Effect of the Repeated Recycling on Hot Mix Asphalt Properties

By

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Abstract

A significant growth has been shown in recycling of the old asphalt pavement as a technically and environmentally preferred way of rehabilitating the existing pavements during the three decades. However, savings acquired by using this technology may be lost through excessive maintenance processes if the recycled pavement exhibits too much deterioration.

The current design methods for recycled HMA hypothesize a state of complete blending between the recycling agent and RAP binder. In practice, the complete blending does not occur as the recycling agent does not penetrate the whole layer of the aged binder around RAP particles (Carpenter and Wolosick, 1980). As a result of this, the resultant binder within the recycled mix differs from the desired binder, leading to dissimilarity in properties of the recycled and virgin mixes. Consequently, if the recycled mix was subjected to ageing and recycling for second time, the respond of its resultant binder will not the same as if it was the desire binder. This in turn may make the performance of recycled mix of second cycle differs from that of first cycle. Therefore studying the effect of repeated recycling on performance of the recycled HMA was the aim of this research.

First, three types of RAP (reclaimed asphalt pavement) were manufactured in the laboratory and were utilized to produce three types of recycled HMA. After testing the recycled mixes, they were aged again to the same ageing time and temperature, then were crushed to be used as RAP for next generation of recycling. This process was repeated three times. Bitumen 40/60 pen and 70/100 pen were used for the virgin and recycled mixes respectively. All virgin and recycled mixes were designed to have identical aggregate grading, bitumen content, air voids, and binder viscosity.

Stiffness and fatigue characteristics were measured after each cycle by the Indirect Tensile Stiffness Modulus test (ITSM) and Indirect Tensile Fatigue Test (ITFT). The results showed that, in spite of, presence deterioration in stiffness or fatigue resistance after the first cycle, the repeated recycling had no further significant effect on deterioration of these properties.

Because there was considerable degradation in performance of recycled mixes after the first cycle, certain factors that were believed to improve the efficiency of mixing of these types of mixtures were investigated. These factors included size of RAP agglomeration, mixing temperature, dry mixing time between superheated aggregate and RAP, warming of RAP, and mixing mechanism. The results showed the importance of all factors in improving the mechanical properties of recycled mixes. However, the most influential factors were mixing temperature and warming of RAP.

Durability of recycled mixes to resist moisture damage was assessed by the water sensitivity test. The results demonstrated that the recycled mixes were not susceptible to moisture damage and can resist the harmful action of water better than the virgin mix.

An interesting element in this research was the possibility of using the Hirsch model to estimate the rheological properties of effective binder within recycled mixes without applying recovery process.

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At the beginning, I am eternally grateful to God for the gift of life.

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In the end, I would like to extend my profound thanks to all my family.

Declaration

The research reported in this thesis was conducted at the University of Nottingham, Department of Civil Engineering, Nottingham Transportation Engineering Centre, between November 2008 and January 2013. I declare that the work is my own and has not been submitted for a degree at another university.

Usama Heneash

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Glossary

AC	Asphalt Concrete
ANOVA	Analysis of Variance
CCPR	Cold Central Plant Recycling
CIR	Cold In-Place Recycling
CP	Cold Planning
CR	Cold Recycling
DBM	Dense Bitumen Macadam
FDR	Full Depth Reclamation
FHWA	Federal Highway Administration
HIR	Hot In-Place Recycling
HMA	Hot Mix Asphalt
ITFT	Indirect Tensile Fatigue Test
ITSM	Indirect Tensile Stiffness Modulus
NAT	Nottingham Asphalt Tester
NTEC	Nottingham Transportation Engineering Centre
PCC	Portland Cement Concrete
RAP	Reclaimed Asphalt Pavement
RLAT	Repeated Load Axial Test
R-mix	Recycled mix
RTFOT	Rolling Thin Film Oven Test
SHRP	Strategic Highway Research Programme
SPSS	Statistical Analysis Software
TxDOT	Texas Department Of Transportation
VMA	Voids in Mineral Aggregate
V-mix	Virgin Mix
WMA	Warm Mix Asphalt
WRT	Warming RAP Temperature
WTT	Wheel Tracking Test
ZSV	Zero Shear Viscosity

1 Introduction

1.1 Review

Economic and environmental considerations have encouraged the recycling of steel, aluminium, plastic, and many other materials. Reclaimed asphalt pavement, RAP, is one of these recyclable materials. A substantial growth has been shown in recycling of the old asphalt pavement as a technically and environmentally preferred way of rehabilitating the existing pavements during the last 35 years. Comparing to conventional pavement reconstruction, recycling of asphalt pavement has achieved savings in energy, natural resources, and petroleum binder costs (ARRA, 2001). However, if the recycle of pavement shows too much deterioration, the cost and energy savings achieved during construction may be lost through excessive maintenance processes (Noureldin and Wood, 1987).

Much effort has been done for evaluating and assessing the performance of recycled hot-mix asphalt (Al-Rousan et al., 2008, Huang et al., 2005, Kandhal et al., 1995, McDaniel and Anderson, 2001, Nguyen, 2009, Oliver, 2001, Tabakovic et al., 2006, Tran and Hassan, 2011, Widyatmoko, 2008), establishing design methods for these types of mixtures (ex. ASTM D 4887, Asphalt Institute's manual MS-2, and Superpave technology design method), and modifying the production protocols and the equipments to accommodate this technology (Nguyen, 2009, ARRA, 2001).

1.2 Problem statement

The recycled HMA are produced by using a recycling agent in order to recover the physical and rheological properties of the aged RAP binder (Sondag et al., 2002). At the same time, the current design methods of recycled HMA, as it is known, hypothesize 100% contribution for the RAP binder from the RAP materials, in addition to the assumption of complete blending state between the new and RAP binder, which are not found in practice (Al-Qadi et al., 2007, Chen et al., 2007, McDaniel and Anderson, 2001). It has been reported that the diffusion process -hence blending- of the recycling agents occur over the majority of the aged layer of RAP binder except at the aggregate-binder interface (Carpenter and Wolosick, 1980).

Accordingly, the resultant binder within the recycled HMA differs in its properties from the desired binder from the design method, which in turn results in dissimilarity between the properties of the recycled and virgin HMA. Now, if these recycled HMA were subjected to another cycle of ageing and recycling, will the respond of this resultant binder exactly the same as if it was the desired binder? Or will the properties of recycled HMA after the second or third cycle of recycling differ from those after first cycle? This issue of studying the effect of repeated recycling on behaviour of the recycled HMA has not been investigated yet and is still unclear. Therefore, this issue was the primary aim of this study.

1.3 Aims and objectives

This study primarily aims to investigate influence of the repeated recycling of RAP on the mechanical properties of recycled HMA. In order to meet this aim, the following tasks were carried out:

- A literature review on recycling of asphalt pavement and evaluation of the behaviour of recycled hot asphalt mixtures with the purpose of better understanding the way in which the RAP behaves when it is recycled several times.
- Establish an experimental program which allows repeating of the recycling process more than once and testing of the recycled mixtures after each cycle.
- Study the effects of the ageing process on the properties of recycled asphalt mixtures.

In achieving the primary aim of the research, it was found that the blending process between the new and old binder within the recycled mix represents a significant obstacle to the production of recycled hot mix asphalt (HMA) with similar characteristics to conventional mixes. Therefore, another aim has been added to investigate the possibility of improving the efficiency of the mixing process, which in turn leads to improvements in the mechanical properties of recycled mixtures. To achieve this aim the following tasks were implemented:

- Study the difference between normal mixing practice and total blending and their effect on the characteristics of recycled mixtures.
- Explore the factors by which mixing efficiency can be improved.
- Investigate whether blending between aged and new binder with in recycled HMA continues over time after the production stage due to long-term diffusion. This has been done via investigating the mechanical properties assuming that they reflect the degree of mixing and diffusion between the binders.

1.4 Research Methodology

1.4.1 Studying the effect of repeated recycling on the mechanical properties of recycled HMA

Laboratory cylindrical specimens of virgin HMA were fabricated, artificially aged in a forced draft oven by exposing them to three protocols of ageing (40hrs @105°C, 65hrs @125°C, and 2weeks @125°C) in order to simulate the long-term ageing that takes place throughout the service life of roads. The aged specimens were then crushed into small fractions with a maximum size of 20 mm to produce three kinds of RAP material which were utilized afterwards for manufacturing three different types of recycled HMA. Then, the recycled specimens were aged, using the same ageing protocol, and crushed to be used as RAP materials for the next generation of recycled mixes. This process of repeated recycling has been conducted over three rounds.

Both the virgin and recycled mixes were designed to have identical aggregate grading (10mm Dense Bitumen Macadam, DBM), bitumen content (5.2%), and air voids (5.0%). The viscosity of the binder in both mixes was also designed to be identical, assuming complete blending between the RAP binder and the added fresh binder. Bitumen 70/100 dmm was used for the recycled mixes instead of bitumen 40/60 dmm, which was used for the virgin mix, as a means of rejuvenation and compensation for the ageing of the RAP binder. The only difference between the recycled mixes, in all rounds of recycling, was the percentage of RAP which was varied slightly from cycle to cycle. Table 1 indicates the RAP contents of the recycled mixes in all different rounds of recycling.

Table 1 RAP content for all recycled mixes in all rounds of recycling

	RAP content %		
	1st Cycle	2nd Cycle	3rd Cycle
1st recycled mix	62	65	69
2nd recycled mix	45	55	57
3rd recycled mix	29	25	26

A range of tests were carried out on gyratory compacted specimens and the recovered binders from these specimens after each round of recycling. The Indirect Tensile Stiffness Modulus (ITSM) and Indirect Tensile Fatigue Test (ITFT) were applied on compacted samples to measure the stiffness and fatigue resistance respectively. The Dynamic Shear Rheometer (DSR) test was performed on the recovered binder to measure the rheological properties. Also, the physical properties of the recovered binder were determined via the Penetration test and ring and ball test.

1.4.2 Comparison between the normal practice and total blending cases

Two recycled mixes were designed to be identical, but the production methods were different. The first mix was manufactured with 45% RAP according to standard practice (blending the RAP with the superheated aggregate before adding the new bitumen 70/100 dmm). The second mix was produced to ensure total blending (blending 45% of the aged binder with the new bitumen 70/100 dmm, then adding this blend to the virgin aggregate). The aged binder was obtained by ageing the virgin bitumen 40/60 dmm via the Rolling Thin Film Oven Test (RTFOT) so that it had the same properties of recovered binder from RAP. The two mixes were subjected to the ITSM and ITFT tests to compare their mechanical properties.

1.4.3 Investigating the factors by which the mixing efficiency can be improved

Effect of RAP size

Three recycled mixes with different RAP contents (30%, 55%, and 65%) were manufactured with 20 mm maximum nominal size of RAP particles. Then, another three recycled mixes (similar to the previous ones) were also produced but with 13 mm maximum nominal size of RAP particles. All mixes were tested using the ITSM and ITFT for their stiffness and fatigue resistance.

Effect of mixing temperature

Two recycled mixes with the same RAP content of 29% were produced but with 135 °C mixing temperature for one of them and 160 °C for the other. Stiffness and fatigue properties were measured by the ITSM and ITFT tests of both mixes.

Effect of dry mixing time, RAP warming temperatures, and mixing mechanism

A number of the recycled mixes of 45 % RAP were fabricated with different dry mixing times (2, 8, 16 min), RAP warming temperatures (20, 40, 80 °C), and types of mixers (normal mixer and inclined drum mixer). All the mixes were examined by the ITSM test to measure their stiffness, and then all results were compared to each other.

1.4.4 Studying whether the blending between aged and new binder continues over time due to long-term diffusion

Two groups of 15 virgin specimens and recycled samples of 45% RAP content were produced. Each group was divided into three sets of 5 samples which were stored in cabinets at different storage temperatures: 5, 20, and 30 °C. All samples were tested according to the ITSM test periodically every month for 9 and 7 months for the virgin and recycled samples respectively. Before carrying out the ITSM test, the samples had been conditioned at 20 °C for a minimum of 7 hrs. All the test results have been collected and compared.

1.5 Thesis Organisation

Chapter (1) outlines a statement of the problem followed by the aims and objectives. Methodologies for fulfilment of these objectives are also introduced.

Chapter (2) presents an up-to-date literature review about the topics discussed in this thesis. These topics contributed to understanding of the research field and included: methods of recycling asphalt pavements, performance of recycled HMA, moisture damage, and diffusion of rejuvenators into the aged binder film.

Chapter (3) illustrates the experimental work program as an important step to achieve the goal of this thesis. Laboratory work included manufacturing of RAP materials in the laboratory, running the repeated recycling process over three cycles, and description of tests used. Estimating the zero shear viscosities of different binders (virgin or recovered) from the DSR results are also included.

Chapter (4) contains an analysis and discussion of laboratory results from the repeated recycling investigation. Results of the comparison between the total blending case and standard practice are also discussed in this chapter. An interesting element is the possibility of using the Hirsch model for back calculating the complex shear modulus (G*) of the effective binder within recycled mixes.

Chapter (5) presents using of the Hirsch model in predicting the dynamic complex modulus $|E^*|$ of virgin and recycled mixes from the available data of mixture volumetrics and the ITSM test. the interesting part in this chapter is using the model for back calculating the complex shear modulus (G*) of the effective binder within recycled mixes.

Chapter (6) studies of the factors that are believed to have an effect on improving the efficiency of the mixing process of recycled HMA. Moreover, the durability of recycled mixes to resist damage by moisture was evaluated via a water sensitivity test.

Chapter (7) presents and discusses the results from studying the effect of long-term diffusion between the new and aged binders within recycled mixes on increasing their stiffness properties.

Chapter (8) summarizes the main conclusions of the research and recommendations for future work.

2 Review

2.1 Pavement

A pavement is a structure composed of one or more layers to assist the passage of traffic over terrain. They can be categorized into flexible, rigid, and composite pavements.

Flexible pavements typically consist of several layers with a top layer made of bituminous materials. These types of pavements are called “flexible” because the whole pavement structure bends or deflects due to traffic loads.

Rigid pavements are usually constructed with a layer of Portland cement concrete, PCC. They are called "rigid" because they are substantially stiffer than flexible pavements due to the rigidity of PCC.

Composite pavements are a combination of rigid and flexible pavement. Sometimes they are initially constructed as composite pavements, but some are the result of pavement rehabilitation (e.g., HMA overlay of PCC).

Flexible and rigid pavements distribute the load over the subgrade in different manners. Rigid pavements distribute the load over a relatively wider area due to the high stiffness of PCC, while flexible pavements distribute loads over a smaller area and rely on the combination of layers for transmitting the load to the subgrade, see Figure 2-1 (Russel W. Lenz, 2011).

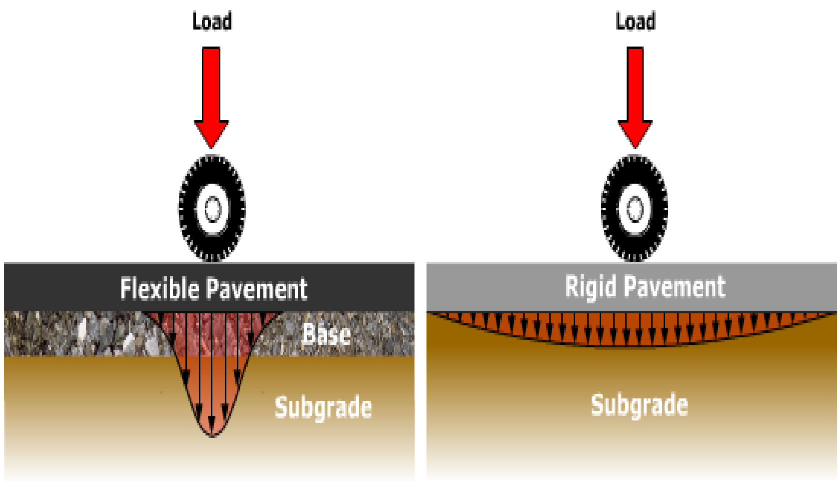


Figure 2-1 Stress distribution under the rigid and flexible pavement

2.2 Asphalt concrete mixtures

Asphalt or bituminous concrete (AC) is a composite material consisting of mineral aggregate and bitumen mixed together then placed and compacted on roads. It is commonly used in constructing the road surface in highway pavements, airports and parking lots. The strength of these kinds of mixture depends principally on the mineral aggregate with different size fractions which acts as a skeleton. At the same time the bitumen acts as a binder to bind aggregate particles together (Read and Whiteoak, 2003). Hot mix asphalt is a type of the asphalt concrete which is produced at elevated temperature (150 - 175 °C).

2.2.1 Classification of asphalt mixture according to grading

Based on aggregate gradation, HMA can be categorized into dense-graded, open-graded, and gap-graded. Dense-graded mixes have a continuous particle size distribution. Therefore, its structural performance depends mainly on the interlock between aggregate particles, with the hypothesis that smaller particles fill the voids generated by the larger particles (Roberts et al., 1996). Dense coated macadam represents an example of this type of mixes. In open-graded mixes, the gradation curve has a nearly vertical drop in intermediate size range; normally including a single size of coarse aggregate. As for gap-graded mixes, they consist of particles ranging from coarse to fine with some intermediate sizes missing or present in very small amounts. Stone mastic asphalt and hot rolled asphalt are examples of this type. Figure 2-2 depicts the common gradation of these types of HMA (Russel W. Lenz, 2011).

In open-graded mixes, the voids content is relatively high due to presence of a single size of coarse aggregate. This type of mixes is suitable to be used with additives such as rubber or fibers (Russel W. Lenz, 2011). In gap-graded mixes, the voids are filled with filler and bitumen, producing the mortar of bitumen and filler which is responsible for the structural strength of this type of mixes (Russel W. Lenz, 2011).

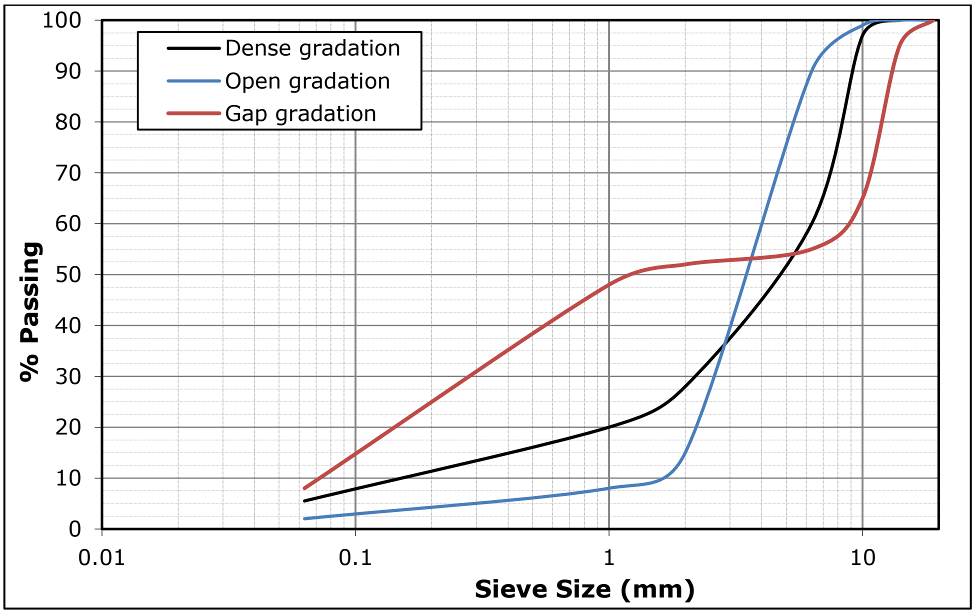


Figure 2-2 Gap and continuous graded asphalt mixture (Read, 1996)

2.2.2 Asphalt concrete mixtures components

An asphalt concrete pavement consists of a combination of layers, which include an asphalt concrete surface constructed over granular or asphalt concrete base and subbase. The pavement can be constructed using hot asphalt mix or cold mix asphalt.

Hot asphalt mix consists of fine and coarse aggregate with bitumen that is mixed, placed, and compacted in a heated condition.

Cold asphalt mix is a mix of emulsified or foamed bitumen and aggregate, produced, placed, and compacted at ambient air temperature.

The components of asphalt concrete are aggregate, bitumen, and mineral filler.

2.2.2.1 Aggregate

Aggregate materials normally form 95% of asphalt mixes by mass, and always have weighty influence on their properties and performance. Appropriate aggregate grading, strength, shape, and toughness are needed for mixture stability.

Gradation: The size distribution of aggregate particles should be a blend of sizes that causes the optimum balance between voids (density) and pavement strength.

Shape: Aggregate particles should be angular in shape to minimize surface area. Flat or elongated particles should be avoided.

Texture: Particles should be rough instead of smooth texture to diminish the stripping of binder.

Strength: Particles should have sufficient strength to resist degradation or breakdown under compaction or traffic.

Durability: Particles should be durable enough to remain intact under variable climatic conditions and/or chemical exposure.

Absorption: Absorption of aggregates refers to the amount of voids within particles that may be filled with bitumen, air, or water. Using a high absorptive aggregate is not desirable as it needs more bitumen.

Moreover, there are other properties that affect the performance of pavements such as specific gravity and deleterious components...etc.

2.2.2.2 Bitumen

The bitumen content typically comprises about 5 to 7 % by mass of the total asphalt mixture. The main role of bitumen is to coat and bind the aggregate particles together. Selection of proper bitumen grade is essential for the performance of asphalt mixture under traffic and climatic conditions.

2.2.2.3 Mineral Filler

Mineral fillers (particles lying between 50 to 75 μm) consist of very fine, inert minerals that are added to an asphalt mix to improve density and strength. They form less than 6 % of HMA concrete by mass. Mineral fillers serve a dual purpose when added to asphalt mixes. The proportion of the mineral filler that is finer than the thickness of the bitumen film forms a mortar or mastic with bitumen that contributes to improve stiffening binder (Anderson, 1996). The particles larger than the thickness of the bitumen film behave as mineral aggregate, thus contribute to the contact points between individual aggregate particles.

2.2.3 Properties of Asphalt Mixtures

During the service life of an asphalt pavement, there is a threat of one or more of the major pavement distress modes namely poor stiffness, early failure under repeated loads (fatigue) and permanent deformation (rutting). These distress modes may occur due to insufficient design, extreme loading or weathering conditions. Failure of asphalt pavements primarily depends on their mechanical properties such as stiffness, fatigue characteristics, and permanent deformation resistance (Thom, 2008, Read and Whiteoak, 2003).

2.2.3.1 Stiffness

The stiffness of an asphalt mixture could be defined as the stress divided by the accumulated strain at a certain loading time and temperature. The following equation is a simple relation to determine the stiffness.

$$S = \frac{\sigma}{\varepsilon} \qquad \text{Equation 1}$$

Where

S : Stiffness modulus σ : Applied stress ε : Induced strain

Bituminous mixtures act visco-elasically: thus their stiffness normally contains elastic and viscous components. The proportion of these two components basically depends on the time of loading and temperature. The stiffness of an asphalt mixture is directly linked to the stiffness of its binder and the volumetric properties of the other components inside the mixture. Bitumen is basically considered to be responsible for the visco-elasic properties, whereas the elastic and plastic properties are related to the mineral skeleton (Abubaker, 2008, Nguyen, 2009, Read and Whiteoak, 2003).

Measuring of stiffness modulus

The stiffness of an asphalt mix can be measured via a diversity of laboratory and empirical methods. Various laboratory methods have been employed to measure this property of asphalt such as bending beam test, direct uniaxial/triaxial test, and indirect tensile modulus test, ITSM. If it is infeasible to carry out these tests, stiffness can be estimated by empirical methods with an acceptable accuracy. Figure 2-3 shows a nomograph produced by Shell Company to estimate the stiffness. As the ITSM test was used in this research to measure the stiffness of mixes, it is explained in detail in chapter 3. The ITSM test has been developed for use in the Nottingham Asphalt

Tester (NAT) and has gained a widespread reputation in much of Europe (Cooper and Brown, 1989).

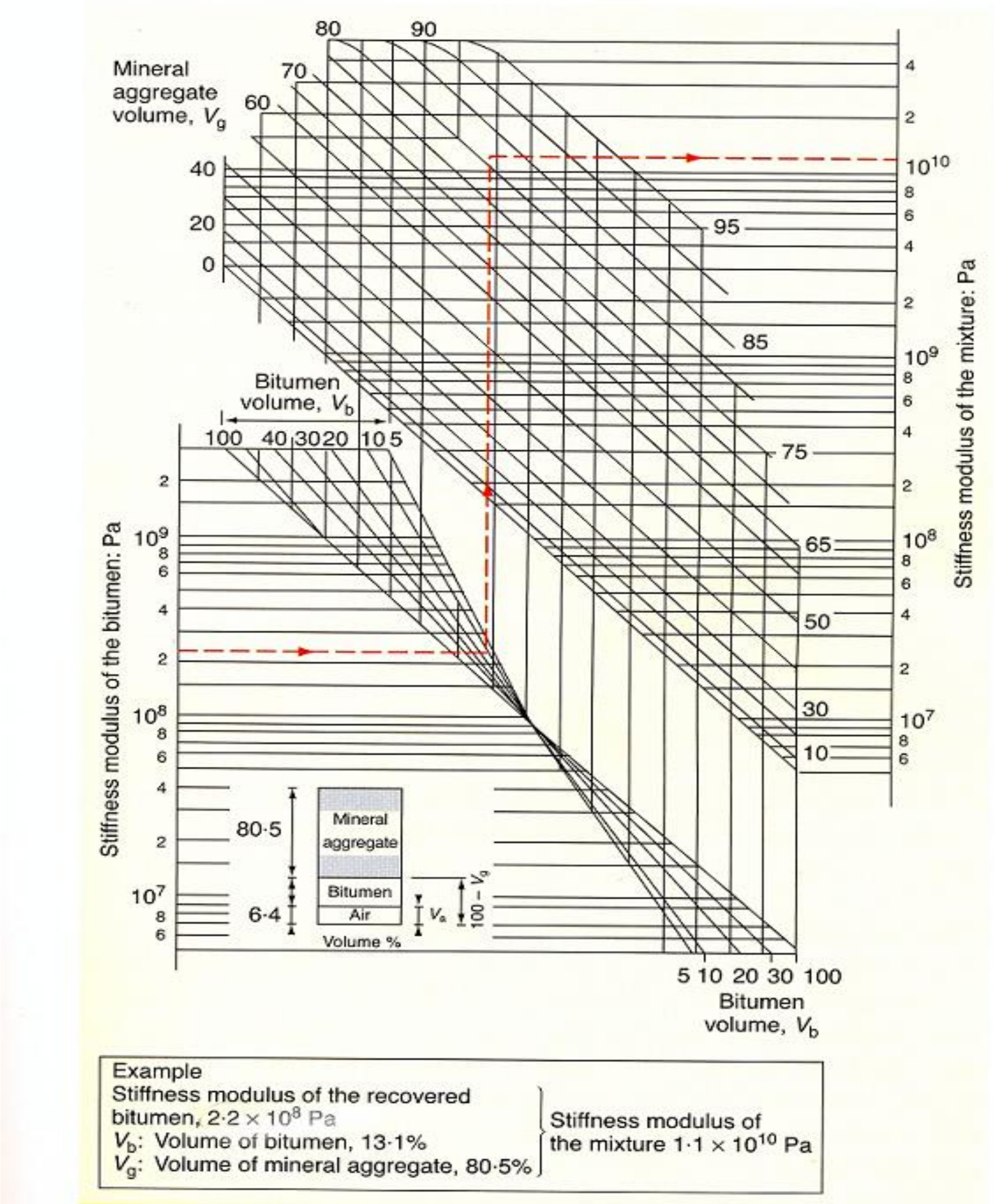


Figure 2-3 Nomograph for predicting stiffness of asphalts (Bonnaure et al., 1977)

2.2.3.2 Fatigue

Fatigue of asphalt pavements is one of the most common and significant modes of distress associated with repeated traffic load (Raad et al., 2001). Fatigue can be globally defined as "The phenomenon of cracking. It consists of two main phases, crack initiation and crack propagation, and is caused by tensile strains generated in the pavement by not only traffic loading but also temperature variations and construction practices" (Read and Whiteoak, 2003). The empirical data showed that at tensile strains in the range of 30 to 200 microstrain, the possibility of cracking by fatigue occurs (Pell, 1988).

