130	157	242	217	297
		CV (%)	4.05	13.1	14.5	13.3	14.9	11.4	14.3

Table 6.4: Resilient modulus and air void, Upgraded Mixing (UPG)

Stdev: standard deviation of three test repetitions

CV : coefficient of variation of three test repetitions

6.2 Test result analysis

6.2.1 Master Curve Construction

Asphalt mixtures are known to behave visco-plastic. When asphaltic mixtures are in their linear visco-elastic phase, the time-temperature superposition principle holds. A master curve of a bituminous mix at any reference temperature (T_{ref}) can be defined as the relationship between the mix stiffness and the reduced frequency. Master curves are constructed by using the time-temperature superposition principle. The master curves are constructed by shifting the data points obtained at test temperatures above the reference horizontally to the left (lower frequencies) and the data points obtained at test temperatures below the reference temperature to the right (higher frequencies). The data at the reference temperature remain unchanged. The resulting master curve of the stiffness composed in this way describes the time dependency of the material. The shift value required at each temperature to form the master curve describes the temperature dependency of the material.

In this study, the master curves at the reference temperature of 15 ^{o}C were constructed from the resilient modulus results obtained at different test temperatures and loading frequencies. The shift factors were determined using Arrhenius equation and the curve fittings were done using the model given by (Medani, Huurman and Molenaar, 2004). The shift factor α_T is calculated by means of an Arrhenius type of equation:

$$\alpha_T = e^{\frac{\Delta H}{R}\left(\frac{1}{T}-\frac{1}{T_{ref}}\right)} \qquad \text{Eq. (6.2)}$$

Where:

ΔH = activation energy [J/mol]

R = ideal gas constant [8.314 J/mol.K]

T = considered temperature in Kelvin [K]

T_{ref} = reference temperature in Kelvin [K]

α_T = f_{red}/f

f_{red} = reduced frequency [Hz]

f = loading frequency [Hz]

The master curve fitting model is given as:

$$S_{mix} = a_0 \left\{ 1 - e^{-\left(\frac{f_{red}}{a_1}\right)^{a_2}} \right\} \qquad \text{Eq. (6.3)}$$

In this formula S_{mix} is the mixture stiffness and a_0, a_1 and a_2 are regression constants. The ΔH and the values of the coefficients are obtained using the non-linear Excel – Solver analysis, using solver to minimize the mean squared error of the measured and model mixture stiffness.

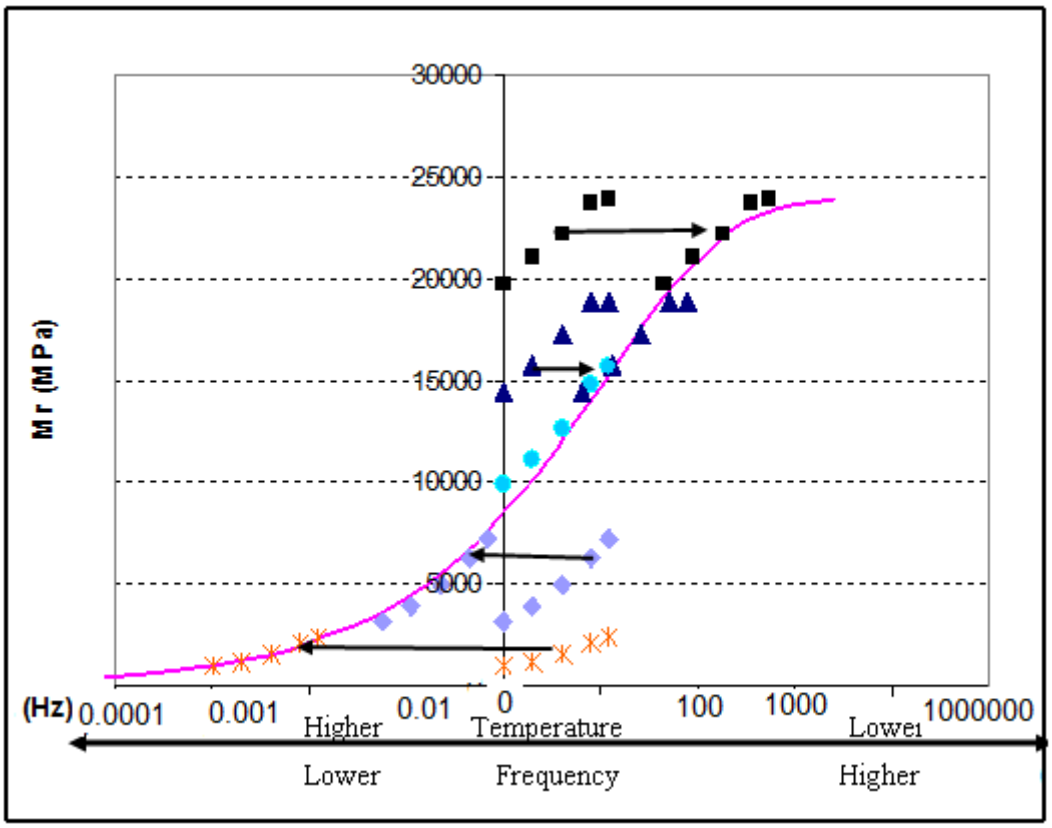

Figure 6.1: Example of the construction of master curve

The values of the constants of the sigmoidal model and the activation energy are given in Table 6.5 for all mixing methods and percentage RAP. The shift factors determined for each temperature are summarized in Table 6.6.

Mixing Method	RAP (%)	Specimen Code	ΔH (kJ/mol)	a_0	a_1	a_2
Standard Mixing (SM)	40	SM 40	248.6	25527	18.3	0.331
	50	SM 50	254.2	23850	11.654	0.342
Partial Warming (PW)	40	PW 40	252	20756	8.674	0.373
	50	PW 50	250.4	22338	7.430	0.337
Upgraded (UPG)	40	UPG 40	254	20509	21.444	0.373
	50	UPG 50	252.7	22753	13.587	0.368

Table 6.5: Values of curve fitting constants of the model at T_{ref} 15 ^{o}C

Temperature (^{o}C)	Shift factor Log α_T		Shift factor Log α_T		Shift factor Log α_T	
	SM 40	SM 50	PW 40	PW 50	UPG 40	UPG 50
5	1.622	1.659	1.644	1.634	1.657	1.649
10	0.797	0.815	0.808	0.803	0.814	0.810
15	0	0	0	0	0	0
23	-1.219	-1.246	-1.236	-1.228	-1.245	-1.239
35	-2.921	-3.000	-2.959	-2.959	-3.00	-2.96

Table 6.6: Shift factors at different temperature

It was observed from Table 6.6 that the shift factors are independent of the mixing method. The plots of the logarithm of the shift factor vs. temperature are presented in Figure 6.2. The data presented in the figure showed a straight line approximation for five testing temperatures. The log shift factor vs. temperature curve provides an indication of the temperature susceptibility of the mix, from Figure 6.2 it can be observed that all mixing methods have the same slope. With linear extrapolation techniques it is possible to determine the shift factors for other temperatures by using Figure 6.2.

Acceptable predictions of the mix stiffness at different temperature and frequency can be made.

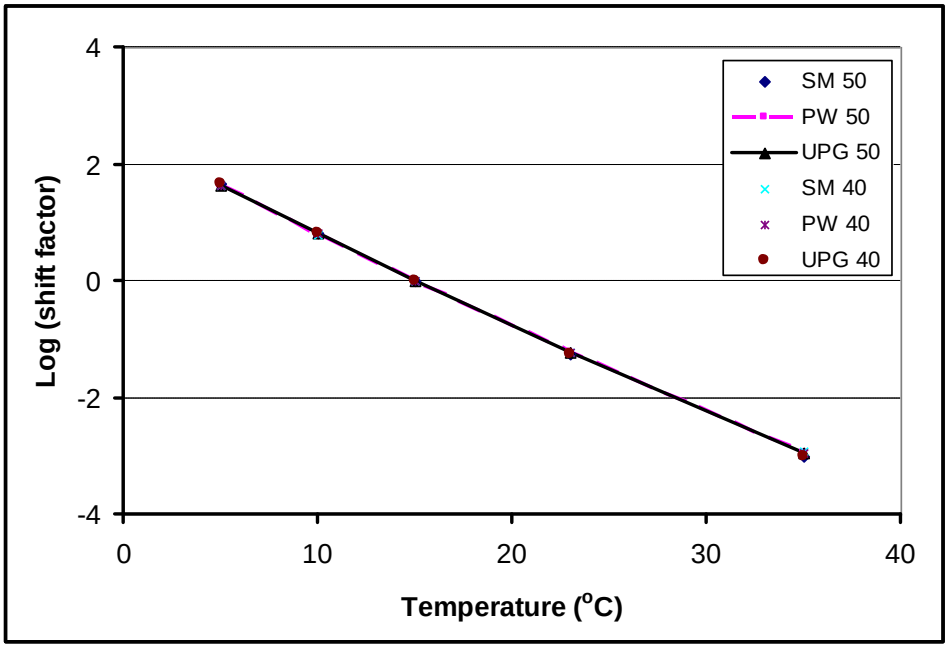

Figure 6.2: The logarithm of shift factor vs. temperature for Tref = 15 ^{o}C

With the model parameters described in Table 6.5 and the shift factors in Table 6.6, the master curves for all the three mixing methods with 40 % and 50 % of RAP at Tref 15 ^{o}C are reduced and given in Appendix C. Figure 6.3 shows a typical master curve plotted on log-normal scale to demonstrate the differences in stiffness at the high end of the graph (high frequency and low temperature) and in Figure 6.4 the log-log scale is given to demonstrate the differences in stiffness at the low end of the graph (low frequency and high temperature).

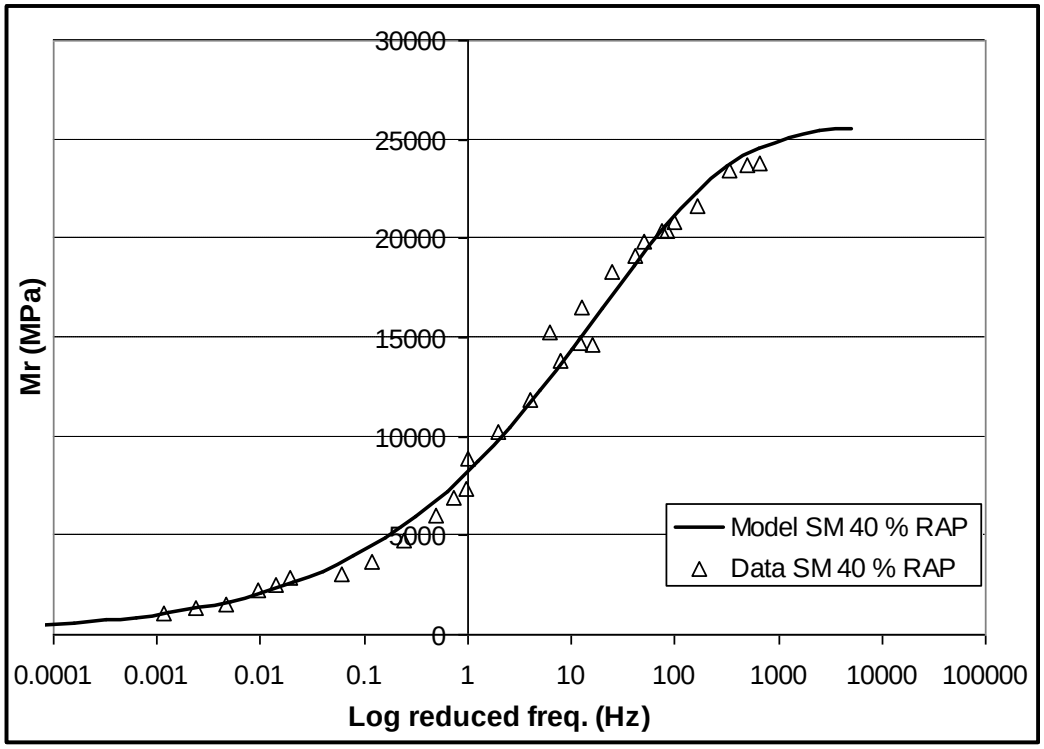

Figure 6.3: Master curve of stiffness, Tref = 15 ^{o}C (Log-Linear: freq. Mr.)

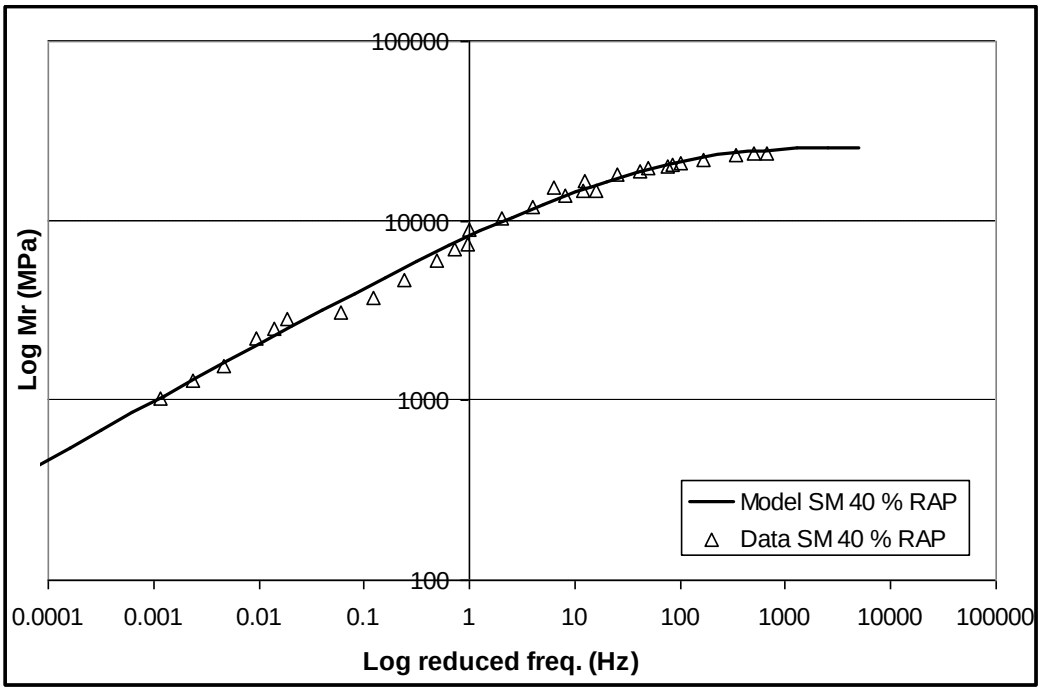

Figure 6.4: Master curve of stiffness, Tref = 15 ^{o}C (Log-Log : freq. Mr.)

6.2.2 Comparison of the Slopes of the Master curves

The slope of the master curve is an important parameter since it reveals information on fatigue and permanent deformation characteristics of the mixture. The slope of the fatigue line “n” is a material property and depends on the slope of the master curve. In addition, the slope of the master curve indicates the sensitivity of the change in the modulus with time of loading. The higher the slope, the greater the change in modulus for a corresponding changes in frequency or vehicle speed. Figures 6.5 and 6.6 show the plot of the master curve (stiffness vs. reduced loading time) in log-log scale with 40 and 50 % RAP contents respectively. It can be seen from Figures 6.5 and 6.6 that the highest absolute value of the slopes are observed for the UPG method and the lowest absolute value of the slopes are observed for the SM method with 40 and 50 % RAP contents.

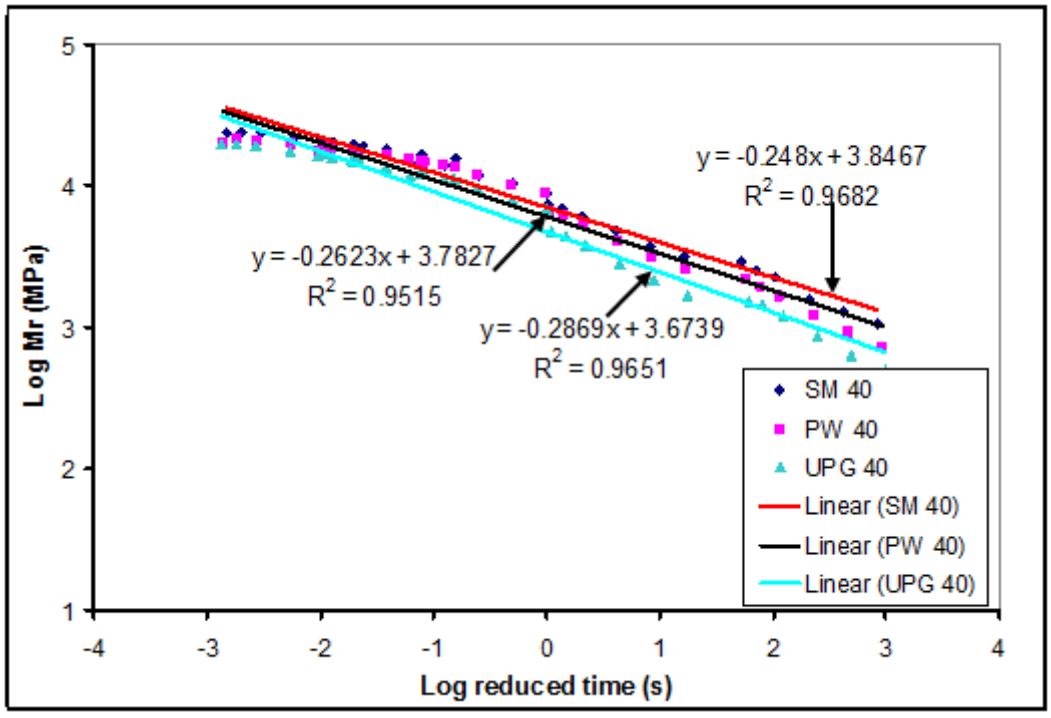

Figure 6.5: Slope of Master curves for different mixing methods (40 % RAP)

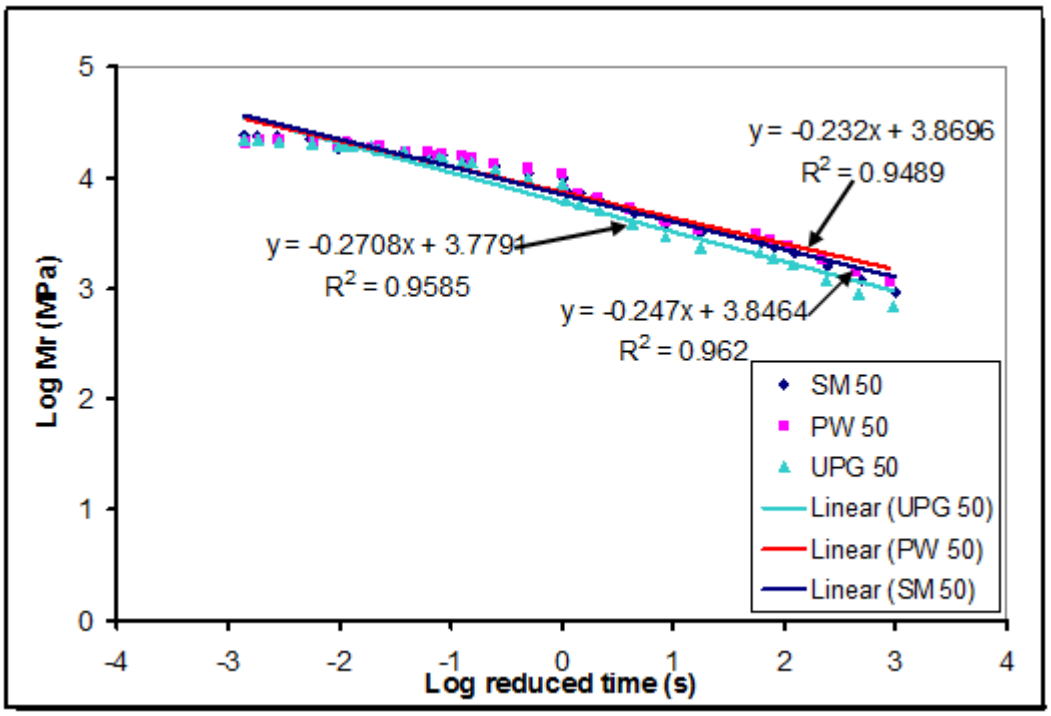

Figure 6.6 : Slope of Master curves for different mixing methods (50 % RAP)

6.3 Effect of mixing method on resilient modulus

The heating and mixing operations in production of asphalt mixes with RAP have a significant effect on the mixture stiffness. To analyze the effect of mixing method on the stiffness of the mixture at different frequencies and temperatures a master curve was plotted. Comparisons of the mix stiffness for different mixing methods at low and high temperature will be discussed in this section. The master curves for different mixing methods with 40 % RAP in Log-Linear and Log-Log scale are shown in Figure 6.7 and 6.8 respectively.

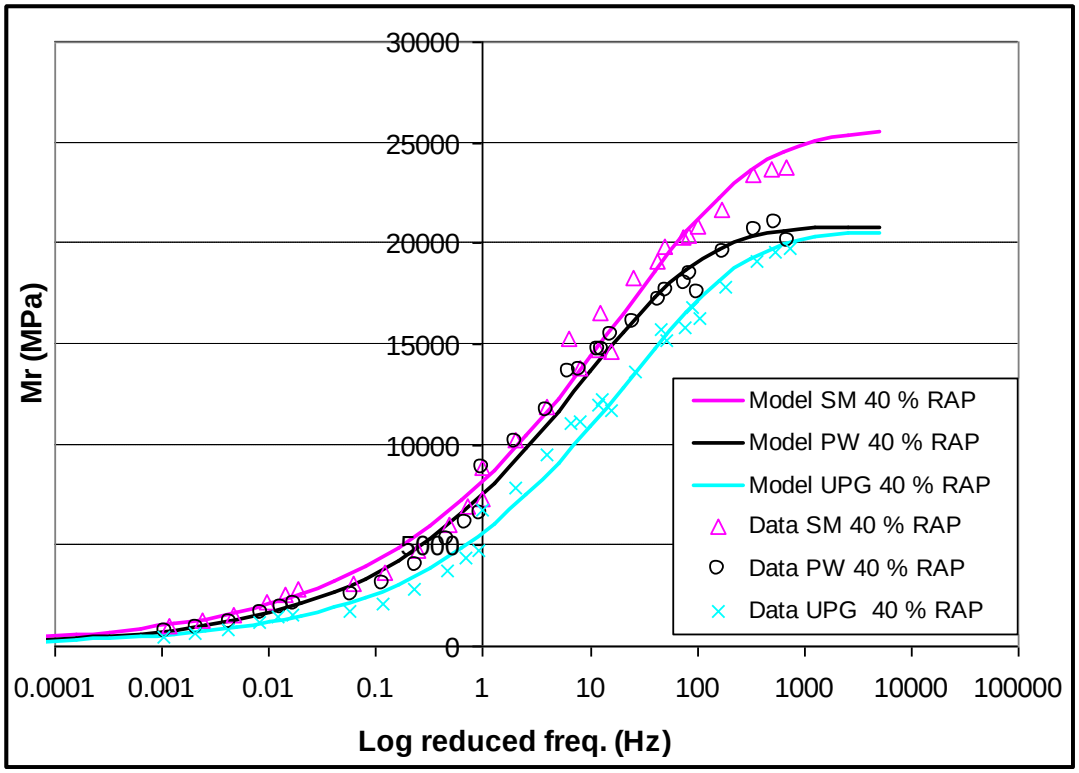

Figure 6.7: Master curves of stiffness with 40 % RAP at Tref 15 ^{0}C (Log-Linear scale)

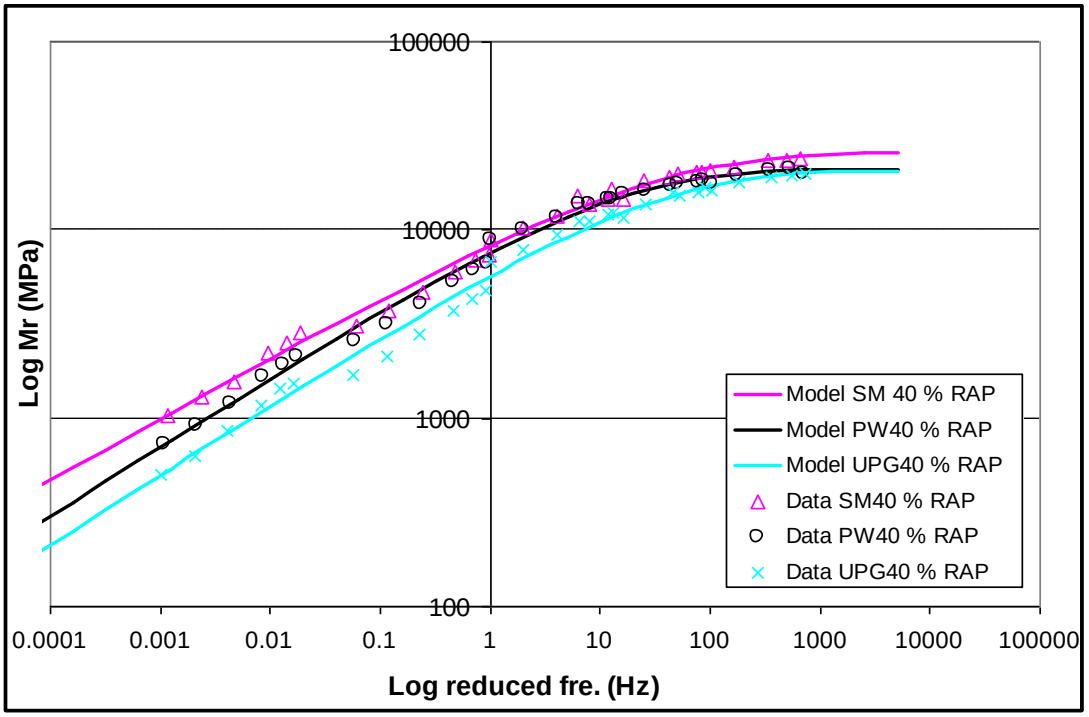

Figure 6.8: Master curves of stiffness with 40 % RAP at Tref 15 ^{o}C (Log-Log scale)

The comparison of the master curves of the mixtures with 50 % RAP in Log-Linear and Log-Log scale are shown in Figure 6.9 and 6.10 respectively.

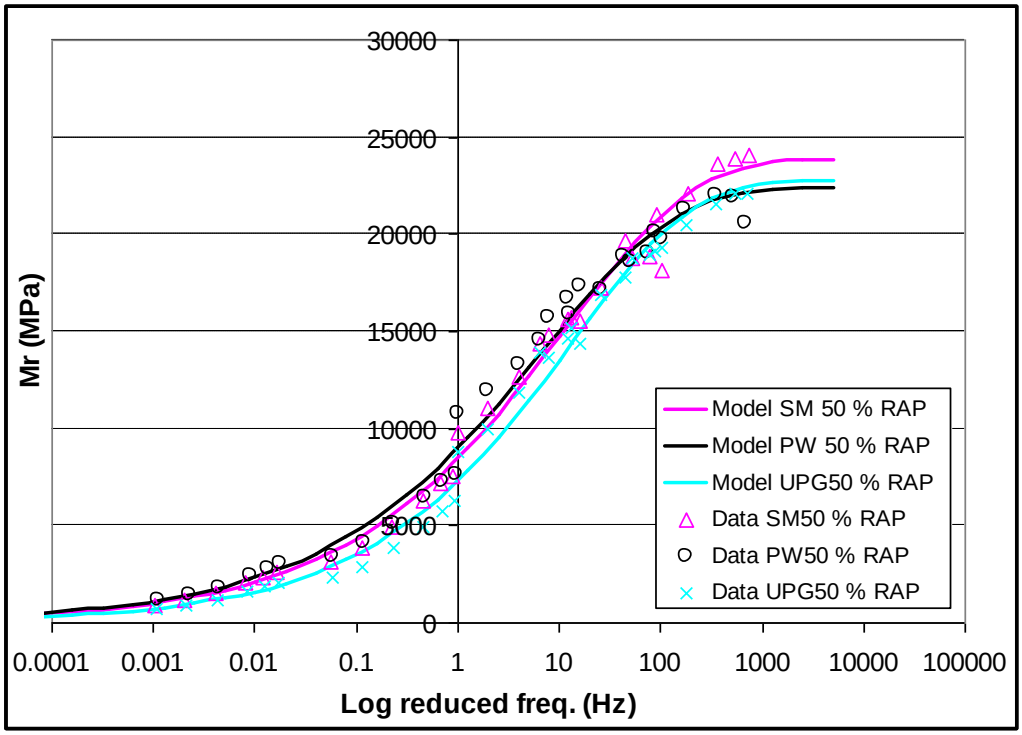

Figure 6.9: Master curves of stiffness with 50 % RAP at Tref 15 ^{o}C (Log-Linear scale)

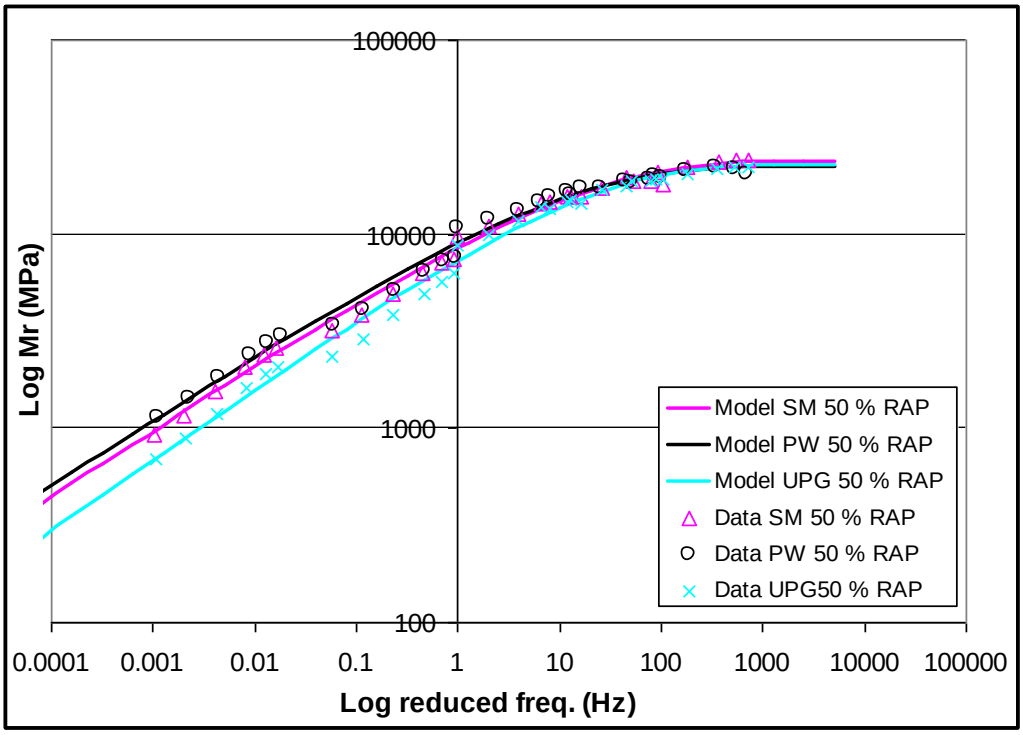

Figure 6.10: Master curves of stiffness with 50 % RAP at Tref 15 ^{o}C (Log-Log scale)

From the results of master curves of the three mixing methods it can be observed that:

- In almost all cases, the stiffness values decrease with increasing temperature and decreasing of frequencies.
- The stiffness of the mixture increases with increasing preheating temperature of the RAP (RAP heating temperature 0, 130 and 170 ^{o}C for UPG, PW and SM methods respectively).
- For 40 % RAP the highest mixture stiffness at low temperature (high frequency) occurs for the mixture made with the SM method and the lowest stiffness was observed at high temperature (low frequency) for the mixture made with UPG method.
- For 50 % RAP the highest mixture stiffness at low temperature (high frequency) occurs for mixtures made with SM method and the lowest stiffness was observed at high temperature (low frequency) for mixture made with UPG method.
- Heating RAP to a temperature of 130 and 170 ^{o}C results in extra ageing of the already aged binder in the RAP stiffer during the preheating time of the RAP prior to the mixing which results more stiffer mix.
- From the master curves it was observed that the stiffness of the mixtures prepared with the SM method showed the highest stiffness at low temperature (high frequency), but the stiffness alone does not give the full picture of the overall performance properties of the mixtures, because the ductility or brittleness of the mixture will also affect the performance with respect to cracking. The 50 % RAP mixture made with the SM method had the highest aged binder, and this could results in more brittle mixtures.

Figures 6.11 and 6.12 show the percentage increase in stiffness at different temperature for SM and PW mixing methods compared with stiffness of UPG method. It can be seen that the highest change in stiffness by mixing

methods observed for the two test temperatures 23 and 35 ^{o}C, than lowest and intermediate test temperatures.

Figure 6.11 shows that the stiffness of SM method is 48 % higher than the stiffness of the UPG method with 40 % RAP at 35 ^{o}C, whereas at 5 ^{o}C the stiffness of the SM method is 18 % higher than the stiffness of the UPG method. Similarly, Figure 6.12 with 50 % RAP shows the change in stiffness is higher for the two highest temperatures (23 and 35 ^{o}C). From Figure 6.11 and 6.12 it was observed that the highest percentage increase in stiffness by mixing method was observed for mixture with 40 % RAP contents.

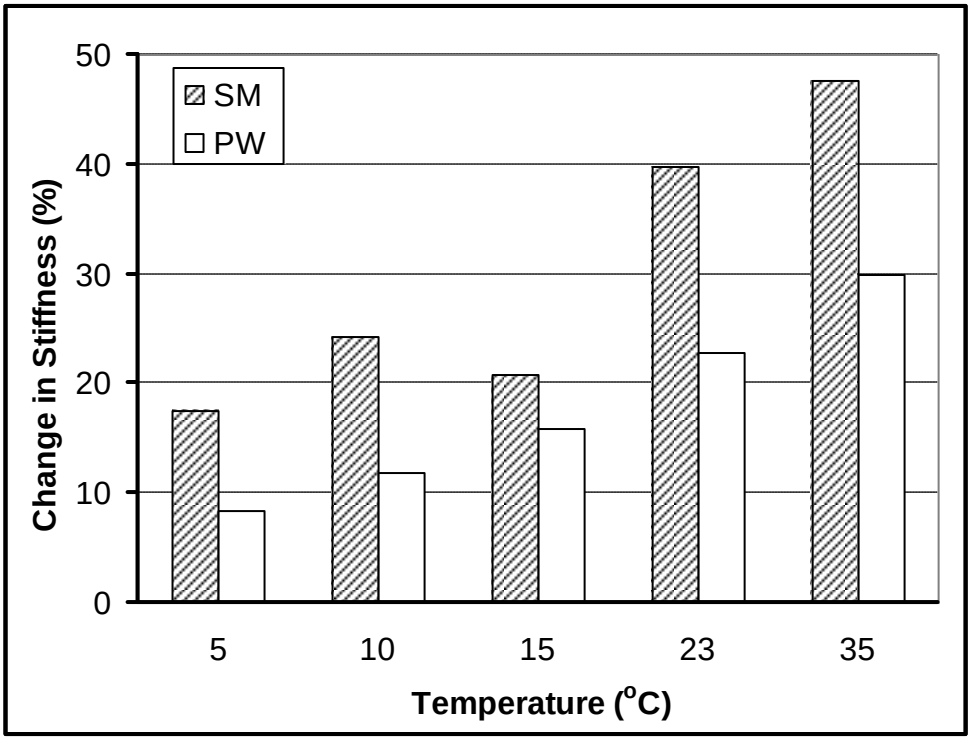

Figure 6.11: Percentage increase in stiffness at different temperature in compared to UPG method (40 % RAP)

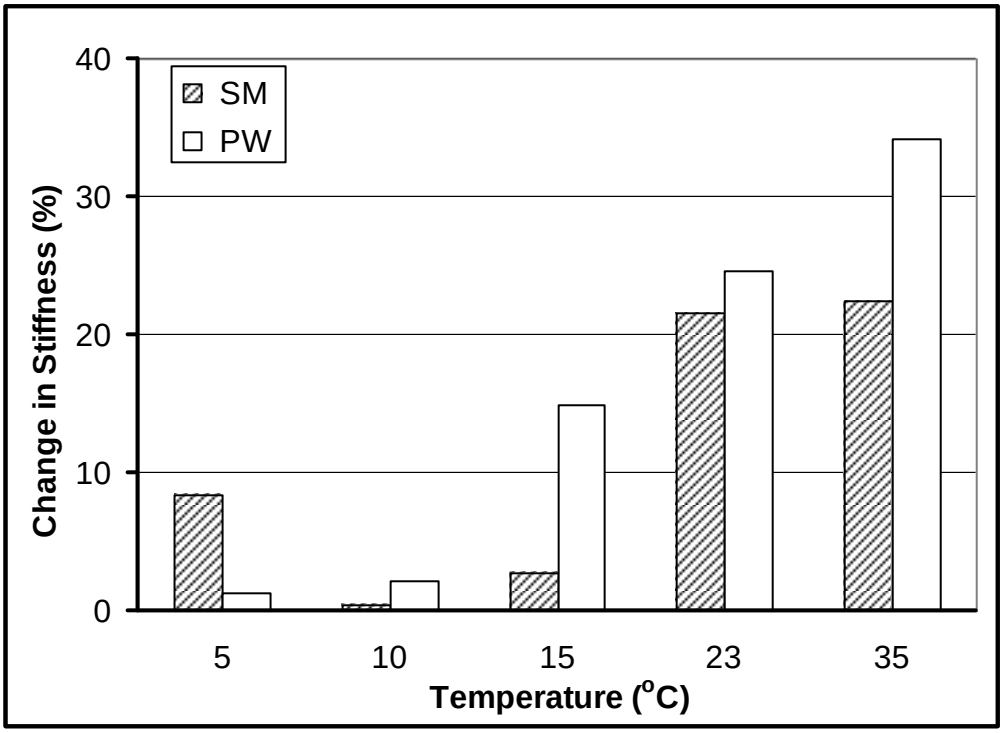

Figure 6.12: Percentage increase in stiffness at different temperature in compared to UPG method (50 % RAP)

6.4 Effect of percentage of RAP in resilient modulus

The addition of RAP to the mixture has a pronounced effect on the stiffness of the mixture. In this study it was tried to see the effect of increasing the percentage of RAP from 40 to 50 % on the stiffness of the mixture. Figures 6.13, 6.14 and 6.15 show the comparison of the master curves for each mixing method with 40 and 50 % RAP content (each master curve represents average of three test replicates).

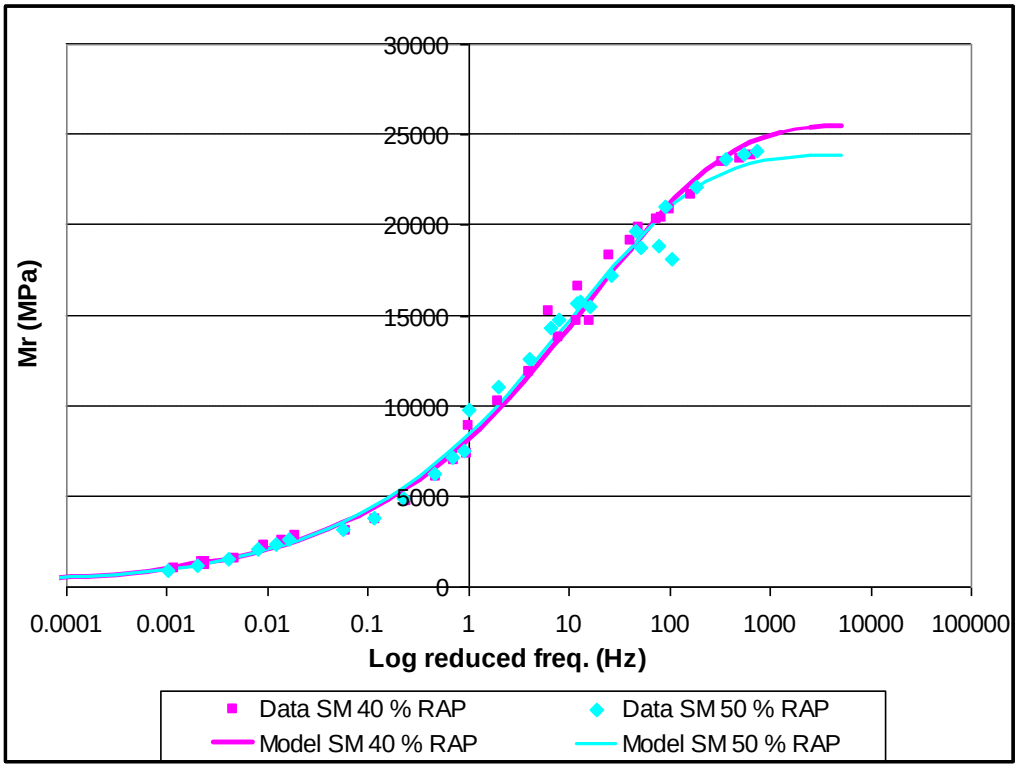

Figure 6.13: Master curves at 40 and 50 % RAP, Tref = 15 ^{o}C (SM method)

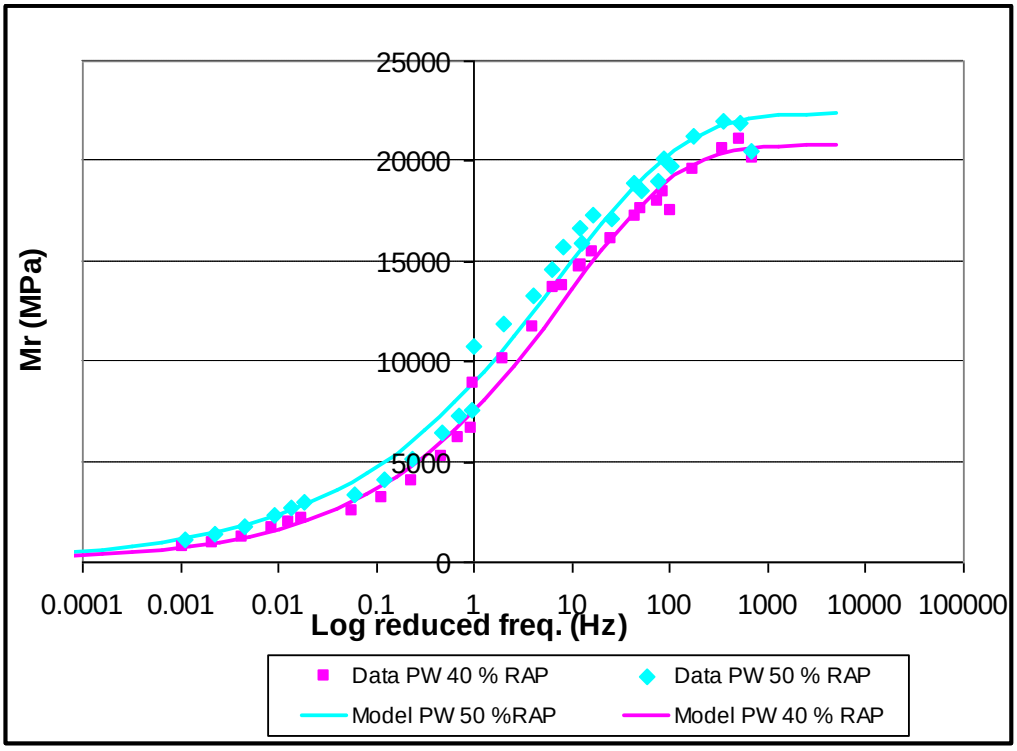

Figure 6.14: Master curves at 40 and 50 % RAP, Tref = 15 ^{o}C (PW method)

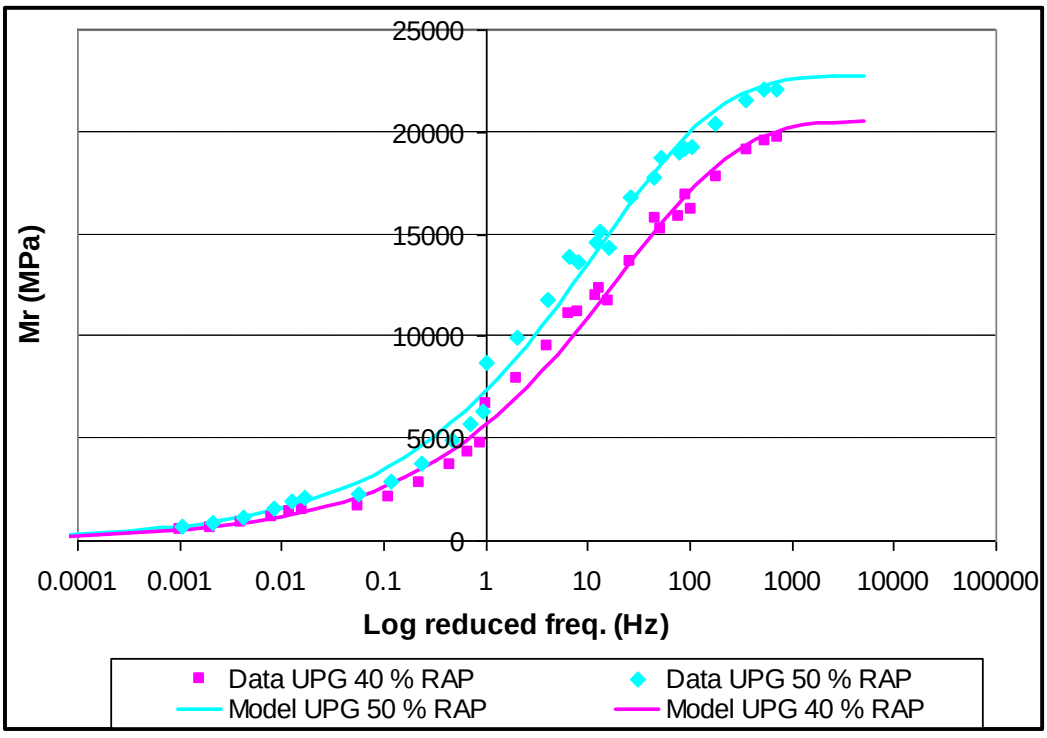

Figure 6.15: Master curves at 40 and 50 % RAP, Tref = 15 ^{o}C (UPG method)

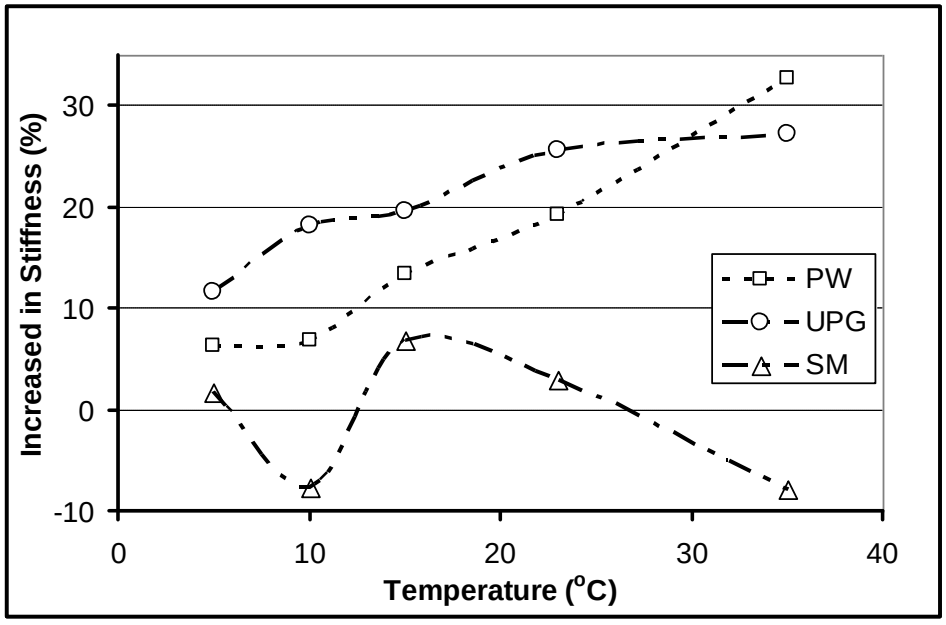

Figure 6.16: Increase in % of stiffness at different temperature by increasing RAP from 40 to 50 %.