The factors that affect the fatigue behaviour of a pavement relate to the characteristics that affect the stiffness (air voids, binder content and type, grading and type of aggregate), and the test method and mode of loading (frequency and magnitude of stress, temperature, etc.) (Baburamani, 1999). The general relationship defining the fatigue life of a bituminous mixture in terms of initial tensile strain is:

$$N_f = c(\varepsilon_f)^m \qquad \text{Equation 2}$$

Where

N_f : Number of load applications to initiate a fatigue crack

ε_f : Applied value of tensile strain

c, m : Factors depend on the composition and properties of mixture; m is slope of the strain/fatigue life line

Measuring of fatigue life

A number of tests have been recently developed in order to evaluate the fatigue characteristics of asphalt pavements. Most of laboratory fatigue tests are carried out under uniaxial conditions, either in bending such as the three point beam test or cantilever tests or in direct loading such as the indirect tensile fatigue test (ITFT). The ITFT has been recently developed as a national standard at University of Nottingham; it can be run in the NAT machine (Read, 1996, Tangella et al., 1990). The test is explained in chapter 3 as it has been utilized in this study. Also, the fatigue performance can be predicted with sufficient accuracy, for pavement design purpose, via the nomograph developed by Shell, see Figure 2-4.

2.2.3.3 Permanent Deformation

Permanent deformation is the phenomenon that irrecoverable strain is accumulated after the load is released in each loading cycle. Figure 2-5 illustrates the strain response to the applied load. The strain starts increasing when the load is applied. Once the load is released, the elastic component of the strain will recover instantaneously. There is also a component called visco-elastic strain which will recover with time. However, the permanent deformation, due to plastic characteristics of the asphalt mixture, cannot be recovered (Perl et al., 1983). Although this viscous and plastic deformation is small after each loading cycle, the accumulation will become large after millions of loads, Figure 2-6. This will cause the rutting phenomenon in the pavement structure.

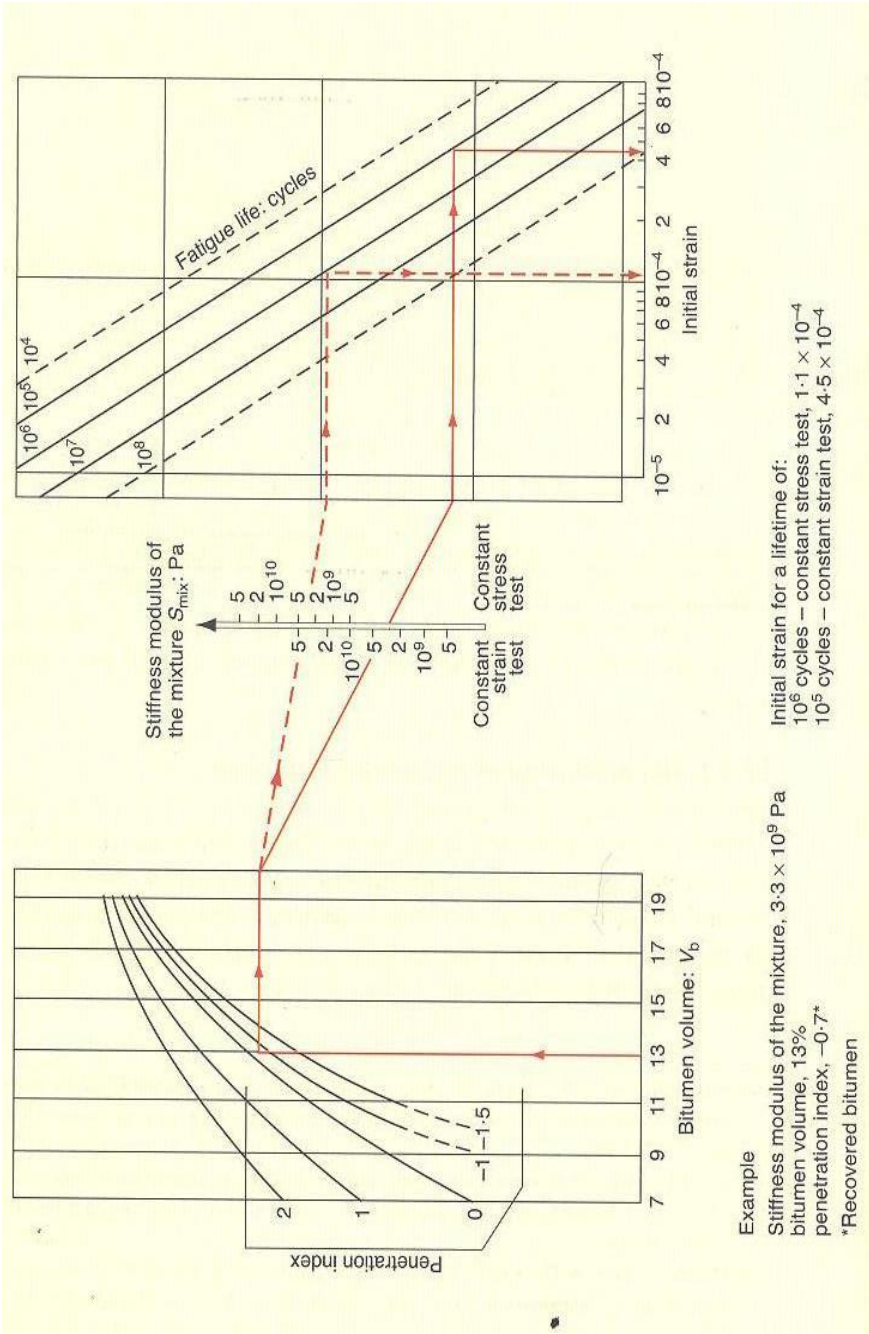


Figure 2-4 Nomograph for predicting the laboratory fatigue performance of asphalt mixtures (Bonnaure et al., 1980)

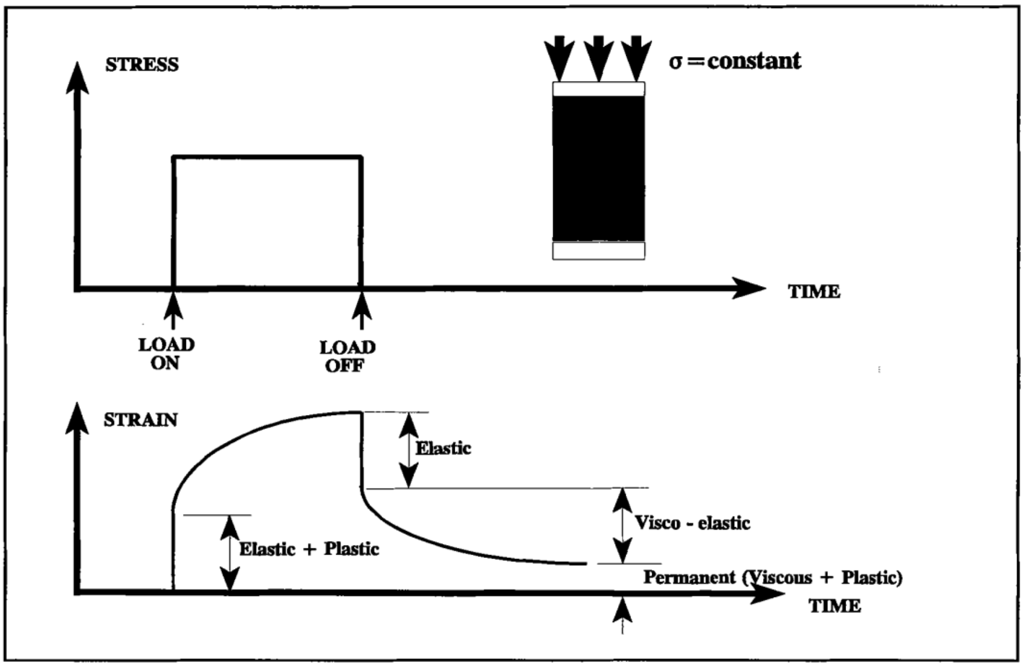


Figure 2-5 Strain response due to applied stress of visco-elasto-plastic constitutive model (Perl et al., 1983)

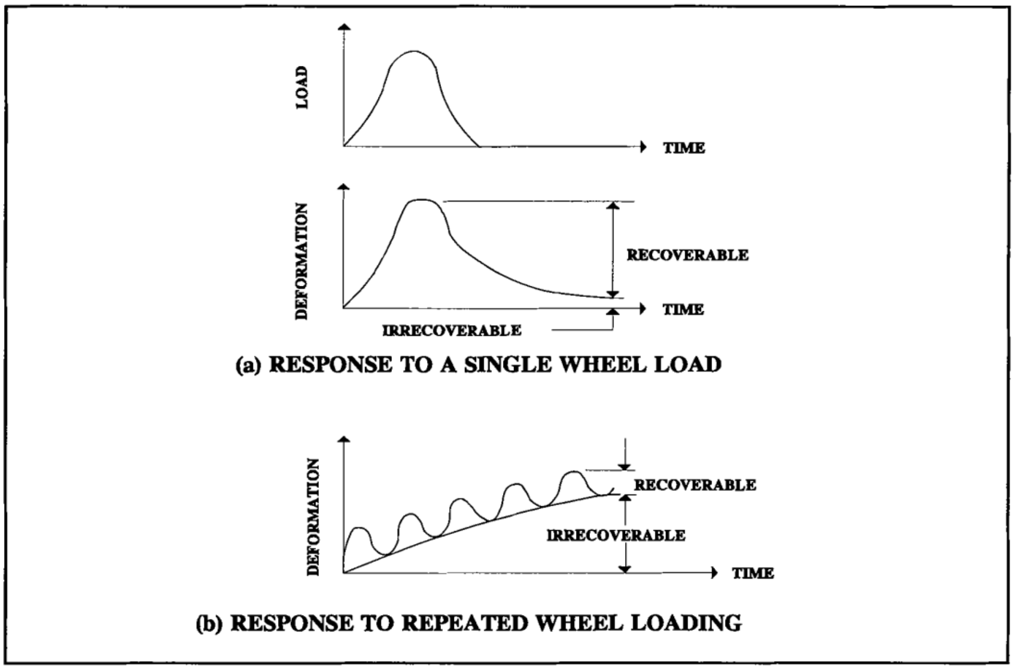


Figure 2-6 Visco-elastic response to millions of load application (Read, 1996)

2.3 Methods for Asphalt Recycling

Recycling can be defined as reuse of a material that already has served its first intended purpose. In pavement recycling, there are several methods available and they could be defined by the following five broad categories: cold planing, hot in-plant recycling, hot in-place recycling, full depth reclamation, and cold recycling. The main common benefits between all of these recycling methods compared to traditional reconstruction methods include (ARRA, 2001):

- Conservation of non-renewable natural resources
- Preservation of the environment by reduction of land filling
- Energy conservation via reducing truck hauling costs
- Preservation of existing roadway geometry and clearances
- Capability to correct defects, profile, and cross-slope of pavement
- Higher productivity with less disruption to the public

It is essential to evaluate each project being considered for recycling to determine the most appropriate recycling method. Some of these factors are (ARRA, 2001, Kandhal and Mallick, 1997):

1. Type, condition, and layers thickness of the existing pavement
2. Environmental conditions of the region (temperature and rainfall)
3. Type, frequency and cost of past maintenance activities
4. Required design life for pavement to be recycled
5. Construction considerations such as restriction imposed by bridges
6. Type and severity of distress of the existing pavement.

Guides for selection the suitable recycling method to each distress type are exist in elsewhere (ARRA, 1992). A brief explanation of asphalt recycling methods is presented below.

2.3.1 Cold Planing (CP)

CP is defined as removal of an existing pavement to a required depth, longitudinal profile, and cross-slope. The textured resulting surface as indicated in Figure 2-7 becomes free of humps, ruts and any other surface imperfections. Therefore, it can be immediately used for driving or any further treatments of the other asphalt recycling methods. (ARRA, 2001).

Main advantages of CP involve:

- Removing wheel ruts, deteriorated surfaces, and oxidized binder
- Improving road friction
- Providing surface preparation prior any additional recycling method

Figure 2-7 Textured surface of CP [ARRA, 2001]

2.3.2 Hot In-Plant Recycling (HIPR)

HIPR is a process of combining RAP with new aggregates and bitumen in central plant to produce a recycled mix. Modified or specially designed batch or drum mix plants are used to produce these recycled mix (Kandhal and Mallick, 1997). Figure 2-8 and Figure 2-9 show introduction of RAP in batch and drum plant respectively. The amount of RAP used in HIPR has some practical limitations which are related to plant technology, RAP aggregates gradation, physical properties of RAP binder, and gaseous emission. The content of RAP used HIPR has been as high as (85%-90%). However, it is more typically around (15%-25%) for batch plants, and (30%-50%) for drum plants. Once the recycled mix has been produced, it is transported, placed, and compacted with conventional HMA equipment (ARRA, 2001).

Hot recycling advantages include:

- Provides the same, if not better, performance as pavements constructed with virgin materials (Kandhal and Mallick, 1997)
- Problems relating to aggregate gradation and/or RAP binder can be corrected with proper selection of virgin aggregates and binder

Figure 2-8 Asphalt batch plant with RAP infeed (ARRA, 2001)

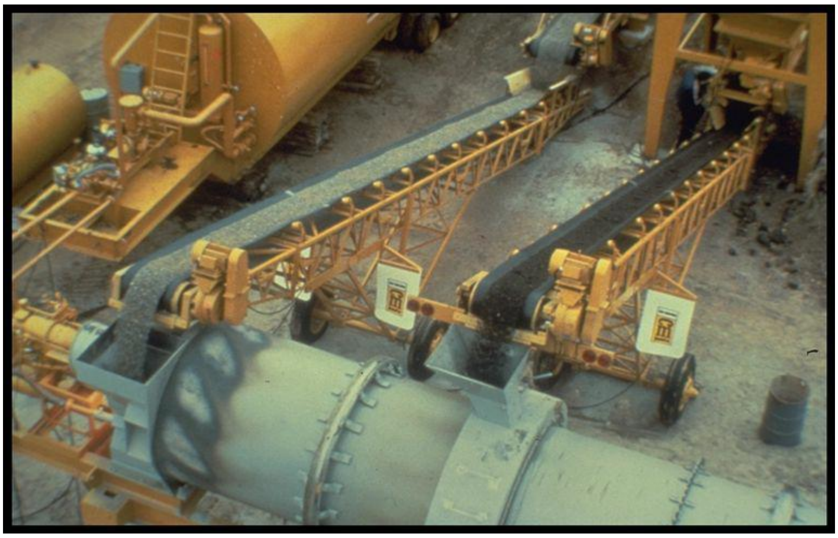


Figure 2-9 RAP introduction in asphalt drum plant (Kandhal and Mallick, 1997)

2.3.3 Hot In-Place Recycling (HIR)

HIR is a process of producing the recycled HMA on site. It contains three main steps: heating, softening, and scarifying of the existing pavement (Kandhal and Mallick, 1997). The loosened asphalt pavement is then mixed with additional virgin aggregates and bitumen. Generally, the limiting rate of virgin aggregate is constrained by the equipment to be less than 30% (ARRA, 2001). Three sub-categories of HIR are Surface Recycling, Remixing, and Repaving. Since HIR utilizes plenty of pieces of equipment varying from heaters, scarifiers, mixers, pavers, and rollers and occupies a long distance, the combined equipment is often referred to as "train", see Figure 2-10.

Surface Recycling is the oldest HIR form in which the pavement surface is heated, softened, then scarified. Once the surface has been scarified, the recycling agent is added. Then, the loose recycled mix is mixed and placed with standard pavers. It is necessary to state that no new HMA or virgin aggregates are added during surface recycling, thus the overall pavement thickness remains fixed (ARRA, 2001).

Remixing is commonly used when the properties of the existing pavement require significant modification. Remixing process consists of the same three main steps of surface recycling, but the difference is the possibility of adding virgin aggregate, new bitumen, and recycling agent, if required.

Repaving combines the Surface Recycling or Remix process with a simultaneous or consecutive placement of new HMA overlay (Kandhal and Mallick, 1997).

HIR advantages include:

- Reducing truck haulage compared to other recycling methods
- Treatment of complete roadway width or only the driving lanes
- The possibility of rejuvenating the oxidized binder by using of recycling agents
- Providing hot or thermal bond between longitudinal joints
- Little traffic disruption and the roadway is opened to traffic at the end of day

Figure 2-10 HIR train equipment (ARRA, 2001)

2.3.4 Full Depth Reclamation (FDR)

FDR is a process of blending part or full thickness of pavement with a proportion of underlying materials (base, subbase and/or subgrade) without implementation of heat to produce homogenous base material (PIRAC, 2003). FDR equipment contains reclaimer unit, stabilizing additive unit, motor grader, and rollers, Figure 2-11. In the case of using stabilizing additives, a curing period (1-14 days) should follow the final compaction and shaping process (ARRA, 2001).

FDR advantages include:

- Possibility of fixing deficiencies of subgrade by stabilization
- Deteriorated base can be reshaped to restore surface profile
- Significant structural improvement can be obtained through utilizing of stabilizing additives.
- Produces thick, homogeneous bound layers

Figure 2-11 FDR reclaimer and stabilizing additive tanker (ARRA, 2001)

2.3.5 Cold Recycling (CR)

CR is a process of recycling the asphalt pavement with no heat. These types of mixes need high compactive effort than conventional HMA. This is due to the high internal friction generated between particles, the higher viscosity of the aged binder, and colder compaction temperatures. The compacted CR mixes must be adequately cured from several days to 2 weeks before a wearing surface is placed

(ARRA, 2001). CR includes two sub-categories; cold in-place recycling (CIR) and cold central plant recycling (CCPR).

CIR is undertaken on site and in general uses 100 percent of the RAP (ARRA, 2001). There are different types of CIR trains which differ from one another according to how the RAP is removed and sized, how the recycling additives and modifiers are added, how they are mixed and controlled, and how the resultant mix is placed. Figure 2-12 shows one of these different types.

CCPR is the process in which the asphalt recycling occurs in cold mix plants. The RAP and new aggregate are stockpiled at the plant location. Asphalt emulsions or emulsified recycling agents are typically used as recycling additive (ARRA, 2001).

***CR advantages include*:**

- Surface irregularities and cracks are interrupted
- Rutting, potholes, and ravelling are eliminated
- base and subgrade materials are not disturbed

Figure 2-12 Multi-unit CIR train (ARRA, 2001)

The massive advantages of recycling asphalt pavement were appeared through studying the various techniques of pavement recycling. However, on the other side, there are some disadvantages and limitations for implementation of these techniques.

Disadvantages of recycling in-plant include:

- Excess moisture in the RAP decreases plant production rates (ARRA, 2001)
- Stockpiling RAP materials requires additional space in plant location (PIRAC, 2003)
- High inconsistency of RAP materials especially when they milled from different projects and stored in single stockpile (NAPA, 2007)
- Gaseous emissions emitted from drying RAP inside the mixer need to be ventilated, otherwise they will reduce plant production rate (NAPA, 2007)

Disadvantages of recycling in-place include (PIRAC, 2003)**:**

- Recycled pavement can be less homogenous
- Possible appearance of longitudinal cracks if adjacent strips are not correctly bonded
- Longer rehabilitation time than that required by a simple overlay with bituminous mixtures where no milling is necessary

limitations of use recycling methods are (PIRAC, 2003, NAPA, 2007)**:**

- Presence of geotextiles at a layer interface of layers to recycle
- Existence of many services exits and manholes
- Climatic conditions (ex. too low temperature and/or frequent rainfall)
- Unsuitable characteristics of in-place materials such as presence of large size paving blocks, important content of clayey materials
- Availability of the crushing and screening equipment for processing RAP either in plant or in-place

2.4 Bitumen

Bitumens are byproducts of the distillation process of crude oils. They are black, oily, viscous, flammable materials. Bitumen was used throughout prehistory as a sealant, an adhesive, building mortar, and waterproofing. Ancient Egyptians utilized bitumen in the embalmment of their mummies, after 1100 BC. The word from which mummy is derived "mum" means bitumen in Arabic and Persian (Ikram and Dodson, 1998).

2.4.1 Chemical Composition of Bitumen

Bitumen, from the chemistry point of view, is a complex hydrocarbon material including components of many chemical forms. The chemical composition of bitumen is extremely complex and varies widely according to the source of the crude oil. The chemical composition of bitumens, as well known, has a large influence on their performance (Van Der Ven, 1998). Based on the analysis of bitumen manufactured from a variety of crude oil sources, most of bitumens consist of the following elements; see Table 2.

Table 2 Common bitumen component (Read and Whiteoak, 2003)

Element	Percentage
Carbon	82% - 88%
Hydrogen	8% - 11%
Sulphur	0% - 6%
Oxygen	0% - 1.5%
Nitrogen	0% - 1%

Based on molecular weight, the main four constituents of bitumen are asphaltenes, resins, aromatics, and saturates.

Asphaltenes: Asphaltenes are complex hydrocarbons insoluble black or brown amorphous solids. Molecules in this fraction are strongly attached and difficult to disperse. The atomic ratio of hydrogen/carbon (H/C) is about 1:1. Asphaltenes, which constitute 5 to 25% of the bitumen, are the main factor influencing the rheological properties of bitumen. Increasing the asphaltene content makes bitumen harder and more viscous (Read and Whiteoak, 2003).

Resins (Polar Aromatics): Resins are similar to asphaltenes in composition of carbon and hydrogen. They are soluble dark brown solid or semi-solid with H/C atomic ratio of 1:3 to 1:4. They are strongly adhesive because of their polarity nature, and can also serve as dispersing agents (peptisers) for asphaltenes (Van Der Ven, 1998).

Aromatics (Non-Polar Aromatics): These are dark brown viscous soluble liquids having the lowest molecular weight. They constitute the greatest volume of bitumen (40% to 65%). Since aromatics have high dissolving ability for other high molecular weight hydrocarbons, they act as the main proportion of dispersion medium for peptizing asphaltenes. Aromatics are supposed to protect the oily components of bitumen from oxidation during the ageing process (Van Der Ven, 1998).

Saturates: Saturates are white non-polar viscous soluble oils, similar in molecular weight to the aromatics. They contain most of the waxy components of the bitumens and usually contribute between 5% and 20% of the total bitumen constituent.

2.4.2 Bitumen Structure

Bitumen is conventionally regarded as a colloidal system consisting of high molecular weight asphaltene micelles dispersed in maltenes. Maltenes are viscous liquids composing of resins and oils (Asphalt Institute, 1980). The micelles are considered to be asphaltenes together with an absorbed thin outer layer of resins which act as stabilising solvating layer. In the presence of sufficient quantities of resins and aromatics, the asphaltenes are fully peptised and the resultant micelles have good mobility within bitumen. These are known as SOL type bitumens. If the aromatic/resins fraction does not exist in enough quantity to peptise the micelles, the asphaltenes unite together resulting in an irregular open packed structure of linked micelles. These types of bitumens are known as GEL type. Figure 2-13 depict a schematic of the two types of bitumen.

The colloidal behaviour of the asphaltenes in bitumens results from their agglomeration. The degree to which they are peptised will have a significance influence on the resultant viscosity of the system. The agglomeration effect decreases with increasing temperature:

consequently the GEL character might be lost when bitumens are heated to high temperatures. The saturates fraction decreases the ability of the medium (maltenes) to solvate the asphaltene agglomerations, thus increasing the viscosity and GEL character of the bitumen. Therefore, viscosity of bitumens is not only affected by asphaltenes content but also saturates content (Read and Whiteoak, 2003).

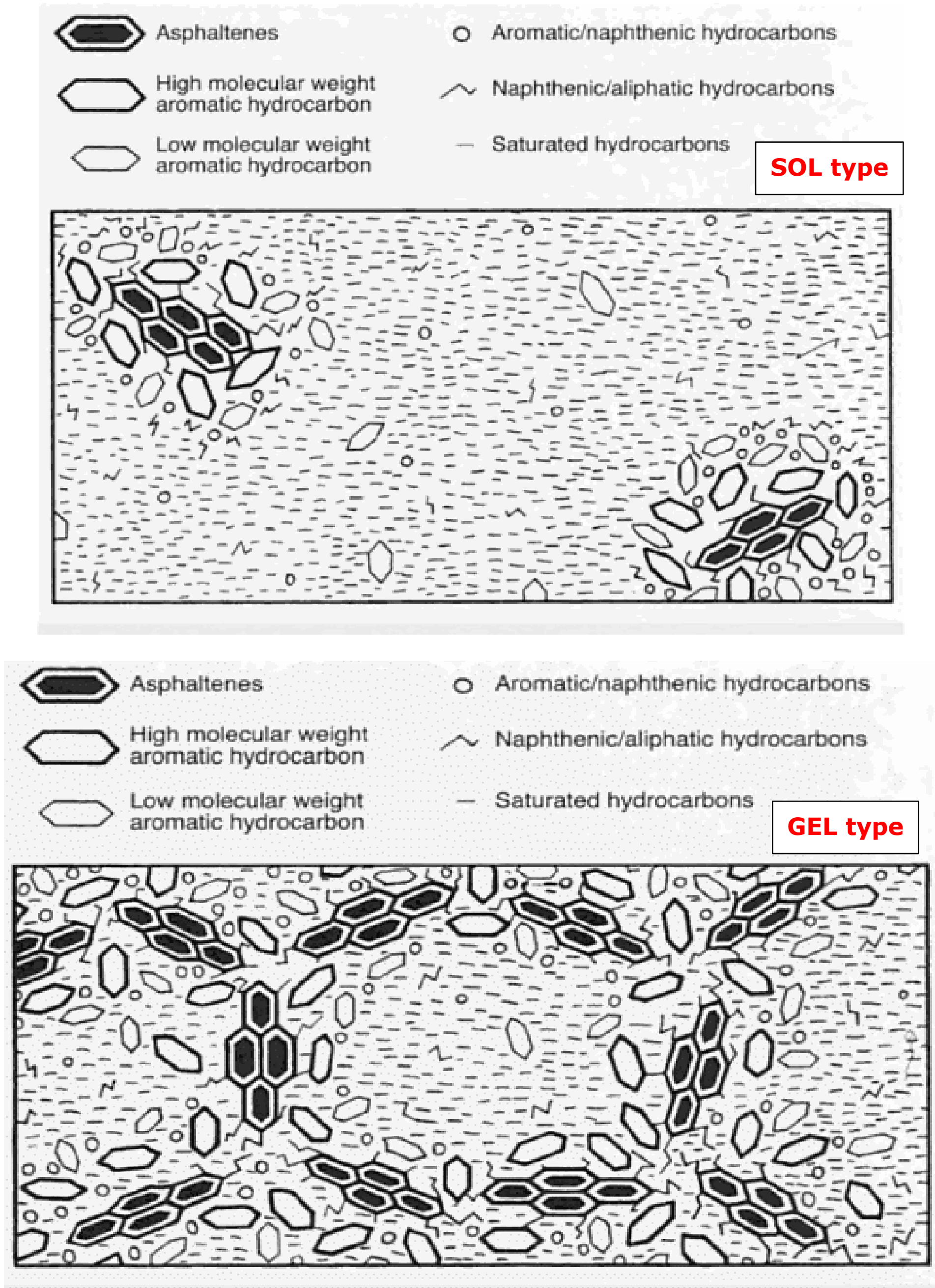


Figure 2-13 Schematic of SOL and GEL types bitumens (Read and Whiteoak, 2003)

2.4.3 Ageing of Bitumen

Being an organic material, bitumen can be affected by temperature, oxygen, and ultraviolet radiation. These external factors cause it to aged and consequential stiffening of the asphalt mix. Ageing of binder within an asphalt mix can have positive action by increasing both cohesion and stiffness, which improves the resistance to permanent deformation and the load-bearing capacity. at the same time, it has a negative effect by reducing the flexibility of the pavement that leads to more possibility for cracks especially by fatigue (Nunn and Ferne, 2001, Vallerga, 1981, Robertson et al., 1991).

Ageing of bitumen in asphalt mixes could be divided into short and long term ageing. Short-term ageing occurs during the mixing and construction process as a result of loss of volatile components and oxidation of bitumen. The long-term ageing takes place through the whole service life of the road via further oxidation of the in-place material (Airey, 2003).

Regarding chemical composition of bitumen through ageing, the asphaltenes content is observed to rise, while the resins and aromatics contents drop. The rise in asphaltenes content makes the bitumen more hard (stiff) and that could be easily manifested as decreasing of penetration and increasing softening point and viscosity.