From the results of the three master curves (Figure 6.13, 6.14 and 6.15) and from Figure 6.16 it can be observed that:

- It was observed that stiffness tends to increase for the higher RAP content in most instances, except for SM method. It is not clear that the increasing RAP content for SM method did not have any effect on the mix stiffness.
- From Figures 6.13 and 6.14 it can be observed that increasing percentage of the RAP from 40 to 50 % significantly increase the mixture stiffness.
- Increasing RAP content from 40 to 50 % increased higher temperature mix stiffness more than lower temperature stiffness for PW and UPG methods. It was observed from Figure 6.13 that the stiffness of the mixture increased by 33 % at temperature of 35 ^{o}C, but at low temperature (5 ^{o}C) the stiffness increased by 6 % for mixtures prepared using PW method. Similarly it was observed from Figure 6.13 that the increase in

stiffness by 27 and 12 % at 35 and 5 ^{o}C respectively for mixtures prepared using UPG method.

- From Figure 6.15 it was observed that the highest increase in stiffness for a wide temperature range was observed for UPG method when the percentage of RAP increased from 40 to 50. Such increase in stiffness in wide temperature ranges are beneficiary in improving the mixture performances.
- Another interesting observation from Figure 6.15 was increasing the RAP content by 10 % improved the high temperature stiffness (33 % for PW and 27 % for UPG methods) which is important for rutting resistance.

6.5 Indirect Tensile Strength test results

Moisture sensitivity in an asphalt mixture is typically manifested by a gradual loss of strength over a period of time resulting in the development pavement distress. Loss of strength is due to the weakening of the bond between the asphalt cement and aggregate. Stripping may occur, which can lead to aggregate particles becoming detached from the asphalt concrete matrix. This section contains test results of Indirect Tensile strength (ITS) and Indirect Tensile Strength Ratio (ITSR) for different mixing methods and percentage of RAP content.

The Indirect Tensile Strength was measured by applying a vertical load at a constant rate of deformation of 50 mm/min. The strength test was stopped when the applied load went to zero (i.e. total failure of the specimen occurred).Typical Indirect Tensile Strength test results consists the measurements of compressive vertical load and vertical displacements. A typical result of the output is given in Figure 6.17. The maximum value of the load used to compute the Indirect Tensile Strength of the specimen using eq. (3.3).

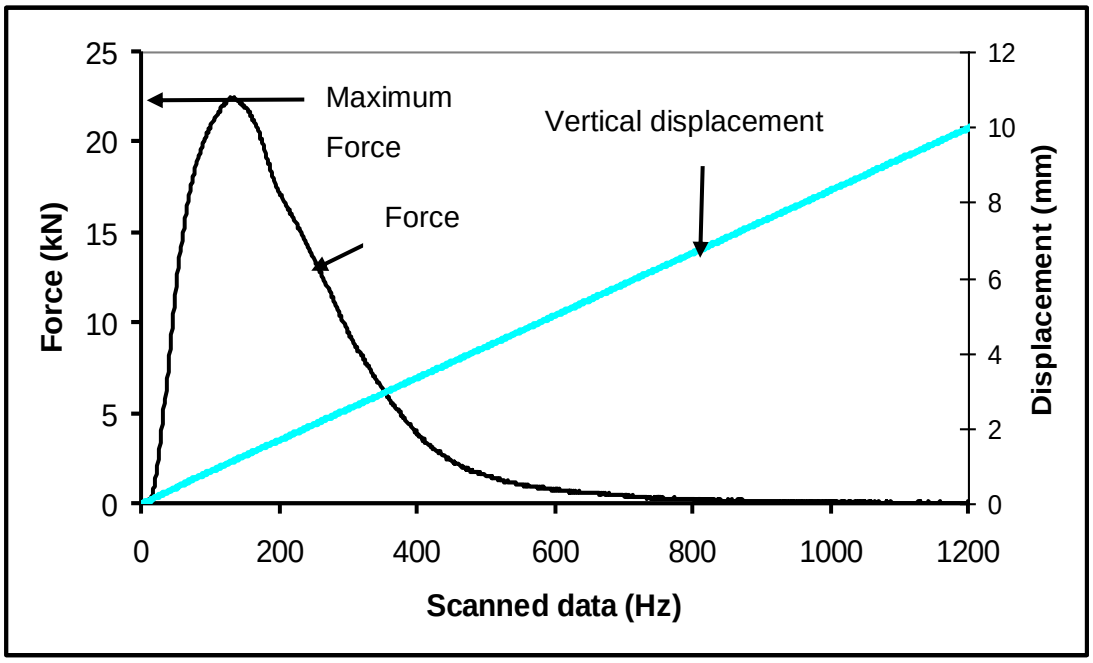

Figure 6.17: Typical Force, displacement results vs. scanned data in Indirect Tensile Strength test

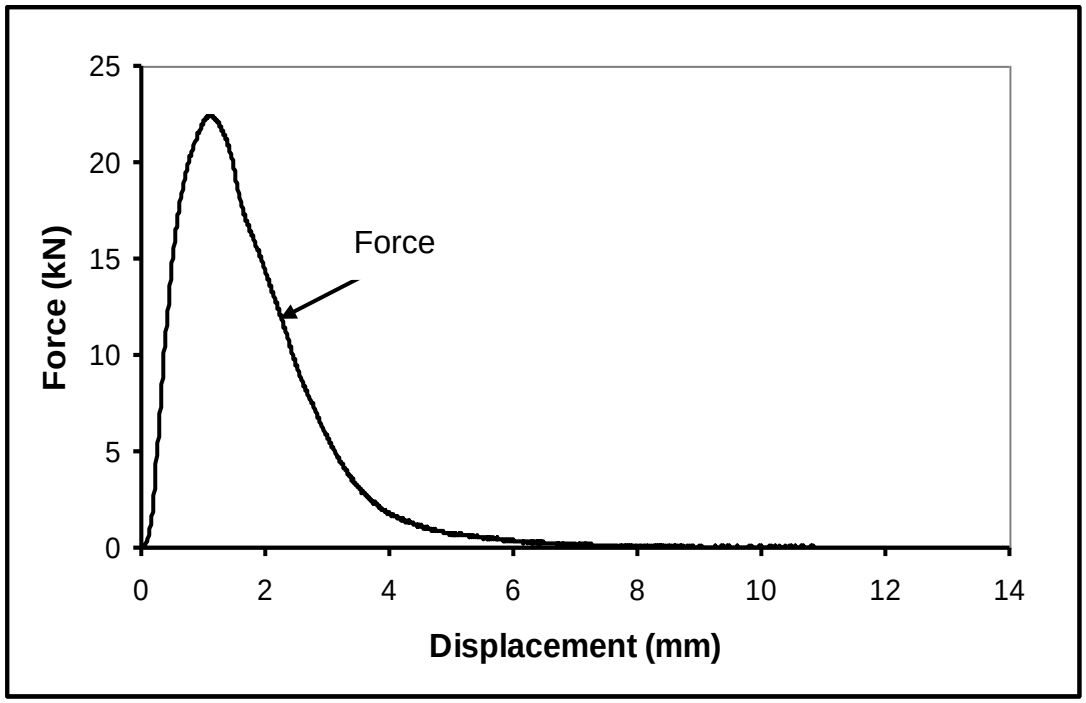

Figure 6.18: Illustration showing the determination of Indirect Tensile Strength

6.5.1 Effect of mixing method in water sensitivity (ITSR)

Results of the indirect tensile strength tests for both conditioned and unconditioned specimens are summarized in Table 6.7. The indirect tensile strength test results for all specimens are attached in Appendix D. The moisture sensitivity is measured by the percentage of the retained tensile strength ratio of the conditioned (wet) specimens compared to unconditioned (dry) specimens. The Dutch RAW 2005 standard requires that the retained tensile strength to be greater than 80 % for base course mix (STAC 0/22). Figure 6.19 is the graphical presentation of the test results for the three mixing methods with 40 and 50 % RAP. From Table 6.7 it can be seen that the ITSR value for all mixtures found to be above the minimum requirement 80 %.

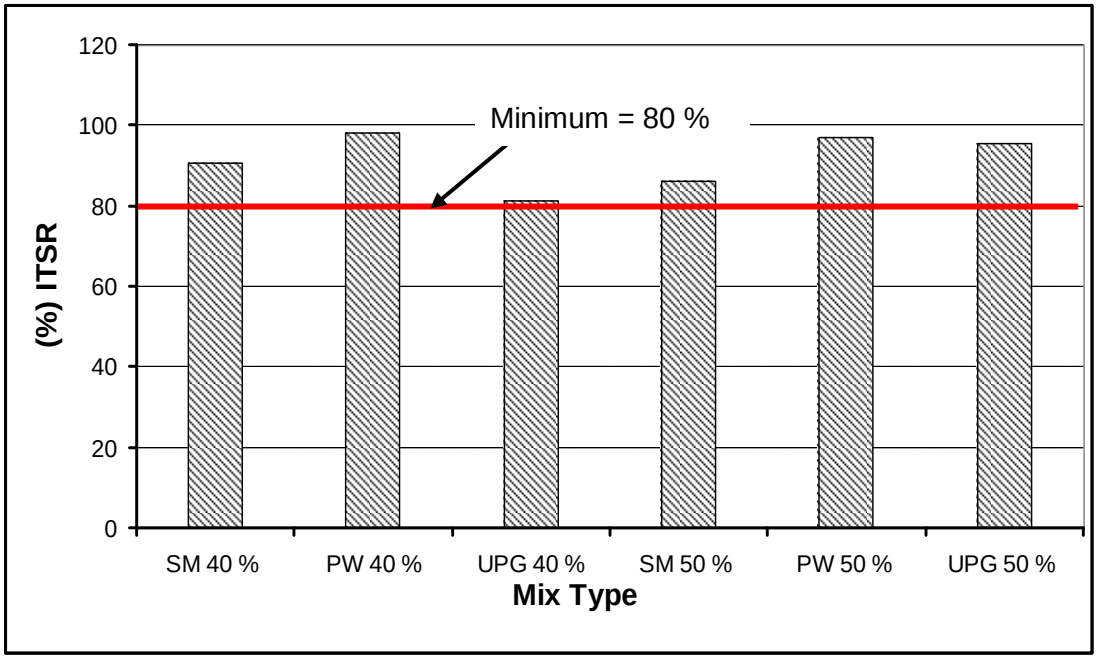

Figure 6.19: Indirect Tensile Strength Ratio (ITSR)

Mixing Method	RAP (%)		Air Voids Unconditioned (%)	Air Voids Conditioned (%)	ITS Unconditioned (MPa)	ITS Conditioned (MPa)	ITSR (%)
Standard Mixing (SM)	40	Average	4.39	4.66	3.50	3.17	90.6
		Stdev	0.30	0.42	0.26	0.29	
		CV (%)	6.89	8.99	7.41	9.07	
	50	Average	4.32	4.89	3.45	2.98	86.2
		Stdev	0.18	0.25	0.33	0.05	
		CV (%)	4.09	5.21	9.66	1.85	
Partial Warming (PW)	40	Average	4.41	4.47	2.99	2.94	98.4
		Stdev	0.34	0.17	0.09	0.27	
		CV (%)	7.76	3.72	3.01	9.22	
	50	Average	4.48	4.29	3.30	3.20	97.1
		Stdev	0.43	0.15	0.32	0.35	
		CV (%)	9.69	3.47	9.57	10.78	
Upgraded Mixing (UPG)	40	Average	4.28	4.63	2.84	2.31	81.4
		Stdev	0.31	0.42	0.18	0.25	
		CV (%)	7.15	9.00	6.42	10.86	
	50	Average	4.21	4.59	3.26	3.11	95.5
		Stdev	0.24	0.42	0.32	0.25	
		CV (%)	5.74	9.13	9.81	7.94	

Table 6.7: Summary of indirect tensile strength test results

6.5.2 Effect of mixing method on Indirect Tensile Strength

Figures 6.20 and 6.21 present the results of indirect tensile strength test with 40 and 50 % RAP contents. Each value in the figure represents the average of three test replicates. From Figures 6.20 and 6.21 it can be seen that the highest tensile strength observed for mixtures prepared using SM methods 40 and 50 % RAP. Figures 6.20 and 6.21 also show that the lowest indirect tensile strength value observed for UPG method. It can be observed that the increase in tensile strength had relation with increasing in RAP heating temperature (0, 130 and 170 ^{o}C for UPG, PW and UPG methods respectively). This trend seems logical, because the SM method with the most aged binder exhibited the highest stiffness too (section 6.3).

From Figures 6.20 and 6.21 it can be observed that higher difference in tensile strength by mixing method was observed with 40 % RAP than 50 %.

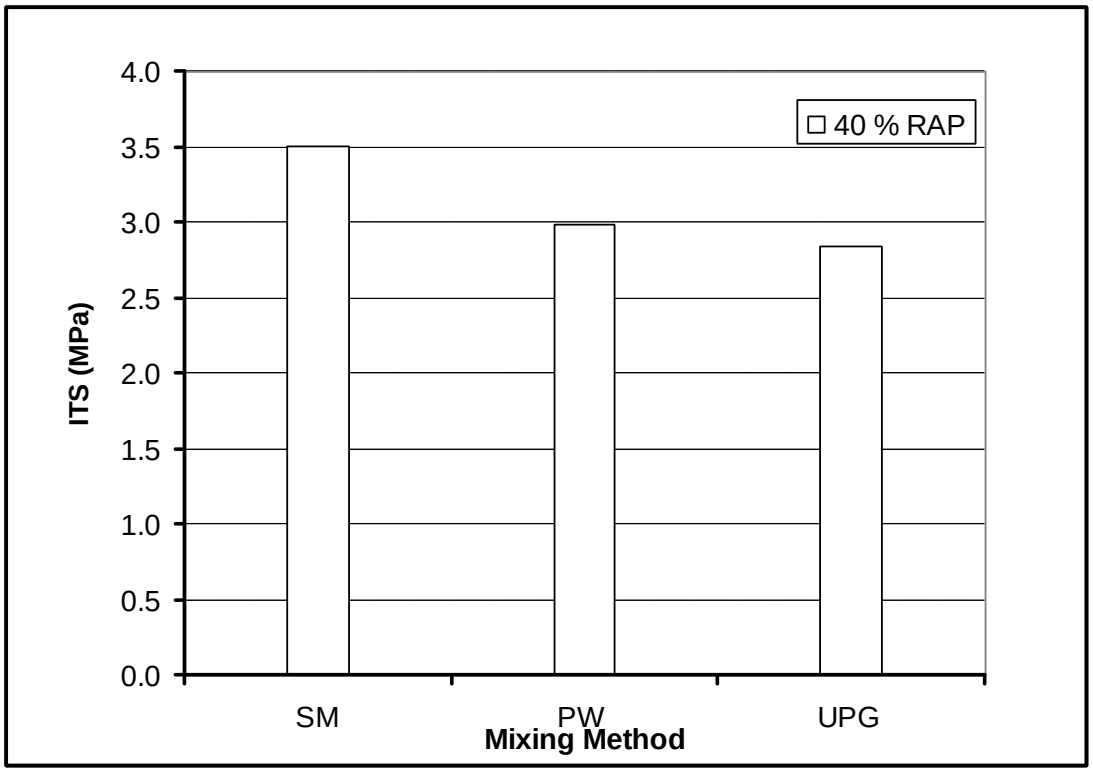

Figure 6.20: Comparison of Indirect Tensile Strength (unconditioned) by mixing method 40 % RAP

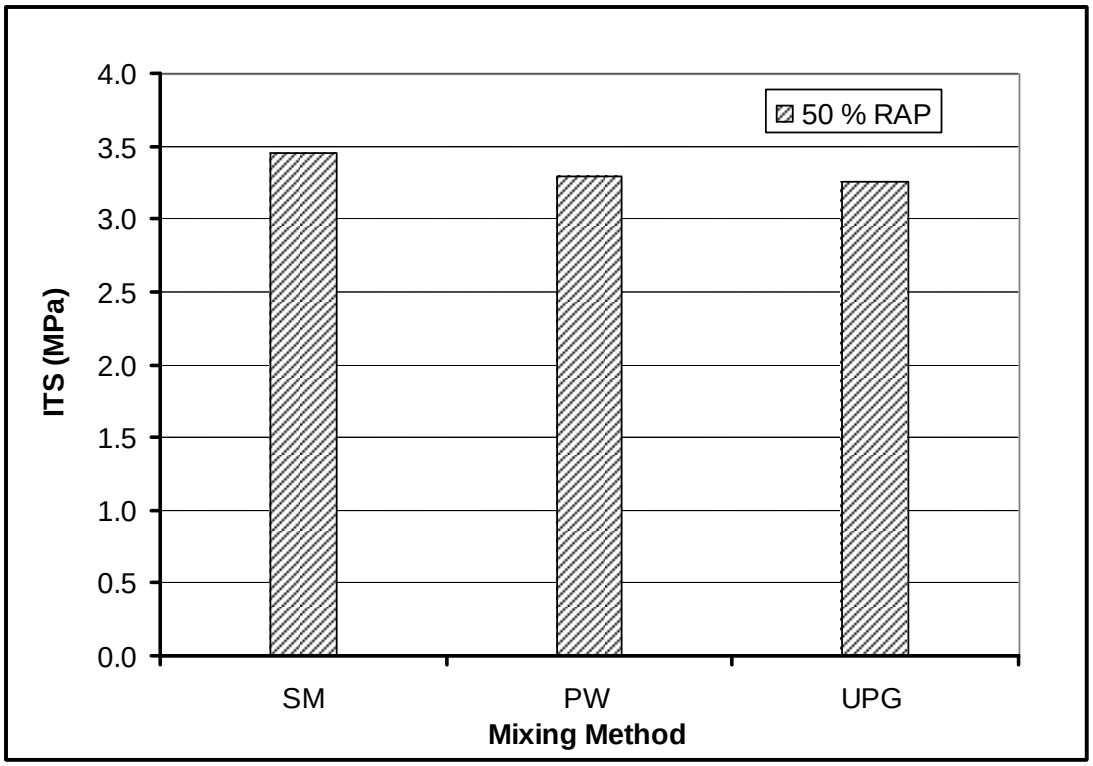

Figure 6.21: Comparison of Indirect Tensile Strength (unconditioned) by mixing method 50 % RAP

6.5.3 Effect of percentage of RAP on indirect tensile strength

Figures 6.22 and 6.23 present the indirect tensile strength results of the unconditioned (dry) and conditioned (wet) specimens with 40 and 50 % RAP. Each value in the figures represents the average of three test replicates. Figure 6.22 shows the tensile strength (unconditioned) results for different mixing methods with 40 and 50 % RAP. From Figure 6.22 it can be observed that the tensile strength increased with increasing percentage of RAP for PW and UPG methods, whereas for SM method increasing percentage of RAP content did not increase the tensile strength (Figure 6.22). Similar trend already observed for SM method the stiffness values did not show an increase with increasing RAP content (section 6.4).

Figure 6.23 also show tensile strength (conditioned) results for different mixing methods with 40 and 50 % RAP contents. From Figure 6.23 it can be seen that the tensile strength increased with increasing RAP percentage for

PW and UPG methods, whereas the SM method showed a reduction in tensile strength when RAP content increased.

It can be observed that from Figures 6.22 and 6.23 that increasing RAP percentage did not increase the tensile strength in proportion to the amount of RAP added. The highest increase in tensile strength was observed in UPG method followed by PW method.

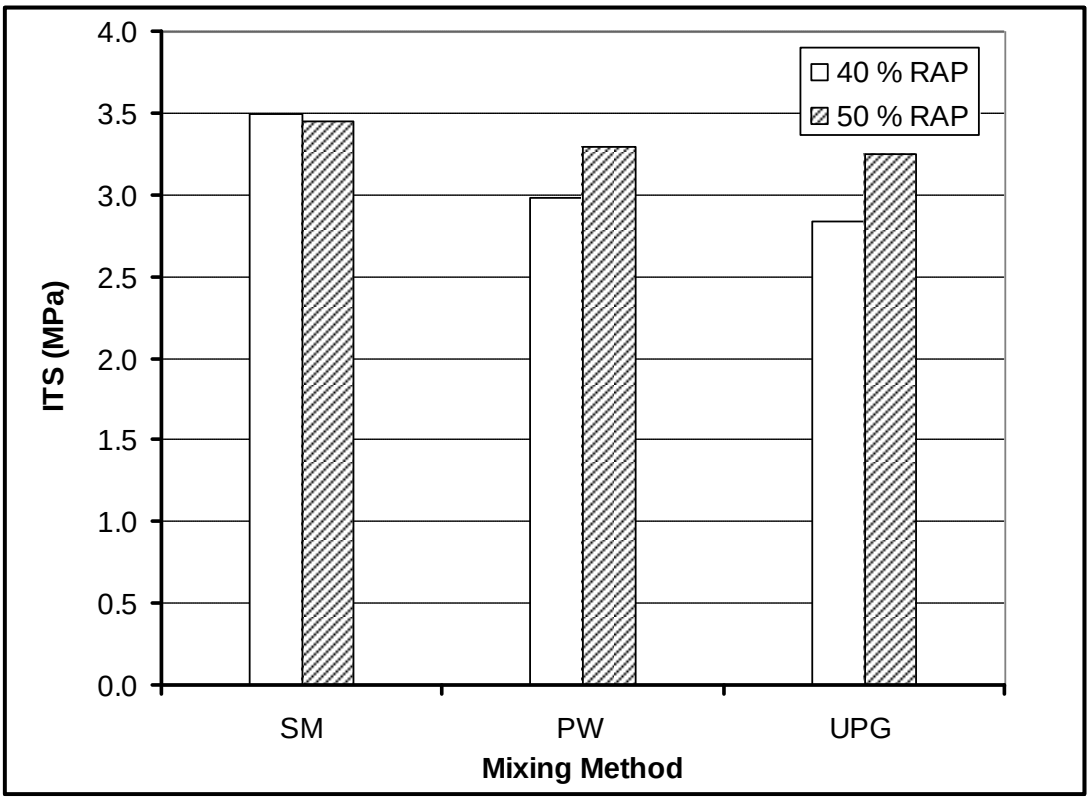

Figure 6.22: Indirect Tensile Strength results (unconditioned) 40 and 50 % RAP

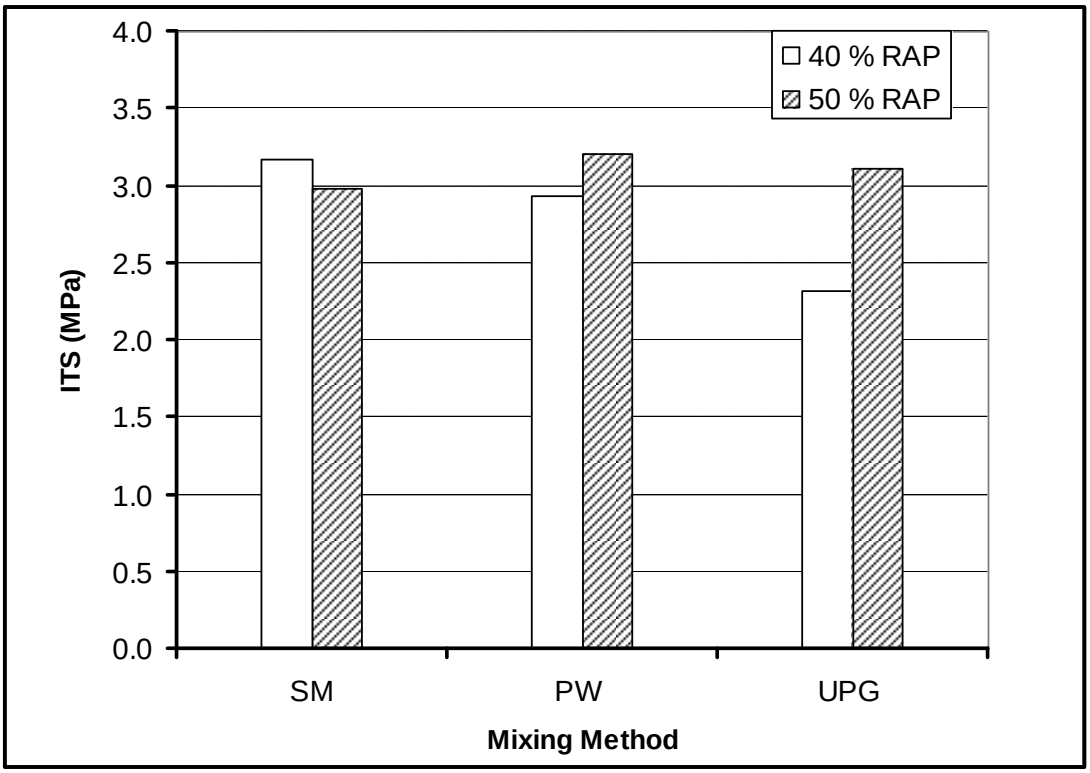

Figure 6.23: Indirect Tensile Strength results (conditioned) 40 and 50 % RAP

6.6 Permanent deformation results

This section contains the results and analysis of the permanent deformation tests. The tests were done for three different mixing methods (SM, PW and UPG) and with 40 and 50 % RAP. The main objectives of the permanent deformation test program are:

- To determine effect of mixing method on the resistance of the permanent deformation of mixture.
- To analyse the effect of increasing RAP content on the permanent deformation of the mixture.