The molecules in bitumen can be divided according to their sizes into large molecular size, LMS, (asphaltenes), medium molecular size, MMS, (resins) and small molecular size, SMS, (oil). Noureldin (1995) studied the changes in molecular size distribution caused by oxidation via thin film oven test (TFOT). It was revealed that the changes in molecular size distribution can be described as increases in LMS percentage and viscosity and decreases in MMS, SMS, and penetration. Also, ageing by oxidation makes the resins and oily components transform into asphaltenes (Noureldin, 1995). The increasing proportion of asphaltenes, plus the fact that the maltenes phase is not sufficient to disperse asphaltenes, elevates viscosity of bitumen.

Figure 2-14, shows the changes in the compositional structure of the bitumen with time when ageing is in progress.

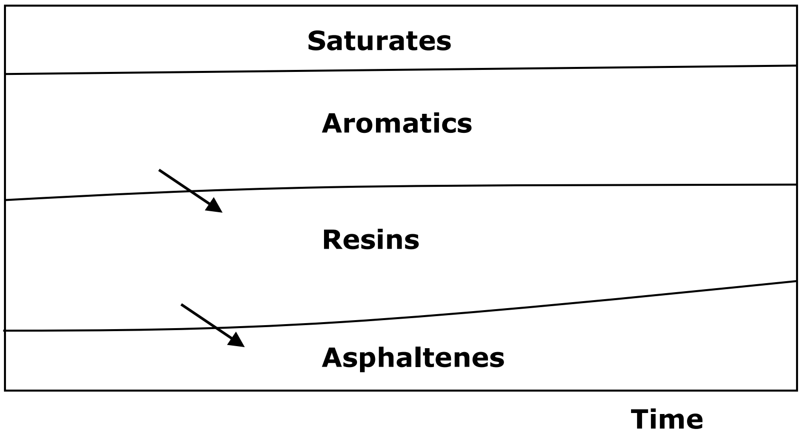


Figure 2-14 Ageing effect on the chemical composition of the bitumen

2.4.3.1 Ageing mechanism in bituminous mixture

There are approximately 15 reasons which are believed to be responsible for bitumen ageing. These factors have been identified by various researchers (Airey, 2003, Petersen, 1984, Traxler, 1963, Vallerga, 1981, Vallerga et al., 1957). Ageing mechanisms can be divided into reversible and irreversible processes. Physical hardening is a reversible process in which the main features of bitumen can be recovered via reheating. In irreversible ageing, the chemical changes that take place in the bitumen structure are not recoverable, except by blending with materials such as modifiers or rejuvenators. Although fifteen causes are believed to be responsible for bitumen ageing, four of them are universally accepted as dominant mechanisms. These mechanisms are volatilisation, exudation of oils, steric or physical hardening, and oxidation (Lu and Isacsson, 2002, Airey, 2003).

Loss of volatiles

Loss of volatiles depends primarily on the temperature and the exposure condition. Since bitumen is not a highly volatile substance, the amount of ageing due to volatilization is usually small and the major part of this process occurs during the mixing and construction stage (Read and Whiteoak, 2003, Al-Qadi et al., 2007). (Malan, 1989) mentioned that loss of volatiles through the mixing and laying process causes the binder to shrink at the surface layer resulting in shrinkage stresses at the asphalt surface and eventually cracking.

Exudation

Exudation of oily ingredients from the bitumen and absorption by the surrounding mineral aggregate reduces the percentage of these oily components in bitumen. This in turn makes the bitumen less flexible and more viscous. Susceptibility for exudative ageing is a function of aggregate porosity. The aggregate used in this study is limestone which is considered one of the more porous aggregates, therefore some ageing due to exudation might be expected.

Physical hardening

Physical hardening of binders is observed at low temperatures. It is a slow and gradual process that affects all those properties which depend on temperature. This phenomenon can be defined as a time-temperature dependent process that makes changes in the rheological and physical properties of binder (Struik, 1977). Several researchers attribute physical hardening to the reorientation of bitumen molecules in order to achieve an optimum thermodynamically stable state (Lu and Isacsson, 2002, Petersen, 1984, Read and Whiteoak, 2003). Further research has indicated that the amount of physical hardening observed in some binders is dependent on their chemical composition (Anderson et al., 1994, Claudy et al., 1992).

Oxidation

Bitumen does not differ from any other organic material in oxidising on contact with oxygen. Oxidation could be considered the principal reason for bitumen ageing. Consequences of severe oxidation are separation of structural components, rise in viscosity, embrittlement and loss of cohesion and adhesion of the binder (Mill et al., 1992). Formation of polar hydroxyl carbonyl and carboxyl groups in large and more complex molecules converts the bitumen to a harder and less flexible substance (Read and Whiteoak, 2003).

The degree of oxidation is strongly dependent on temperature, time, and thickness of bitumen film exposed to air. This phenomenon occurs not only in mixing and construction stages, but also through the service life of pavement. Nearly 30% loss in bitumen penetration happens during mixing process (Read and Whiteoak, 2003). Ageing by oxidation, during the service life of a road, occurs only in the top layer of an asphalt pavement. Researchers have estimated values ranging from few microns to approximately 5 mm of an asphalt layer allowing diffusion of oxygen (Berkers, 2005).

2.4.3.2 Physical hardening from binders to mixtures

The physical hardening effect on bitumen is well known and documented. However, few studies have been conducted to address its impact on the behaviour of asphalt mixes, which is still not clear.

Romero et al. (1999) studied this effect by testing asphaltic samples at low temperature by the Thermal Stress Restrained Test (TSRT). The authors used two types of bitumen (AAM-1 and AAM-2) designed by SHRP to be particularly susceptible to physical hardening. Prior to testing, two groups of specimens were conditioned unrestrained at -15 ºC and held isothermally for a period of 1hr and 24 hrs. The test started after specimens were restrained and held at constant length, and then the temperature was dropped at a rate of 15 ºC per hour until the specimens fractured.

The test parameters (at time of fracture) were stress, temperature, and the slope of temperature-stress curve. It was found that low-temperature physical hardening had no significant effect on the low-temperature properties of mix of bitumen AAM-1. However, significant effect on mix of bitumen AAM-2 was recorded. Moreover, physical hardening that affects the performance of binder in many forms might not necessarily transfer into mixture behaviour, since there are other factors such as mineral filler, aggregate, and air voids that could affect behaviour of a mixture at low temperature (Romero et al., 1999).

In later research, Cannon et al. (2011) studied the physical hardening effect on creep stiffness of asphalt mixes at low temperature, and compared the changes observed in asphalt mixes with the corresponding ones in binders. Bending Beam Rheometer (BBR) creep tests were applied on laboratory-prepared beams of binder and asphalt mix. Four binders were utilized for manufacturing the asphalt specimens containing limestone and granite aggregates. Another set of four field binders were extracted from different pavement cores and were used to produce the BBR binder beams. Later, asphalt mix beams were cut from laboratory gyratory cylinders and field cores. Description of the binders and mixes along with the temperatures at which BBR creep tests were performed are displayed in Table 3 and Table 4. The tested beams were conditioned at the test temperature for 1 hr and 24 hrs.

Table 3 Types of binders, laboratory asphalt mixture and creep test temperatures (Cannone Falchetto and Marasteanu, 2011)

Binder			**Asphalt Mixture**		
Type	Symbol	Test Temperature	Granite	Limestone	Test Temperature
PG58-34, modifier 1	58-34 M1	-24, -30, -36 (ºC)	58-34:M1:GR	58-34:M1:LM	-12, -24 (ºC)
PG58-34, modifier 2	58-34 M2		58-34:M2:GR	58-34:M1:LM	
PG64-34, modifier 1	64-34 M1		64-34:M1:GR	64-34:M1:LM	
PG64-34, modifier 2	64-34 M2		64-34:M2:GR	64-34:M2:LM	

Table 4 Field extracted binders and asphalt mixture along with creep test temperatures (Cannone Falchetto and Marasteanu, 2011)

Binder				**Asphalt Mixture**	
Specimen symbol	Original grade	Equivalent Grade	Test Temperature	Specimen symbol	Test Temperature
MnROAD 03	120/150	PG58-28	-18, -30 ºC	MnROAD 03-M	-6, -18 ºC
MnROAD 19	AC-20	PG64-22	-18, -30 ºC	MnROAD 19-M	-6, -18 ºC
WI US 45	PG58-34	PG58-34	-24, -30, -36	WI US 45-M	-12, -24 ºC
WI STH 73	PG58-28	PG58-28	-18, -24, -30	WI STH 73-M	-6, -18 ºC

The measured parameters were in forms of creep stiffness curves from which the m-value (rate of change of stiffness in BBR test) can be calculated. Figure 2-15 and Figure 2-16 show an example of creep stiffness curves for binders and asphalt mixes respectively. Figure 2-17 and Figure 2-18 indicate the changes in creep stiffness and m-value with conditioning time (1hr to 24hrs) for all binders and mixes respectively. For all binders, the results demonstrate that the additional conditioning time increased creep stiffness and reduced the m-values. However, the creep stiffness of asphalt mix indicates more complex behaviour (positive and negative changes with conditioning time). A similar trend was observed for the field mixtures and the extracted binders from them, whereas the increases in mixture creep stiffness and the decrease in the m-value were much less than those of the extracted binder (see Figure 2-19 and Figure 2-20). Also, the authors reported that an increase in binder creep stiffness in excess of 30% is manifested in the asphalt mix as an increase of only 5%, suggesting that just a small proportion of the changes transferred from binder to mixture. They also revealed that the type of aggregate appears to play a significant role in transferring these changes.

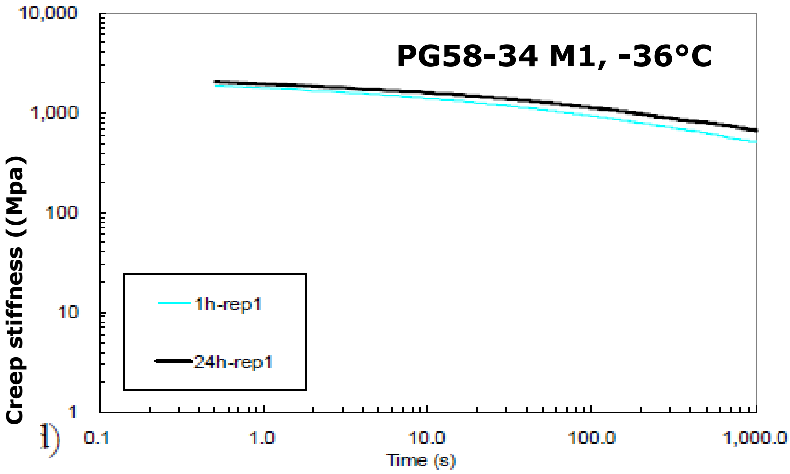
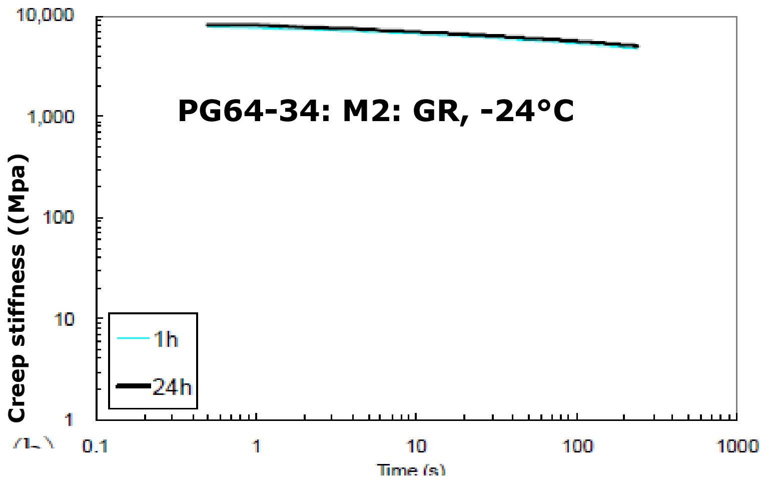


Figure 2-15 Creep stiffness curves of binders(Cannone Falchetto and Marasteanu, 2011)



Times (s)
Figure 2-16 Creep stiffness curves of asphalt mixtures(Cannone Falchetto and Marasteanu, 2011)

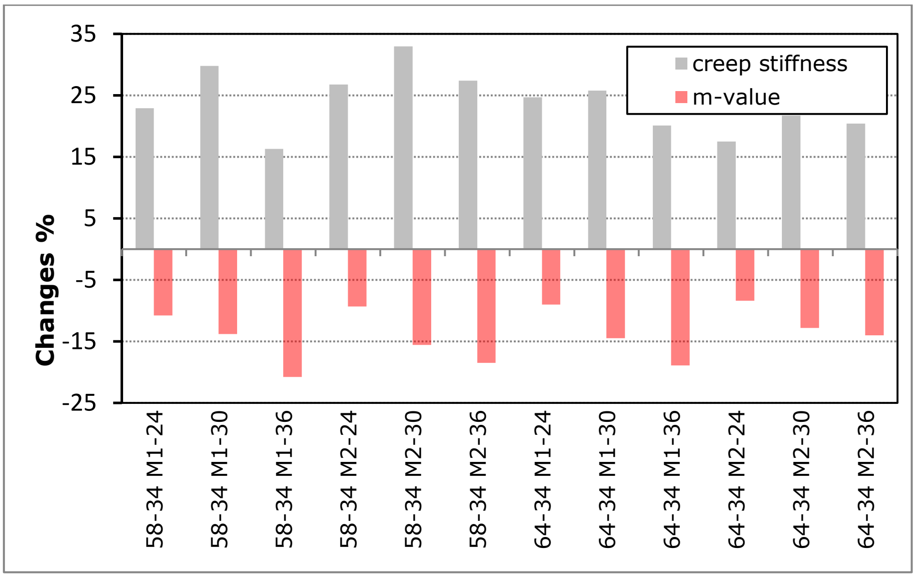


Figure 2-17 Change in creep stiffness and m-value for binder (Cannone Falchetto and Marasteanu, 2011)

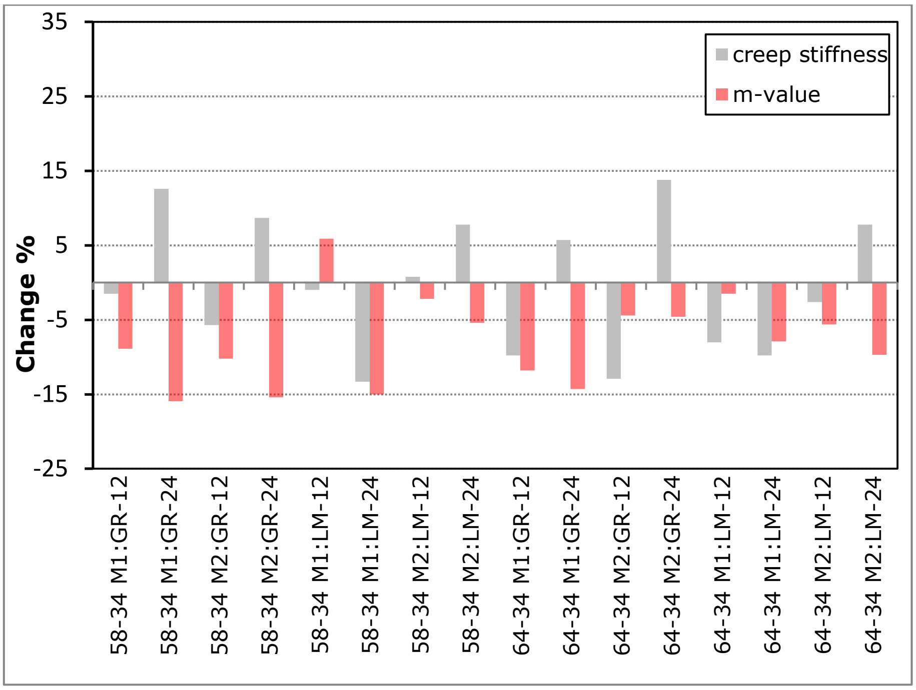


Figure 2-18 Change in creep stiffness and m-value for asphalt mixtures (Cannone Falchetto and Marasteanu, 2011)

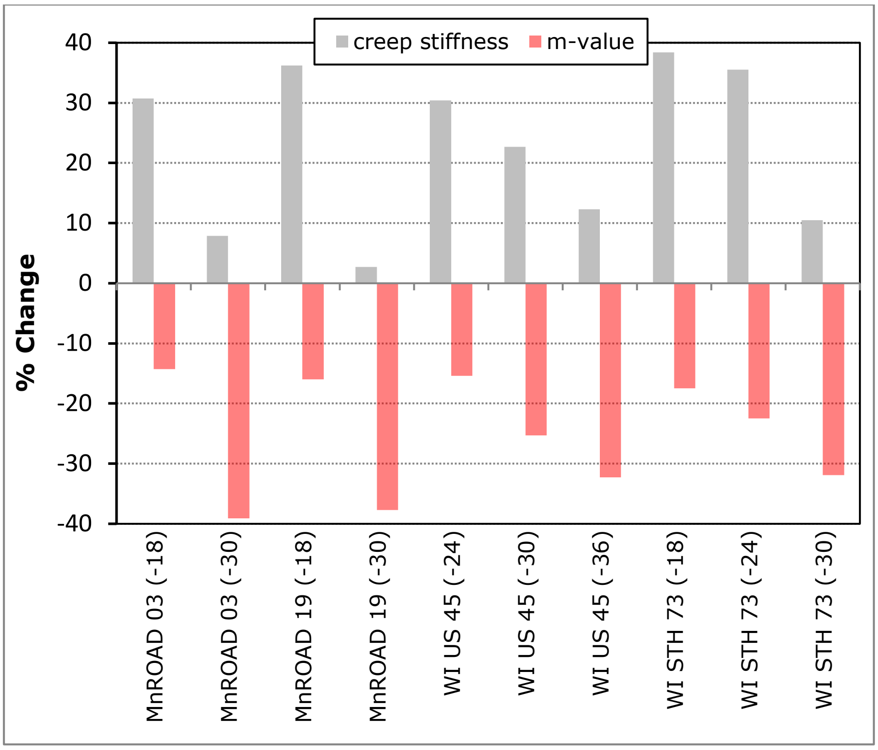


Figure 2-19 Change in creep stiffness and m-value for extracted binder (Cannone Falchetto and Marasteanu, 2011)

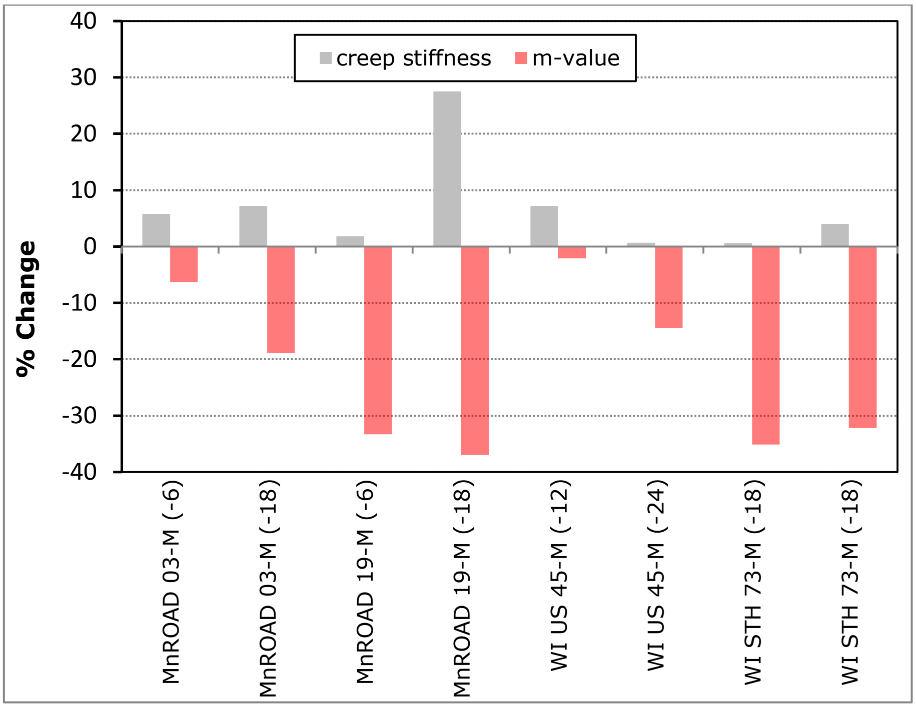


Figure 2-20 Change in creep stiffness and m-value for field asphalt mixtures (Cannone Falchetto and Marasteanu, 2011)

2.5 Properties of RAP

Properties of RAP materials are mostly based on the properties of the constituent materials i.e. RAP aggregate and RAP binder. Once the decision has been made to utilize RAP materials in hot or cold asphalt recycling, it is crucial to characterize both RAP aggregate and RAP binder. Sampling and testing must be conducted to estimate the material's quality with respect to standards. In addition, it is essential to ensure that the RAP materials are compatible with the virgin materials, and the final blend meets all mixture and binder requirements. The Federal Highway Administration (FHWA) developed specific recommendations based on experience for inclusion of the RAP into Superpave mixture design procedures (FHWA, 1997). The major requirements include:

- 100% passing the 50 mm sieve
- Maximum 2% deleterious materials
- Moisture content within RAP materials should be initially determined to facilitate batching for mix design
- Further ageing of RAP binder should be avoided in particular during heating the material to mixing temperature. Therefore, heating time for RAP should be kept at a minimum, not more than one hour at mixing temperature
- Specific gravity of virgin bitumen could be used as for RAP binder
- Mixing and compaction temperatures for the virgin and RAP binder can be obtained from typical virgin binder
- When the RAP contains highly absorptive materials, the amount of absorbed bitumen should be estimated and used to back calculate the bulk specific gravity of the aggregate
- The gradation of RAP aggregate should be used in calculation of the mix gradation

The properties of RAP binder and aggregate in addition to the methods for determining these properties are explained below.

2.5.1 RAP Variability

One of the major concerns that worry the agencies, contractors as well as researchers is the variability of RAP. This problem is an important consideration in the design of HMA incorporating RAP. RAP variability includes not only the gradation of RAP but also the content and origin of RAP binder. This issue derives from the presence of patches, chip seals, deleterious materials when the pavement is removed from the old roadway. Also, in some cases, RAP may include material from base and intermediate courses. RAPs from several projects are sometimes mixed in a single stockpile. Consequently, high inconsistency in binder content and/or aggregate gradation of RAP most probably causes high variation in properties of recycled HMA (Solaimanian et al., 1995, Solaimanian and Savory, 1996, Pratheepan, 2009, NCHRP, 2011).

Some states have limited the amount of RAP used in new bituminous mixtures due to this problem. However, some researchers consider that higher percentages of RAP could be used if the materials were milled off the same project in which the new mix will be placed (McDaniel et al., 2000). Other researchers believe that the issue of RAP variability is controllable by good stockpile management (Nady, 1997, Davidson et al., 1978). In the case of stockpiling the materials from several projects, a crushing or screening process for RAP can help to mix the pile and reduce the variability between RAPs (Roberts et al., 1996). It has been reported that if amount of RAP ≤ 10%, then a 10% change in its grading will change that of the recycled mix by 1% at most, which is insignificant. However, if large proportions of RAP are to be used and the RAP source is variable, extensive processing will be needed to ensure a consistent grading (Carswell et al., 2010). In general, experience has indicated that mixture quality can be most easily controlled by using less than 25% RAP (Asphalt Institute, 2001).

2.5.2 Moisture in RAP

Moisture is a property present in RAP as it is in the virgin aggregate. It is important to know how much moisture is in the RAP. Determination the percentage of moisture content helps in calculating the actual batch weight of RAP in the plant. If the weight of the moisture is not accounted for, the actual weight of RAP added will be lower than that required because part of the weight will be moisture instead of RAP. Using RAP with high moisture content consumes a lot of time and energy to dry heat, leading to a decrease in the asphalt plant production. In batch plants, high moisture contents can produce steam clouds in the pugmill that need to be vented (NAPA, 2007, McDaniel and Anderson, 2001).

Moisture content is expressed as weight of water, indicated by the change in mass before and after drying, divided by the dry weight of the RAP, Equation 3.

$$\%\mathbf{Moisture} = \frac{\mathbf{w_w} - \mathbf{w_d}}{\mathbf{w_d}} \times \mathbf{100} \qquad \text{Equation 3}$$

Where
w_w = mass of wet RAP
w_d= mass of RAP after drying to constant mass
Often, it is required to calculate the weight of wet RAP (with moisture) to provide a certain dry mass, see Equation 4.

$$\mathbf{w_w} = \mathbf{w_d}\ (1+\%\text{Moisture}) \qquad \text{Equation 4}$$

2.5.3 RAP Aggregate Properties

Why do we need to know RAP aggregate properties? Because the RAP contains some aggregates which were allowed in the past and may not be today. From this point of view, and to ensure that quality material is being added to the new mixtures, some engineering properties of the recovered aggregate from RAP such as shape, specific gravity, consensus properties and gradation should be specified.

- ***RAP Aggregate Gradation***

Aggregate gradation analysis and blending the aggregates to obtain the required gradation are essential in hot mix asphalt design. To obtain the aggregate cleared for testing, an extraction and recovery process should be done in advance for RAP materials. Then, the recovered aggregate should be thoroughly dried in an oven or in front of a fan before testing for grading distribution. It is important to state that the aggregate in the RAP should be smaller than one-half of the layer thickness. RAP aggregate gradation from road cores might be appreciably different from RAP aggregate gradation from milling. The latter is usually finer due to possible crushing by the milling machine. The mix design gradation based on cores will not be representative of the actual gradation during construction (Solaimanian and Savory, 1996).

- ***RAP Aggregate Specific Gravity***

Calculating the voids in the mineral aggregate (VMA) requires knowing the bulk specific gravity of the combined aggregate. When RAP materials are included, the determination process can be more complicated. Hence, it is initially necessary to calculate the bulk specific gravity of each aggregate component (virgin and RAP aggregate). Measuring specific gravity of the RAP aggregate would require extracting, sieving the RAP aggregate into coarse and fine fractions, and determining the specific gravity of each fraction. It should be stated that the extraction process might change the aggregate properties and the amount of fine material as well, which could affect the specific gravity.

- ***Consensus Properties***

To control the quality of the materials used in asphalt mixes, specifications require the consensus properties on the blend to be within limits. Therefore, the RAP aggregate may be tested for its consensus properties as is done for virgin aggregates. The following considerations should be taken into account when dealing with RAP aggregate.

- RAP aggregate should not have a high percentage of flat or elongated particles. If so, it can be blended with more cubical aggregate to achieve the requirements.
- The percentage of fine clay particles contained in the fine aggregate should be calculated, because it is an indication of how clean the fine aggregate is and how well the binder can coat the fine aggregate.
- The absorption properties of the RAP aggregate may be determined because the aggregate particles in RAP materials are covered with a certain amount of bitumen. And this in

turn makes the absorption properties of the RAP aggregate differ from the virgin aggregate.

2.5.4 RAP Binder Properties

The properties of RAP binder are necessary to be determined when using high percentages of RAP (>25%) (McDaniel and Anderson, 2001, Kandhal and Foo, 1997). The most crucial characteristic of RAP material that would seriously affect the properties and performance of recycled mixes is ageing of its binder. ageing of binder occurs during construction and also the service life of asphalt pavements via some major mechanisms such as oxidation, volatilization, exudation, and separation (Traxler, 1963, Karlsson and Isacsson, 2006, Airey, 2003, Petersen, 1984). The level of ageing is affected by many factors such as voids content of the HMA, level of damage (either by traffic loading or weathering conditions) of the asphalt pavement prior to recycling, and stockpiling.

Kemp (1981) observed a substantial increase in stiffness of binder recovered from porous HMA (Kemp and Predoehl, 1981). McMillan and Palsat (1985) revealed that stockpiled RAP materials are prone to ageing as they are exposed to oxygen (McMillan and Palsat, 1985). Also, some researchers have reported that the more damage (cracking, stripping, ravelling) in asphalt pavement before recycling, the more ageing of RAP binder takes place (Amirkhanian and Williams, 1993, Karlsson and Isacsson, 2006). The most necessary properties of RAP binder, in the design procedure for recycled HMA, are the complex shear modulus and phase angle (which can be measured by DSR test), and viscosity (which can also be measured by DSR test, see sec 3.3). These properties can be measured by applying the relevant tests after recovering the binder from RAP materials. It has been reported that the chemical, physical, and rheological properties of RAP binder are greatly influenced by ageing (Al-Qadi et al., 2007).