6.6.1 Test methods and calculations

The cyclic permanent deformation test was conducted by application of a haversine axial compressive load to a specimen with 100 mm diameter and 80 mm thickness. The duration of the loading pulse was 0.4 seconds followed by a rest period of 0.6 seconds. The test duration was approximately 3 hours for 10000 loading cycles. The vertical deformation of the specimen was monitored with the actuator LVDT and two LVDTs mounted on the specimen. During the testing a constant all round confining pressure of 50 kPa was applied. The accumulated permanent strain is reported in percentage computed as average permanent deformation divided by specimen thickness.

Figure 6.24 illustrates a typical relationship between the percentage cumulative axial strain and number of load cycles. The cumulative axial permanent strain curve is generally divided in three phases: the primary, secondary and tertiary creep phase. In the primary phase, permanent deformations accumulate rapidly. The incremental permanent deformations decrease reaching a constant value in the secondary zone. Finally, the incremental permanent deformations again increases and permanent deformation accumulate rapidly in the tertiary phase.

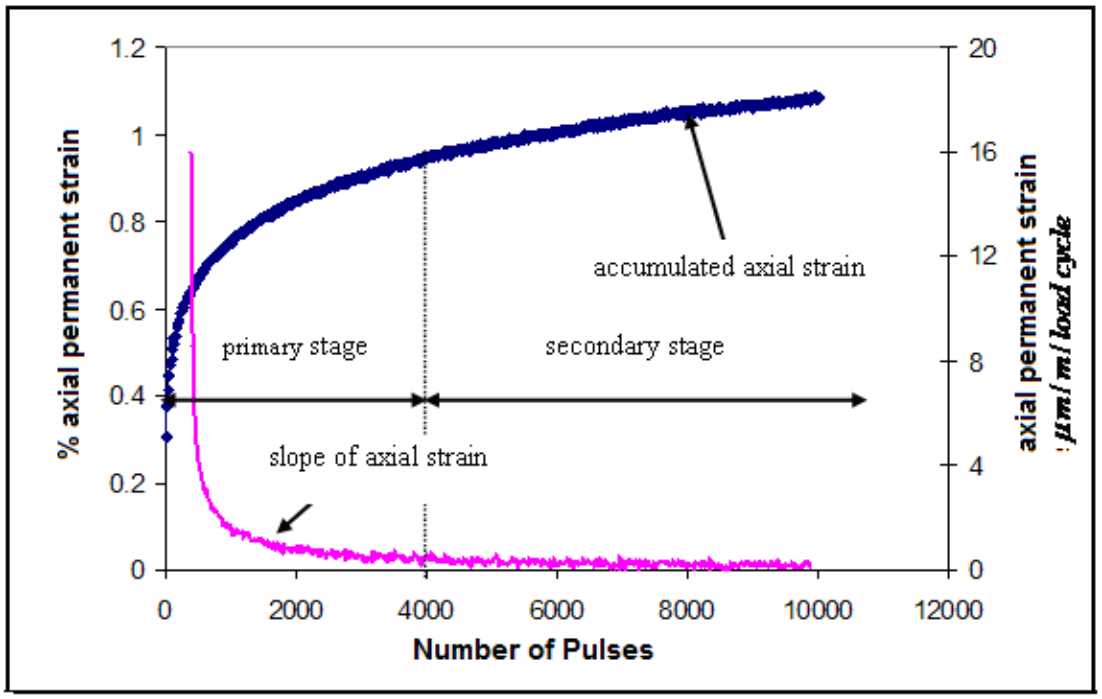

Figure 6.24: Typical plot of percentage permanent axial strain and strain slope vs. number of pulses

It can be seen from the plot in Figure 6.24 that only primary and secondary stages of the curve were reached. On the same Figure 6.24, the plot of the rate of change of axial permanent strain (slope) versus loading cycles also presented. It can be seen that in the primary stage, the rate of change of axial permanent strain decreases rapidly; in the secondary stage the strain rate is becoming almost constant.

The results of the permanent deformation test in terms of the percentage cumulative axial permanent strain versus the number of loading cycles were analysed by using the method described in European standard EN 12697-25. The description of the analysis method will be presented as follows:

- **Method 1: Determination of the creep rate 'f_c':** From the linear (secondary) portion of the permanent axial strain - load repetitions relationship 'f_c' (the rate of change in loading cycles) determined from the least square linear fit. The following equation used to analyse the test result for linear portion of the graph:

$$\varepsilon_n = a + b \ .n \qquad \text{(Eq. 6.4)}$$

Where:

ε_n Cumulative axial strain of the specimen after 'n' load applications (%)

a Intercept, the permanent deformation at first load cycle

f_c slope b but expressed in micro strain/loading cycle

Figure 6.25 shows the determination of the creep rate using the aforementioned procedure.

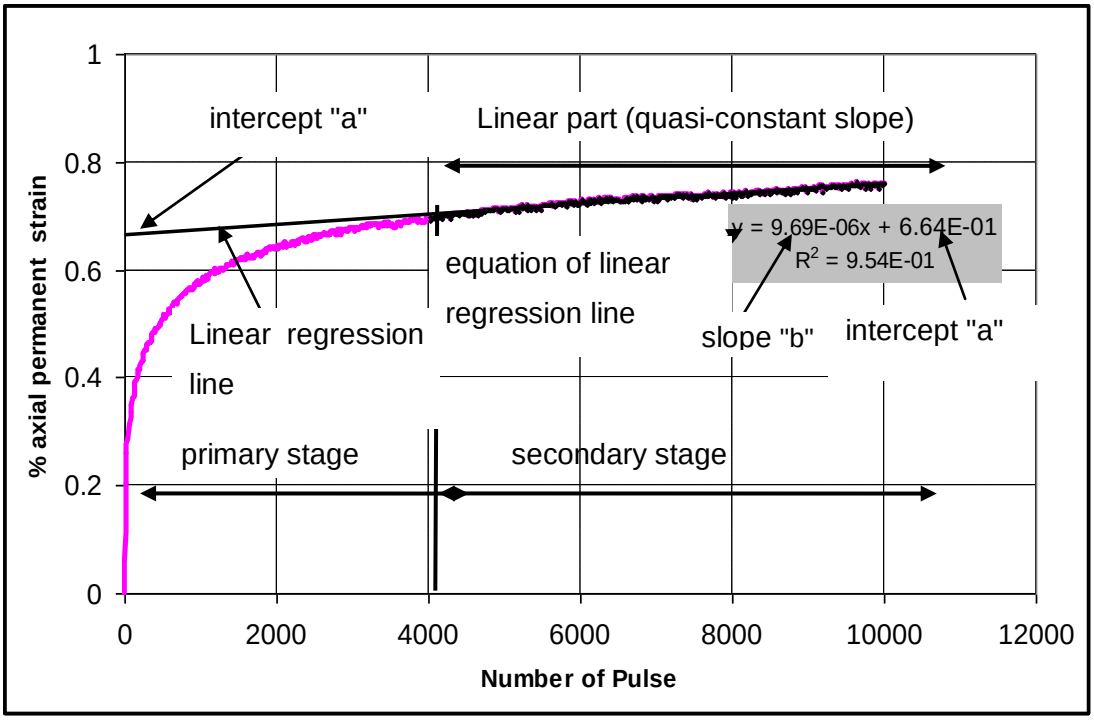

Figure 6.25: Determination of regression constants from % axial permanent strain vs. number of load pulses plot

- **Method 2: Determination of the parameters 'b' and $\varepsilon_{1000cal}$:** From the relationship of axial permanent strain and the number of load cycles for the linear part of the curve, intercept 'a' represents the axial permanent strain for the first cycle, whereas the slope 'b' represents the rate of change in loading cycles. These two regression constants determined using the least square power fit curve fitting techniques for the linear part of the curve. The following equation used to analyse the test results for the linear portion of the graph:

$$\varepsilon_n = a.n^b \qquad \text{(Eq. 6.5)}$$

Where:

ε_n cumulative axial strain of the specimen after n load Applications (%);

b power of the least square power fit.

After determination of the regression constants, the permanent deformation after 1000 load cycles, $\varepsilon_{1000,cal}$, in percent can be computed using:

$$\varepsilon_{1000,cal} = a.1000^b \qquad \text{(Eq. 6.6)}$$

The parameters 'b' and $\varepsilon_{1000,cal}$ are used to characterize the resistance to permanent deformation. Figure 6.26 shows the curve fitting parameters used in the aforementioned method.

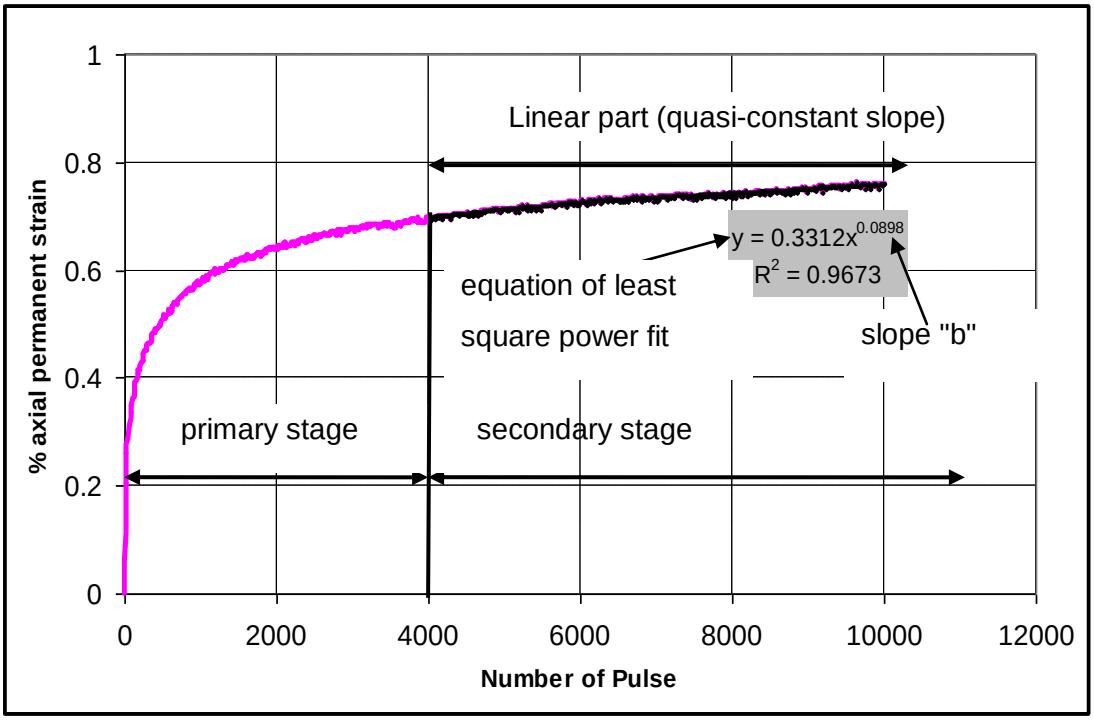

Figure 6.26: Determination of regression constants from % axial permanent strain vs. number of load pulses plot.

6.6.2 Analysis and comparison of test results

The resistance to permanent deformation of the mixtures can be expressed by parameters obtained from axial permanent strain versus loading cycles curves. In all tests in this research, only primary and secondary stages were observed in axial permanent strain versus loading cycles curves. The permanent strain at 1000 pulses together with the slope of strain in the linear part (secondary stage) of the curve used for comparisons of the results of different mixing methods and RAP content.

The results of the repeated load permanent deformation tests for all the three mixing methods and two percentage of RAP were summarized and reported in Appendix E. The percentage of axial permanent strain corresponding to the number of load repetitions for different mixing methods and RAP contents is plotted in Figure 6.27 (each plot represents an average of three test replicates). Table 6.8 contains the average values of the percentage of axial permanent strain at 1000 and 10000 cycles. Table 6.9 shows the regression constants (a-intercept and b-slope) obtained using different models.

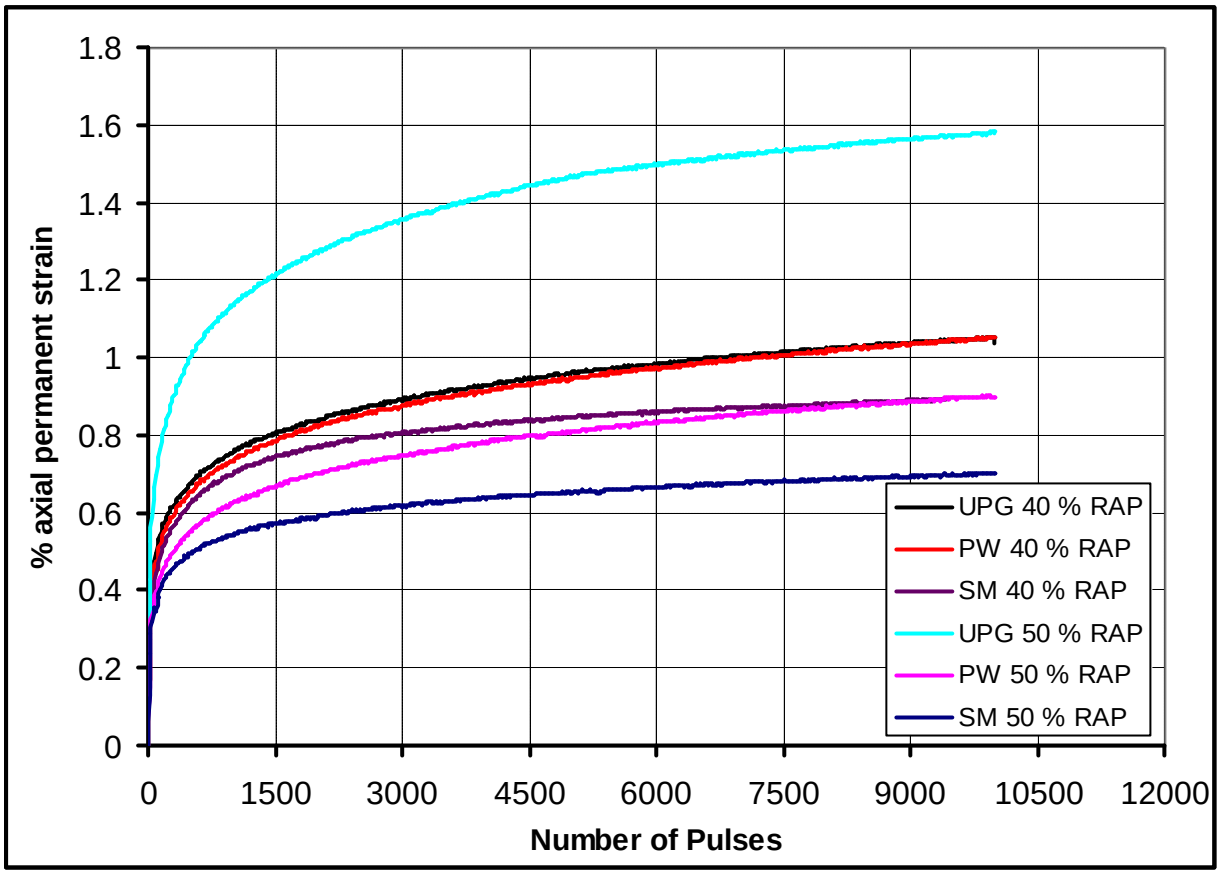

Figure 6.27: Summary of the % axial permanent strain vs. number of pulses

Mixing Method	RAP (%)	Axial cumulative permanent strain at 1000 cycles			Axial cumulative permanent strain at 10000 cycles			Axial cumulative permanent deformation at 10000 cycles		
		Average (%)	Stdve (%)	CV (%)	Average (%)	Stdve (%)	CV (%)	Average (mm)	Stdve (mm)	CV (%)
Standard Mixing (SM)	50	0.555	0.07	12.41	0.702	0.08	11.23	0.561	0.06	11.23
	40	0.739	0.18	24.86	0.899	0.27	30.17	0.720	0.22	30.31
Partial Warming (PW)	50	0.633	0.10	15.77	0.900	0.24	27.18	0.721	0.20	27.25
	40	0.742	0.20	27.05	1.050	0.29	27.83	0.841	0.23	27.82
Upgraded Mixing (UPG)	50	1.220	0.25	20.61	1.581	0.39	24.41	1.265	0.31	24.38
	40	0.774	0.05	5.95	0.843	0.03	4.22	0.829	0.03	4.22

Table 6.8: Axial cumulative permanent strain and deformation results

Mixing Method	RAP (%)	Model Fitted						
		$\varepsilon_n = a + b.n$				$\varepsilon_n = a.n^b$		
		a	b	f_c	R^2	a	b	R^2
Standard Mixing (SM)	50	0.6032	1.01E-05	0.1013133	0.9587	0.279233	0.101767	0.9708667
	40	0.79246	1.08E-05	0.1080733	0.9343333	0.422733	0.08	0.9510333
Partial Warming (PW)	50	0.7129333	1.95E-05	0.1951	0.954	0.2361	0.1469	0.9864
	40	0.8369667	2.22E-05	0.2220667	0.9823	0.261133	0.150767	0.9923333
Upgraded Mixing (UPG)	50	1.339	2.53E-05	0.2529	0.9646	0.564867	0.1104	0.9851
	40	0.8612667	1.98E-05	0.1981667	0.9780333	0.320033	0.133833	0.9896

Table 6.9: Permanent deformation resistance parameters (regression constants)

6.6.3 Effect of mixing method on resistance to permanent deformation

To see the effect of mixing method on the permanent deformation behaviour of the mixtures, the slope of axial permanent strain and the % axial permanent strain after 1000 and 10000 load pulses were compared for the three mixing methods. The following points can be seen from the test results:

- From Figure 6.28 and 6.29 it can be seen that for all mixing methods and percentage of RAP, only the primary and secondary stages in the plots of % axial permanent strain vs. number of pulses were reached.
- The data shown in Figure 6.28 suggest that with 40 % RAP, the % axial permanent strain of the SM method is lower than the PW and UPG methods. The % axial permanent strain of PW and UPG methods is 1.3 times higher than SM method.
- Figure 6.29 shows that with 50 % RAP the SM method exhibited better performance in comparison to PW and UPG mixes. The UPG method showed a higher % axial permanent strain.
- Figures 6.30 and 6.31 show that for all mixing methods the slope of axial permanent strain for all mixing methods were less than the maximum acceptable slope (requirement) of the Dutch RAW 2005 standard (fcmax = $0.4\ \mu m/m$/load cycle).
- Figures 6.30 and 6.31 show that the SM method with 40 and 50 % RAP had the lowest slope. The slope for mixes produced with UPG method UPG method is 2.5 times higher than the slope in the SM method with 40 % RAP and 2 times higher with 50 % RAP.
- For all mixtures with 40 and 50 % of RAP in Figures 6.32 and 6.33, it can be observed that 80 % of the cumulative axial permanent strain occurred in the first 1000 number of pulses.