Because of losing some components of the binder during the ageing process, the rheological behaviour will consequently differ from the virgin binder. If the old binder is too stiff, the blend of old and virgin binders may not perform as expected. At small percentages up to 20% of RAP, the aged binder does not considerably change the properties of the blend (Kennedy et al., 1998). However, at intermediate to higher percentages, the aged binder can significantly influence the properties of the blend and may change the grade of the resultant binder. So recent modifications such counter flow drum mixers and microwave heaters have been incorporated to conventional asphalt plants in order to reduce ageing of the RAP binder during the mixing stage. Although, the heating by microwave is more easily absorbed by the aggregates than binder, it is still expensive technology (Al-Qadi et al., 2007, NAPA, 2007).

2.5.5 Extraction and Recovery Methods

When the amount of RAP used in the hot-mix asphalt exceeds 25%, the mix design process takes into account the amount of bitumen in RAP materials (Abdulshafi et al., 2002, Zofka et al., 2004, McDaniel and Anderson, 2001). Therefore, characterization of the recovered bitumen and aggregate is a crucial step for design, quality control, performance prediction, and research purposes. This important piece of information could be determined after carrying out the extraction and recovery process for RAP to obtain the recovered binder and aggregate for further testing. Extraction is a process of separating the binder off the aggregate by dissolving in suitable solvent, while recovery is a process of separating the binder from the solvent by distillation.

2.5.5.1 Extraction methods

Centrifuge and Reflux techniques are the most popular methods for extraction. Previous research has indicated that the Reflux method appears to increase the ageing of the recovered bitumen (Burr et al., 1993). Vacuum extraction and Ignition oven procedures are alternative methods but not as widespread (Peterson et al., 2000). The Asphalt Institute modified SHRP extraction method (developed from AASHTO TP2) has been demonstrated to cause the least severe changes to the recovered binder properties (Peterson et al., 2000).

2.5.5.2 Recovery methods

All of the recovery methods are based mostly on concentrating the bitumen solution (bitumen and solvent) by distillation. The recovered bitumen can afterwards be exposed to further testing. Recovery of the aggregate can be done by some process such as the wash route (by adding another solvent and water), or the dry route (by evaporating the solvent via heating) (Mulder et al., 1994). The most common recovery methods are Abson, Rotary Evaporator (Rotavapor), and Fractionating Column. In the Abson method, the bitumen is recovered by boiling the solvent off and leaving the bitumen behind. However, in the Rotavapor and Fractionating Column methods, the bitumen is recovered by vacuum distillation and atmospheric distillation respectively (BS EN 12697-4, 2005, ASTM D 5404, 2003, ASTM D 1856-98a, 2003, BS EN 12697-3, 2005).

2.5.5.3 Types of Solvents

There are a number of solvents found to be able to extract bitumen from asphalt mixtures. These solvents can be divided into three main categories: halogenated, aromatic, and aliphatic solvents. One example for each type are dichloromethane, toluene, and heptane respectively (Mulder et al., 1994). Table 5 indicates the common solvent for each extraction method.

Research has been done to evaluate the effect of different solvents on the properties of the recovered aggregate and bitumen. Mulder (1994) carried out research as a trial to develop a process to recover all the raw materials from the RAP. Three different solvents (dichloromethane, toluene, and heptane with 10% methanol) were selected in a preliminary study (liquid to solid, L/S, ratio =1 l/kg). It was observed that dichloromethane and toluene were equally good, but the former has better characteristics for inflammability and boiling point. The results showed that a two stage counter–current extraction with toluene (as a solvent) seems to be convenient to get the mineral fraction (gravel and sand) containing 0.1 % asphalt and the filler holding about 1.5 % asphalt (Mulder et al., 1994).

Table 5 Common solvents for extraction and recovery methods

Solvent	Extraction method	Recovery method
trichloroethylene	centrifuge , reflux	Abson, rotavapor, fractionating column
methylene chloride (dichloromethane)	centrifuge , reflux, vacuum	rotavapor, fractionating column
normal-propyl bromide	centrifuge , reflux	rotavapor
1,1,1-trichloroethane	centrifuge , reflux	Rotavapor, fractionating column
toluene	centrifuge	rotavapor, fractionating column
benzene	centrifuge	rotavapor, fractionating column, Abson

2.6 Methods of Designing the Recycled Mixtures

The proper design and construction of recycled HMA lead to production of recycled mixes similar in their properties to those of virgin HMA. Thus, application of a rational mix design is the first and most important step to produce mixes with acceptable engineering properties. The Asphalt Institute method and Superpave method are two common procedures for design of recycled mixes. Both methods are based on using blending charts to estimate the amount and grade of required virgin binder and/or recycling agents. The Asphalt Institute developed a viscosity blending chart according to the Arrhenius equation which was shown to be applicable to determine the amount of the softening agent required to meet the target viscosity (Chen et al., 2007). For the Superpave method, the blending chart was constructed based on the rutting factor $G^*/\sin\delta$ (G^* and δ are the complex modulus and phase angle) (Kandhal and Mallick, 1997, Asphalt Institute, 2001, Kandhal and Foo, 1997).

The design procedures of recycled mixes involve evaluation of the materials by identifying a) aggregate gradation of RAP; b) bitumen content of RAP; c) consistency and rheological properties of RAP binder. The objective of the mix design is to determine the combined gradation of the aggregates, the type and percentage of new binder, and percentage of recycling agent if required. The recycling agent should satisfy standards such as AASHTO, ASTM, or British standards etc. A series of trial mixes are then made with different bitumen contents. The optimum bitumen content for the recycled mix is selected based on Marshall, Hveem, or Superpave volumetric mix design procedures.

2.6.1 Asphalt Institute design method for recycled HMA

The Asphalt Institute have adopted a similar approach for recycled mixes as in ASTM D 4887 (ASTM D 4887, 2005). The Asphalt Institute approach uses a viscosity blending chart in order to specify the RAP content, the grade and amount of new bitumen plus recycling agent, if needed. Figure 2-21 shows a flow chart for procedure of design of recycled mixture (Asphalt Institute, 2001).

Gradation of RAP aggregate, bitumen content of RAP, and viscosity of RAP binder

⇓

Gradation of new aggregate

⇓

1- Determine combined gradation in recycled mix

⇓

2- Estimate the bitumen content of combined gradation

⇓

3- Determine new bitumen content in the recycled mix

⇓

4- Select grade of new Bitumen

⇓

5- Trail mix design

⇓

6- Select Job Mix Formula

Figure 2-21 Flow chart for recycled mix design procedure

1- Combined aggregates in the recycled mixture

Using the gradation of RAP aggregate and new aggregate, a combined gradation to meet the overall desired gradation is determined. After the blending of new and RAP aggregates has been established, the amount of new aggregate is calculated and expressed as r in percent.

2- Approximate bitumen binder demand of the combined aggregates

The most practical approach to determine the bitumen content for the combined aggregates of the recycled HMA is to be equal to that of virgin HMA. The following empirical equation is commonly used to estimate the approximate bitumen content:

$$P = 0.035a + 0.045b + KC + F \qquad \text{Equation 5}$$

Where:

P: approximate total bitumen demand

a: percent of mineral aggregate retained on 2.36 mm sieve,

b: percent of mineral aggregate passing the 2.36 mm sieve and retained on the 75 μm sieve

C: percent of mineral aggregate passing the 75μm sieve

K: 0.15 for (11-15) percent passing 75 μm sieve

0.18 for (6-10) percent passing 75µm sieve
0.20 for 5 percent or less passing 75 µm sieve
F: 0.0 to 2.0 percent (Based on aggregate absorption property).
0.7 is suggested in case of absence the data.

After calculating the approximate bitumen content, a series of trial mixes is designed varying in their bitumen contents by 0.5 % increments on either side of the approximate bitumen content.

3- Determine new bitumen content in the recycled mix

The required amount of new bitumen for the trial mixes of the recycled HMA is calculated by the following formula:

$$P_{nb} = \frac{(100^2 - rP_{sb})P_b}{100(100-P_{sb})} - \frac{(100-r)P_{sb}}{100-P_{sb}} \qquad \text{Equation 6}$$

Where:
P_{nb} , r: Percent of new bitumen and new aggregate, respectively
Pb :percent of estimated bitumen content of recycled mix
Psb : percent of bitumen content within RAP materials

4- Select grade of new bitumen

The grade of new bitumen is determined using the log-log viscosity blending chart, Figure 2-22. By selecting a target viscosity for the blend of the recovered RAP binder and new bitumen, and by calculating the percentage of new bitumen from Equation 7, point B can be located on the graph.

$$R = \frac{100\,P_{nb}}{P_b} \qquad \text{Equation 7}$$

Plot the viscosity of the RAP binder on the left vertical scale, point A. Draw a straight line from A to B until it intersects the right vertical scale at point C. Point C represents the viscosity of new bitumen required to blend with the RAP binder to hold the target viscosity.

5- Trial mix design

Trial mix designs are then made using the Marshall or Hveem method. The formulae shown in Table 6 are used for proportioning the ingredients by weight of total mix.

6- Select Job-Mix Formula

The optimum bitumen content is selected based on the test data obtained in the preceding step.

Table 6 Formulas for proportioning materials for recycled hot mix

% New Bitumen, P_{nb}	$\frac{(100^2 - rP_{sb})P_b}{100(100 - P_{sb})} - \frac{(100 - r)P_{sb}}{100 - P_{sb}}$
% RAP, P_{sm}	$\frac{100(100 - r)}{100 - P_{sb}} - \frac{(100 - r)P_b}{100 - P_{sb}}$
% New Aggregate, P_{ns}	$r - \frac{rP_b}{100}$

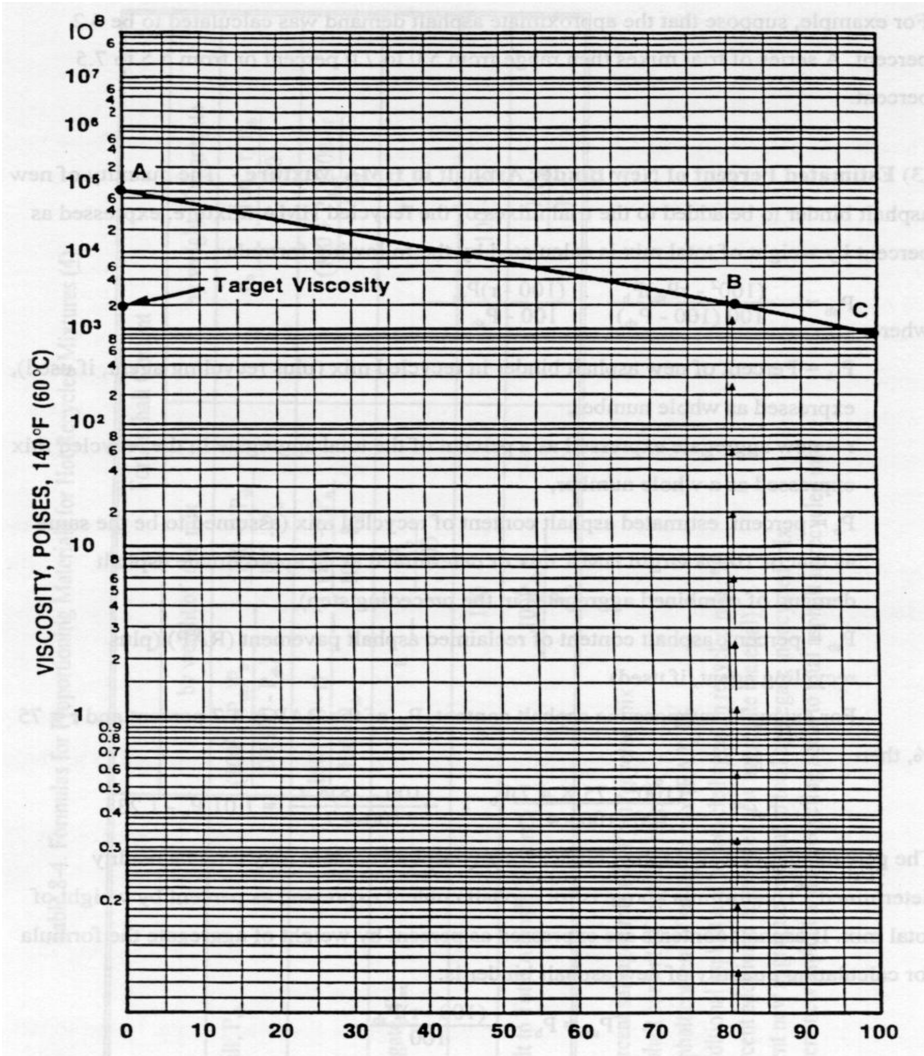


Figure 2-22 Viscosity blending chart

2.6.2 Superpave technology design method for recycled HMA

Superpave technology is a part of the Strategic Highway Research Program, SHRP, which evolved a performance-related specification for bitumen. The performance grade (PG) of bitumen is designed to improve the performance of a pavement at three service temperatures, high, intermediate, and low. The PG grading system commonly includes two numbers that represent high and low service temperatures for the pavement. For example, a PG 64-28 binder is designed to minimize rutting at the high pavement temperature of 64ºC and to minimize low temperature cracking down to -28ºC. (Kandhal and Mallick, 1997, Kandhal and Foo, 1997).

The Superpave approach suggests the following procedures for design of recycled HMA. This approach resembles the Asphalt Institute method in most of its steps.

Step 1, 2, and 3

The first three steps are the same as in the Asphalt Institute method.

(4) Select grade of new bitumen

The following three tiers are recommended to select the PG grade of the new bitumen (Kandhal and Foo, 1997):

- ❖ Tier 1 (up to 15 % RAP): use the same PG grade as that used in 100 percent virgin HMA mixture.
- ❖ Tier 2 (16 to 25 % RAP): select the new binder one grade softer than normal (ex. Use PG 58-28 if PG 64-22 is normally used).
- ❖ Tier 3 (more than 26 % RAP): a blending chart as shown in Figure 2-23 is recommended to be used.

This blending chart is used to specify the minimum and maximum amounts of virgin bitumen, consequently maximum and minimum percentages of RAP could be calculated. The X-axis in this blending chart represents percentage of virgin bitumen while the Y-axis is for rutting factor (G*/sin δ) obtained at the high service temperature for the specific PG grade. For example, if a PG 64-28 is used for the virgin mixtures, G*/sin δ of RAP binder and new bitumen should be determined at 64 ºC. The minimum and maximum ratios of new bitumen are obtained from Figure 2-23_at the two horizontal lines at stiffnesses of 1 kPa and 2 kPa.

An example of using the grade blending chart is presented below. Suppose PG 64-28 was specified for a paving project; the G*/sin δ measured at 64 ºC of PG 64-28 and RAP binder were determined and equal 1.13 and 100 kPa, respectively. These two values can be plotted as Point A (represents RAP binder) and Point B (represents new bitumen) on Figure 2-23, then the line AB intersects the 2.0 kPa horizontal stiffness line at 85%. So, the amount of added new bitumen PG 64-28 is 85% to 100%. This means RAP content ranges from 0% to 15 %. By substituting PG 64-28 with PG 58-34 as virgin bitumen, the G*/sin δ at 64ºC becomes 0.65 kPa, and then is plotted as point C. The line AC intersects the 1.0 kPa and 2.0 kPa stiffness lines at 72% and 89%, respectively. So, the amount of new bitumen PG 58-34 that can be used in the recycled mix is 72% to 89% (i.e. 11% to 28% RAP). It should be noted that the low temperature grade of the selected new bitumen should always be at least one grade below the specified PG grade.

(5) Trial mix design

Trial mix designs are made using the Superpave Gyratory Compactor following Superpave volumetric mix design procedures.

(6) Select Job Mix Formula

The optimum bitumen content is selected based on the test data obtained in the Superpave volumetric mix design procedure (Step 5). The recycled mix must meet all criteria applicable to the virgin mix.

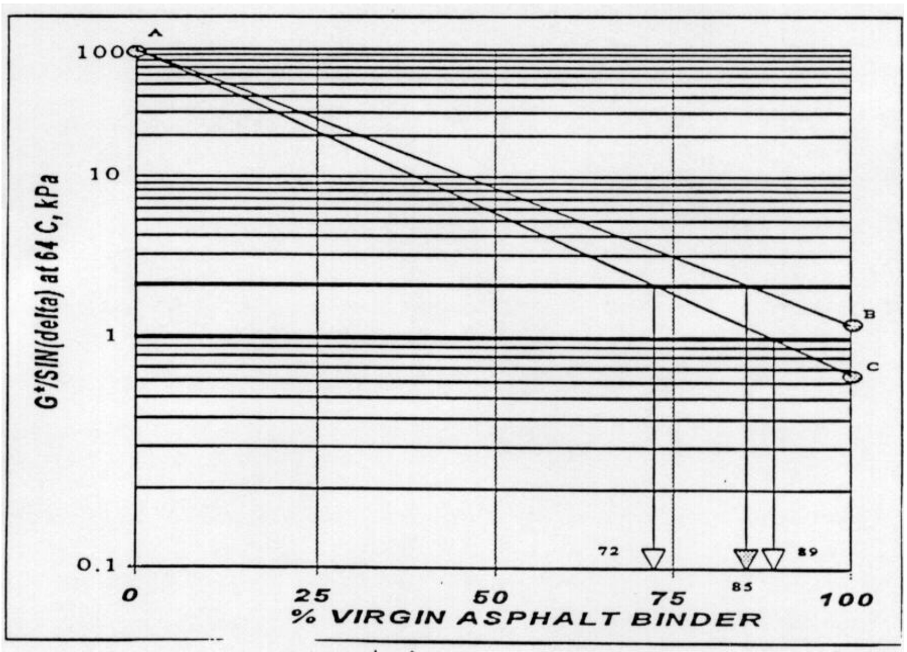


Figure 2-23 Example of Determine Minimum and Maximum Amount of Virgin Bitumen (Kandhal and Foo, 1997)

2.7 Performance of Recycled Mixtures

Considerable amount of work has been done for studying the performance of recycled HMA. These researches have varied from investigating the degree of blending between the aged and virgin binders, to evaluating the mechanical properties of recycled HMA, to explore the factors that can improve these mechanical properties.

2.7.1 Studying blending level

To get benefit from RAP binder in producing the recycled mix, it should be blended with a recycling agent to restore its properties to the state of desired bitumen (Sondag et al., 2002). Initially, recycling agents should be identified.

Recycling agent

Recycling agent can be defined as an organic material with chemical and physical characteristics selected to restore the aged binder to desired specifications. The recycling agent can be divided to softening and rejuvenating agents. Softening agents lower the viscosity of the aged binder while rejuvenating agents restore its physical and chemical properties (Roberts et al., 1996). Examples of softening agents include flux oil, slurry oil, and soft bitumen while rejuvenating agents consist of lubricating and extender oils, which contain a high proportion of maltenes constituents (Terrel and Epps, 1989). The important concern in selection of the rejuvenating agent is to be compatible with the aged binder. Rejuvenating agents with low saturate content and high aromatic content are usually compatible with aged binder (Dunning and Mendenhall, 1978).

Many studies have been done to answer the question of whether RAP acts as black rock or some blending does occur between the virgin and RAP binders. The black rock issue means that RAP binder does not blend with the virgin binder (Soleymani et al., 2000).

Stephens et al. (2001) studied the effect of preheating time of RAP on blending level between the virgin and aged binders. Eleven recycled HMA of 15% RAP content were produced with the same aggregate, the only difference was the preheating time of RAP (0 to

504 min). A twelve mix was also made with the same aggregates but 100% virgin binder. Figure 2-24 shows variation of the indirect tensile and unconfined compression strengths with preheating time. The recycled HMA at no preheating time achieved increase in compression and tension strengths by nearly one third compared to the virgin mix. This increase of strength indicates occurrence of some blending between the aged and virgin binders immediately after adding the RAP to the mix, then the preheating increased both the strengths further. (Stephens et al., 2001).

In another study, NCHRP 9-12 was directed to test if RAP acts as black rock or not. The experimental program included fabricating mixes simulating black rock (BR), standard practice (SP), and total blending (TB) cases. The BR and TB represented the possible extreme cases of blending. The BR mixes were made by extracting the binder from RAP then blending the recovered RAP aggregate with new aggregate and new bitumen. The TB samples were made by physically blending the recovered RAP binder with new bitumen, then mixing the resultant blend with new and recovered RAP aggregates. The SP samples were produced by adding RAP to the new aggregate and new bitumen similar to practice in HMA plant. Bitumen content and aggregate grading were kept constant in all cases, and two RAP contents were used (10 and 40%).

A series of laboratory tests (Frequency Sweep FS, Repeated Shear at Constant Height RSCH, Simple Shear SS, and Indirect Tensile Strength ITS tests) were conducted on fabricated specimens. It was concluded that, at 10% RAP, no significant difference existed between the various blends. However at 40% RAP, the BR case was statistically different from the SP and TB cases. These results indicated that no change in binder grade is required at low RAP content. Moreover, neither the BR nor the TB conditions exist in real HMA plant where RAP is usually mixed with new bitumen and aggregate for less than one minute (McDaniel et al., 2000).

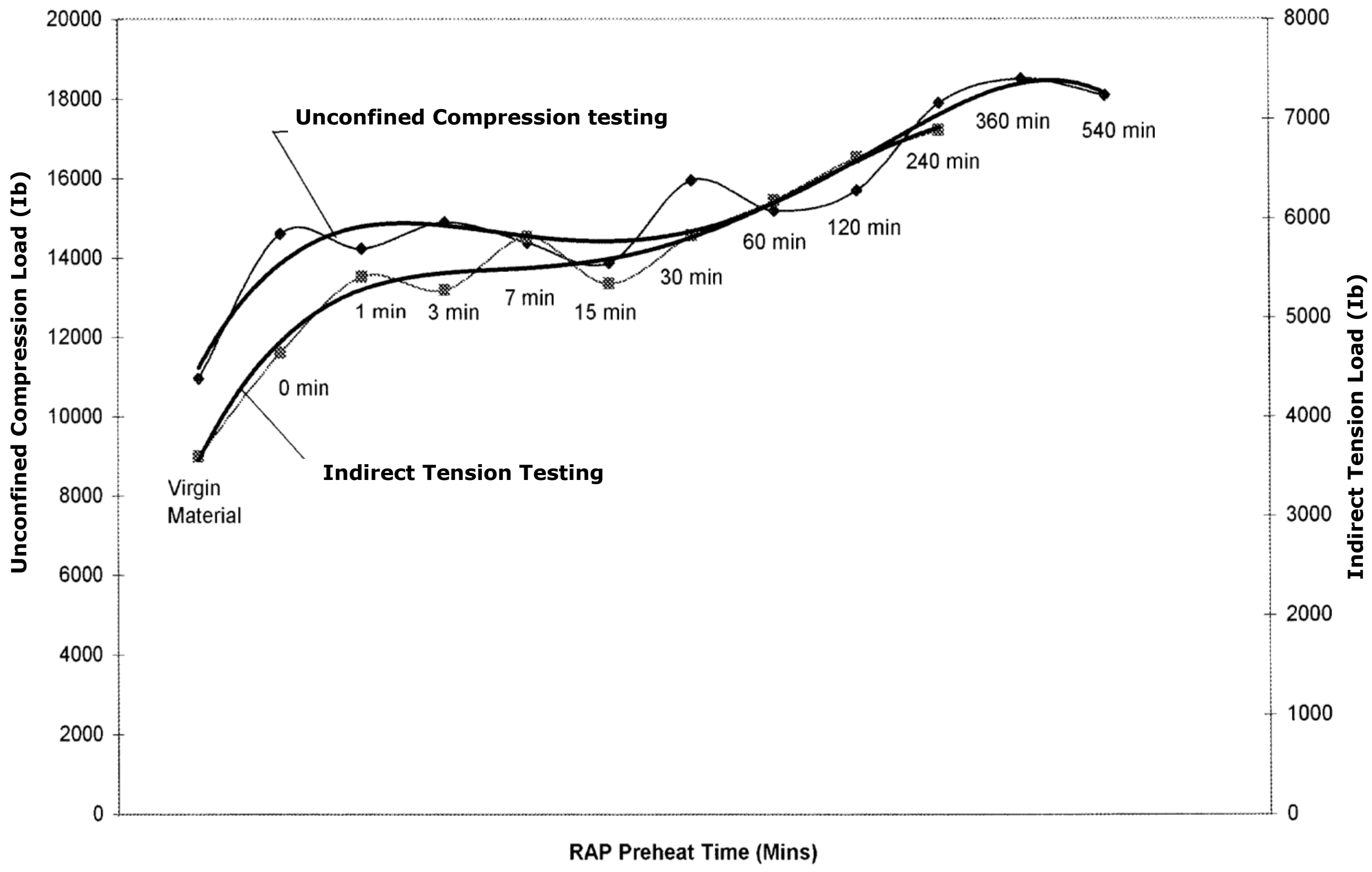


Figure 2-24 Effect of RAP preheating time on unconfined compression and indirect tensile strength (Stephens et al., 2001)

Chen et al. (2007) studied the blending level between the aged binder and the recycling agents through evaluating three different scenarios of blending (BR, SP, and TB). Three types of RAP differed in age (4, 6 and 10 years) were chosen to produce the recycled HMA of 40% RAP. These mixes were prefixed as RAP-1, RAP-2 and RAP-3. The aggregate grading and bitumen content were kept constant for different mixes. The properties of all mixes were assessed by measuring the resilient modulus and the tensile strength via conducting repeated load indirect tension test and indirect tension test respectively. The results, as shown in Figure 2-25, indicated that the SP case was closer to the TB case than to BR. Also, as more aged RAP is included in the asphalt mixture, the ability of the mix to resist the deformation increases (Chen et al., 2007).

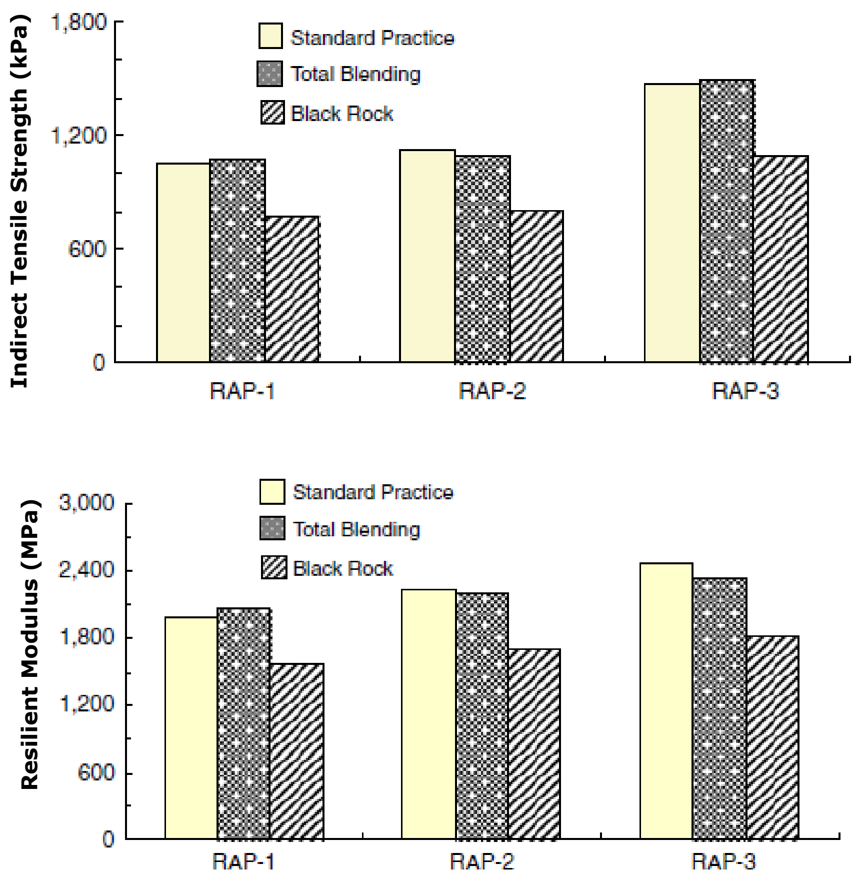


Figure 2-25 Tensile strength and resilient modulus of asphalt mixtures containing 40% RAP (Chen et al., 2007)

Huang et al. (2005) studied the extent that the RAP binder could leave RAP particles under the dry blending only (i.e. RAP and virgin aggregate only). In this study, one type of RAP (passing sieve No. 4) was blended with virgin coarse aggregate (retained on sieve No. 4) at different percentages 10%, 20%, and 30%. The used RAP had 6.8% binder content. The blending process lasted for 3 min at 190 °C. After dry mixing and separation of the RAP and virgin aggregate, oven ignition tests were performed to obtain the bitumen content from RAP. Figure 2-26 shows that, regardless of RAP proportion, the binder content of RAP reduced from 6.8% to 6.0 % (11% loss of binder due to purely dry blending).