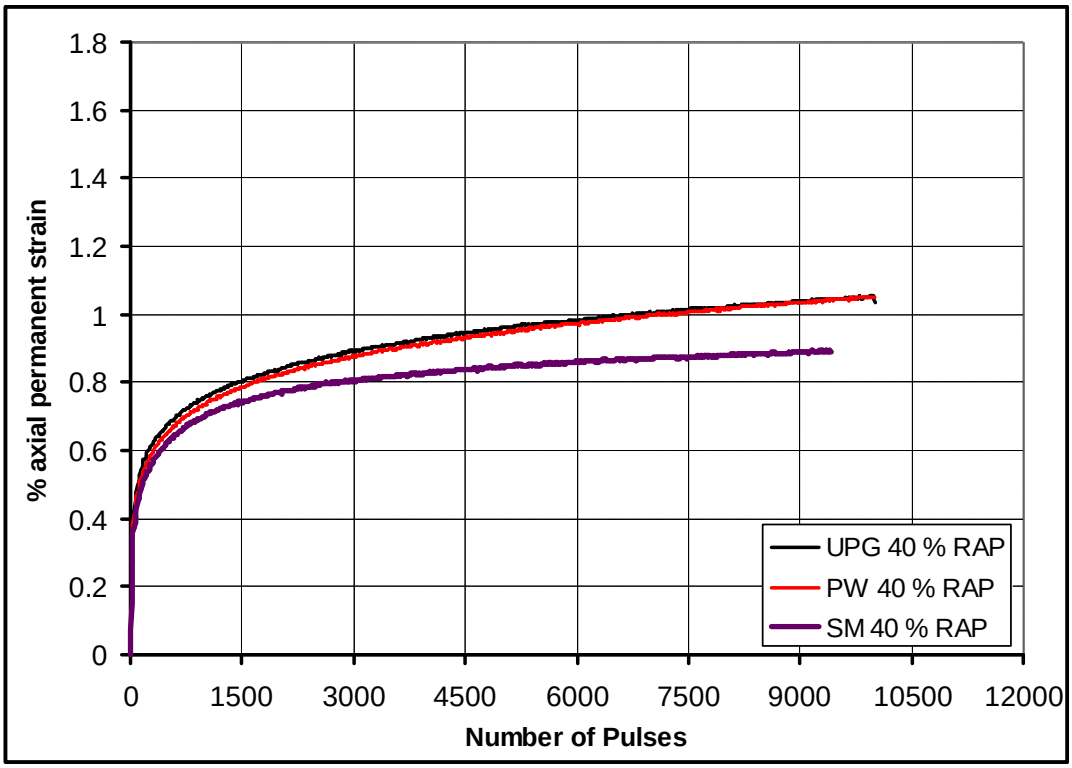

Figure 6.28: % axial permanent strain vs. number of pulses (40 % RAP)

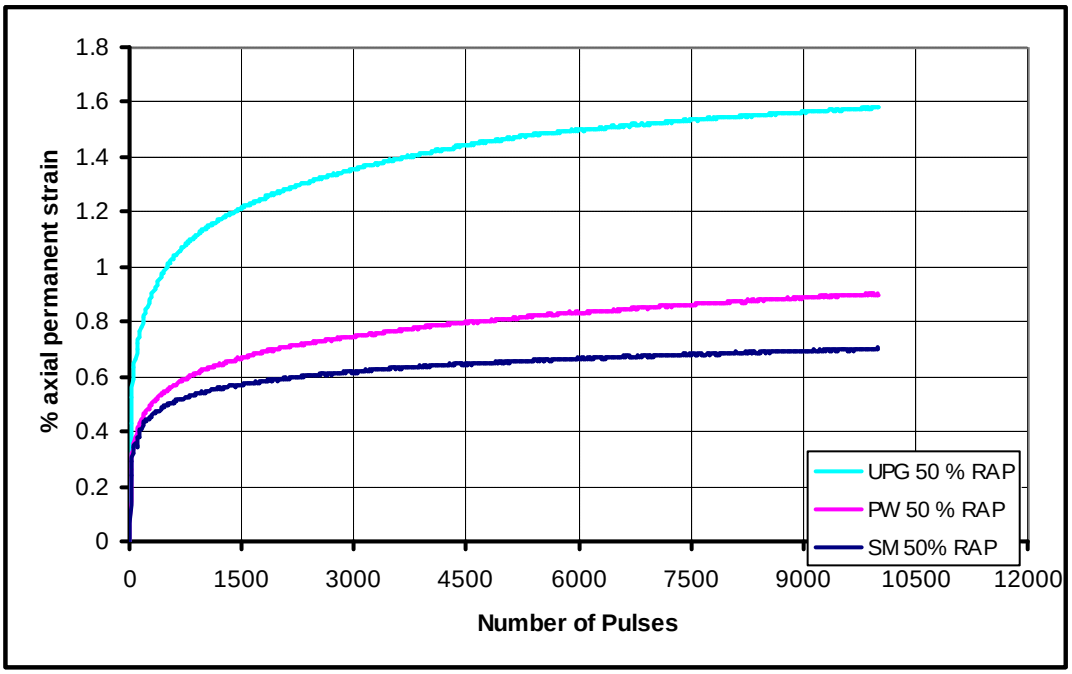

Figure 6.29: % axial permanent strain vs. number of pulses (50 % RAP)

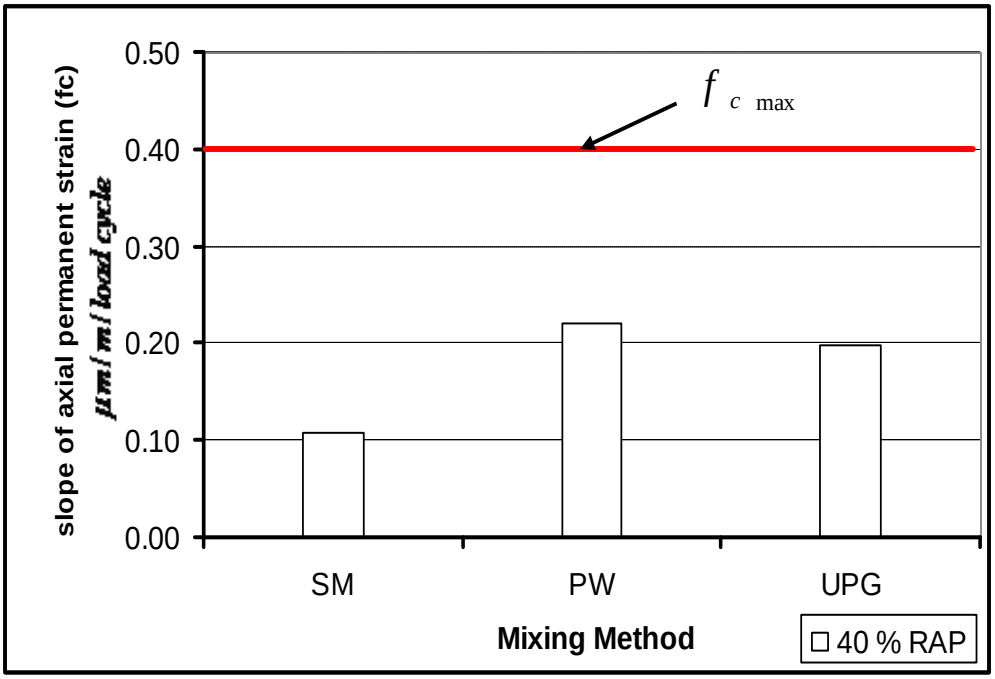

Figure 6.30: Rate of axial permanent strain 'fc' (40 % RAP)

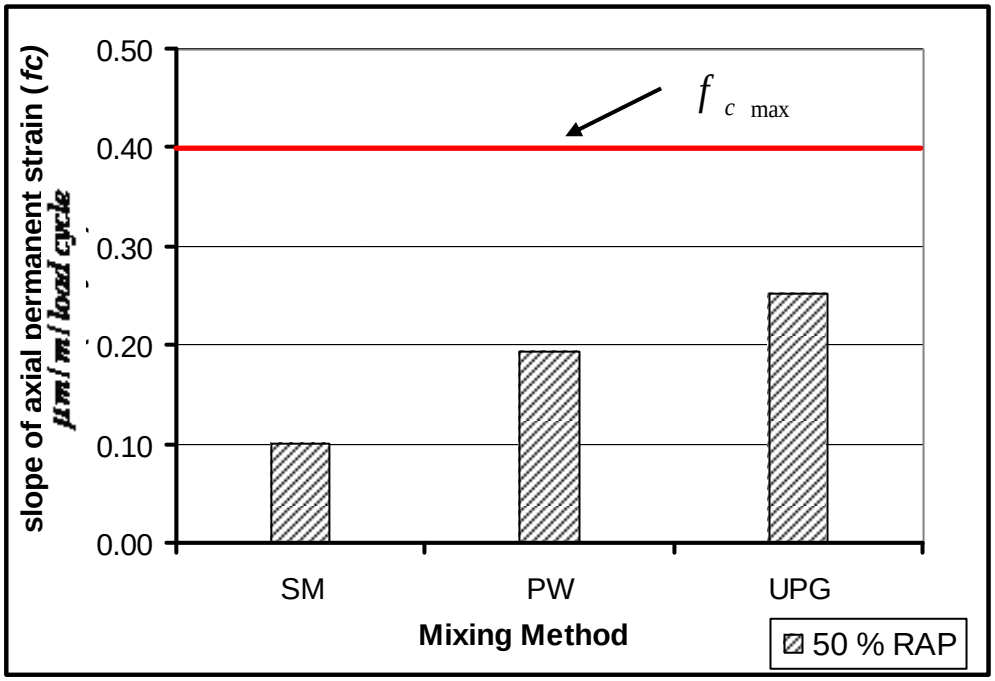

Figure 6.31: Rate of axial permanent strain 'fc' (50 % RAP)

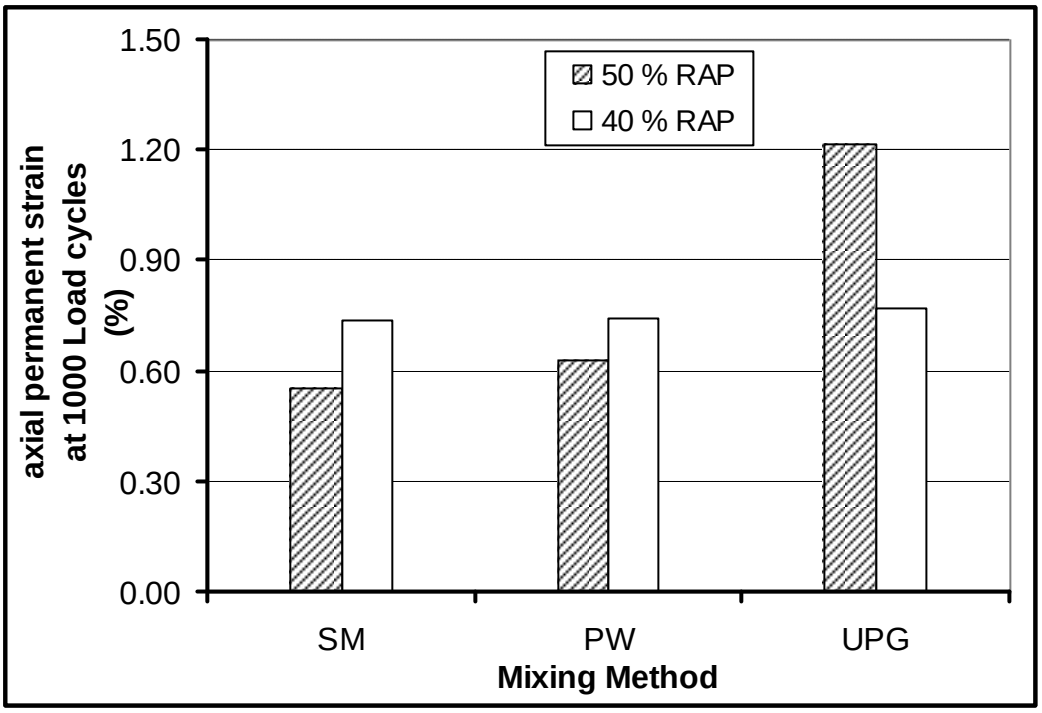

Figure 6.32: % cumulative axial permanent strain at 1000 load cycles

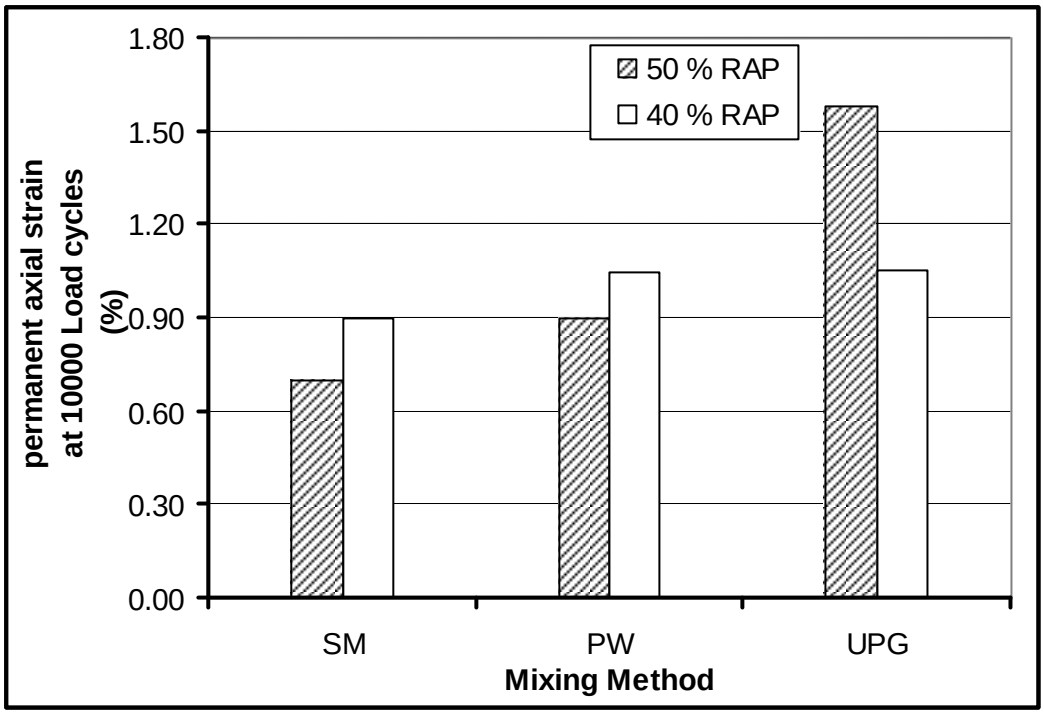

Figure 6.33: % cumulative axial permanent strain at 10000 load cycles

6.6.4 Effect of RAP content on permanent deformation

The influence of increasing RAP content from 40 to 50 % on the permanent deformation behaviour of the mixtures was studied. The slope of axial permanent strain and the percentage axial permanent strain after 1000 and 10000 load pulses were analysed. Figures 6.34, 6.35 and 6.36 show the plot of % axial permanent strain vs. number of pulses for each mixing method with 40 and 50 % RAP content. The slope of axial permanent strain and the percentage axial permanent strain after 1000 load pulses were mentioned in the Tables 6.8 and 6.9.

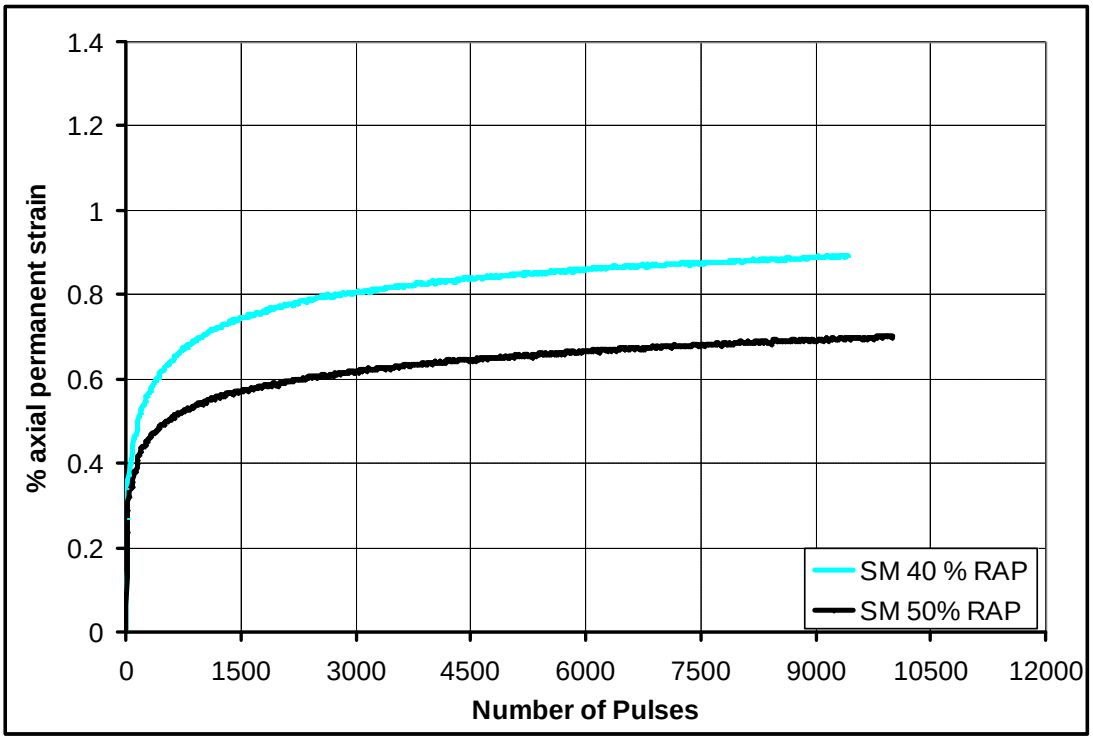

Figure 6.34: % axial permanent strain vs. number of pulses with 40 and 50 % RAP (SM method)

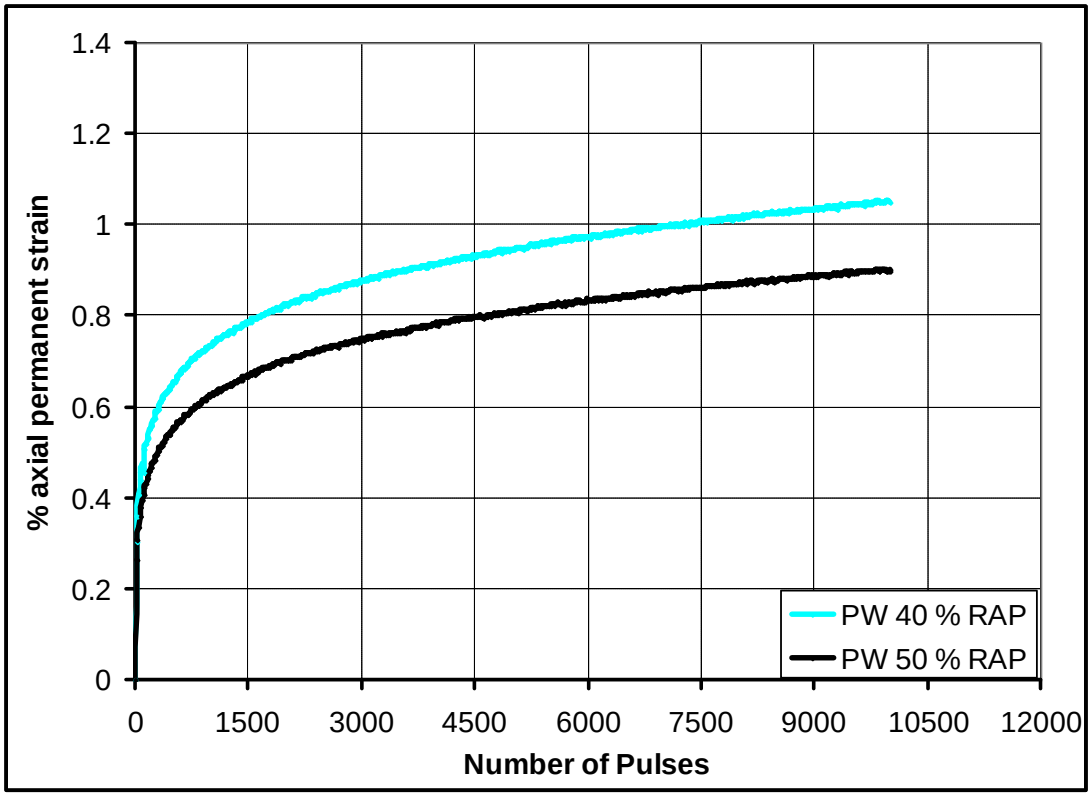

Figure 6.35: % axial permanent strain vs. number of pulses with 40 and 50 % RAP (PW method)

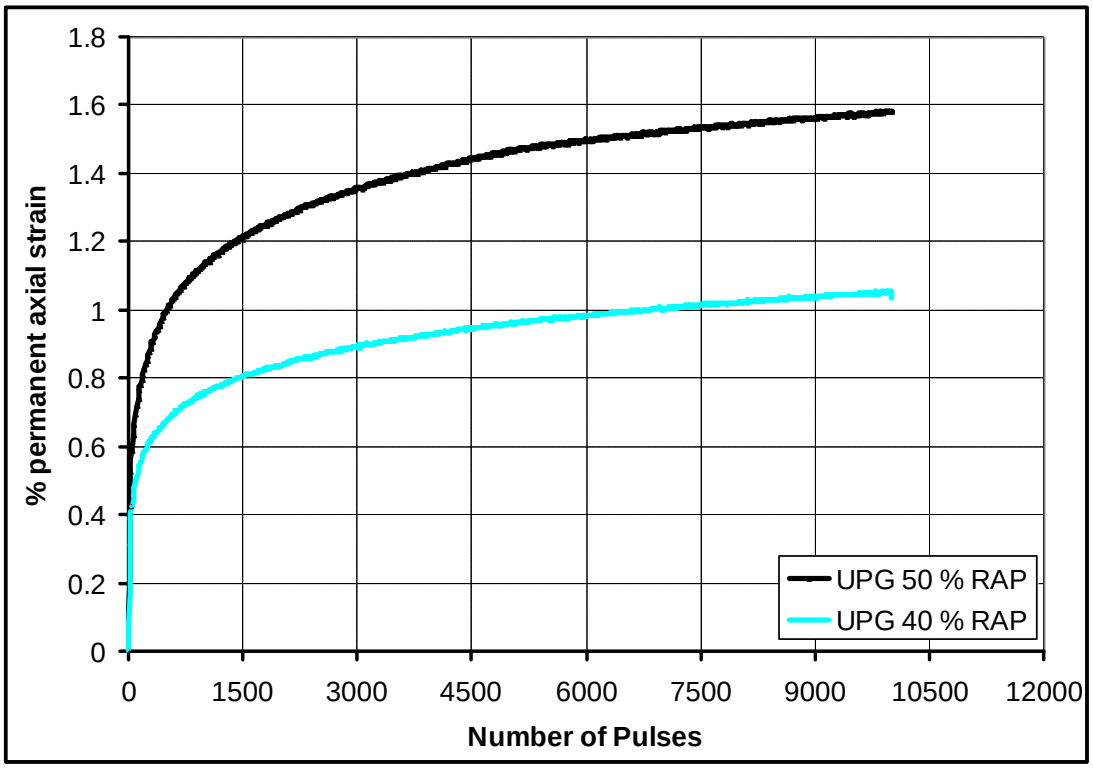

Figure 6.36: % axial permanent strain vs. number of pulses with 40 and 50 % RAP (UPG method)

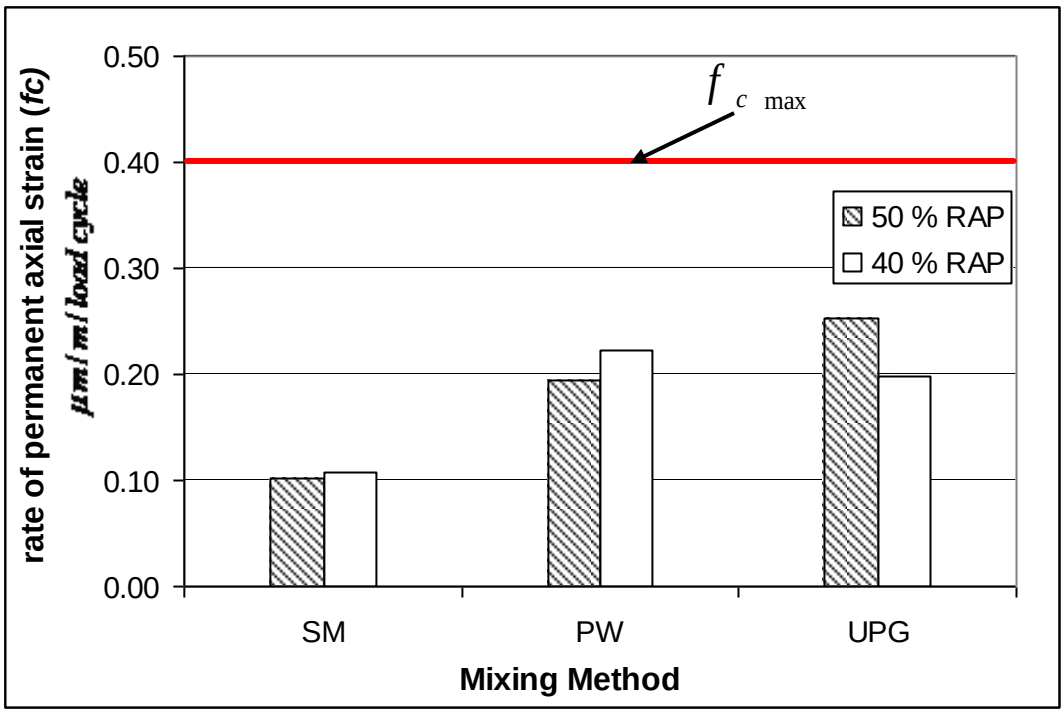

Figure 6.37: Rate of axial permanent strain vs. mixing method

From the Figures 6.34, 6.35, 6.36 and 6.37 it can be observed that:

- Increase in RAP content from 40 to 50 % reduces the percentage axial permanent strain by 22 and 14 % for SM and PW methods respectively (Figures 6.34 and 6.35).
- Figure 6.36 shows that increasing the RAP content from 40 to 50 % almost doubles the percentage axial permanent strain for the UPG method.
- Figure 6.37 showed that increasing the RAP content from 40 to 50 % results in a decrease in slope by 6 and 12 % for SM and PW methods respectively. For UPG method increasing the RAP content increased the slope by 22 %.
- Except for the UPG with 4 % moisture, increasing RAP content improves the permanent deformation resistance of the mixture as shown in Figures 6.34 and 6.35.

Chapter 7 Conclusions and Recommendations

This chapter discusses the conclusions drawn from the different tests performed and analyzed in this study for the three laboratory mixing methods used. The conclusions include observations of the different mixing methods, effect of mixing methods and RAP content on mixture stiffness, water sensitivity, resistance to permanent deformation and general conclusions. The recommendations for further research are given at the end of this chapter.

7.1 Conclusions

7.1.1 Mixing Methods

- Laboratory handling of the RAP material prior to mixing has impact on the performance properties of asphalt mixes.
- In the UPG method with 4 % moisture content, the heating temperature of the virgin aggregate should be sufficient enough to remove the moisture from RAP and soften the RAP binder so that blending with virgin binder could take place to the extent possible.
- The sequence of mixing of materials in the right order and time is important to maximize the temperature transfer from virgin aggregate to RAP material.
- Minimizing the heat loss during the mixing process of the UPG method is important. All the mixing equipment and the surrounding environment need to be equipped with a heat insulation system.
- The UPG mixing method minimizes the extra hardening of the RAP binder by avoiding the preheating of RAP before mixing and minimizing the availability of free oxygen during mixing process.
- The mineralogical composition of the virgin aggregate does not change by heating the virgin aggregate to the high temperatures (300 – 400 ^{o}C) in the UPG method.

7.1.2 Effect of mixing method on performance properties

Effect of mixing method on Stiffness

- This research has shown that the stiffness of the mixture increases with increasing preheating temperature of the RAP (RAP heating temperature 0, 130 and 170 ^{o}C for UPG, PW and SM methods respectively).
- Although stiffness of mixture impacted by aggregate gradation and air voids, the most significant factor is the stiffness of the binder.
- The degree to which the RAP binder blends with the virgin binder is also related to the degree to which the RAP is heated during mixing. If the RAP material is not heated sufficiently, the RAP binder does not blend with the virgin binder to the extent possible and the RAP then tends to act more like a black rock material. In such case only the softer virgin binder becomes the binding agent which subsequently cause lower stiffness mix.
- The highest change in mixture stiffness by mixing method was observed at high temperature for both 40 and 50 % RAP content.

Effect of mixing method on water sensitivity and indirect tensile strength

- All mixtures exhibited a high value of ITSR ratio than the minimum requirement. No clear relationship was observed in this study the effect of mixing method on water sensitivity.
- The study has clearly shown the increase in tensile strength with increasing the RAP heating temperature. The highest tensile strength in 40 and 50 % RAP content was observed for SM method and the lowest for UPG method. Similar trend is also observed in mixture stiffness too.
- With 40 % RAP content higher difference on tensile strength by mixing method was observed than 50 %.

Effect of mixing method on permanent deformation

- This research has shown that generally mixture rutting resistance increased with increasing preheating temperature of the RAP (RAP heating temperature 0, 130 and 170 ^{o}C for UPG, PW and SM methods respectively).
- For all mixing methods the percentage axial permanent strain per load cycles '*fc*' was found to be below the maximum requirement (f_{cmax} = 0.4 μ m/m/load cycle) set by Dutch RAW 2005 standard.
- For all mixing methods it was found that 80 % of the cumulative axial permanent strain occurred in the first 1000 number of pulses.
- The effect of the mixing method on axial permanent deformation and on axial strain slope is higher for 50 % RAP than 40 %.

7.1.3 Effect of increasing RAP content on performance properties

Effect of increasing RAP content on mixture stiffness

- In almost all cases, the stiffness of the mixtures tends to increase with increasing RAP content from 40 to 50 %, except for the SM method.
- For PW and UPG methods increasing RAP content increased the high temperature mixture stiffness than the low temperature stiffness. Such increase in stiffness at high temperature would be beneficiary for rutting resistance.

Effect of increasing RAP content on water sensitivity and indirect tensile strength

- Increasing RAP content also increased the tensile strength for PW and UPG methods, but this trend was not observed in SM method. Similar phenomena were also observed for the stiffness of the mixtures produced with SM method.
- Although increasing RAP content improves both the dry and wet tensile strength, in this study no clear relation was found between increasing RAP content and indirect tensile strength ratio (ITSR).

Effect of increasing RAP content on permanent deformation

- Increasing RAP content from 40 to 50 % reduces the percentage axial permanent strain by 22 and 14 % for SM and PW methods respectively. For the UPG method increasing RAP content from 40 to 50 % almost doubles the percentage permanent axial strain.
- Increasing the RAP content from 40 to 50 % decreased the slope of permanent axial strain for SM and PW methods.

7.1.4 General Conclusions

Based on the results obtained from this research, the following general conclusions were made. Laboratory handling of RAP material has impact on the measured performance properties of the final mix. Therefore, mix design with high RAP content highly depends on the heating time and temperature of the RAP material prior to mixing with virgin aggregate. In addition, the existing standard mix design procedure (RAP and virgin materials heated to the same temperature) does not simulate the mixing processes in parallel and double drum mixers. Therefore, the performance properties of laboratory made mixes prepared using standard mixing method can not be used to predict the performance properties of mixes made in parallel and double drum mixers.

The higher value of the stiffness observed for mixes produced with SM method may improve the rutting resistance of the mixture.

More research is needed to fully understand the effect of mixing method on performance properties keeping in mind that this study was conducted for only one source of RAP, two different RAP contents, one type of virgin binder, one set of virgin materials, one moisture content in the RAP and one type of mix.

7.2 Recommendations for further Research

This research focused on the effect of different mixing methods on mixture performance properties with 40 and 50 % RAP. The following future research works are recommended:

- More investigations are needed to fully understand the effect of mixing method on performance properties of mixes with different RAP content, RAP source and virgin binder types.
- Additional work should be performed to compare the performance properties of laboratory and plant made mixes.
- The effect of moisture in the RAP and the presence of steamy environment on mixing process need to be studied for the UPG method. In this study only one moisture content (4 %) was used for the UPG method.
- Additional work should be performed on the mixture stiffness by conducting dynamic modulus test using four point bending test. The dynamic modulus test provides information about the effect of mixing method and high RAP content both on storage and loss modulus of a mixture.
- The thermal (low temperature behaviour) resistance and fatigue life of the mixture at high RAP content and different mixing method need to be studied.
- The degree of blending between the aged RAP binder and the virgin binder need to be investigated and research need to be done on the applicability of the log-penetration rule at high RAP content.
- The influence of RAP aggregate properties like shape, angularity and high fine content on mixture performance properties need to be studied.

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Appendix A : Volumetric properties of the specimens

Table A.1: Volumetric properties for specimens tested for resilient modulus

Specimen Code	Weight Measured (gm)			Specimen density (kg/m^3)	Air Voids % (v/v)	VMA % (v/v)	VFB % (v/v)
	Dry	Under water	Surface Dry				
SM401	983.1	584.88	985.06	2451.98	4.44	15.14	70.65
SM402	965.43	573.18	966.96	2447.04	4.64	15.31	69.72
SM403	967.27	574.89	968.9	2450.27	4.51	15.20	70.33
SM503	947.2	559.94	947.9	2436.85	4.55	15.18	70.03
SM505	966.34	570	966.9	2430.09	4.81	15.42	68.77
SM506	985.2	583.87	987.05	2438.93	4.47	15.11	70.43
PW402	970	573.24	970.6	2436.47	5.0	15.68	67.80
PW403	941.23	558.42	943.05	2442.46	4.8	15.47	68.88
PW406	985.3	587.35	987.44	2458.02	4.2	14.93	71.82
PW504	964.59	571.21	966.34	2436.56	4.56	15.19	69.98
PW506	966.41	572.8	969.38	2432.23	4.73	15.34	69.16
PW511	988.9	585.3	990.3	2437.09	4.54	15.17	70.08
UPG 502_4	964.14	567.68	964.85	2422.91	5.10	15.67	67.47
UPG 503_4	957.72	566.88	959.87	2432.38	4.72	15.34	69.19
UPG504_4	963	568.53	965.01	2424.26	5.04	15.62	67.71
UPG 402_4	960.57	568.9	961.23	2443.72	4.77	15.43	69.11
UPG 403_4	956.69	565.32	957.25	2436.33	5.05	15.68	67.78
UPG405_4	963.33	570.96	964.35	2444.14	4.75	15.41	69.19

Table A.2: Volumetric properties for specimens tested for water sensitivity

Specimen Code	Weight Measured (gm)			Specimen density (kg/m^3)	Air Voids % (v/v)	VMA % (v/v)	VFB % (v/v)
	Dry	Under water	Surface Dry				
UPG 401_ 4	980.26	583.1	981.81	2453.91	4.37	15.07	71.02
UPG 402_ 4	957.2	569.7	958.2	2459.15	4.16	14.89	72.04
UPG 403_ 4	959.57	566.9	960.23	2434.97	5.11	15.73	67.54
UPG 404_ 4	978.2	581.28	979.3	2453.00	4.40	15.11	70.85
UPG 405_ 4	970.79	575.67	971.62	2447.14	4.63	15.31	69.74
UPG 406_ 4	981.22	585.7	983.5	2461.93	4.06	14.80	72.59
UPG 501_ 4	978.21	581.23	979.7	2450.25	4.02	14.71	72.65
UPG 502_ 4	970.74	576.26	972.4	2445.84	4.20	14.87	71.77
UPG 503_ 4	964.9	572.37	967.3	2438.58	4.48	15.12	70.36
UPG 504_ 4	975.26	580.22	977.88	2447.84	4.12	14.80	72.16
UPG 505_ 4	953.25	561.96	954.38	2424.54	5.03	15.61	67.76
UPG 506_ 4	962.64	569.35	963.6	2437.06	4.54	15.17	70.07
SM 501	970.69	575.7	973.63	2433.98	4.66	15.28	69.49
SM 502	960.7	567.56	962.15	2429.32	4.84	15.44	68.63
SM 503	958.21	565.3	960.2	2421.12	5.17	15.73	67.16
SM 504	975.51	579.09	977.59	2442.57	4.33	14.98	71.13
SM 505	960.7	569.14	962.3	2438.16	4.50	15.13	70.28
SM 506	978.85	580.53	979.64	2447.19	4.14	14.82	72.03

Continued from Table A.2

Specimen Code	Weight Measured (gm)			Specimen density (kg/m^3)	Air Voids % (v/v)	VMA %(v/v)	VFB % (v/v)
	Dry	Under water	Surface Dry				
SM 401	979.35	581.56	979.59	2455.08	4.32	15.03	71.25
SM 402	981.46	584.34	982.43	2460.00	4.13	14.86	72.21
SM 403	960.9	571.7	962.86	2451.14	4.48	15.17	70.49
SM 404	959.83	568.92	960.66	2444.78	4.72	15.39	69.30
SM 405	953.81	563.15	954.13	2434.17	5.14	15.76	67.39
SM 406	980.35	582.8	981.4	2454.07	4.36	15.07	71.05
PW 501	962.54	570.23	963.3	2443.39	4.29	14.95	71.29
PW 502	968.82	574.41	969.51	2446.69	4.16	14.84	71.94
PW 503	950.35	560.59	951.45	2426.08	4.97	15.56	68.04
PW 504	981.94	582.64	983.9	2441.76	4.36	15.01	70.97
PW 505	960.94	569.36	962.2	2440.75	4.40	15.04	70.78
PW 506	976.83	579.7	977.89	2447.78	4.12	14.80	72.15
PW 401	962.1	573.28	964.12	2456.94	4.25	14.97	71.61
PW 402	960.4	571.55	961.4	2458.83	4.18	14.90	71.98
PW 403	970.4	575.95	972.45	2442.76	4.80	15.46	68.93
PW 404	960.42	571.28	962.13	2452.59	4.42	15.12	70.77
PW 405	956.88	568.3	958.68	2446.49	4.66	15.33	69.62
PW 406	981.61	583.57	982.7	2454.70	4.34	15.05	71.17

Table A.3: Volumetric properties for specimens tested for permanent deformation resistance

Specimen Code	Weight Measured (gm)			Specimen density (kg/m^3)	Air Voids %(v/v)	VMA % (v/v)	VFB % (v/v)
	Dry	Under water	Surface Dry				
PW 401	1513.74	895.24	1514.91	2436.95	5.03	15.66	67.89
PW 404	1521.42	905.75	1523.16	2458.28	4.20	14.92	71.87
PW 405	1508.37	891.73	1509.57	2435.50	5.09	15.71	67.63
PW 501	1512.61	895.45	1514.16	2438.91	4.47	15.11	70.42
PW 502	1509.91	895.56	1511.48	2445.59	4.21	14.88	71.72
PW 503	1521.96	905.01	1524.61	2450.46	4.02	14.71	72.69
SM 401	1520.3	903.25	1522.44	2449.41	4.54	15.23	70.17
SM 402	1525.71	907.96	1527.53	2456.62	4.26	14.98	71.54
SM 405	1526.7	908.43	1528.24	2457.26	4.24	14.96	71.67
SM 501	1522.26	904.4	1524.94	2447.23	4.14	14.82	72.04
SM 504	1519.25	901.2	1520.75	2446.30	4.18	14.85	71.86
SM 505	1509.58	892.94	1511.77	2433.56	4.68	15.30	69.41
UPG402_4	1517.44	904.76	1520.2	2459.70	4.14	14.87	72.15
UPG403_4	1518.76	903.69	1521.3	2453.19	4.40	15.10	70.88
UPG404_4	1526.7	907.66	1527.69	2456.39	4.27	14.99	71.50
UPG501_4	1524.32	904.72	1526.3	2447.67	4.13	14.80	72.13
UPG502_4	1500.61	884.99	1503.26	2422.50	5.11	15.68	67.40
UPG505_4	1516.24	898.49	1518.11	2442.40	4.33	14.99	71.09

Appendix B : Resilient modulus test results

Table B. 1: Resilient modulus test results (SM method 40 % RAP)

Mixing Method	Temp. (°C)	Sample ID	Air Voids (%)	Resilient Modulus (MPa) at different frequencies (Hz)					
				1	2	4	8	12	16
Standard Mixing Method (SM) 40 % RAP	5	SM 401_5	4.44	19913	21020	22452	24317	24354	23875
		SM 402_5	4.64	20105	21621	23055	24920	25344	24619
		SM 403_5	4.51	17251	18590	19529	21072	21361	22974
		Av.SM 40%	4.53	19089	20410	21679	23436	23686	23822
		Stdev	0.10	1595	1605	1886	2069	2074	824
		CV (%)	2.16	8.4	7.9	8.7	8.8	8.8	3.5
	10	SM 401_5	4.44	15127	16249	17909	19427	20104	20949
		SM 402_5	4.64	15210	16676	18594	20002	20071	21865
		SM 403_5	4.51	15434	16749	18372	20047	20865	19645
		Avg.SM 40%	4.53	15257	16558	18292	19825	20347	20819
		Stdev	0.10	158	270	350	346	449	1116
		CV (%)	2.16	1.0	1.6	1.9	1.7	2.2	5.4
	15	SM 401_5	4.44	9195	10725	12368	13794	14886	13774
		SM 402_5	4.64	8599	9906	11638	13876	14785	15555
		SM 403_5	4.51	8924	10160	11562	13720	14470	14603
		Avg.SM 40%	4.53	8906	10263	11856.0	13797	14713	14644
		Stdev	0.10	298.2	419.2	444.9	77.6	217.2	891
		CV (%)	2.16	3.3	4.1	3.8	0.6	1.5	6.1

Continued from Table B.1

Mixing Method	Temp. (°C)	Sample ID	Air Voids (%)	Resilient Modulus (MPa) at different frequencies (Hz)					
				1	2	4	8	12	16
Standard Mixing Method (SM) 40 % RAP	23	SM 401_5	4.44	2983	3590	4646	5984	6920	7331
		SM 402_5	4.64	2968	3495	4571	5857	6842	7285
		SM 403_5	4.51	3322	4024	4976	6310	7112	7466
		Avg.SM 40%	4.53	3091.0	3702.8	4731.0	6050.2	6958.1	7360.8
		Stdev	0.10	200.6	282.0	215.5	234.1	139.3	94.3
		CV (%)	2.16	6.5	7.6	4.6	3.9	2.0	1.3
	35	SM 401_5	4.44	1048	1318	1318	2245	2569	2846
		SM 402_5	4.64	914	1168	1555	2081	2407	2728
		SM 403_5	4.51	1151	1430	1808	2366	2636	2947
		Avg.SM 40%	4.53	1037.9	1305.6	1560.5	2230.8	2537.5	2840.3
		Stdev	0.10	118.6	131.3	244.9	142.9	117.7	109.4
		CV (%)	2.16	11.4	10.1	15.7	6.4	4.6	3.9

Table B. 2: Resilient modulus test results (SM method 50 % RAP)

Mixing Method	Temp. (^{o}C)	Sample ID	Air Voids (%)	Resilient Modulus (MPa) at different frequencies (Hz)					
				1	2	4	8	12	16
Standard Mixing Method (SM) 50 % RAP	5	SM 503_5	4.55	19720	21145	22453	23847	23975	24806
		SM 505_5	4.81	19366	20631	21879	23239	24124	23438
		SM 506_5	4.47	19931	21198	21982	23916	23552	24054
		Av. SM 50 %	4.61	19672	20991	22105	23667	23884	24099
		Stdev	0.18	286	313	306	373	297	685
		CV (%)	3.93	1.5	1.5	1.4	1.6	1.2	2.8
	10	SM 503_5	4.55	13891	15315	16702	18369	18581	17874
		SM 505_5	4.81	14662	16047	17684	19168	20110	19198
		SM 506_5	4.47	14530	15894	17274	18871	17762	17398
		Av. SM 50 %	4.61	14361	15752	17220	18803	18818	18156
		Stdev	0.18	412	386	493	404	1192	933
		CV (%)	3.93	2.9	2.5	2.9	2.1	6.3	5.1
	15	SM 503_5	4.55	9768	10866	12593	14820	15864	16045
		SM 505_5	4.81	9638	10867	12464	14605	15066	13617
		SM 506_5	4.47	10048	11512	12816	14949	16000	16905
		Av. SM 50 %	4.61	9818	11081	12624	14791	15643	15522
		Stdev	0.18	210	373	178	174	505	1705
		CV (%)	3.93	2.1	3.4	1.4	1.2	3.2	11.0

Continued from Table B.2

Mixing Method	Temp. (^{o}C)	Sample ID	Air Voids (%)	Resilient Modulus (MPa) at different frequencies (Hz)					
				1	2	4	8	12	16
Standard Mixing Method (SM) 50 % RAP	23	SM 503_5	4.55	3136	3756	4914	6287	7151	7528
		SM 505_5	4.81	3013	3690	4673	6038	6981	7356
		SM 506_5	4.47	3347	4068	5114	6525	7362	7636
		Av. SM 50 %	4.61	3165	3838	4901	6283	7164	7507
		Stdev	0.18	169	202	220	244	191	141
		CV (%)	3.93	5.3	5.3	4.5	3.9	2.7	1.9
	35	SM 503_5	4.55	833	1065	1446	1922	2238	2343
		SM 505_5	4.81	862	1084	1433	1929	2201	2445
		SM 506_5	4.47	1080	1376	1788	2371	2678	3018
		Av. SM 50 %	4.61	925	1175	1555	2074	2373	2602
		Stdev	0.18	135	174	201	257	265	364
		CV (%)	3.93	14.6	14.9	12.9	12.4	11.2	14.0

Table B. 3: Resilient modulus test results (PW method 40 % RAP)

Mixing Method	Temp. (^{o}C)	Sample ID	Air Voids (%)	Resilient Modulus (MPa) at different frequencies (Hz)					
				1	2	4	8	12	16
Partial Warming Method (PW) 40 % RAP	5	PW 402_5	5.05	16940	18168	19131	19992	20947	18043
		PW 403_5	4.81	17930	19165	20323	21347	21140	20698
		PW 406_5	4.21	16785	18067	19175	20547	20990	21608
		Av.PW 40 %	4.69	17218	18467	19543	20629	21026	20117
		Stdev	0.43	621	607	676	682	101	1852
		CV (%)	9.24	3.61	3.28	3.46	3.30	0.48	9.21
	10	PW 402_10	5.05	13650	14767	16210	17254	17644	17092
		PW 403_10	4.81	12924	14036	15259	16696	17082	16432
		PW 406_10	4.21	14338	15476	16924	18904	19299	19064
		Av.PW 40 %	4.69	13638	14760	16131	17618	18008	17529
		Stdev	0.43	707	720	835	1148	1153	1369
		CV (%)	9.24	5.2	4.9	5.2	6.5	6.4	7.8
	15	PW 402_15	5.05	8938	10075	11754	13734	14872	15574
		PW 403_15	4.81	8458	9806	11853	13684	14325	14911
		PW 406_15	4.21	9253	10516	11555	13763	14953	15874
		Av.PW 40 %	4.69	8883	10133	11721	13727	14717	15453
		Stdev	0.43	400	358	152	40	342	492
		CV (%)	9.24	4.5	3.5	1.3	0.3	2.3	3.2

Continued from Table B.3

Mixing Method	Temp. (^{o}C)	Sample ID	Air Voids (%)	Resilient Modulus (MPa) at different frequencies (Hz)					
				1	2	4	8	12	16
Partial Warming Method (PW) 40 % RAP	23	PW 402_23	5.05	2496	3136	4045	5291	6077	6557
		PW 403_23	4.81	2501	3016	3931	5042	5876	6412
		PW 406_23	4.21	2715	3297	4233	5475	6462	6853
		Av.PW 40 %	4.69	2571	3150	4070	5269	6139	6607
		Stdev	0.43	125	141	152	217	298	225
		CV (%)	9.24	4.9	4.5	3.7	4.1	4.8	3.4
	35	PW 402_35	5.05	726	935	1220	1668	1964	2141
		PW 403_35	4.81	736	927	1201	1652	1907	2094
		PW 406_35	4.21	707	889	1169	1652	1924	2119
		Av.PW 40 %	4.69	723	917	1196	1657	1932	2118
		Stdev	0.43	15	25	26	9	29	24
		CV (%)	9.24	2.1	2.7	2.2	0.6	1.5	1.1

Table B. 4: Resilient modulus test results (PW method 50 % RAP)