However, the dry blending mixing as conducted by the authors is not enough to determine the amount of RAP binder that can leave RAP particles and can be available for use as effective binder. This is because the rejuvenation of the aged binder by blending with virgin binder (which takes place during mixing stage) may facilitate separation of aged binder from RAP materials.

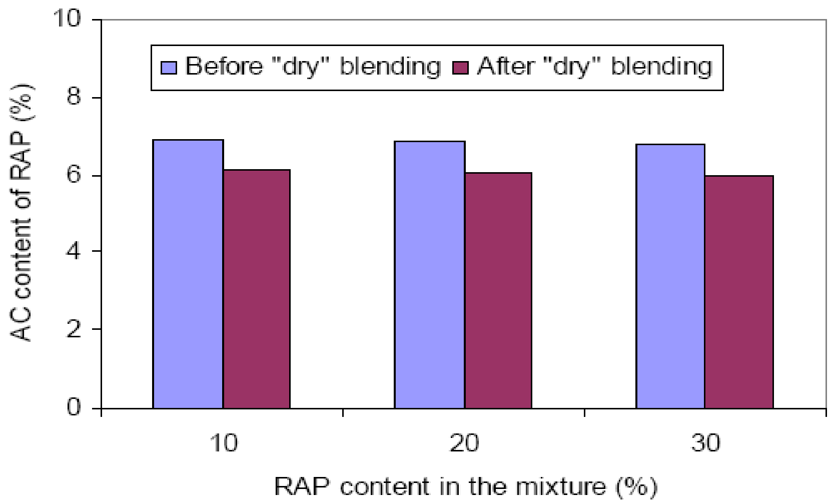


Figure 2-26 Asphalt contents before and after dry blending (Huang et al., 2005)

In order to simulate the actual plant mixing, Huang at al. fabricated recycled HMA of 20% RAP. The virgin aggregate was mixed with RAP and virgin bitumen (PG 64-22) for 3min at 190 °C. After production the samples, the staged extraction and recovery programme was set up to obtain the binder from various layers coating RAP aggregate. The properties of each recovered layer was characterized and assessed through the DSR and rotational viscometer tests. The results indicated that the outside layers were much softer than the inside ones. In terms of percentages, about 60% of the aged binder did not blend with the virgin binder while 40% of the outside binder was a blend between aged and virgin binders.

The authors proposed that only a small proportion of aged RAP binder, actually, participates in the re-mixing process, while the remainder forms a stiff coating around RAP aggregates and RAP functionally acts as "composite black rock" (Huang et al., 2005).

2.7.2 Evaluating the mechanical properties of recycled HMA

No decisive findings can be drawn from the past research projects that have investigated and assessed the behaviour of recycled HMA. A number of researchers have pointed out that using RAP improved stiffness properties (Al-Rousan et al., 2008, Huang et al., 2004, Sargious and Mushule, 1991, McDaniel and Shah, 2003, Tran and Hassan, 2011) while others have reported the opposite (Oliver, 2001, Widyatmoko, 2008). Also, at the time that some studies have revealed improving of fatigue resistance with using RAP (Oliver, 2001, Tabakovic et al., 2006, Widyatmoko, 2008), other studies have reported some degradation (Al-Rousan et al., 2008, Huang et al., 2004, McDaniel and Anderson, 2001, Tam et al., 1992). Furthermore, improving deformation resistance has been reported by some researchers (Al-Rousan et al., 2008, Chen et al., 2007, Tabakovic et al., 2006, Sargious and Mushule, 1991) but decreasing of this resistance have been noticed by other researchers (Oliver, 2001, Widyatmoko, 2008)

Oliver (2001) compared between the performance of recycled and virgin HMA. The recycled specimens of 50% RAP along with virgin samples were manufactured so as to have the same aggregate grading, 5% bitumen content, and the same viscosity of binder within specimens (based on assumption of design method that complete blending occur between the aged and virgin binder). The mechanical properties were measured through Wheel Tracking, Fatigue, and Indirect tensile tests.

The laboratory results, Table 7, showed degradation in stiffness and resisting permanent deformation properties of recycled HMA. However, there was substantial improvement in resisting fatigue. The author believed that the two binders in recycled mix had not been completely blended. Reasons for this were proposed, by author, as follows. Some of new bitumen, which failed to penetrate aggregate/binder or filler/binder lumps, forms a “shell” around the aged binder, resulting in creating regions of low and high viscosity inside the body of the recycled mix. The low viscosity regions would lead to reduction in rutting resistance and stiffness modulus, and at the same time improve fatigue resistance (Oliver, 2001).

Table 7 Mechanical properties of tested virgin and recycled mixes

	Stiffness modulus @25 °C (Mpa)	Wheel Tracking Rate @ 60 °C (mm/K cycle)	Fatigue Life @20 °C (cycles)
Recycled mix	6,842	0.27	238,375
Virgin mix	7,924	0.18	89,485

In research to analyze the fatigue characteristics of recycled mixtures, Huang et al. (2004) tested mixes of 0, 10, 20, and 30 % RAP. Laboratory fatigue characteristics were evaluated through indirect tensile strength, semi-circular bending (SCB) and semi-circular notched fracture tests. The tests were conducted on un-aged and long-term aged mixtures (3days@100 °C). Results of tests were compared and they indicated that the inclusion of RAP generally increased the tensile strength, stiffness, and resistance to fracture failure; in addition, they reduced the post-failure tendency. (Huang et al., 2004).

Daniel and Lachance (2005) investigated how the volumetrics and mechanical properties of asphalt mixes could be affected with addition of RAP. One control virgin mix and three mixes of 15%, 25%, and 40% RAP were manufactured and tested under dynamic modulus, creep compliance, and creep flow tests. The researchers observed an increase in VMA (Voids in Mineral Aggregate) at the 25%

and 40% RAP levels. Also, there was an increase in dynamic modulus from the control to the 15 % RAP level, but the mixes of 25% and 40% RAP had dynamic modulus similar to that of the control mix. The author attributed that to the increase in the VMA values for these mixes (Daniel and Lachance, 2005).

Tabakovic at al. (2006) studied the mechanical performance of a 20mm binder course asphalt mix containing RAP at the levels of 10%, 20% and 30%. The effect of introducing RAP into asphalt mixes was assessed through a series of laboratory tests (Marshall, ITSM, ITFT, and Circular Wheel Track). A 70/100 pen bitumen was utilized in all mix and voids content was fixed as 6%. The results showed that the introduction of RAP to asphalt mixes led to improvements of their mechanical properties in terms of stiffness, fatigue resistance, and rutting resistance (Tabakovic et al., 2006).

As an initial attempt to investigate the applicability of HMA containing RAP in Jordon, Al-Rousan (2008) assessed two types of mixes: one was virgin and the other contained 30% RAP. Indirect tensile strength, water sensitivity, dynamic creep and fatigue tests were performed on samples of the two mixes. Based on the experimental results, the author reported that the recycled mix performed better than the virgin mix in resisting stripping, creep and Marshall Stability, while it showed shorter life in fatigue. The researcher attributed these changes in the mechanical properties to the ageing of binder of RAP materials (Al-Rousan et al., 2008).

The mechanical properties and durability of wearing course and base course materials containing RAP were examined by Widyatmoko (2008). The ITSM, RLAT (Repeated Load Axial), WTT (Wheel Tracking Test), and ITFT tests were carried out on one virgin mix and six recycled HMA. Three different percentages of RAP were used; 10%, 30% and 50%. Bitumen 80/100 pen was used with and without rejuvenating oil for recycled mixes, while bitumen 60/70 pen was used for the virgin mix. Based on the results of the study, the author reported that the asphalt mixes containing RAP (either for wearing course or base course) showed inferior stiffness and resistance to permanent deformation when compared to equivalent mixes without RAP. However, the fatigue performance was improved with increasing RAP contents. Overall, Widyatmoko concluded that the recycled mixtures performed at least similar to, or better than, conventional asphalt mixes (Widyatmoko, 2008).

The performance of recycled HMA designed according to Australian practice was evaluated by Tran and Hassan (2011). A laboratory experimental program was conducted to measure the mechanical and volumetric properties of mixes containing 0%, 10%, 20%, and 30% RAP. All virgin and recycled mixes were designed with the same aggregate gradations. All virgin aggregates and RAPs were sourced from one supplier to ensure consistency among the mixes. Bitumen C320 (48 pen) was used for the virgin and 10% RAP mixes; while a lower grade bitumen C170 (80 pen) was used for the other two recycled mixes. All the mixes were tested for their volumetrics, and resilient modulus via the indirect tensile modulus test.

Results showed that the addition of RAP led to a stiffer mix, and this effect increased with increasing RAP content. Also, adding of RAP reduced the required binder content, voids in mineral aggregate (VMA), and voids filled with bitumen (VFB). The author attributed the reduction in VMA with increasing RAP content to:

- With increasing RAP, the required binder content decreased, leading to reduction in the effective binder content and, ultimately, VMA.
- The increment in proportion of fine materials (passing sieve No. 0.075mm) due to increasing the proportion of RAP resulted in greater surface area of aggregates, hence reducing the effective binder content and lowering the VMA.
- Using softer binder (C170) in the 20% and 30% recycled mixes contributed to increased absorption of binder which caused lowering of the effective binder content, hence the VMA.

The CIRCLY 5 analysis program was applied to a full depth asphalt pavement to study the impact of increasing in stiffness (due to using RAP) on pavement response. The results indicated that the tensile strains in the surface layer changed to compressive strains when RAP was involved. This demonstrates that the higher stiffness of surface layer, due to the presence of RAP, enables more resistance to stress induced by traffic loading, and reduces the stresses transmitted to the lower layers. Thickness of base layer can be also reduced, thus using RAP in the surface layer is advantageous not only for savings in binder content and disposal fees but also for savings in pavement thickness (Tran and Hassan, 2011).

2.7.3 Factors influencing the blending between the aged and virgin binder

Many factors have been explored and found to have impact on improving the degree of blending between the aged and virgin binders within recycled HMA.

The effect of preheating time of RAP on improving the properties of the recycled HMA via enhancing the blending between the aged and new binders was examined by many researchers (Daniel and Lachance, 2005, Stephens et al., 2001). To test whether per-heating time of RAP has an effect on the mix volumetrics, Daniel and Lachance (2005) prepared several specimens with 40% RAP heated for 2, 3.5, and 8 hours at the mixing temperature. The results are presented in Figure 2-27. The authors mentioned that at shorter heating time, the RAP is not heated enough to allow its particles to break up into smaller pieces and blend with the virgin materials. On the other hand, at the longer heating time, the RAP has likely aged more and its particles have hardened and even fewer of them are able to break down and blend with the virgin material. Therefore, the researchers believed that there is an optimum pre-heating time of RAP to allow for the greatest extent of blending between the virgin and RAP materials.

In his research Stephens et al. (2001) found a profound impact of pre-heating time of RAP on both tensile and compression strength, Figure 2-24. The authors also stated that more blending between the aged and virgin binders complete occurs when the RAP reaches a temperature that softens its RAP binder.

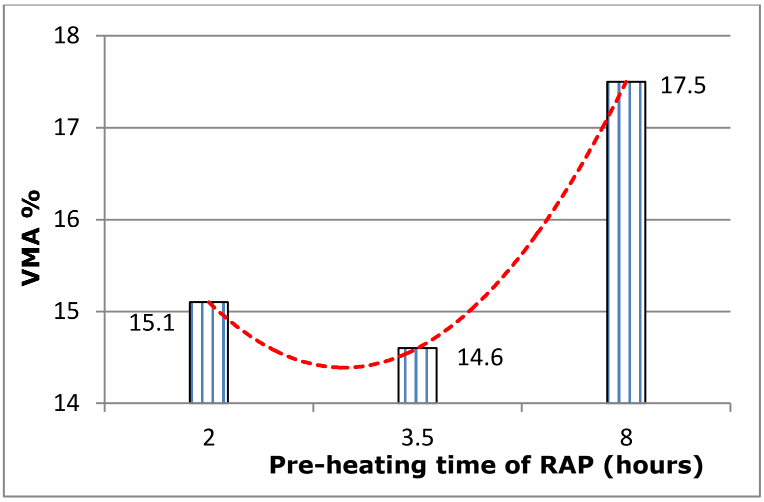


Figure 2-27 Effect of pre-heating time of RAP on VMA

RAP size effect on homogeneity of the recycled HMA was examined by (Nguyen, 2009). Two nominal maximum sizes of RAP were used (40 and 20mm) to produce recycled mixes with 40%RAP. Homogeneity of recycled mixes was assessed by conducting the ITSM test and by using virgin bitumen with a different colour. It was found that the mixture composed of small RAP size was more homogenous than that made from large RAP particles. Also, the effect of RAP size became negligible when pre-heating of RAP was applied.

Nguyen (2009) also studied the effects of different mixing methods on stiffness of the recycled HMA incorporating 40% RAP. These methods were: black rock BR, total blending TB, SHRP (mixing the conditioned RAP at 110°C for 2 hrs with the conditioned virgin aggregate at 150°C for 8 hrs, then adding the virgin bitumen), and field simulation FS (mixing the RAP with the superheated virgin aggregate for some time before adding the virgin bitumen).

It was found that the stiffness moduli of the mixes produced by SHRP and FS were close to each other and nearer to TB than BR mixing procedures. Also, RAP sizes significantly affect stiffness of recycled mixes made by FS method. On the contrary, RAP sizes have no effect on stiffness of recycled samples made by SHRP. Overall, results indicated that better mixing can generate more durable recycled HMA

2.8 Moisture damage definition

Generally, the expression 'damage' can be defined as the degree of loss of functionality of a system, while water damage broadly depicts any deterioration occurring in the material as a result of water intrusion which attacks the particle or the system through a destructive process. Within this context, moisture damage in asphalt mixtures can be comprehensively defined as "the progressive functional deterioration of a pavement mixture by loss of the adhesive bond at the binder-aggregate interface and/or loss of the cohesive resistance within the binder or binder-filler mastic principally from the action of water" (Airey et al., 2008, Kiggundu et al., 1988).

2.8.1 Mechanism of moisture damage

The collapse of the adhesion bond at the bitumen-aggregate interface and/or failure of the cohesion of binder or mastic are the final step in a process starting with different patterns of moisture transport through the internal structure of the pavement system. Two stages are considered to be the major elements of the water damage mechanism (Caro et al., 2008, Scholz, 1995):

- Moisture transport: the process by which the moisture comes to the bitumen-aggregate interface in a state of liquid or vapour via infiltrating the asphalt binder or mastic.
- System response: changes in the internal structure contributing to a lack of load carrying capacity of the material.

Responses of the system are complex phenomena which include thermodynamic, chemical, physical and mechanical processes. These responses could be manifested as reduction of strength and stiffness of the mixture or even loss of material via stripping. This in turn makes the pavement layer fragile hence, reducing the ability of asphalt mixtures to sustain the traffic-induced stresses and strains (Kandhal, 1994, Kennedy, 1985, Terrel and Al-Swailmi, 1994). Types of common response and a description for each are presented in detail in Table 8.

Table 8 System responses for moisture damage (Caro et al., 2008)

System Responses	Description	Nature of the process
Detachment / debonding	Separation of an asphalt film from an aggregate surface by a thin film of water without an obvious break in the binder layer (Little and Jones, 2003)	Chemical, thermodynamic
Displacement	Loss of material from the aggregate surface through a break in the asphalt film and/or possible separation of the aggregate/mastic interface (Little and Jones, 2003)	Mechanical
Dispersion of the mastic	Weakening of the cohesion in the asphalt binder or mastic due to long-term diffusion periods and loss of material due to the presence of flow (Kringos and Scarpas, 2005)	Chemical, thermodynamic
Film rupture / microcracks	Ruptures in the mastic or aggregates. The effect of microcracks is a general deterioration of the structural integrity of material and the generation of new paths for moisture transport	Mechanical, thermodynamic
Desorption of the mastic	Washing away of the outer layers of mastics due to the presence of flow (Kringos and Scarpas, 2005)	Mechanical after other processes
Spontaneous emulsification	emulsification Inverted emulsion of water droplets in binders (Little and Jones, 2003)	Chemical

2.8.2 Factors affecting moisture damage

Many researches have extensively studied the factors affecting damage by water. These factors can be categorized to environmental factors, factors linked to construction practice, and others related to asphalt concrete characteristics. Environmental factors involve climate (ex. high humidity, intense rainfall periods, severe freeze-thaw cycles) and traffic loading. Construction factors include the quality of compaction and weather conditions during construction. Characteristics of asphalt mixtures that accelerate moisture damage are physical characteristics of aggregate and asphalt binder in addition to the type of asphalt mixture (Caro et al., 2008, Hicks, 1991).

Overall, resistance of moisture damage is improved by using clean, rough aggregate with low moisture content and asphalt binder with high viscosity (Hicks, 1991, Little and Jones, 2003). Although controlling air voids content is considered an important factor for reducing damage by moisture, more important is the distribution and connectivity between these voids inside the asphalt mixture (Masad et al., 2006, Caro et al., 2008, Lu and Harvery, 2006). In a study conducted by Lu and Harvey (2006) to investigate the parameters that influence moisture damage, it was revealed that air void, rainfall, pavement structure, and pavement age have the highest influence on moisture damage, while repeated loading and cumulative truck traffic have a marginal effect (Lu and Harvery, 2006).

2.8.3 Evaluation of resistance of recycled HMA to moisture damage

Durability of recycled mixes to resist damage by moisture has been studied and assessed by many researchers via water sensitivity tests. In their study, Tabakovic et al. (2006) revealed that moisture damage was not an issue for asphalt mixes containing 0%, 10% and 20% RAP. However, recycled mix with 30% RAP manifested more sensitivity to water than the other mixes. The authors pointed out that further increase of RAP content in the mix could initiate moisture damage (Tabakovic et al., 2006). However, Widyatmoko (2008) concluded that the recycled mixes (either for wearing course or base course) showed non-susceptibility to moisture damage, even at high percentages of RAP such as 30% and 50% (Widyatmoko, 2008). Another study by Al-Rousan et al. also showed that recycled HMA of 30% RAP had better resistance to the action of water than the virgin mix (Al-Rousan et al., 2008).

Doyle et al. (2011) examined the moisture damage of warm mix asphalt (WMA) containing RAP by measuring the tensile strength ratio (TSR). Moisture susceptibility was evaluated for three RAP contents (0, 25, and 50%), two aggregates types (limestone and crushed gravel), and three mixing temperatures (129, 146, and 160 ºC). The authors found that resistance to moisture susceptibility increased with increasing RAP content and mixing temperature. Moreover, the WMA made of limestone aggregate generally met moisture susceptibility requirements; however, some failed to meet the requirements when crushed gravel with hydrated lime was used (Doyle et al., 2011).

Overall, and as indicated from past research, it can be concluded that recycled mixes perform better than virgin mixes in resisting the harmful action of water. The reason for this has been reported by a number of researchers (Gregory and Tuncer, 2009, Guthrie et al., 2007, Huang et al., 2005, Karlsson and Isacsson, 2006). They proposed that the aged binder tends to stick to the RAP aggregates, reducing absorption of water when RAP materials are used as their aggregates are coated with a thick layer of binder.

2.9 Diffusion

Generally, diffusion refers to the random-thermal motion of particles. It can be defined as spreading of particles through random motion from regions of higher to lower concentration.

2.9.1 Diffusion mechanism of rejuvenators into the aged binder film in recycled mixes

It is well known that the RAP binder has rheological properties that make it undesirable for reuse without modification. In recycling operations, recycling agents are commonly used to restore the properties of aged binder to a condition that resembles the properties of virgin bitumen. Rejuvenating the properties of aged binder occurs via dispersal the molecules of recycling agent through the layer of aged binder. The diffusion process takes place not only during the mixing phase, but also could continue after the mixing stage via the long-term diffusion. Knowing the mechanism by which the recycling agent could spread and soften the aged layers of binder is required in order to better understand how the blending between the new and old binders happens within the recycled mixture. Carpenter and Wolosick outlined the mechanism by which the recycling agent diffuses through the aged binder film as follows (Carpenter and Wolosick, 1980):

1. The rejuvenator creates a very low-viscosity region surrounding the aggregate coated with aged binder
2. Molecules of the rejuvenator start to penetrate into the old binder layer resulting in a decrease of the amount of raw rejuvenator and at the same time softening the old bitumen.
3. The penetration and softening process continues thus the viscosity of the inner layer is reduced and the viscosity of the outer layer is gradually elevated.
4. Equilibrium is approached over the majority of the aged binder layer except at the binder-aggregate interface, which may remain at a higher viscosity level.

2.9.2 Factors affecting rate of diffusion

Diffusion is a time-dependent process and very slow on a macroscopic scale. All the movements of molecules are driven by heat energy that does not move the molecule in a particular direction but pushes it randomly in any direction. The rate of diffusion can be predicted from the Stoke-Einstein equation in both gases and liquids. Equation 8 gives a good understanding of the parameters governing the rate of diffusion (Karlsson and Isacsson, 2003).

$$D = \frac{k_B T}{6\pi\mu(R)}$$ Equation 8

The term k_BT is the internal heat energy in which k_B is Boltzmann's constant (1.3807×10^{-23} J/K) and T is absolute temperature, R is the mean of molecular radius of the diffusing molecule, and μ represents the viscosity of the substance. Temperature, diffusant properties, and properties of the media in which the diffusion takes place are three key parameters that affect diffusion. Some factors that affect the rate at which molecules diffuse are indicated below:

- **Temperature**: As the temperature increases, the amount of energy available for diffusion is increased, resulting in more motivation for particles to respond or diffuse. In more than one study, it was revealed that the rate of diffusion could be increased by raising the temperature (Karlsson and Isacsson, 2003, Oliver, 1974). The apparent great effect of temperature on diffusion originates from its influence on viscosity.
- **Molecular size (weight), shape, and polarity**: Heat is the main source of energy to motivate the particles to move. At a given temperature, lighter or smaller molecules will diffuse faster. Karlsson and Isacsson (2003) studied the effect of size, polarity and shape of diffusing molecules on rate of diffusion. The authors revealed that a substance of heavier molecular weight diffuses at a slower rate, and the polarity of molecules is

inversely proportional to diffusion rate. Also, it was observed that as molecule shape became more oblong, the mean molecular radius increased which substantially decreased diffusion rate (Karlsson and Isacsson, 2003).

- **Concentration difference**: When a substance is spreading between two compartments, the greater the concentration difference between them, the faster the substance will diffuse.
- **Surface Area**: When a substance is diffusing between two compartments (through a membrane, for example), the greater the surface area of the membrane, the greater the probability that a particle will pass through it.
- **Property of diffusion media**: Viscosity of diffusion media is the major factor that governs diffusion rate. It is clear from the Stoke-Einstein equation (Equation 8) that there is inverse proportionality between diffusion rate and viscosity. Karlsson and Isacsson (2002) concluded that diffusion is mainly influenced by the properties of the maltenes phase and its viscosity is the controller for the diffusion rate rather than viscosity of the bitumen as a whole (Karlsson and Isacsson, 2002).

2.9.3 Diffusion of rejuvenator into the aged binder film

Noureldin and Wood (1987) studied diffusion of three types of rejuvenators (AC-2.5, AE-150, and a commercial product Mobilsol-30) through the aged binder film that coats the aggregate. A partial extraction technique which involved dividing the whole quantity of trichloroethylene (the solvent used in the extraction process) into four successive amounts to obtain the bitumen films in four microlayers was used. First a sample of 1200 g was soaked in 200, 200, 300, and 700 mL of trichloroethylene for 5 minutes, then binders of each microlayer were recovered by the Abson method. After that, consistency of these recovered binders was determined.

Three types of mixes were included; a mix containing RAP only, another including RAP and rejuvenator, and a third containing RAP + virgin aggregate + rejuvenator. The virgin aggregate was crushed limestone. Characteristics of the recovered RAP binder are shown in Table 9. Three combinations of old binder and rejuvenator were included (40% RAP binder with 60% AC-2.5, 45% RAP binder and 55% AE-150, and 85% RAP binder with 15% Mobilsol-30). The target of design of the recycled mixture with rejuvenators was to produce mixtures with bitumen having properties approximately similar to that of AC-20. Table 10 presents penetration and viscosity of bitumen film microlayers of all different mixtures together with specifications of AC-20.

Table 9 Characteristics of RAP binder (Noureldin and Wood, 1987)

Property	Value
Penetration at 25 °C, (dmm)	28
Viscosity at 60 °C (Pa.s)*	2089
Kinematic Viscosity @ 135 °C (cSt)	726
Softening Point (°C)	60

* Pa.s = 10 poises

Several important findings were revealed from this study as follow:

- Partial extraction of the mix containing only RAP indicates that the two outer microlayers of the old film of binder were severely aged due to direct subjecting to weathering action. In contrast, the inner two microlayers (at the binder-aggregate interface) were slightly aged; this might be due to the tendency of limestone aggregate to absorb the light fraction of binder.
- Concerning the mixture of RAP with rejuvenators, the results suggested that the three rejuvenators could restore the consistency of the two outer microlayers. However, the two inner microlayers were almost unaffected; see the highlighted cells of (RAP + Rej) column, Table 10.
- As for the combination of RAP + rejuvenator + virgin aggregate, both rejuvenators (AC-2.5 and Mobilsol-30) were attracted and softened the fourth inner layer, see the highlighted cell of column (RAP + Rej + agg), Table 10. However, the properties of microlayers of the mix containing AE-150 similar characteristics to those of (RAP + rejuvenator) case.

- In general all rejuvenators exhibited good efficiency in diffusing through the aged bitumen film and restoring its properties.

The research investigated only the diffusion during the mixing process and did not take into account the effect of time on this process, i.e. long-term diffusion. The results might have been different if the long-term diffusion had been considered.

Table 10 Consistency tests results on reclaimed staged-extraction of all mixes used (Noureldin and Wood, 1987)

solvent increment	Layers order	Rej* type	RAP only		RAP + Rej*		RAP + Rej +agg*	
			Pen dmm	Viscosity Pa.s*	Pen* dmm	Viscosity Pa.s	Pen dmm	Viscosity Pa.s
200	1 st	No Rej	24	2400				
200	2 nd		33	1500				
300	3 rd		65	250				
700	4 th		57	330				
200	1 st	AC-2.5			67	167	60	210
200	2 nd				68	188	51	289
300	3 rd				59	239	52	247
700	4 th				50	300	130	81
200	1 st	AE-150			75	168	70	197
200	2 nd				70	201	67	173
300	3 rd				62	229	60	242
700	4 th				49	302	50	361
200	1 st	Mobilsol-30			75	186	73	205
200	2 nd				69	198	80	166
300	3 rd				63	204	90	126
700	4 th				48	315	100	124
AC-20 specification			**Pen = 60+**		**Viscosity = 160 – 240**			

* Pa.s = 10 poises, Rej = rejuvenator, agg = aggregate, Pen = penetration

The impact of long-term diffusion on the properties of hot recycled mixture containing high RAP content prepared with an industrial rejuvenator was investigated by (O'Sullivan, 2011). The dynamic moduli of recycled mixes were measured periodically via the dynamic modulus test over an eleven week period. The following mixes with various amount of the rejuvenator were evaluated: two control mixes (one of RAP aggregate and virgin binder and the other of heated RAP only) and three recycled mixes with Renoil 1736 rejuvenator; 1% Rej, 0.5% Rej, and 0.5% Rej with 0.5% virgin binder PG 64-22.

The percentages of RAP in recycled mixes were 90% for the 0.5% RJ and 80 % for the others two mixes. The recycled samples were kept - between testing days - in an oven at 60 °C to facilitate the action of the rejuvenator. Two types of ovens were employed: a conventional and an inert gas oven in order to distinguish between the aging and diffusion process. The inert gas oven provides an environment where oxidation-related ageing can be controlled or eliminated and it was used only for the 1% RJ mix. Figure 2-28 and Figure 2-29 exhibit examples of trend lines of dynamic modulus and phase angle for all mixes at 21.1 °C and 10Hz respectively.