Mixing Method	Temp. (°C)	Sample ID	Air Voids (%)	Resilient Modulus (MPa) at different frequencies (Hz)					
				1	2	4	8	12	16
Partial Warming Method (PW) 50 % RAP	5	PW 504_5	4.56	19452	20744	22131	23138	23627	23074
		PW 506_5	4.73	18100	19335	20584	21048	20860	17581
		PW 511_5	4.54	19142	20192	21033	21767	21323	20963
		Av. PW 50 %	4.61	18898	20090	21249	21984	21937	20539
		Stdev	0.10	708	710	796	1062	1482	2771
		CV (%)	2.26	3.7	3.5	3.7	4.8	6.8	13.5
	10	PW 504_10	4.56	15036	16387	17579	18965	19519	20415
		PW 506_10	4.73	13874	15263	16625	18215	18883	19451
		PW 511_10	4.54	14770	16026	17317	18559	18710	19310
		Av. PW 50 %	4.61	14560	15892	17174	18579	19038	19725
		Stdev	0.10	608	574	493	376	426	602
		CV (%)	2.26	4.2	3.6	2.9	2.0	2.2	3.1
	15	PW 504_15	4.56	10253	11368	12833	15227	16256	16714
		PW 506_15	4.73	10512	11704	12992	15365	16428	17212
		PW 511_15	4.54	11668	12737	14048	16564	17337	18008
		Av. PW 50 %	4.61	10811	11936	13291	15719	16674	17311
		Stdev	0.10	753	714	660	735	581	653
		CV (%)	2.26	7.0	6.0	5.0	4.7	3.5	3.8

Continued from Table B.4

Mixing Method	Temp. (^{o}C)	Sample ID	Air Voids (%)	Resilient Modulus (MPa) at different frequencies (Hz)					
				1	2	4	8	12	16
Partial Warming Method (PW) 50 % RAP	23	PW 504_23	4.56	3046	3698	4690	5988	6886	7274
		PW 506_23	4.73	2985	3610	4599	5823	6721	7109
		PW 511_23	4.54	4142	4964	6064	7587	8301	8421
		Av. PW 50 %	4.61	3391	4091	5118	6466	7303	7602
		Stdev	0.10	651	758	821	974	869	715
		CV (%)	2.26	19.2	18.5	16.0	15.1	11.9	9.4
	35	PW 504_35	4.56	1039	1297	1661	2137	2406	2638
		PW 506_35	4.73	962	1223	1614	2081	2410	2650
		PW 511_35	4.54	1395	1760	2194	2944	3423	3744
		Av. PW 50 %	4.61	1132	1427	1823	2387	2746	3011
		Stdev	0.10	231	291	322	483	586	636
		CV (%)	2.26	20.4	20.4	17.7	20.2	21.3	21.1

Table B. 5: Resilient modulus test results (UPG method 40 % RAP)

Mixing Method	Temp. (^{o}C)	Sample ID	Air Voids (%)	Resilient Modulus (MPa) at different frequencies (Hz)					
				1	2	4	8	12	16
Upgraded Mixing Method (UPG) 40 % RAP	5	UPG 402_5	4.77	16343	17271	17454	18596	18758	20239
		UPG 403_5	5.05	14090	15302	16485	17372	18491	17397
		UPG 405_5	4.75	16796	18042	19522	21273	21505	21651
		Av.UPG 40%	4.86	15743	16872	17820	19081	19585	19762
		Stdev	0.17	1450	1413	1551	1995	1669	2167
		CV (%)	3.52	9.2	8.4	8.7	10.5	8.5	11.0
	10	UPG 402_10	4.77	12059	13385	14678	16196	16806	17281
		UPG 403_10	5.05	8980	10096	11426	12885	13615	14428
		UPG 405_10	4.75	12163	13372	14809	16577	17150	16995
		Av.UPG 40%	4.86	11067	12284	13638	15219	15857	16235
		Stdev	0.17	1808	1895	1917	2031	1949	1571
		CV (%)	3.52	16.3	15.4	14.1	13.3	12.3	9.7
	15	UPG 402_15	4.77	7770	8812	10770	12243	12831	12513
		UPG 403_15	5.05	5251	6567	8184	9788	10781	9405
		UPG 405_15	4.75	7177	8290	9674	11433	12405	13092
		Av.UPG 40%	4.86	6733	7890	9543	11155	12006	11670
		Stdev	0.17	1317	1175	1298	1251	1082	1983
		CV (%)	3.52	19.6	14.9	13.6	11.2	9.0	17.0

Continued from Table B.5

Mixing Method	Temp. (^{o}C)	Sample ID	Air Voids (%)	Resilient Modulus (MPa) at different frequencies (Hz)					
				1	2	4	8	12	16
Upgraded Mixing Method (UPG) 40 % RAP	23	UPG 402_23	4.77	1976	2444	3240	4260	4894	5406
		UPG 403_23	5.05	1276	1585	2165	2935	3489	3854
		UPG 405_23	4.75	1864	2316	3003	4006	4684	5093
		Av.UPG 40%	4.86	1705	2115	2803	3734	4356	4784
		Stdev	0.17	376	464	564	703	758	821
		CV (%)	3.52	22.0	21.9	20.1	18.8	17.4	17.2
	35	UPG 402_35	4.77	588	744	1005	1393	1671	1764
		UPG 403_35	5.05	380	490	671	938	1177	1265
		UPG 405_35	4.75	529	660	886	1202	1490	1558
		Av.UPG 40%	4.86	499	631	854	1178	1446	1529
		Stdev	0.17	107	129	169	229	250	251
		CV (%)	3.52	21.5	20.5	19.8	19.4	17.3	16.4

Table B. 6: Resilient modulus test results (UPG method 50 % RAP)

Mixing Method	Temp. (^{o}C)	Sample ID	Air Voids (%)	Resilient Modulus (MPa) at different frequencies (Hz)					
				1	2	4	8	12	16
Upgraded Mixing Method (UPG) 50 % RAP	5	UPG 502_5	5.10	18367	19929	21009	22760	22595	22753
		UPG 503_5	4.72	17440	18676	20077	21029	21200	21315
		UPG 504_5	5.04	17509	18904	20270	20796	22600	22162
		Av.UPG 50%	4.95	17772	19170	20452	21528	22132	22076
		Stdev	0.20	516	667	492	1073	807	723
		CV (%)	4.05	2.9	3.5	2.4	5.0	3.6	3.3
	10	UPG 502_10	5.10	18367	19929	21009	22760	22595	22753
		UPG 503_10	4.72	12774	14048	15431	17331	17729	17759
		UPG 504_10	5.04	14527	15851	17457	19299	19004	19573
		Av.UPG 50%	4.95	15223	16609	17966	19797	19776	20028
		Stdev	0.20	2861	3013	2823	2748	2523	2528
		CV (%)	4.05	18.8	18.1	15.7	13.9	12.8	12.6
	15	UPG 502_15	5.10	9201	10331	11772	13949	14851	14452
		UPG 503_15	4.72	8322	9556	11321	13163	14136	15053
		UPG 504_15	5.04	8753	10001	12343	13893	14816	13577
		Av.UPG 50%	4.95	8759	9963	11812	13668	14601	14361
		Stdev	0.20	439	389	513	438	403	742
		CV (%)	4.05	5.0	3.9	4.3	3.2	2.8	5.2

Continued from Table B.6

Mixing Method	Temp. (^{o}C)	Sample ID	Air Voids (%)	Resilient Modulus (MPa) at different frequencies (Hz)					
				1	2	4	8	12	16
Upgraded Mixing Method (UPG) 50 % RAP	23	UPG 502_23	5.10	2609	3208	4168	5401	6137	6703
		UPG 503_23	4.72	2096	2622	3499	4560	5292	5927
		UPG 504_23	5.04	2289	2826	3819	4919	5743	6335
		Av.UPG 50%	4.95	2331	2885	3829	4960	5724	6322
		Stdev	0.20	259	297	334	422	423	388
		CV (%)	4.05	11.1	10.3	8.7	8.5	7.4	6.1
	35	UPG 502_35	5.10	798	1040	1347	1861	2091	2355
		UPG 503_35	4.72	623	788	1035	1378	1665	1764
		UPG 504_35	5.04	664	858	1164	1614	1948	2103
		Av.UPG 50%	4.95	695	895	1182	1618	1902	2074
		Stdev	0.20	91	130	157	242	217	297
		CV (%)	4.05	13.1	14.5	13.3	14.9	11.4	14.3

Appendix C : Master curves at Tref 15 ^{o}C

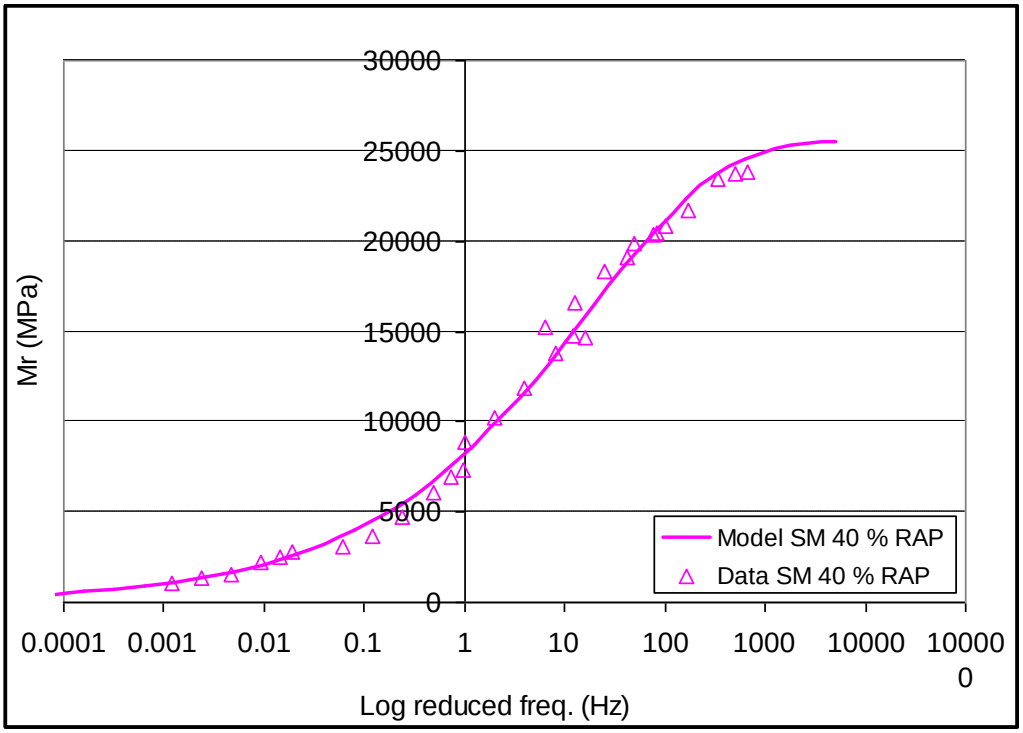

Figure C.1: Master curve of mix stiffness at Tref = 15 ^{o}C for SM method 40 % RAP Log-Linear scale (average of 3 specimens)

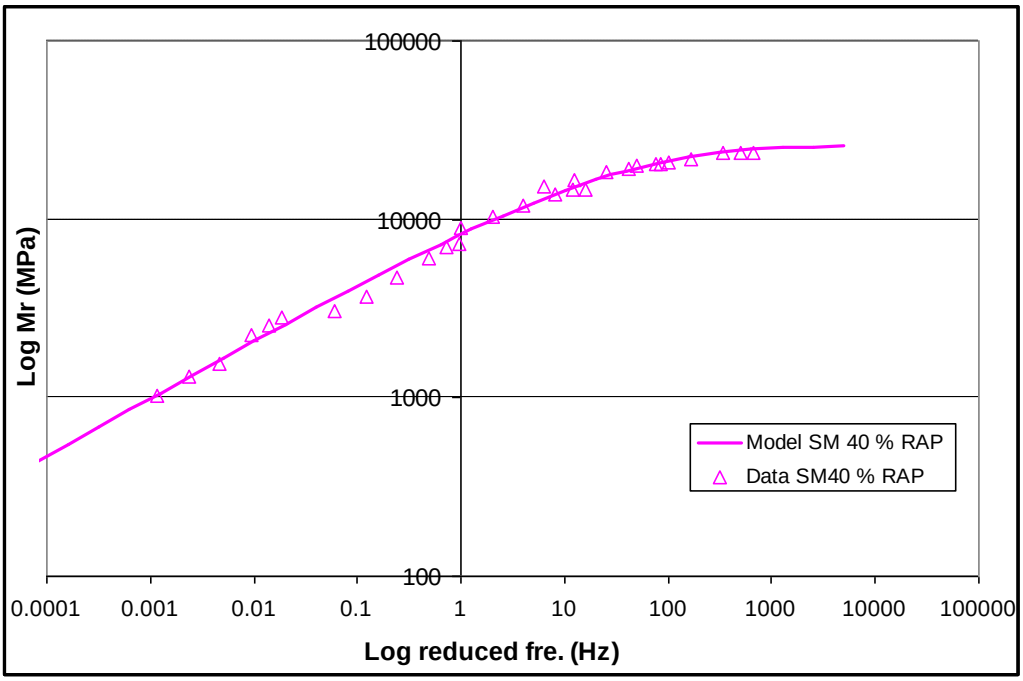

Figure C.2: Master curve of mix stiffness at Tref = 15 ^{o}C for SM method 40 % RAP Log-Log scale (average of 3 specimens)

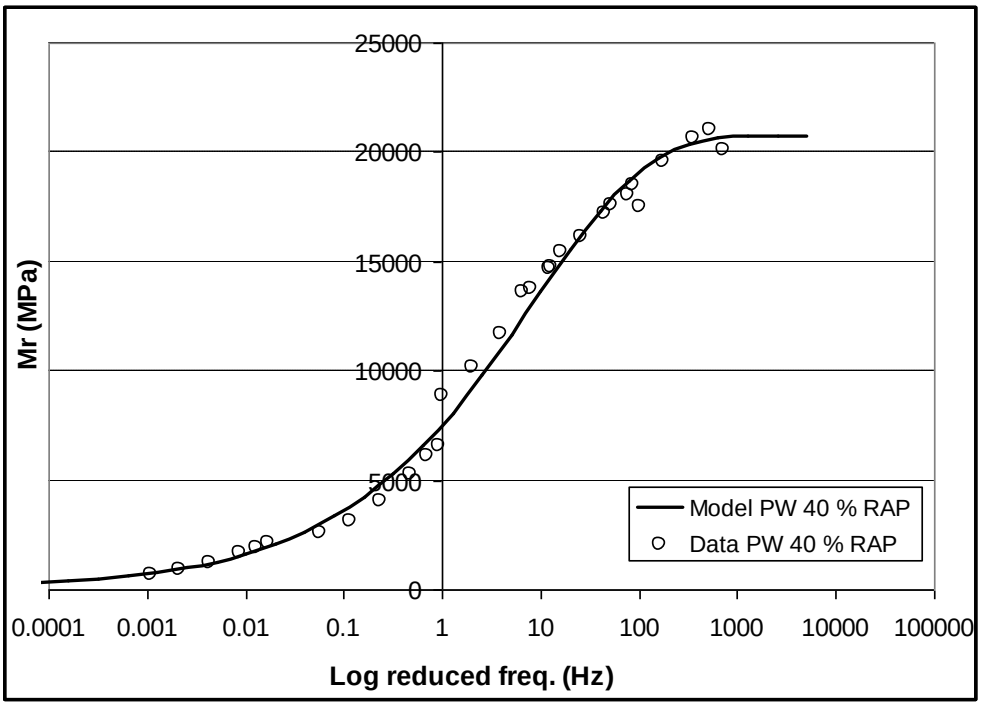

Figure C.3: Master curve of mix stiffness at Tref = 15 ^{o}C for PW method 40 % RAP Log-Linear scale (average of 3 specimens)

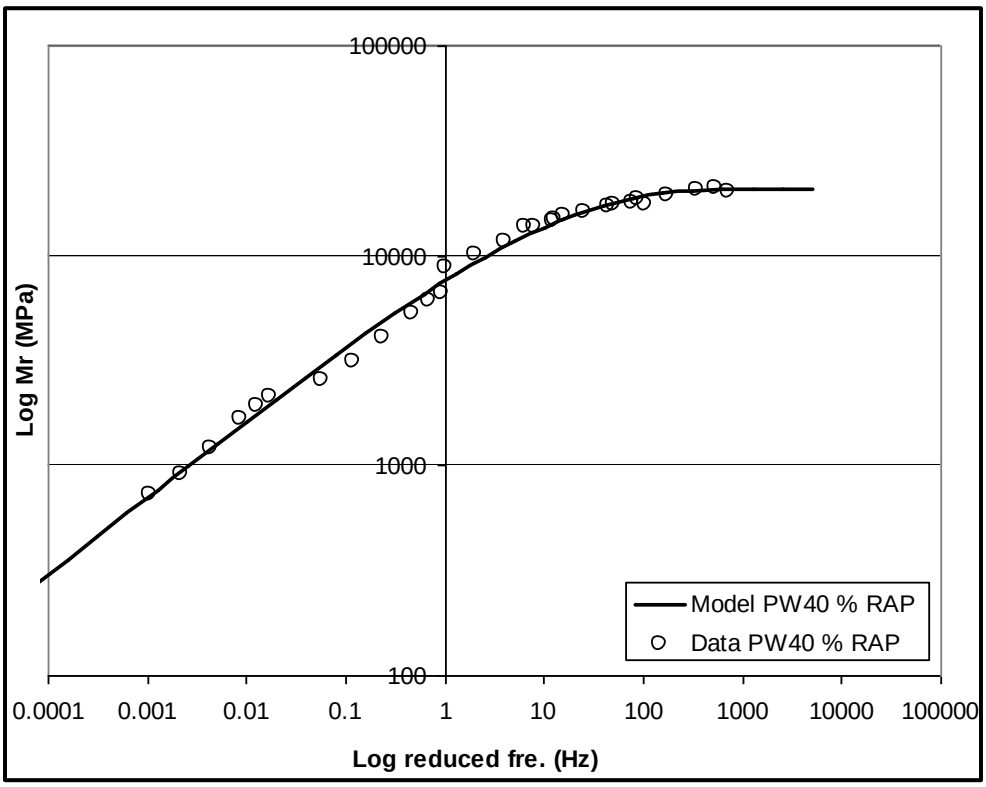

Figure C.4: Master curve of mix stiffness at Tref = 15 ^{o}C for PW method 40 % RAP Log-Log scale (average of 3 specimens)

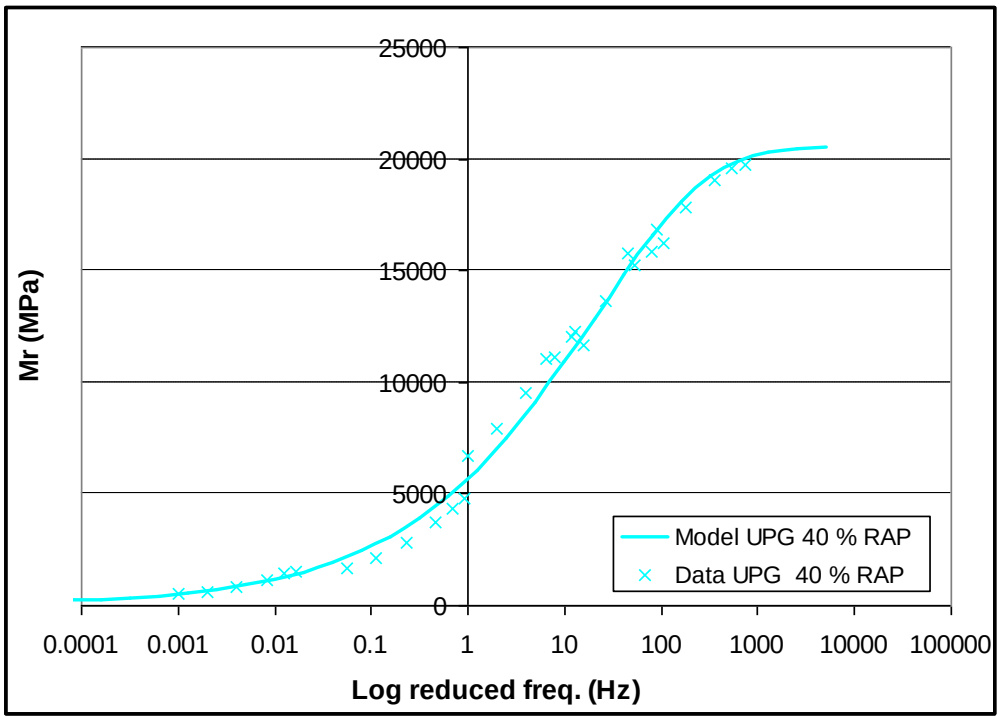

Figure C. 5: Master curve of mix stiffness at Tref = 15 ^{o}C for UPG method 40 % RAP Log-Linear scale (average of 3 specimens)

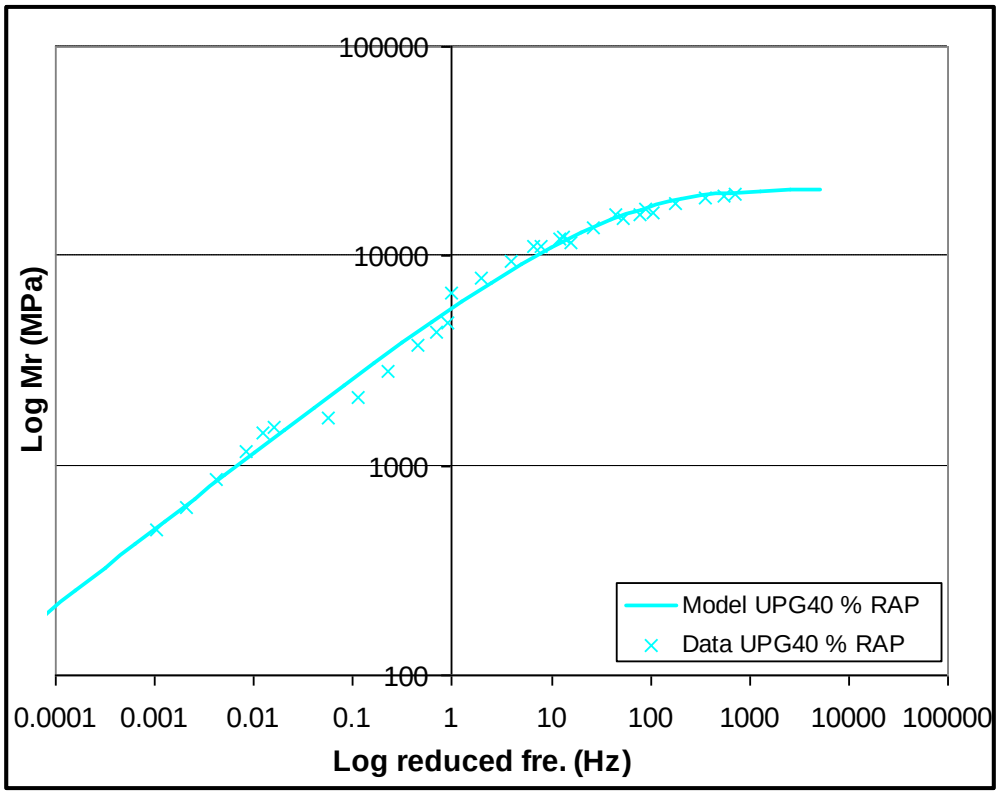

Figure C. 6: Master curve of mix stiffness at Tref = 15 ^{o}C for UPG method 40 % RAP Log-Log scale (average of 3 specimens)

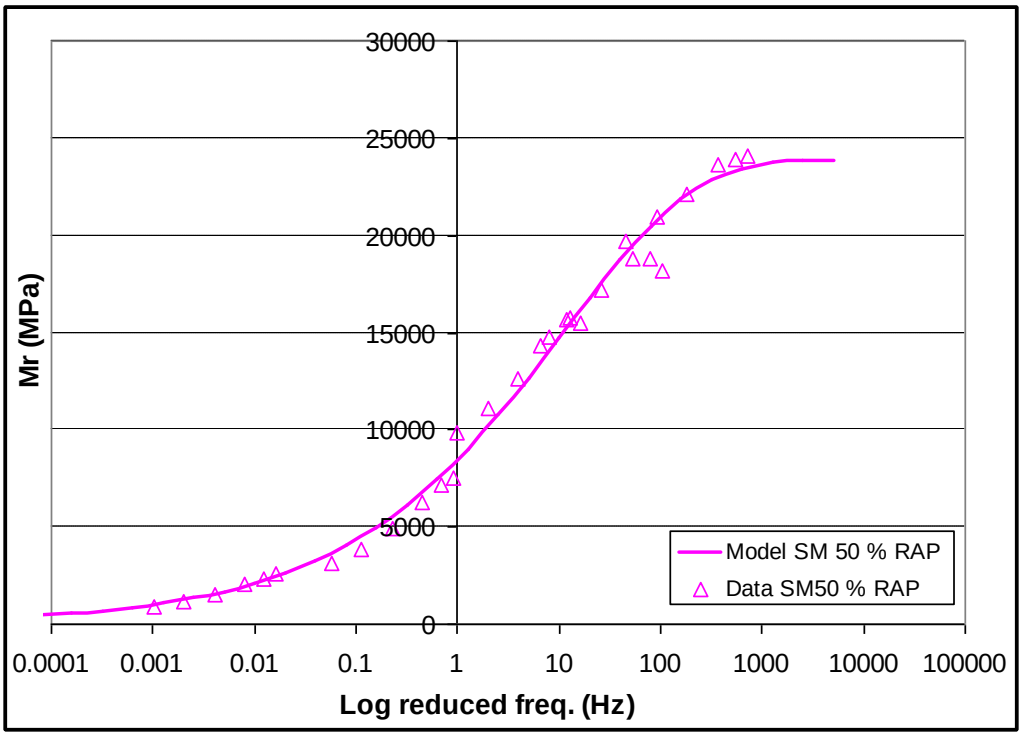

Figure C. 7: Master curve of mix stiffness at Tref = 15 ^{o}C for SM method 50 % RAP Log-Linear scale (average of 3 specimens)

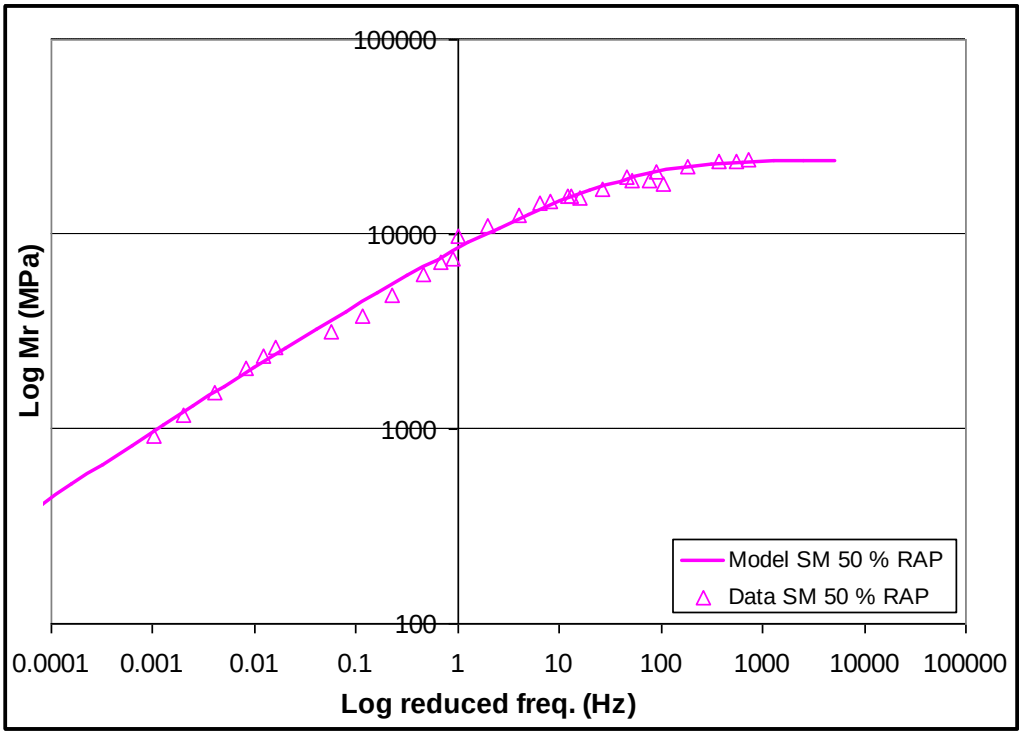

Figure C. 8: Master curve of mix stiffness at Tref = 15 ^{o}C for SM method 50 % RAP Log-Log scale (average of 3 specimens)

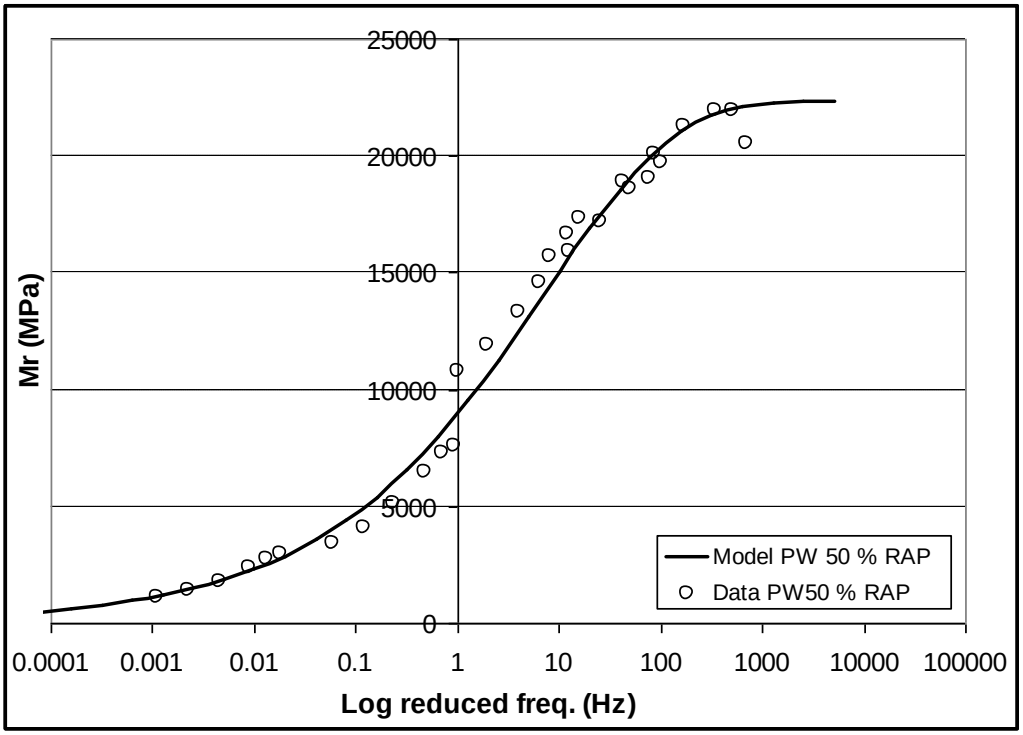

Figure C. 9: Master curve of mix stiffness at Tref = 15 ^{o}C for PW method 50 % RAP Log-Linear scale (average of 3 specimens)

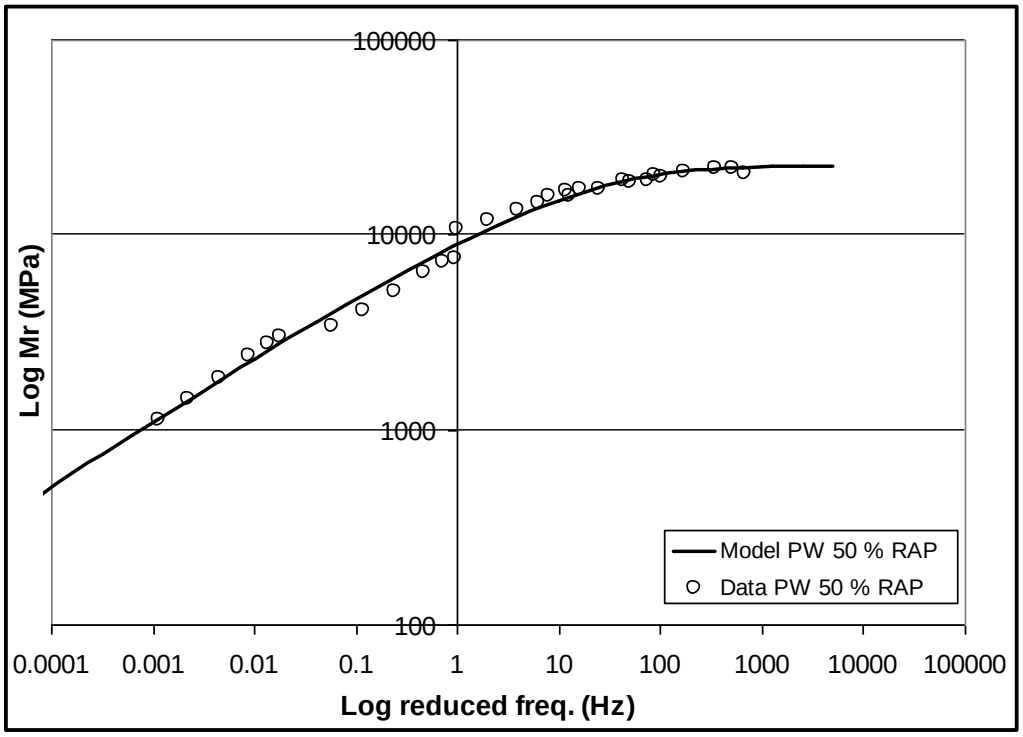

Figure C. 10: Master curve of mix stiffness at Tref = 15 ^{o}C for PW method 50 % RAP Log-Log scale (average of 3 specimens)

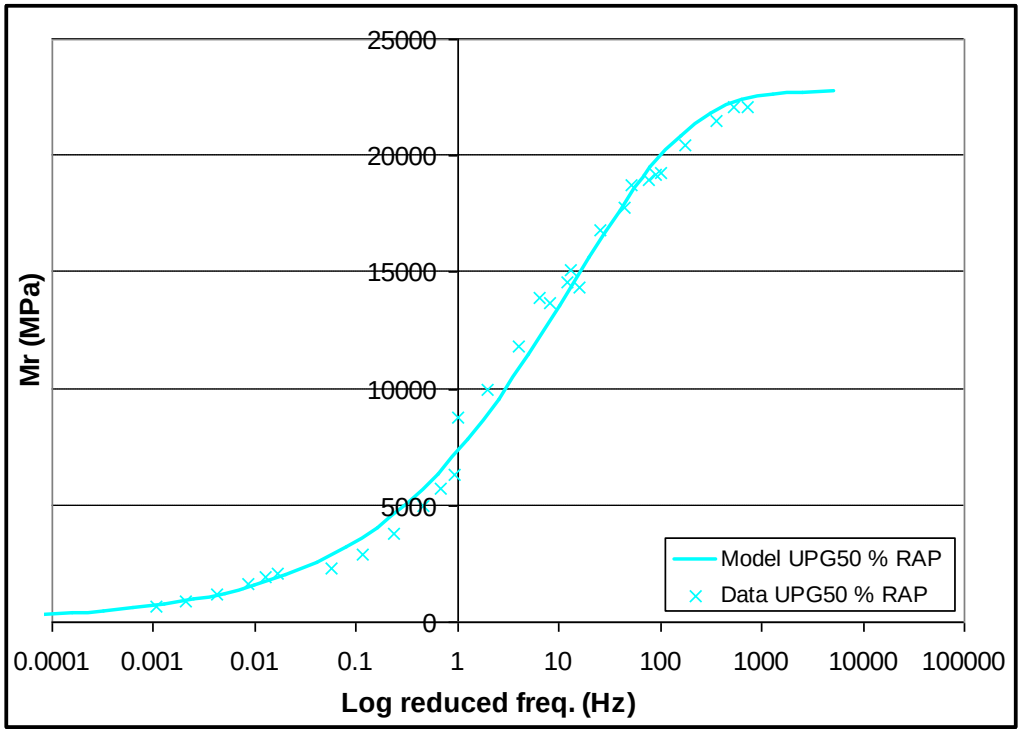

Figure C. 11: Master curve of mix stiffness at Tref = 15 ^{o}C for UPG method 50 % RAP Log-Linear scale (average of 3 specimens)

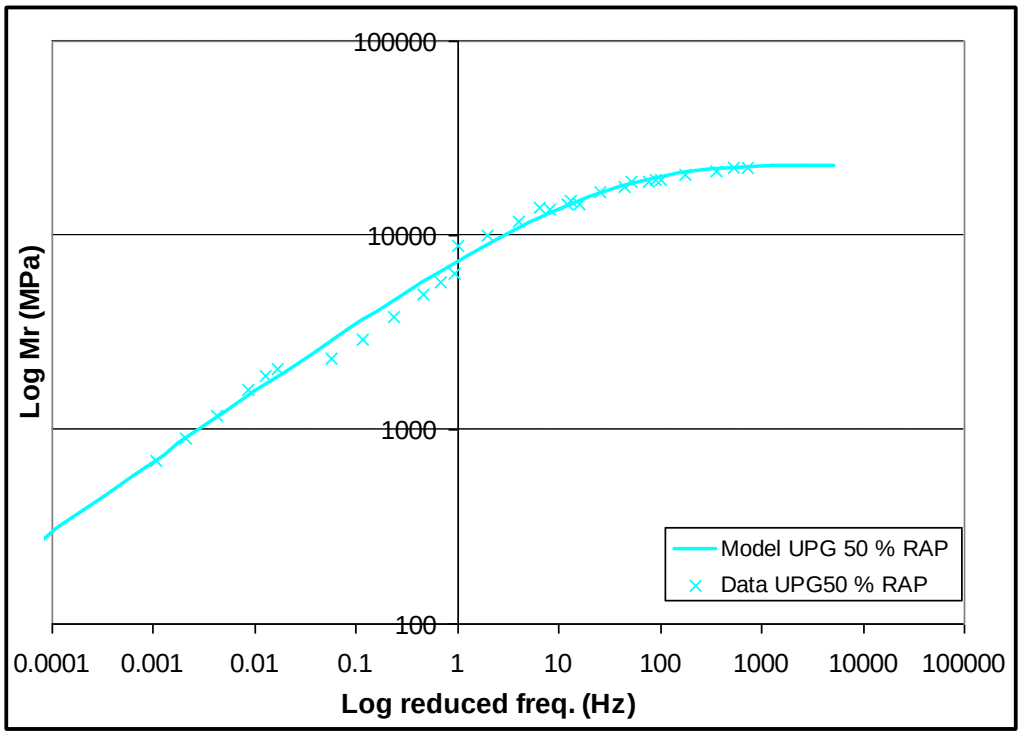

Figure C. 12: Master curve of mix stiffness at Tref = 15 ^{o}C for UPG method 50 % RAP Log-Log scale (average of 3 specimens)

Appendix D : Indirect Tensile Strength test results

Table D. 1: Indirect Tensile Strength test results

Mixing Method	RAP (%)	Specimen Code	Temp. (^{o}C)	Test Condition	Air Voids (%)	Max. Force (kN)	Tensile Stress (MPa)	Average tensile Stress (MPa)	STDEV. (MPa)	CV (%)	ITSR (%)
Standard Mixing (SM)	40	SM_401	15	Dry	4.32	27.6	3.52	3.50	0.26	7.41	90.60
		SM_402	15		4.13	29.5	3.75				
		SM_404	15		4.72	25.1	3.23				
		SM_403	15	Wet	4.48	25.5	3.27	3.17	0.29	9.07	
		SM_405	15		5.14	22.4	2.85				
		SM_406	15		4.36	26.2	3.40				
	50	SM 504	15	Dry	4.33	28	3.59	3.45	0.33	9.66	86.21
		SM 505	15		4.50	24	3.07				
		SM506	15		4.14	29	3.70				
		SM 501	15	Wet	4.66	23.5	3.01	2.98	0.05	1.85	
		SM 502	15		4.84	23.4	3.00				
		SM 503	15		5.17	22.3	2.91				
Partial Warming Mixing (PW)	40	PW401	15	Dry	4.25	23.7	3.02	2.99	0.09	3.01	98.36
		PW402	15		4.18	23.9	3.05				
		PW403	15		4.80	22.8	2.88				
		PW404	15	Wet	4.42	21.3	2.69	2.94	0.27	9.22	
		PW405	15		4.66	22.7	2.89				
		PW406	15		4.34	26	3.23				

Continued from Table D.1

Mixing Method	RAP (%)	Specimen Code	Temp. (^{o}C)	Test Condition	Air Voids (%)	Max. Force (kN)	Tensile Stress (MPa)	Average tensile Stress (MPa)	STDEV. (MPa)	CV (%)	ITSR (%)
Partial Warming Mixing (PW)	50	PW501	15		4.29	26	3.33	3.30	0.32	9.57	97.08
		PW502	15	Dry	4.16	28	3.60				
		PW503	15		4.97	23	2.97				
		PW504	15		4.36	23.9	2.98	3.20	0.35	10.78	
		PW505	15	Wet	4.40	23.7	3.03				
		PW506	15		4.12	28.2	3.60				
Upgraded Mixing Method (UPG)	40	UPG402	15		4.16	21.3	2.70	2.84	0.18	6.42	81.41
		UPG405	15	Dry	4.63	21.9	2.78				
		UPG 406	15		4.06	23.7	3.05				
		UPG401	15		4.37	19.6	2.46	2.31	0.25	10.86	
		UPG403	15	Wet	5.11	15.9	2.02				
		UPG 404	15		4.40	19.2	2.46				
	50	UPG501	15		4.02	29	3.62	3.26	0.32	9.81	96
		UPG504	15	Dry	4.12	24.5	3.13				
		UPG503	15		4.48	24	3.02				
		UPG502	15		4.20	26	3.34	3.11	0.25	7.94	
		UPG505	15	Wet	5.03	22.2	2.85				
		UPG506	15		4.54	24	3.15				

Appendix E : Permanent deformation test results

Table E. 1: Permanent deformation test results

Specimen Code	$\varepsilon_n = a + b.n$				$\varepsilon_n = a.n^b$			axial strain at 1000 cycles	axial strain at 10000 cycles	axial perm. def at 10000 cycles
	a	b		R^2	a	b	R^2	(%)	(%)	(mm)
SM 401	0.664	9.67E-06	0.097	0.954	0.331	0.090	0.967	0.616	0.760	0.608
SM 402	0.677	4.69E-06	0.047	0.870	0.477	0.045	0.892	0.651	0.726	0.576
SM 405	1.037	1.81E-05	0.181	0.979	0.460	0.105	0.993	0.951	1.212	0.971
Avg	0.792	1.08E-05	0.108	0.934	0.423	0.080	0.951	0.739	0.899	0.718
Stdve	0.212	6.76E-06	0.068	0.057	0.080	0.031	0.052	0.184	0.271	0.219
CV (%)	26.737	62.513	62.513	6.092	18.870	39.092	5.513	24.865	30.168	30.550
SM 501	0.525	8.85E-06	0.089	0.956	0.238	0.102	0.968	0.482	0.611	0.489
SM 504	0.624	1.34E-05	0.134	0.974	0.236	0.126	0.984	0.563	0.754	0.603
SM 505	0.661	8.15E-06	0.082	0.946	0.364	0.077	0.961	0.619	0.740	0.592
Avg	0.603	1.01E-05	0.101	0.959	0.279	0.102	0.971	0.555	0.702	0.561
Stdve	0.070	2.84E-06	0.028	0.014	0.073	0.025	0.012	0.069	0.079	0.063
CV (%)	11.634	28.066	28.066	1.486	26.264	24.175	1.237	12.407	11.235	11.228
PW 401	0.939	2.55E-05	0.255	0.983	0.284	0.155	0.996	0.830	1.187	0.951
PW 404	0.576	1.48E-05	0.148	0.973	0.186	0.147	0.986	0.513	0.713	0.571
PW 405	0.996	2.63E-05	0.263	0.991	0.313	0.150	0.995	0.885	1.251	0.951

Continued from Table E.1

Specimen Code	$\varepsilon_n = a + b.n$				$\varepsilon_n = a.n^b$			axial strain at 1000 cycles	axial strain at 10000 cycles	axial perm. def. at 10000 cycles
	a	b		R^2	a	b	R^2	(%)	(%)	(mm)
Avg	0.837	2.22E-05	0.222	0.982	0.261	0.151	0.992	0.742	1.050	0.824
Stdve	0.228	6.43E-06	0.064	0.009	0.067	0.004	0.006	0.201	0.294	0.220
CV (%)	27.189	28.941	28.941	0.920	25.630	2.706	0.563	27.051	27.980	26.640
PW 501	0.842	3.41E-05	0.341	0.990	0.163	0.214	0.998	0.717	1.169	0.937
PW 502	0.720	1.26E-05	0.126	0.905	0.319	0.105	0.981	0.660	0.840	0.937
PW 503	0.577	1.18E-05	0.118	0.967	0.226	0.121	0.981	0.523	0.691	0.553
Avg	0.713	1.95E-05	0.195	0.954	0.236	0.147	0.986	0.633	0.900	0.809
Stdve	0.133	1.27E-05	0.127	0.044	0.078	0.059	0.010	0.100	0.245	0.221
CV (%)	18.605	64.932	64.932	4.620	33.131	39.980	0.984	15.772	27.176	27.386
UPG 402	0.868	2.24E-05	0.224	0.983	0.277	0.148	0.995	0.771	1.085	0.870
UPG 403	0.833	2.47E-05	0.247	0.977	0.230	0.167	0.993	0.730	1.067	0.853
UPG 404	0.883	1.24E-05	0.124	0.975	0.453	0.086	0.980	0.822	1.004	0.870
Avg	0.861	1.98E-05	0.198	0.978	0.320	0.134	0.990	0.774	1.052	0.865
Stdve	0.025	6.49E-06	0.065	0.004	0.117	0.042	0.008	0.046	0.043	0.010
CV (%)	2.960	32.751	32.751	0.431	36.620	31.512	0.818	5.950	4.043	1.131

Continued from Table E.1

Specimen Code	$\varepsilon_n = a + b.n$				$\varepsilon_n = a.n^b$			axial strain at 1000 cycles	axial strain at 10000 cycles	axial perm. def. at 10000 cycles
	a	b		R^2	a	b	R^2	(%)	(%)	(mm)
UPG 501	1.016	1.34E-05	0.134	0.973	0.540	0.082	0.986	0.949	1.142	0.915
UPG502	1.590	2.94E-05	0.294	0.935	0.662	0.113	0.972	1.446	1.869	1.496
UPG 505	1.411	3.31E-05	0.331	0.986	0.492	0.137	0.997	1.264	1.729	0.915
Avg	1.339	2.53E-05	0.253	0.965	0.565	0.110	0.985	1.220	1.580	1.108
Stdve	0.294	1.05E-05	0.105	0.026	0.088	0.028	0.013	0.251	0.386	0.335
CV (%)	21.934	41.469	41.469	2.719	15.499	24.954	1.314	20.612	24.413	30.263

Appendix F : X-ray Fluorescence Spectroscopy results