It can be observed form Figure 2-28 that almost all mixes showed an increase in dynamic modulus over time. This increase is attributed to the accelerated ageing for all mixes except for the 1.0% RJ-inert mix which was aged in the inert oven rather than the conventional oven. Also the same observation can be shown from Figure 2-29 as all mixtures experienced a decrease in the phase angle over the eleven weeks. It is clear from the two figures that the mix 1.0% RJ-inert followed the same trend as other mixes, suggesting that even in the absence of oxidation there is an increase in dynamic modulus. This change could be referred to long-term diffusion. (O'Sullivan, 2011) revealed that use of an inert gas oven for aging can remove the concern of oxidation of the binder when aged in a conventional oven.

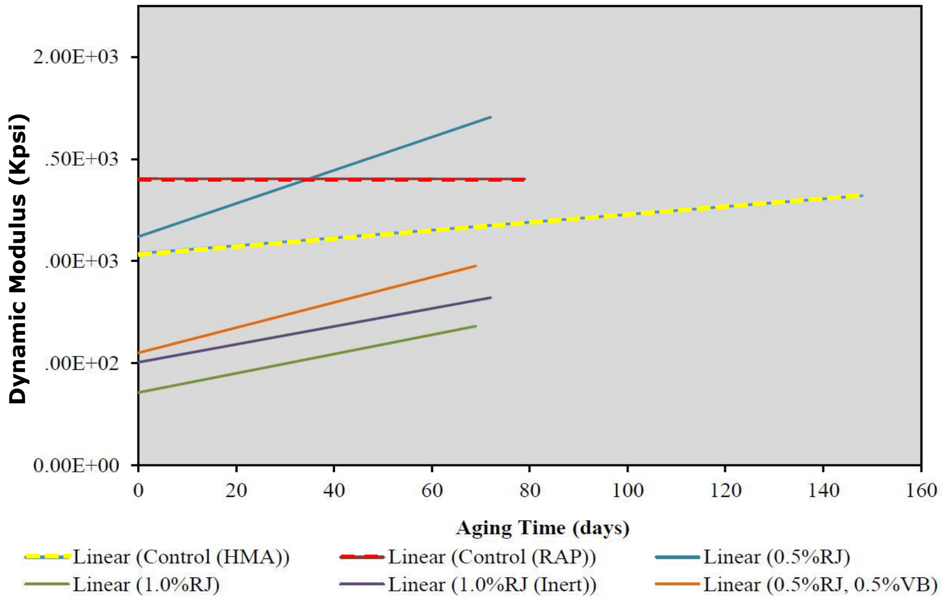


Figure 2-28 Dynamic modulus results of mixes at 21.1 °C and 10Hz

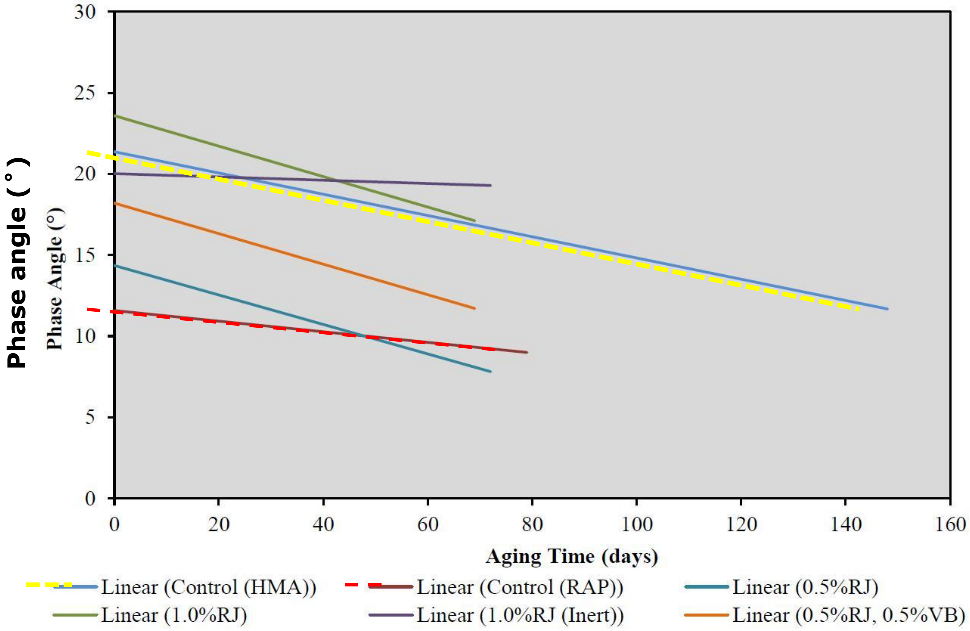


Figure 2-29 Phase angle of mixes at 21.1 °C and 10Hz

2.10 Summary

This chapter addressed some topics related to recycling of asphalt pavement, which in turn contributed for deep understanding the behaviour of recycled HMA. At the beginning, the different methods of recycling asphalt pavement were identified, whether in-place or in-plant, whether hot or cold recycling. Thereafter, the important characteristics of RAP materials and how to use them in design process of recycled HMA have been recognized. Therefore, it was important to consider the design methods of these types of mixes.

One of the main essential topics was evaluating the behaviour and mechanical properties of recycled HMA, as well investigation the factors by which their performance can be improved. Finally, two topics closely associated to the durability of recycled HMA (after production and compaction stage) have been addressed. These topics were the long-term diffusion between the aged and new binders, and resisting moisture damage. Studying all these topics largely supported achieving the objectives of the research.

After studying these topics, the following findings can be drawn

- There is no decisive result that recycled HMA perform better or worse than new HMA. At the time that some researchers have reported that asphalt mixes incorporating RAP improves stiffness, fatigue resistance, and deformation resistance, others have mentioned the opposite.
- State of complete blending between the old and new bitumen (within recycled HMA) does not exist in practice. In addition, RAP materials not act as black rock, on the contrary, they participate in blending process and their participation depends on certain factors such as mixing temperature, use of additives, sizes of RAP particles.
- Diffusion of recycling agent (such as new bitumen) within old binder does not stop after production of recycled HMA, but it continues for some time via long-term diffusion, causing

improvements in the mechanical properties of these mixes. It should be stated that this subject needs through study.

Because the recycled HMA contain RAP, their behaviour differs from that of virgin HMA. And because there are roads in which RAP materials have already been used, the question now is, if these roads were recycled for second time, what would be the effect of this on the behaviour of the second recycled HMA. In other words, to what extent the repeated recycling of RAP could affect the mechanical properties of recycled HMA. The answer for this question is the primary goal of this research.

3 Experimental work of the repeated recycling process of HMA

From literature, it was revealed that the recycled HMA behave differently from virgin HMA. That is because they contain RAP as a compound of their constituents. Also, there are, nowadays, current roads in which recycled mixes have been already used. However, there is an issue still not clear, which is what is the impact of recycling these roads for more than once on properties of produces recycled HMA. Thus the aim of the research is to assess the effect of repeated recycling on the mechanical properties of recycled HMA. To achieve this aim, an experimental programme has been put in place as indicated in the schematic diagram, Figure 3-1. The programme was divided into two main phases; the first part was for to fabricating the virgin (control) mix and producing the RAP materials in the laboratory. The second part included running the repeated recycling process more than once, specifically over three rounds.

Some tests were applied on binders and others conducted on compacted asphalt specimens. Such a test was operated at specific stages as shown in Figure 3-1. Table 11 presents the tests used and their measured parameters. It is worth mentioning that the programme was in serial order i.e. a stage did not start until the end of the previous one. Details about experimental work were explained in this chapter.

Table 11 Tests and measured parameters

Test	Specification	Parameters
ITSM test	(BS EN 12697-26, 2004)	Stiffness modulus
ITFT test	(BS EN 12697-24, 2004)	Fatigue resistance
DSR test	(BS EN 14770, 2005)	Complex shear modulus **G***, phase angle **δ**, complex viscosity (**η**)
Needle Penetration	(BS EN 1426, 2007)	Penetration (**Pen**) at 25 ^{o}C
Ring and Ball Method	(BS EN 1427, 2007)	Softening point in ^{o}C
Asphaltenes Content	(BS 2000-143, 2004)	% asphaltenes in bitumen
Composition analysis	(BS 598-102, 2003)	% Bitumen content

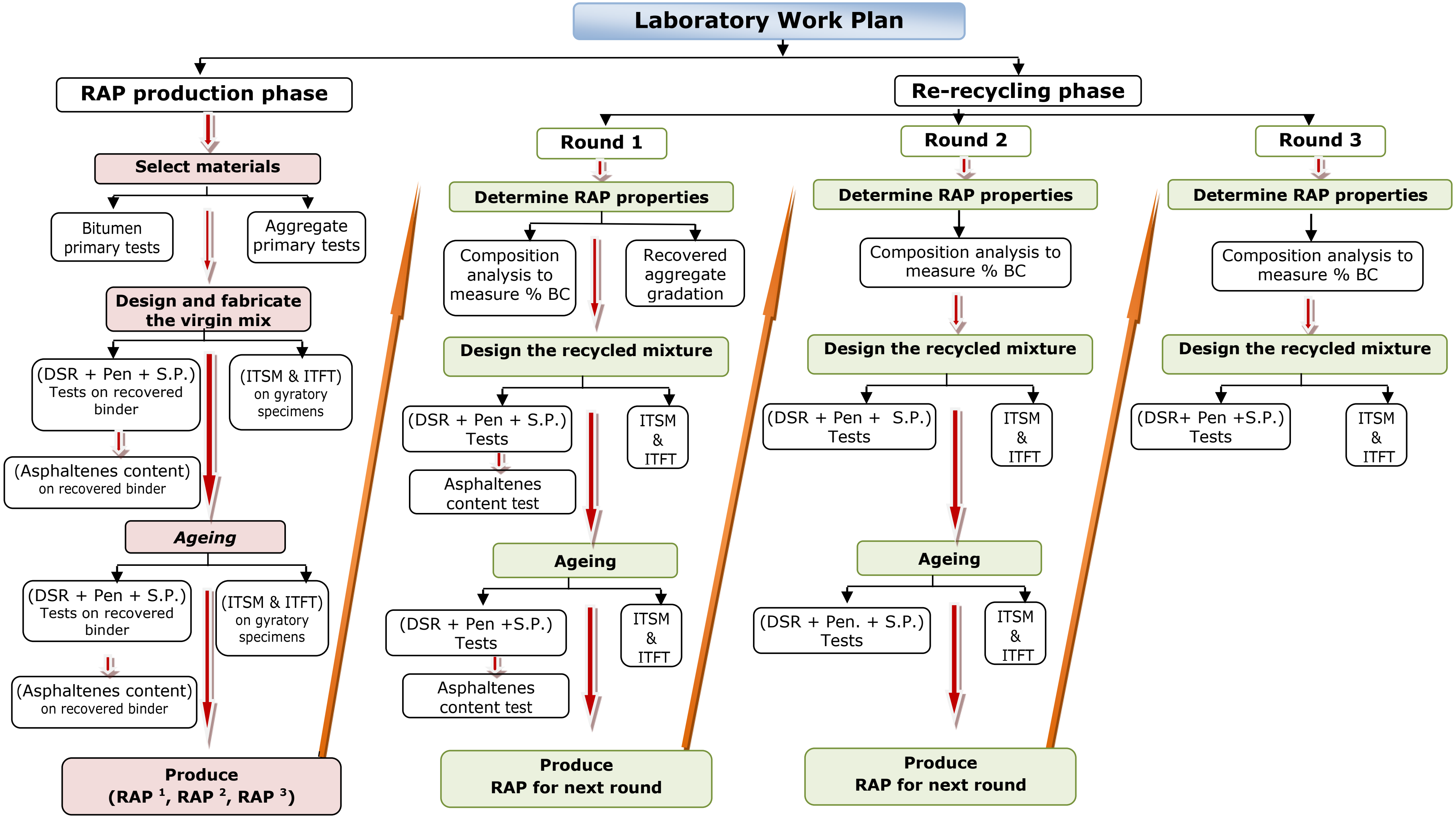


Figure 3-1 Schematic diagram of laboratory work

3.1 RAP Production Phase

The purpose of this stage is to design and fabricate the virgin mixture as well as producing the RAP materials. Making RAP in the laboratory has great importance for controlling the quality and raising the accuracy of the results, eliminating problems of RAP variability such as gradation of RAP particles and/or RAP binder content and origin. McDaniel and Solaimanian reported that the more change there is in RAP binder content and/or gradation of RAP materials, the more variation occurs in properties of HMA (Solaimanian and Savory, 1996, McDaniel et al., 2000). Therefore, a high proportion of RAP materials could be used only if they were taken from the same place, or there was a small difference in their properties (Nady, 1997).

3.1.1 Materials selection

Two types of virgin bitumen and three size fractions of limestone aggregate were selected to be utilized. Table 12 displays all the employed bitumen and aggregate along with their suppliers.

Table 12 Virgin bitumen and aggregate types

Bitumen		Aggregate	
grade	Source	Nominal Maximum Size	Source
40/60	Shell	10 mm limestone	Dene quarry
70/100		6 mm limestone	
		4 mm limestone	

3.1.1.1 Aggregate

Three nominal sizes of limestone aggregate namely 10 mm, 6 mm and dust were chosen and subjected to gradation tests (BS EN 933-1, 1997). A graphical depiction of particle size distribution of each aggregate type is shown in Figure 3-2. The particle density and water absorption were determined according to (BS EN 1097-6, 2000) and are presented in Table 13.

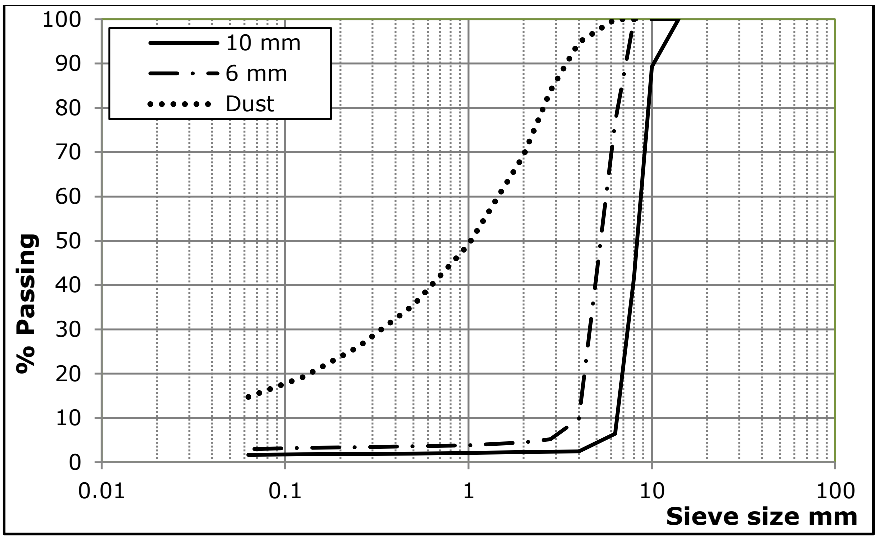


Figure 3-2 Gradation of virgin aggregate particles

Table 13 Physical Properties of virgin aggregates

Aggregate nominal size	**10 mm** limestone	**6 mm** limestone	**Dust** limestone
Particle Density g/cm^3	2.732	2.649	2.670
Apparent Particle Density g/cm^3	2.851	2.726	2.736
Water Absorption %	1.6	1.1	0.89

3.1.1.2 Bitumen

Two types of fresh bitumen were employed. Bitumen 40/60 pen was used to produce the virgin mix, while bitumen 70/100 pen was utilized as a softening agent for manufacturing the recycled mixtures. Also, another virgin mix was prepared with bitumen 70/100 pen. Applied tests on virgin and recovered bitumen were allocated for measuring the physical properties (penetration, softening point, and density (BS EN 15326, 2007)). A Further test such as the DSR test was conducted basically to determine the rheological properties of these binders. Table 14 exhibits the physical and chemical properties of the virgin bitumens. The results obtained are consistent as there is an inverse relationship between penetrations and each of softening points, viscosities, and asphaltenes contents.

The Capillary Viscometer test (BS EN 12596, 2007) was applied on virgin bitumens to measure the dynamic viscosities at 60 °C

(140 °F). Although the test was suitable for the virgin bitumen as it needed roughly 40 g, it was not convenient for recovered binders from RAP as the obtainable quantity of recovered binder was limited. Therefore, a trial has been done to replace the Capillary Viscometer test with the Rotational Spindle test (known as Brookfield Viscometer test) which needed less quantity of bitumen, nearly 10 g. Yet, the Rotational Spindle test failed to test bitumen 40/60 pen because it was too hard to allow the spindle to rotate. Because the majority of the recovered binders in this study were harder than 40/60 pen, this makes applying the test invalid. Consequently, it was decided to use the DSR test for all types of bitumen, whether virgin or recovered, to extrapolate their viscosities at 60 °C at zero-shear or zero-frequency. These viscosities are known as zero shear viscosity, ZSV. Methods used to extrapolate the ZSV are introduced later in section 3.3.

Table 14 Primary tests of virgin binders

Binder type	Pen (dmm)	Softening Point (°C)	Density (g/cm^3)	Dynamic Viscosity @ 60˚C (Pa.s)*	ZSV @ 60˚C Pa.s	Asphaltenes content %	Maltenes content %
40/60	48	54.8	1.031	609	760	16.1	83.9
70/100	91	47	1.029	128	163	11.9	88.1

* Pa.s = 10 poises

3.1.2 Design and manufacture of virgin HMA

3.1.2.1 Select gradation of mixture

Bitumen 40/60 pen was chosen to be mixed with three sizes of limestone aggregates 10mm, 6mm, and 4 mm to produce the virgin HMA. Another virgin mix made from bitumen 70/100 pen was also produced. The designed gradation for both mixes was 10 mm close graded surface course with 5.2% bitumen content (BS 4987-1, 2005). A 5% air voids was selected as a target (design range of air voids from 3 to 5 percent) (Asphalt Institute, 2001). Proportions of each aggregate size were determined, by trial and error via an Excel spread sheet programme, to conform to the 10mm DBM grading requirements, see Table 15. Figure 3-3 depicts the final grading of combined aggregates along with specification limits.

Table 15 Percent of each nominal size and specification limits

Sieve Size		% retained weight			Sum 100 %	%Passing of Combined Aggregate	Specification Limits		
		10 mm	6 mm	Dust			Lower	Mid-Point	Upper
14.0	mm	0.00			0.00	**100.0**	100	**100**	100
10.0	mm	3.65	0.00		3.65	**96.4**	95	**97.5**	100
8.0	mm	16.18	0.00		16.18	80.2			
6.3	mm	11.99	7.91	0.00	19.90	**60.3**	55	**65**	75
4.0	mm	1.33	22.76	1.68	25.76	34.5			
2.8	mm	0.03	1.56	3.47	5.06	29.4			
2.0	mm	0.03	0.24	4.67	4.94	**24.5**	19	**28**	37
1.0	mm	0.06	0.21	6.46	6.73	**17.8**	10	**20**	30
0.500	mm	0.05	0.10	4.37	4.51	13.3			
0.250	mm	0.03	0.06	3.03	3.12	10.1			
0.125	mm	0.03	0.06	2.18	2.27	7.9			
0.063	mm	0.05	0.10	1.42	1.57	**6.3**	3	**5.5**	8
Pan		0.56	1.00	4.71	6.29				
Sum %		**34 %**	**34 %**	**32 %**	100				

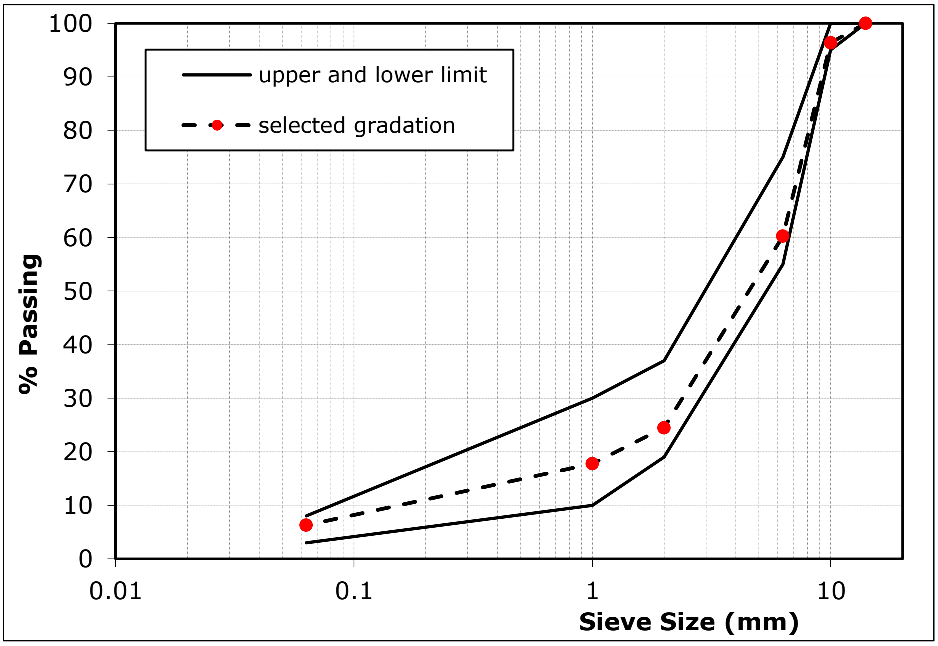


Figure 3-3 Designed gradation of virgin HMA

3.1.2.2 Determine the maximum theoretical density of the bituminous mixture

Using the data in Table 13, Table 14, and Table 15, the maximum theoretical density of the virgin mix was mathematically calculated according to (BS EN 12697-5, 2009) and was found to be 2547 kg/m^3, see Appendix 1. Based on maximum theoretical density and 5 % air voids, the target density was determined as 2547× (100 - 0.05) = 2420 kg/m^3. Utilizing cylindrical specimens of 100 mm in diameter and 60 mm in height, the weight of each sample is calculated as:

$$W = \text{density} \times \text{volume} = 2420 \times \left(0.06 \times \pi \frac{(0.1)^2}{4}\right) = 1.140 \text{ kg.}$$

Table 16 introduces the proportion of each aggregate size and the bitumen content required to produce one cylindrical specimen.

Table 16 Design of Virgin Mixture

Target Air Voids	5 %	**Samples type: Gyros**	(100*60 mm) diameter* height
Target Density	2420 kg/m3		
Bitumen Grade	40/60 or 70/100	**Binder Content**	5.2 %
Aggregate Size	**Mass %**	**Mass g**	
10 mm	34	368	
6 mm	34	368	
Dust	32	346	
Sum	100	1081	
Binder mass	5.2	59	
Total Mass		1140	

3.1.2.3 Fabricating procedure of virgin mixes

The following procedure (as done in previous work (Nguyen, 2009) and recommended by laboratory technicians) was adopted in producing the virgin samples.

- Heat aggregates and bitumen 40/60 pen at 160±5 °C for a minimum of 8 hrs and 3 hrs respectively (135±5 °C for bitumen 70/100 pen)
- Mix heated bitumen and aggregates for 3 min at 160±5 ^{o}C

- Pour the blend inside a metal cylindrical mould and place it back into an oven maintained at 160 °C for a minimum of 30 min before the compaction process
- Compact the loose mix in the gyratory compaction machine (BS EN 12697-31, 2007) at 150±10 °C, 800 kPa pressure and 2.0 ° angle of gyration to achieve the target air voids and density.
- Leave the compacted specimens in moulds over night to cool.
- Remove the compacted specimens from the moulds, and then trim 10 mm from each side to give 40 mm thickness to be ready for further tests.

3.1.3 Ageing procedure

As is well known, there are two kinds of ageing that affect the performance of bituminous mixtures; the short-term ageing which happens during blending and the construction process, and the long-term ageing that occurs slowly and gradually over the whole service life of an asphalt pavement. Recycling of pavements begins only when they reach the end of their service life or suffer severe deterioration. Throughout their service life, the binder within pavement ages due to weathering conditions and becomes stiff enough not to resist crack generation in the pavement body. This in turn does not make pavements perform properly. Consequently maintenance or ultimately recycling of roads is needed.

When pavements are recycled, the aged binder in the RAP definitely differs from its initial state in terms of physical and chemical characteristics. From this stand point, and because the short-term ageing already occurs during the production stage, only the long-term ageing was artificially simulated to produce the RAP materials in the laboratory. The artificial ageing was done by exposing the virgin cores to heat inside an oven for a specific period of time. (Oke, 2011) developed models for estimating the required time of ageing and temperature to decrease the penetration of bitumen 40/60 to any other desired penetration, see Figure 3-4.

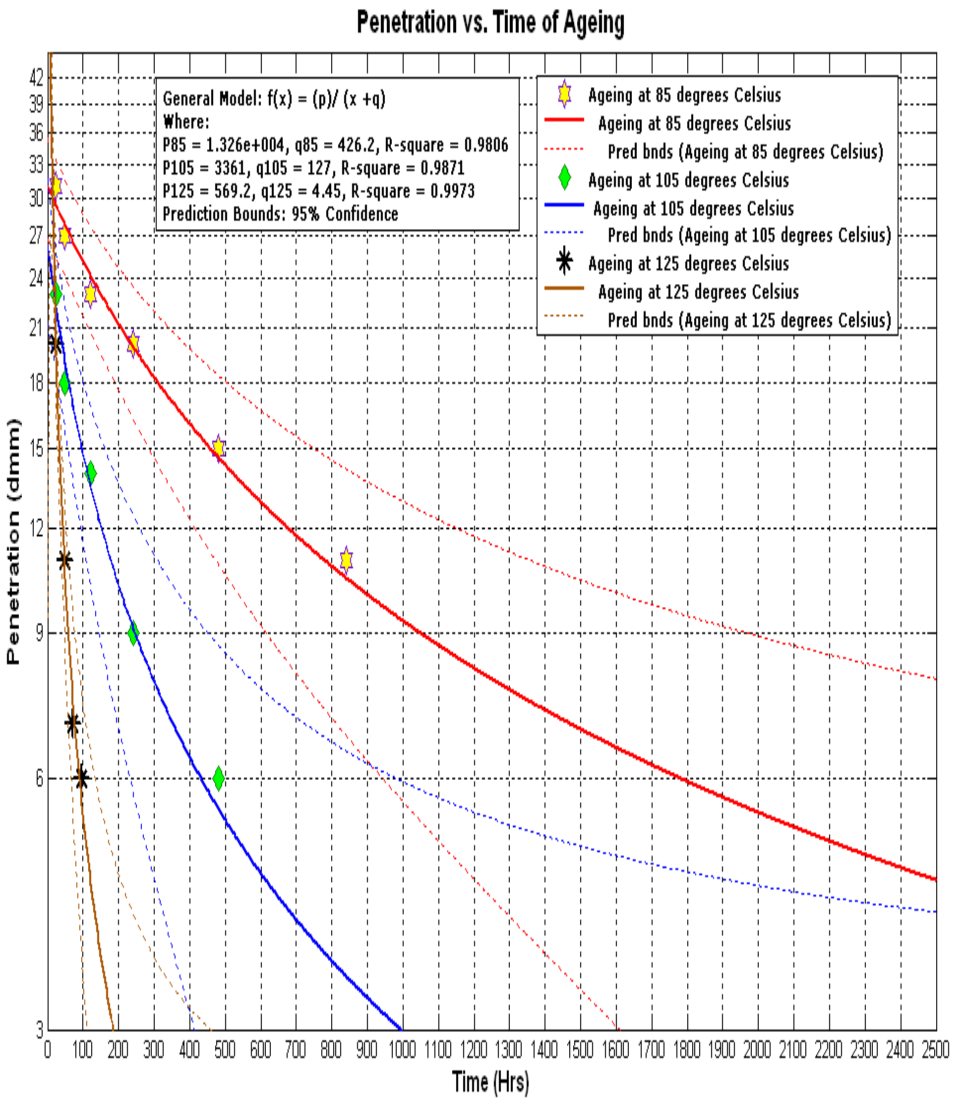


Figure 3-4 Penetration of recovered binders vs ageing time (Oke 2011)

The ageing process aimed to produce three types of RAP that differ from each other in their level of ageing. At first, the three levels of ageing, which were 7hrs@105 °C, 40hrs@105 °C, and 65hrs@ 125 °C, were selected to decrease penetrations of binders within the virgin samples to desired penetrations of around 30, 20, and 10 dmm respectively. These three kinds of ageing level simulate three different cases of field ageing, low, moderate, and severe ageing respectively. Table 17 details the ageing times and temperatures along with the desired and obtained penetrations of the recovered binders after each ageing level. It should be mentioned that penetration of the recovered binder from virgin samples was found to be 37 dmm, which means, after the mixing process, the penetration of the binder decreased from 48 dmm to 37 dmm.

The ageing process was employed only on virgin samples made from bitumen 40/60 pen. Consequently, all the RAP materials used in the laboratory work were produced from this virgin mix.

Table 17 Time of ageing with desired and obtained penetration

Time of Ageing	Desired penetration (Oke's plot)	Penetration of recovered binder	Type of RAP material
7 hrs @ 105 °C	30 dmm	47 dmm	Cancelled
40 hrs @ 105 °C	20 dmm	33 dmm	RAP^1
65 hrs @ 125 °C	10 dmm	23 dmm	RAP^2
2 weeks @ 125 °C		11 dmm	RAP^3
No ageing	Penetration of the recovered binder after mixing = 37 dmm		
Virgin binder	Penetration = 48 dmm		

As presented in Table 17, there were huge differences between the target and obtained penetrations. Also, the first two desired penetrations were achieved by the second and third ageing protocol. Therefore, it was decided to run a fourth ageing protocol which was 2weeks@125 °C to fulfil the third desired penetration of 10 dmm. The reason for the huge variations between the desired and obtained penetrations might be due to the dissimilarity of origin of bitumens used in this and Oke's research (2011), which is unknown for both researchers. Another likely explanation is because Oke applied long-term ageing on the loose mixtures after breaking compacted slabs (305 x 305 x 50mm) by Kango Hammer. However, in this research, the long-term ageing was carried out on the compacted samples. Airey reported that ageing of compacted specimens would require long laboratory ageing times in order to produce the desired properties (Airey, 2003).

By comparing penetrations of the recovered binders from 7hrs@105 °C ageing and no ageing cases (47 dmm compared to 37 dmm respectively), it is clear that this result is illogical and the opposite condition would normally be expected. The reason for this is unknown and could be an error during the recovery and extraction process of recovered binder. Hence it was decided to ignore the first level of ageing and not use its RAP materials. Eventually, three levels of ageing (40 hrs@105 °C, 65hrs@125 °C, and 2weeks@125 °C) were chosen to give penetrations close to the desired ones.

3.1.4 Processing of RAP materials

After the virgin cores (100mm diameter × 60mm height) were aged and the planned tests were implemented, these cores were then crushed by the Jaw Crusher into small pieces. The gap between the two jaws was adjusted – in a static condition - to 16 mm to produce small RAP agglomerations of 19 mm maximum size. At this stage, the RAP materials are ready to be used for the next recycling phase.

3.2 Applied tests

Tests in this study can be divided into two main categories; tests to measure the mechanical properties of the bituminous mixtures and tests to determine the properties of binders. The former type was conducted on the compacted gyratory specimens, while the latter type was employed on the recovered binder. Two tests were chosen to assess the mechanical properties of the asphalt mixtures; the ITSM and the ITFT tests.

3.2.1 Indirect tensile stiffness modulus test (ITSM)

The ITSM is the most common test for determining the stiffness modulus of asphaltic samples via the NAT machine; Figure 3-5. The dimensions of specimens were 100±2 mm diameter and 40±2 mm thickness. The test was carried out under the standard conditions of 5μm target horizontal deformation, 124 ms rise time, 20 °C test temperature. The samples were initially conditioned in a cabinet at 20 °C for at least 7 hrs before testing (BS EN 12697-26, 2004).

Five conditioning pulses are applied before starting the test to make any adaptation for the load needed to produce the target horizontal deformation, and to embed the loading plates correctly over the sample. The system then applies five load pulses to generate the horizontal deformation. Test data (horizontal stress and strains) were measured and stored automatically and the stiffness modulus was easily calculated by Equation 9. The ITSM test was implemented on groups of non-aged and aged samples for both virgin and recycled mixtures. A typical test result is shown in Figure 3-6.

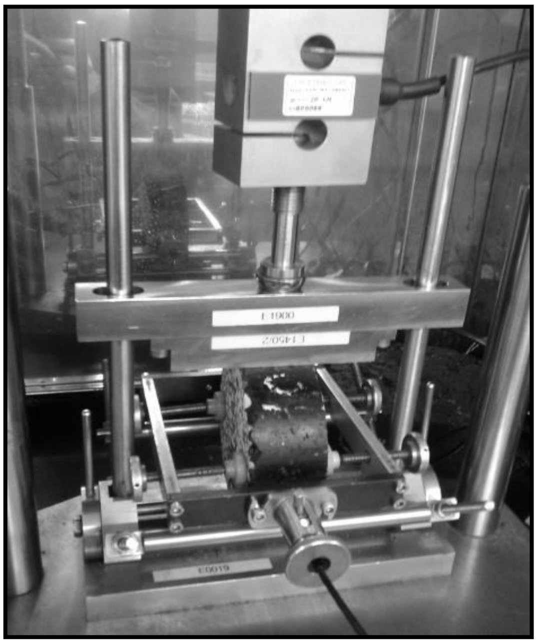
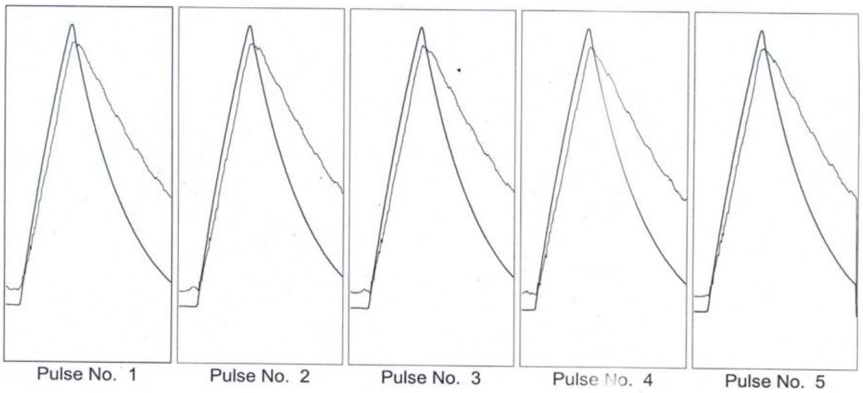


Figure 3-5 Indirect tensile stiffness modulus test



Pulse No.	Vertical force (kN)	Horiz Stress (kPa)	Load area factor		Horiz defm (microns)		Rise Time (m.secs)		Stiffness modulus (MPa) 1st diameter	
			Target	Actual	Target	Actual	Target	Actual	Measured	Adjusted
1	3.09	491.6	0.60	0.56	5	4.8	124	120.0	10056	9748
2	3.21	510.2	0.60	0.56	5	5.0	124	123.0	10003	9709
3	3.23	513.6	0.60	0.56	5	5.1	124	125.0	9897	9596
4	3.23	514.2	0.60	0.56	5	5.0	124	124.0	9991	9711
5	3.22	513.2	0.60	0.55	5	5.0	124	124.0	9987	9668
Mean	**3.20**	**508.6**	**0.60**	**0.56**	**5**	**5.0**	**124**	**123.2**	9987	**9686**

Note: Stiffness adjusted to a load area factor of 0.60

Figure 3-6 Typical result sheet of ITSM test

$$\mathbf{S_m} = \frac{\mathbf{F}}{\mathbf{Z \times h}}(\boldsymbol{\nu} + \mathbf{0.27}) \qquad \text{Equation 9}$$

Where
S_m: Stiffness modulus, MPa
F: Vertical load, N
Z: Horizontal deformation, mm
h: Thickness, mm
υ : Poisson's ratio (0.35 for asphalt)

3.2.2 Indirect tensile fatigue test (ITFT)

Fatigue resistance of asphalt mixtures could be easily assessed in the NAT machine via the ITFT test by using repeated vertical compressive load to damage the cores. The accumulation of vertical deformation is plotted with number of load cycles during the test until failure occurs. Failure was defined as being when 9mm vertical deformation happens, though in reality the specimens usually fail before that deformation. Prior to implementation of the test, the stiffness modulus of the tested specimen should be measured at the stress to be used in the fatigue test. This was done by the Indirect Tensile Stiffness Test (ITST) via the same equipment as the ITSM test. This stiffness is then used to calculate the maximum horizontal tensile strain at the centre of the specimen, using Equation 10. Test temperature was 20±1 °C and the samples were 100mm diameter and 40±2mm thickness. Figure 3-7 indicates how the sample is positioned in the NAT machine. By recording the number of cycles to failure and calculating the maximum tensile strain, the fatigue lines could be plotted on a log–log graph. Each fatigue line was established by testing at least six samples of the same mixture.

$$\boldsymbol{\varepsilon_{max}} = \frac{\boldsymbol{\sigma_{max}}}{\boldsymbol{S_m}}(\mathbf{1} + \mathbf{3}\boldsymbol{\upsilon}) \qquad \text{Equation 10}$$

Where:
ε_{max} : maximum horizontal tensile strain
υ: Poisson’s ratio (0.35)
σ_{max} : maximum tensile stress, MPa
S_m: stiffness modulus, Mpa

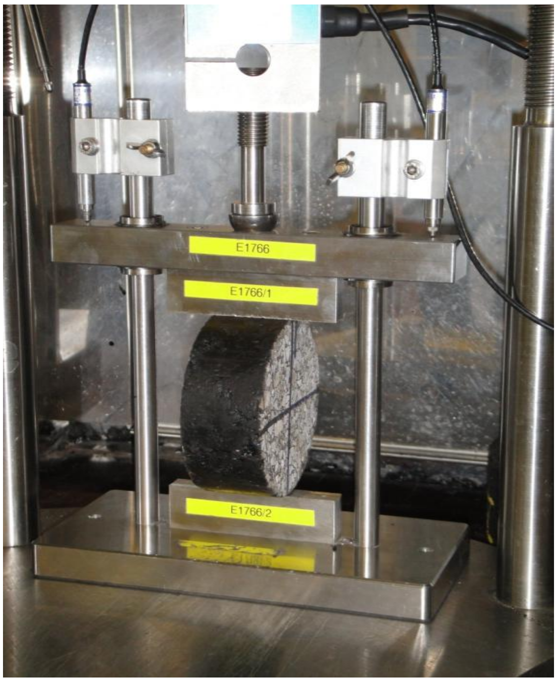


Figure 3-7 Sample position in NAT machine under ITFT

3.2.3 Dynamic shear rheometer test (DSR)

Rheological properties of bitumen can be determined by the DSR test by measuring the complex shear modulus (G^*) and the phase angle (δ). The G* is a similar measure to stiffness modulus for asphalt mixes and equals the ratio of peak stress to peak strain. It is generally used to evaluate the resistance of bitumen to deformation. The δ is the difference in degrees between stress and strain in sinusoidal oscillatory loading, Figure 3-8. It is used to measure the degree of elasticity for the visco-elastic materials such as bitumen. It equals 0° for pure elastic material, while it equals 90° for pure viscous material.

In the DSR test, an oscillating shear stress is applied to a sample of bitumen sandwiched between two parallel plates over ranges of test frequencies and temperatures. The typical idea behind the test is to fix the lower plate and leave the upper to oscillate through which the shear force is applied to the specimen, see Figure 3-9. Data of complex modulus and phase angle can be collected during the test. Test temperature ranged between 10 °C to 80 °C with increments of 10 °C, and frequencies were 0.1 to 10 Hz. The strain ranged between 0.2 % for the more aged binders to 0.5 % for the softer ones. The strain values were chosen to ensure a linear-visco-elastic binder state during the test. It is worth mentioning that the results of the complex viscosity from the DSR test were used in order to extrapolate the ZSV.

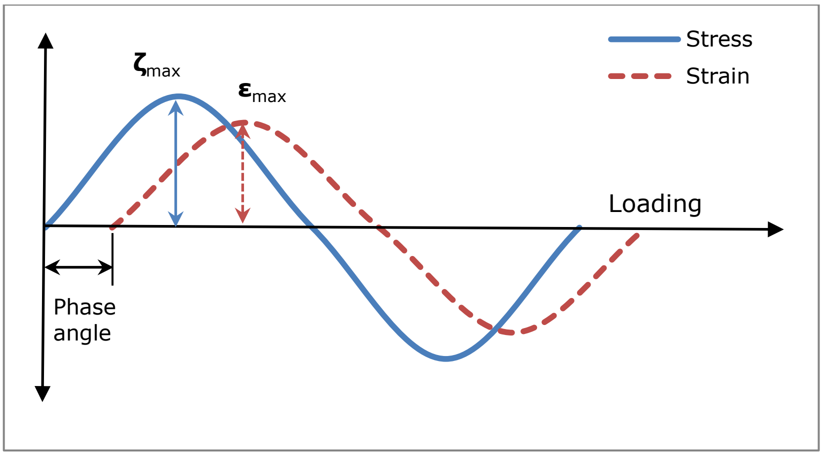
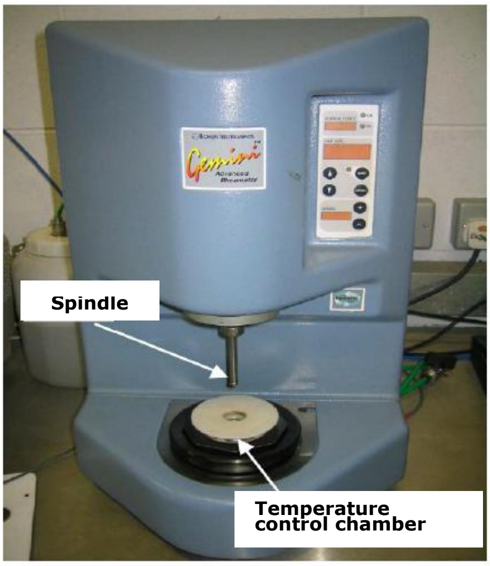


Figure 3-8 DSR oscillatory loading



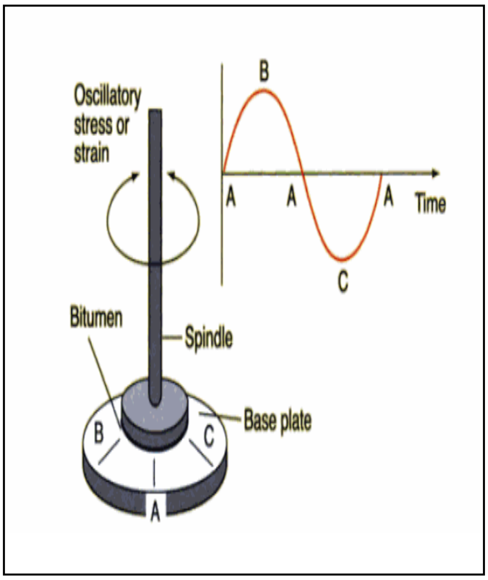


Figure 3-9 The DSR machine and mode of testing

3.3 Zero-Shear Viscosity

3.3.1 Introduction

The Asphalt Institute design method of recycled mixtures uses viscosity blending charts; thus the perfect design depends primarily on estimating the viscosities of the aged and virgin binders. Inaccurate input of these viscosities might result in significant error in prediction of percent of RAP materials used in the recycled mixture. The absolute viscosity can be determined via conventional tests such as the Brookfield Viscometer test and Vacuum Capillary test. However, the limitations of these tests, as the former requires a large amount of bitumen (especially the recovered binder) and the latter failed to run for the highly aged binder, makes their application not feasible. Hence it was decided to calculate the viscosities of all binders used in this study based on the DSR results at an arbitrary temperature of 60 °C.

The ZSV is a theoretical concept which can be defined as the viscosity measured in shear deformation, when shear rate is approaching zero. Recently, especially in Europe, using the ZSV as a specification criterion for bitumens has gained considerable interest. In recent years, the ZSV was used by many researchers as an acceptable property of non-Newtonian liquids such as bitumen (Chaffin et al., 1995, Sybilski, 1996, Anderson et al., 2002, Biro et al., 2009). The ZSV can be measured directly from long-term creep tests, but these tests are time-consuming, in addition, it is hard to obtain a state of steady flow. There are different alternative methods to estimate the ZSV which do not depend on reaching a steady flow state.

Four different methods for estimating the ZSV were examined by Anderson et al (2002). These methods were single creep and recovery test, multiple superimposed creep and recovery tests, application of the Cross model to dynamic viscosity measurements, and extrapolation of dynamic viscosity from a frequency sweep test. All the estimation methods were carried out on 10 different types of binders (four unmodified + five polymer-modified + one special).

Anderson et al. concluded that both the creep and recovery method and application of the Cross model on frequency sweep data gave similar results of estimated ZSV. The authors, in addition, reported that using these two methods may give reliable estimation of the ZSV values. Also, it was revealed that the single creep and recovery tests were impractical as they require several hours to reach the steady state (Anderson et al., 2002).

3.3.2 Extrapolate ZSV from oscillatory measurements

In practice, the ZSV could not be experimentally measured due to capability limits of the equipment (Chaffin et al., 1995). However appropriate mathematical models can be used to extrapolate the ZSV from the complex viscosity data obtained from frequency sweep test via the DSR machine. Two models were used in this study; Cross model (Cross, 1965) and Carreau model (Carreau et al., 1968) for estimation of the ZSV of binders from the measurements of frequency sweep tests. The frequency sweep test was chosen to be applied on all binders by reason of its simplicity in application and because it does not take excessive time, nearly 30 min for each arbitrary temperature.

The Cross model describes a flow curve of pseudo-plastic fluids (fluid whose apparent viscosity or consistency decreases instantaneously with an increase in shear rate) in the form of a four-parameter equation, Equation 11:

$$\eta = \eta_\infty + \frac{\eta_0 - \eta_\infty}{1 + (k\omega)^m} \qquad \text{Equation 11}$$

The Carreau model is also fitted for viscosity measurements to estimate the ZSV, and is given by Equation 12:

$$\eta = \eta_\infty + \frac{\eta_0 - \eta_\infty}{(1 + (k\omega)^2)^m} \qquad \text{Equation 12}$$

Where

η = viscosity, Pa.s η_0 = ZSV, Pa.s

η_∞ = infinite viscosity at infinite shear rate, Pa.s

ω = frequency, rad/s or shear rate, S^{-1} k, m = material constants

When applying the frequency sweep test on a range of frequencies (0.1 – 100) rad/s, it can be assumed that $\eta >> \eta_\infty$, then the above two equations can be simplified to the following three-parameter forms (Anderson et al., 2002, Sybilski, 1996, Wang, 2010).

$$\eta = \frac{\eta_0}{1 + (k\omega)^m} \qquad \text{Equation 13}$$

$$\eta = \frac{\eta_0}{(1 + (k\omega)^2)^m} \qquad \text{Equation 14}$$

Based on complex viscosity data at 60 °C obtained from the DSR test, the theoretical ZSV was extrapolated by the Cross model and Carreau model by using the Solver program in Excel. A third method was also used to estimate values of ZSV by polynomial fitting. Figure 3-10 displays the original measurements of the dynamic complex viscosity in addition to the ZSV values estimated by the Cross and Carreau models versus the corresponding frequencies on a log-log graph for four types of virgin bitumen.

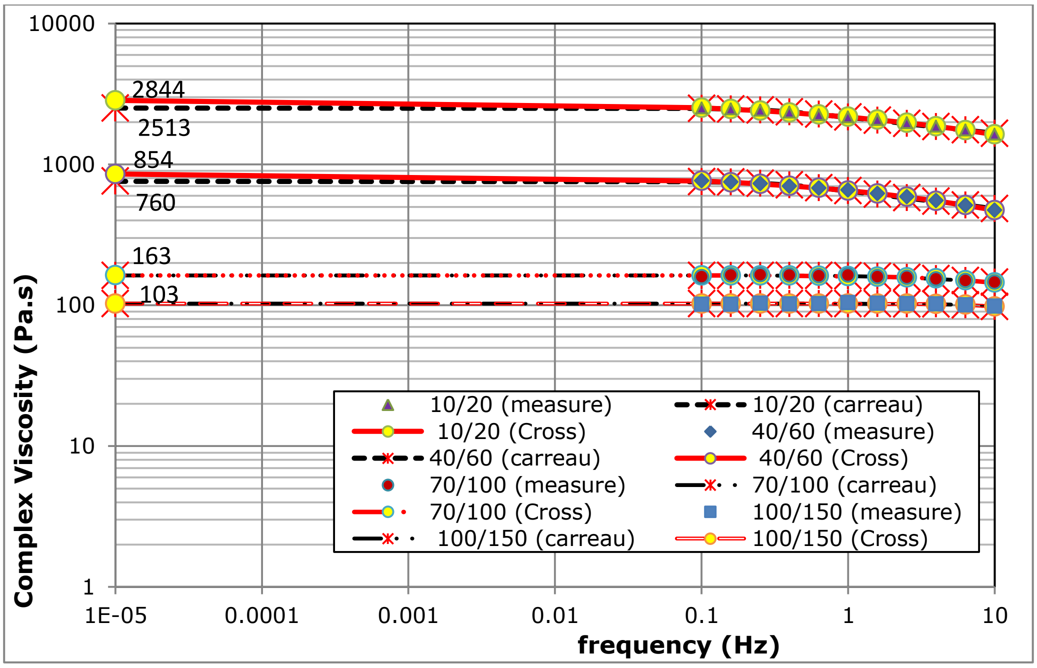


Figure 3-10 Estimated ZSV at 60 °C by Cross and Carreau models for virgin bitumens

It is clear from the figure that both the Cross and Carreau model were perfectly adapted to the measured data at a frequency range of 0.1Hz to 10 Hz. Also, at lower frequencies, the curves of the Carreau model are lower than those of the Cross model. Binard et al. reported that the parameters of the Carreau model forced the formation of a plateau at low frequencies leading to more curvature than that of the Cross model (Binard et al., May 2004). It is also shown from Figure 3-10 that the differences between the Cross model curves and the Carreau model curves increase with an increase in the ageing of bitumen such as 10/20 pen. However, these gaps vanish for soft binders such as 70/100 pen. In general, it can be said that ZSV values calculated from any particular test (Creep, frequency sweep test, etc.) using different models are significantly similar to each other (Biro et al., 2009).

The ZSVs were also extrapolated by polynomial fitting of complex viscosity data obtained from frequency sweep tests, as indicated in Figure 3-11. The figure indicates that the oscillatory measurements can be represented by polynomial fitting in a proper way. Moreover, it appears that ZSV values are close to those of the Cross and Carreau models. However by looking at Figure 3-12, it can be observed that the extrapolated values of complex viscosity at high frequencies could be negative (an illogical result) or increase to a non-reasonable value. Consequently the extrapolation by polynomial fitting was not used because the fitting should describe the data over a wide range of frequency as in the other two models.

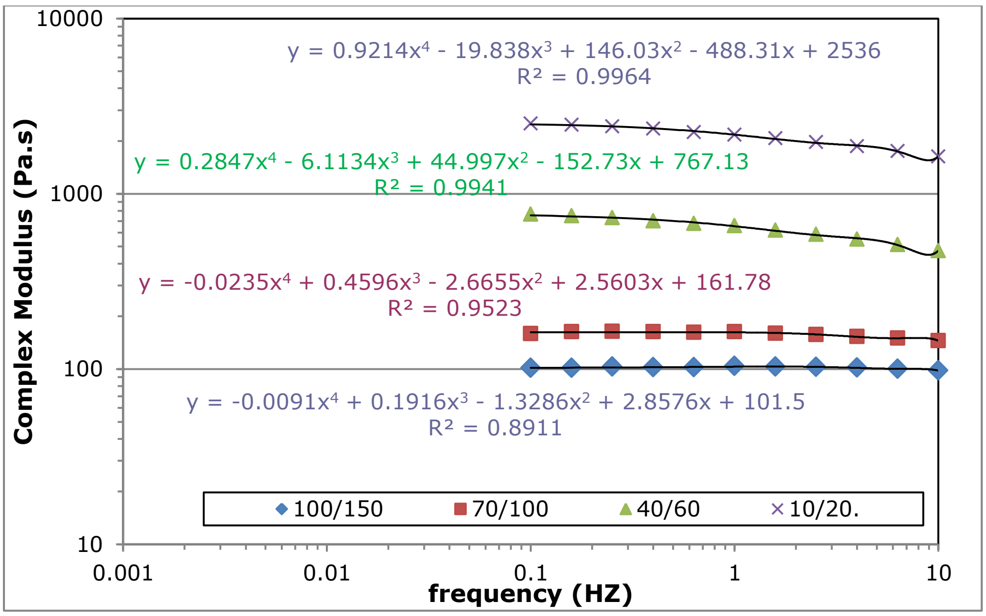
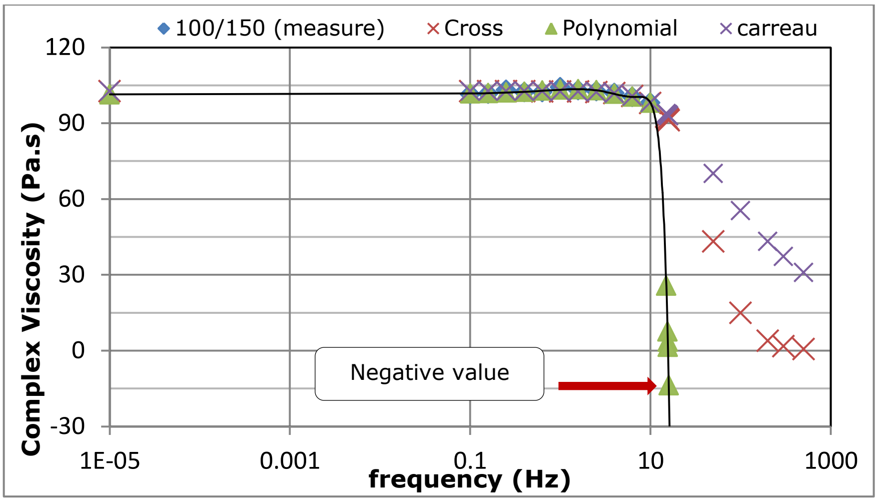


Figure 3-11 Estimated ZSV at 60 °C by Polynomial fitting for virgin bitumens



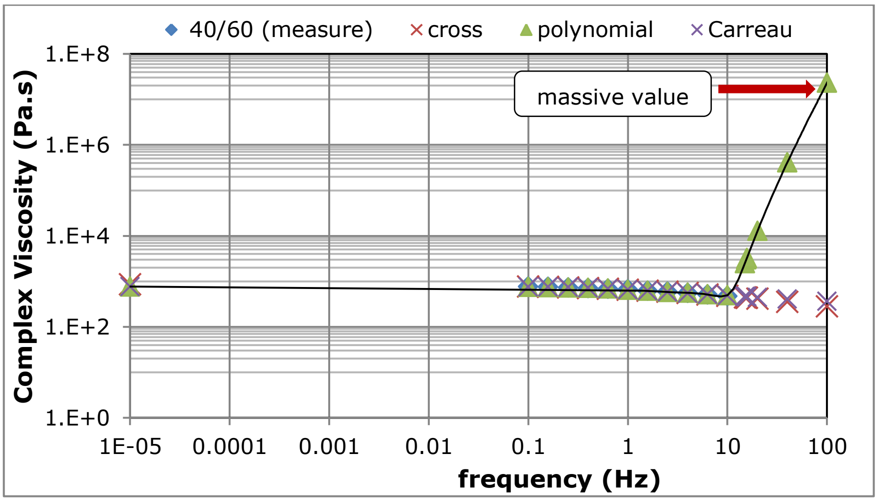


Figure 3-12 Estimated ZSV by polynomial, Cross and Carreau models, binder 100/150 (top) and 40/60 (bottom)

Regarding the Cross model, it was also discarded since in the case that parameter k is negative and parameter m is non-integer, the model cannot be solved by the Solver program except by assuming a limit for parameter k. Hence the Carreau model has been accepted to be used since it avoids the Cross model problem.

Table 18 presents all the extrapolated ZSV values by the Carreau model at 60 °C of all the virgin and recovered binders. The range of frequency was 0.1 – 10 Hz for all binders but was 0.01 - 1.0 Hz for the highly aged binders in order to assure more accurate estimation of the ZSV.

Table 18 Estimated ZSV for all recovered and virgin binder by Carreau model

Bitumen ID	Notes	Frequency range Hz	ZSV (Pa.s)*
10-890 (40/60)	Virgin binder	0.1 – 10	760
10-887 (70/100)			163
	Recovered binder from		
10-1512	Non-aged V-mix	0.1 – 10	1798
10-1631	Aged V-mix (40hr@105 °C)		2560
10-1844	Aged V-mix (65hr@125 °C)		9762
10-2546	Aged V-mix (2 week@125 °C)	0.01 – 1	923240
10-2714	R1-rd1*	0.1 – 10	1527
10-2715	R2-rd1		1074
11-1122	R3-rd1		813
10-300	Aged R1-rd1 (40hr@105 °C)		1307
10-302	Aged R2-rd1 (65hr@125 °C)		3950
11-1071	Aged R3-rd1 (2 week@125 °C)	0.01 – 1	1.9 E+6
11-2724	R1-rd2	0.1 – 10	1027
11-2716	R2-rd2		1320
11-2720	R3-rd2		1267
11-2726	Aged R1-rd2 (40hr@105 °C)		1360
11-2718	Aged R2-rd2 (65hr@125 °C)		2637
11-2722	Aged R3-rd2 (2 week@125 °C)	0.01 – 1	2.7 E+5
11-3256	R1-rd3	0.1 – 10	1240
11-3257	R2-rd3		1390
11-3258	R3-rd3		1209

*** Description of symbols**

Ri-rdj

Where i = 1, 2, 3 (type of RAP) and j =1, 2, 3 (order of recycling round)

<u>Example</u> R2-rd1 (Recycled HMA made from 2nd RAP type at 1st round of recycling)

* Pa.s = 10 poises

3.4 Repeated recycling phase

Aim of design of recycled HMA is to optimize RAP content and produce a mix with good performance in fatigue, rutting, thermal resistance, and overall durability. Further, they need to meet the required volumetric properties including air voids, voids in mineral aggregates, and film index…etc (Tran and Hassan, 2011, Al-Qadi et al., 2007). The first and most important step in design of recycled HMA is to determine the properties of RAP aggregate and RAP binder. The basic required properties of RAP materials are viscosity of their binders, bitumen content they have, and particle size distribution of their aggregate. The design procedures also involve specifying the type of softening bitumen, if used, and the desired viscosity of the recycled mixture.

3.4.1 RAP binder properties

Once the binders were extracted and recovered from RAP materials, their properties need to be determined. The main property required in the design procedure is viscosity. Choosing the percent of RAP depends mainly on the amount of bitumen inside RAP, and how aged this binder is. Hence, determining the binder content of RAP is another essential step in the design process. A composition analysis test (BS 598-102, 2003) was employed to measure the amount of aged bitumen of all kinds of RAP, see Table 19. Some other physical and chemical properties of the recovered binder were measured as was done for the virgin bitumens. Results of these properties are also found in Table 19; highlighted cells in the table are the main required date in the design procedures.

Table 19 RAP binder Properties of used RAP materials

Recovered binder from	binder ID	Pen dmm	S.P. °C	PI	Asphaltenes content %	RAP Binder content %	ZSV (Pa.s)**
RAP1 40hr @ 105°C	10-1631	33	62	0.45	17.8	4.9	2560
RAP2 65hr @ 125°C	10-1844	23	70	1.06	20.3	5.0	9762
RAP3 2weeks@ 125°C	10-2546	11	101	3.48	28.6	4.8	9.23 E+05

* S.P. = Softening Point PI = Penetration Index

** Pa.s = 10 poises

3.4.2 Properties of RAP aggregate

The basic characteristic of RAP aggregate is its particle distribution. To find this, a particle size distribution test (BS EN 933-1, 1997) was applied on a sample of the recovered aggregate from crushed RAP. Also, to evaluate the effect of the crushing process on gradation of RAP aggregate, another sample of recovered aggregate from uncrushed RAP was also tested. Figure 3-13 indicates the particle size distribution of the recovered aggregate from crushed RAP (line 3), along with the original designed gradation (line 2) with the upper and lower limits of the specification (line 1). Gradation of the crushed RAP particles was also included (line 5).

It is clearly shown from Figure 3-13 that gradation of the recovered aggregates from uncrushed RAP (4) deviates slightly from the designed gradation (2). Its grading line locates within specification limits except for filler materials (passing sieve 0.063) which is only 0.7% above the upper limit of 8.0%. It was expected that line 4 would be unchanged from line 2, but this marginal difference might be due to splitting of some coarse aggregate during the production stage which includes mixing, compaction, and particularly the trimming process.

The grading line of the recovered aggregate from crushed RAP (3) deviates from designed gradation (2) more than that from uncrushed (4). However, line 3 still locates within the specification range (1), near to upper limit, except for the percent of filler materials which was 2.8% above the upper limit. The obvious cause for this deviation is mainly because more filler materials were generated, upon crushing, due to splitting of larger particles into small fragments. This increment in the amount of fine materials, in cases of high percentage of RAP, controls the amount of used RAP to accommodate the final gradation of the recycled mixture to be within the specification range, see design of recycled mix R1-rd2, sec 3.4.3.

Figure 3-13 also shows gradation of crushed RAP (5); the lowest dashed line. This gradation contains a high amount of large lumps and small quantity of mineral filler, almost zero. The cause behind this is because the small particles bind together producing larger sized agglomerations.

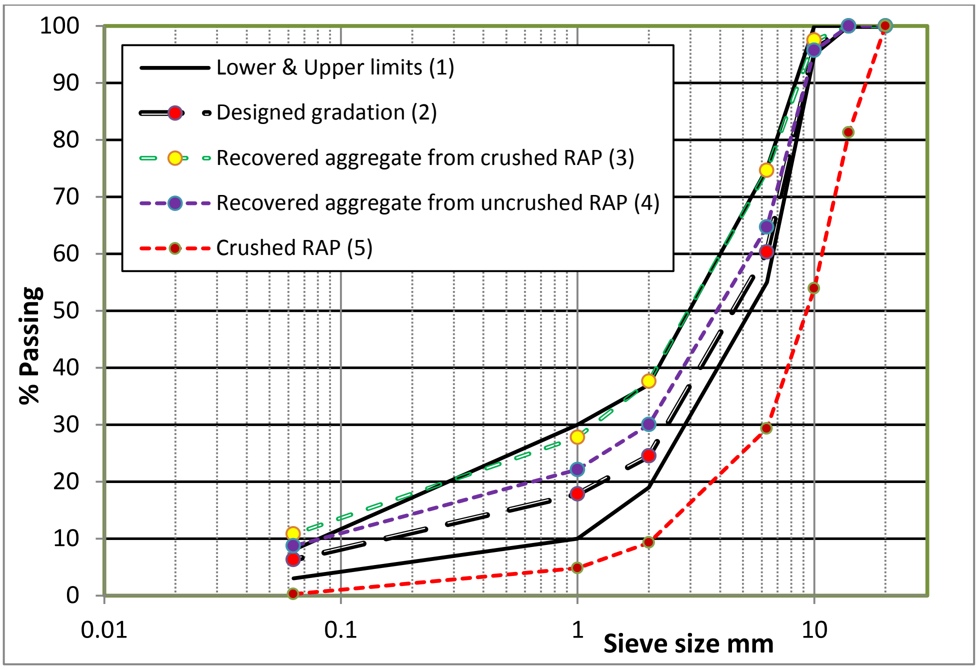


Figure 3-13 Gradation of recovered aggregate

It is worth mentioning that the gradation used in design method, in order to combine with virgin aggregates to preserve the designed gradation, was for line 2. However, the gradation used in production of the recycled HMA was for line 5. In other words the design methods assume that -during and after the mixing- the RAP lumps (line 5) will disintegrate to its initial constituents (line 3). This dissimilarity between the theoretical hypotheses and the practical situation is the main factor responsible for controlling the properties of the recycled mixtures.

3.4.3 Design of the recycled mixtures

The objective from the design process was to produce recycled mixes with the same properties as the control mix (virgin mix made from bitumen 40/60). And because the behaviour of asphaltic mixtures basically depends on properties of their binder, thus viscosities of mixtures (represented by their binder's viscosities) were held constant for both virgin and recycled mixes. This desired viscosity was 760 Pa.s @ 60°C which belongs to bitumen 40/60. Fixing this target viscosity for all mixes permitted comparisons to be made between the virgin and recycled mixes after each round of recycling. Consequently, it was feasible to investigate the impact of repetitive recycling on properties of recycled mixes. The recycled mixes were designed according to the Asphalt Institute design method (Asphalt Institute, 2001) that uses a viscosity blending chart to determine the grade and quantity of the new bitumen.

The required percent of new bitumen to achieve a certain target viscosity could be determined through viscosity blending chart as illustrated in the flow chart in Figure 3-14 and Figure 3-15.

Determine viscosities 60°C for RAP binder (η_1), new bitumen 70/100 (η_2), and target viscosity (η_0)

⇓

Plot η_1 and η_0 on left axis and $\eta 2$ on right axis

⇓

Draw straight line to connect η_1 with η_2

⇓

Draw horizontal line from η_0 to intersect the line η_1 η_2 at point (**C**)

⇓

Projection of point (**C**) gives the required percent (**R**) of new bitumen

⇓

Knowing total bitumen content (P_b) and RAP binder content (P_{sb}), equations in Table 6 can specify required amount of RAP

Figure 3-14 Flow chart describing using of viscosity blending chart

It should be mentioned that η_2 and η_0 were fixed for all recycled mixes, while η_1 was variable. Thus with different η_1, different **R** will be obtained, preserving the target viscosity η_0.

The next example shows the design procedure for first recycled mix at first cycle (R1-rd1).

Design the recycled mixture R1-rd1

From Figure 3-16, R^1 = 42 %

∵ $R^1 = \frac{100\,P_{nb}}{P_b}$ and P_b = 5.2% ∴ P_{nb}= 2.18 %

∵ $P_{nb} = \frac{(100^2 - rP_{sb})P_b}{100(100-P_{sb})} - \frac{(100-r)P_{sb}}{100-P_{sb}}$ and P_{sb}= 4.9%

∴ **r** (percent of new material)=38 % ∴ %RAP = (100-r) = **62 %**

Figure 3-16 shows values of (R) for recycled mixes of the first round of recycling. Appendix 2 shows the proportion of each aggregate size, RAP, and bitumen content required to produce one cylindrical specimen of each recycled mix

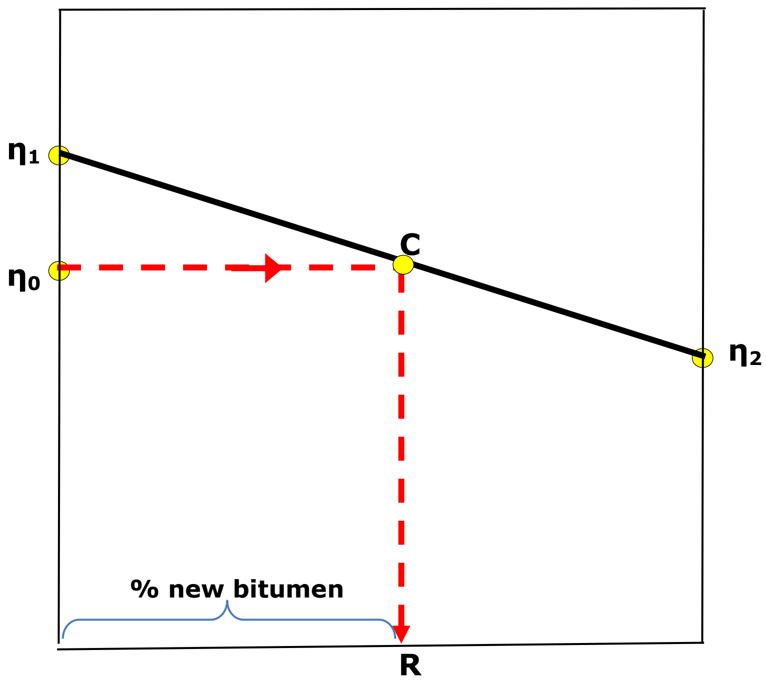


Figure 3-15 Schematic of viscosity blending chart

Before adopting the final percentage of RAP materials, assurance should be made that the aggregate gradation of the recycled mix (combination between the virgin aggregates and RAP materials) does not differ much from the designed gradation of Figure 3-3. Otherwise, modification for RAP proportion is needed to maintain the gradation within specification limits. Proportions of the virgin aggregates and RAP materials along with the amount of new bitumen are presented in Table 20.

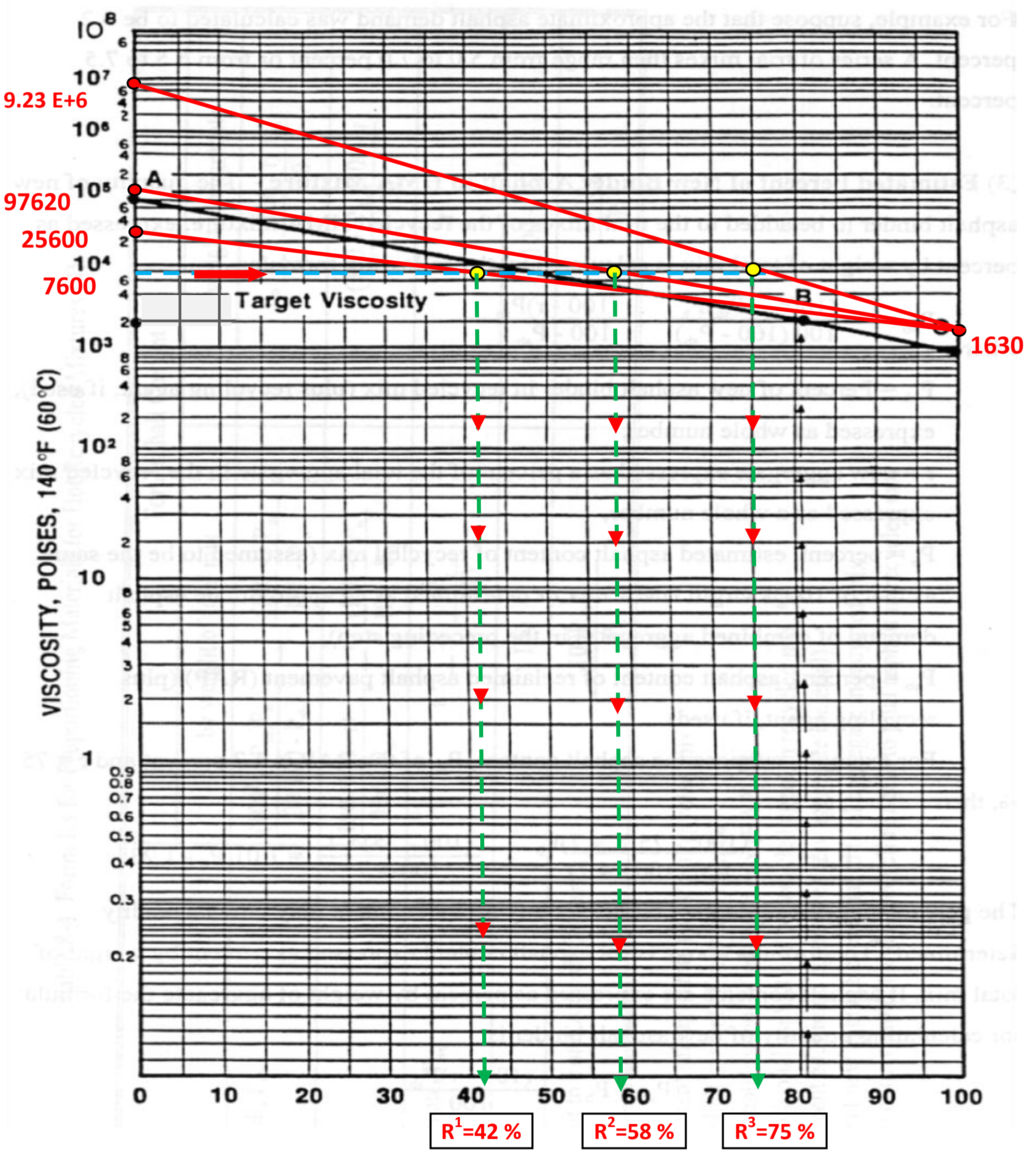


Figure 3-16 Blending chart for all recycled mixtures

Table 20 Design parameter of recycled mixes

	10mm %	6mm %	Dust %	RAP %	new bitumen %
R1-rd1	20	18	0	62	42
R2-rd1	22	27	6	45	58
R3-rd1	28	25	18	29	75
R1-rd2	20	15	0	65 *	37
R2-rd2	20	22	3	55	49
R3-rd2	30	25	20	25	77
R1-rd3	26	5	0	69 *	31
R2-rd3	20	20	3	57	43
R3-rd3	30	25	19	26	75

* Modifications have been made to the percentage of RAP for the recycled mixes R1-rd2 and R1-rd3 in order to maintain the final aggregate gradation within specification limits. The percentages of RAP materials were decreased from 79 % to 65 % and from 73% to 69 % for R1-rd2 and R1-rd3 respectively. In other words, the amounts of new bitumen were increased by 14% and 4%. It is worth mentioning that the increment of 14% affected the mechanical properties of the R1-rd2 mix as will be explained later in chapter 4.

3.4.3.1 Mixing protocol for production of the recycled mixes

It is crucial that there is no great difference between production of the recycled mixes in the laboratory and in an asphalt plant. Therefore, the laboratory protocol carried out by (Nguyen, 2009) matches to a great extent what exists in real asphalt plants. The only difference is the time of the dry and wet mixing because of the massive differences in power and efficiency between the equipment in the laboratory and in asphalt plants. The dry mixing comprises blending the RAP materials with the superheated aggregate in order to heat up the RAP to mixing temperature. The wet mixing blends the whole admixture after adding the hot bitumen. The laboratory mixing protocol is explained below:

- Step 1: Superheat the virgin aggregate at 215 ^{o}C for 8 hrs and preheat the virgin bitumen 70/100 at 135±5 ^{o}C for 2 hrs.
- Step 2: Heat the RAP material to the required warming temperature, see the next section.
- Step 3: Blend the superheated virgin aggregate with the RAP in the mixer maintained at 135 ^{o}C for 8 minutes (Nguyen, 2009).
- Step 4: Mix the combination of RAP and virgin aggregate with virgin binder for 3 minutes.
- The other procedures regarding pouring the blend into the mould, compaction process and trimming stage are exactly the same as that of producing the virgin mixture.

The benefit of the first step is to give the virgin aggregate enough thermal energy to heat the RAP to the mixing temperature. In recycled mixtures with a high amount of RAP, the dispersed heat from the virgin aggregate cannot heat the RAP from room temperature to mixing temperature. Hence the purpose of step 2 is to give the RAP some warming to allow the dispersed heat to raise the RAP temperature to the mixing temperature. As for the third step, the dry mixing helps the RAP to gain the benefit of the heat from the superheated virgin aggregate, hence the RAP lumps can be softened and separated into small particles covered by RAP binder. Also, during this process, RAP binder is transferred onto the surfaces of virgin aggregate particles. The aim of the fourth step is to ensure that the virgin bitumen interacts with and rejuvenates the RAP binder, in addition to ensure that the rejuvenated binder is well distributed all over the mixture and coats every single aggregate particle.

3.4.3.2 Estimate the warming temperature of RAP

Unlike the virgin aggregate, exposure of the RAP materials to direct high temperature causes many undesired problems such as extra ageing of RAP binder. Therefore, heating up the RAP materials in an asphalt plant to the mixing temperature is usually done via heat transfer from the superheated virgin aggregate. The quantity of heat transfer depends mainly on the quantity of the virgin aggregates and their specific heat, in addition to the difference in temperature. Equation 15 represents the required amount of heat to raise temperature of mass M, from T1 to T2 (Cutnell and Johnson, 2004).

$$Q = M\,C\,(T_1 - T_2) \qquad \text{Equation 15}$$

Where:

M: the mass in kg C : specific heat in kJ/kg °C

T_2, T_2: current and desired temperatures in °C

The amount of heat required to raise temperature of RAP from ambient to mixing temperature is:

$$Q_1 = M_{RAP}\, C_{RAP}\, (T_m - T_a) \qquad \text{Equation 16}$$

The amount of dispersed heat from superheated virgin aggregate from the superheated temperature to mixing temperature is:

$$Q_2 = M_{agg}\, C_{agg}\, (T_s - T_m) \qquad \text{Equation 17}$$

Where

M_{RAP}, M_{agg}: Amounts of RAP and virgin aggregate, kg

C_{RAP}, C_{agg}: specific heat of RAP and virgin aggregate, kJ/kg °C

T_s, T_m, T_a: superheated temperature of virgin aggregate, mixing temperature, ambient temperature of RAP, °C.

The heat dispersed from superheated virgin aggregate is assumed to equal the heat absorbed by the RAP materials (i.e. Equation 16 =Equation 17). Knowing T_s = **215** °C, T_m = 135 °C, and % RAP for each recycled mixture, the warming RAP temperature can be calculated for each recycled mix. Table 21 includes the warming temperatures of RAP materials for all designed recycled mixes.

Table 21 Warming temperature of RAP for all recycled mixes

Mixes	Warming Temp. of RAP
R1-Rd1	85 °C
R2-Rd1	40 °C
R3-Rd1	20 °C
R1-Rd2	95 °C
R2-Rd2	70 °C
R3-Rd2	20 °C
R1-Rd3	100 °C
R2-Rd3	70 °C
R3-Rd3	20 °C

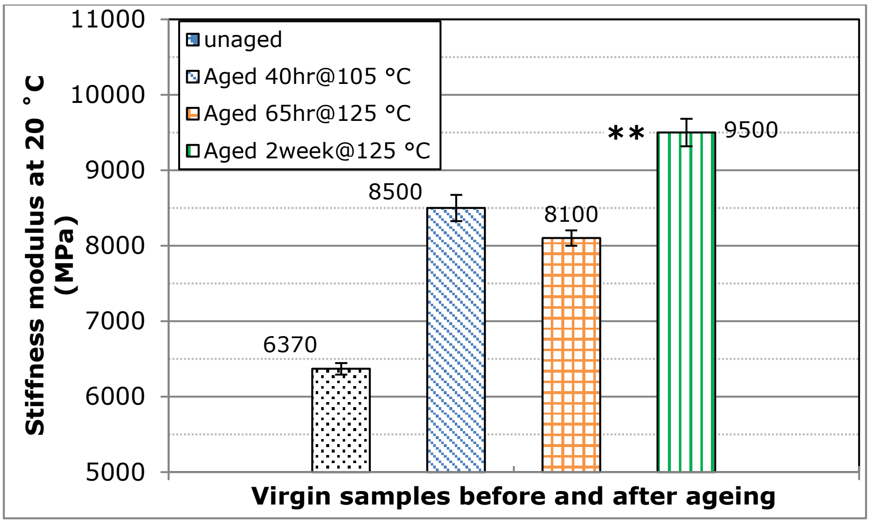
4 Results analysis of the repeated recycling investigation

This chapter presents an analysis and discussion of laboratory results of the repeated recycling investigation. This included, first, the evaluation of the results of the RAP production phase, followed by rational explanations for the results of three rounds of recycling. A comparison between the total blending and standard practice cases was made, and is presented. Another two subsidiary studies to explore the effect of RAP size, and mixing and compaction temperature on the behaviour of the recycled mixture in rutting resistance and fatigue were performed and assessed. The effect of ageing on stiffness and fatigue behaviour was also investigated. Lastly, the dynamic moduli were predicted through the Hirsch model, for all mixes. In addition, the model was used to calculate the complex shear modulus, G*, of the recovered binder from available data of the recycled mixes.

4.1 Evaluation of RAP production stage

4.1.1 Stiffness modulus results

The ITSM test was applied to measure the stiffness moduli of the aged and non-aged virgin samples. The ageing protocol comprised three levels (40hrs@105 °C, 65hrs@125 °C and 2 weeks@125 °C). Figure 4-1 exhibits the stiffness moduli values in MPa at 5.0% air voids. Each value on the graph represents a set of 9 to 16 samples. Full data are displayed in Appendix 3. As expected, the increased ageing level generally led to increased stiffness, as a result of binder ageing within aged samples. However, samples of the second ageing protocol presented anomalous results, as they attained a stiffness of 8100 MPa compared to 8500 MPa for samples of the first ageing protocol, despite an increment in both ageing time (40hrs to 65hrs) and ageing temperature (105 °C to 125 °C). The likely reason for this illogical finding was possibly due to using different NAT machines for running the ITSM test (see Appendix 3). It is known, from a pragmatic viewpoint, that different equipment could produce different results for the same material.



** Error bars calculated from standard error

Figure 4-1 Stiffness modulus of non-aged and aged virgin samples

In order to confirm that there is no problem with ageing protocols, the same NAT machine was used to run the ITSM test. Moreover, the ageing protocols were carried out on the same group of samples, i.e. after applying the ITSM test on aged samples (65hrs@125°C), the same samples were aged for a further period to achieve a total ageing of 2 weeks@125°C, and then tested again. Using the same sample had the benefit of eliminating any error due to sample heterogeneity. The data were presented in terms of Ageing Index (AI), as described in Table 22 and Figure 4-2. As observed, there is an increment in the AI with increasing ageing time and temperature, which provides a reasonable and consistent result.

Table 22 Ageing Index of non-aged and aged virgin samples

Sample ID	**Stiffness Modulus MPa**				
	Non-aged	Aged 40hr @105°C	Non-aged	Aged 65hr @125 °C	aged 2week @125°C
10-2525	5768	7714			
10-2526	5966	7970			
10-2527	5519	7778			
10-2528			6585	9960	12820
10-2529			6339	9430	12990
10-1271			6355	9210	12681
Average	5751	7821	6426	9533	12830
Ageing Index = $S_{aged}/S_{non\text{-}aged}$	1.00	1.36	1.00	1.48	2.00

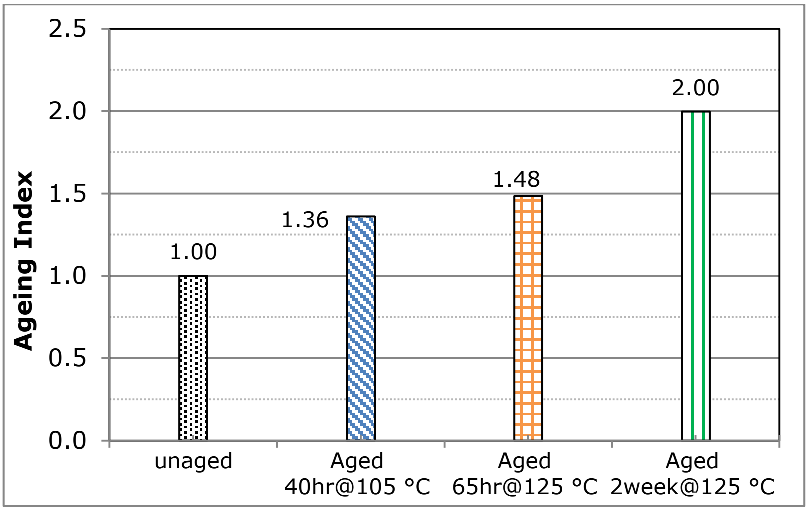


Figure 4-2 Ageing Index of aged virgin samples

4.1.2 Fatigue results

In order to measure the fatigue characteristics of the aged and non-aged virgin samples, the ITFT test was implemented. The ITFT data are displayed in Figure 4-3 in the form of fatigue lines. Analysis of the stress distribution within the sample enables calculation of maximum tensile strain by Equation 10. This permits plotting log-strain to log-life as a linear relationship. The graph clarifies that the non-aged samples had the longest fatigue life, despite having the lowest stiffness modulus compared to the aged samples. The worst behaviour in fatigue was for the 2 week aged samples, which have the highest stiffness. The obvious reason for this is the ageing of bitumen, as it loses some of its oily components through ageing, hence becoming less flexible, which negatively impacts their fatigue behaviour. These aged mixtures can behave better in resisting rutting, as they are stiffer. At the same time, however, their fatigue resistance decreases.

Here, a distinction must be made whether the stiffness of samples resulted from hardening of the binder (by ageing for example), or due to the strength of their structural composition. This means specimen of high stiffness, due to ageing of its binder, have shorter fatigue life than specimen with the same stiffness but its binder was not aged.

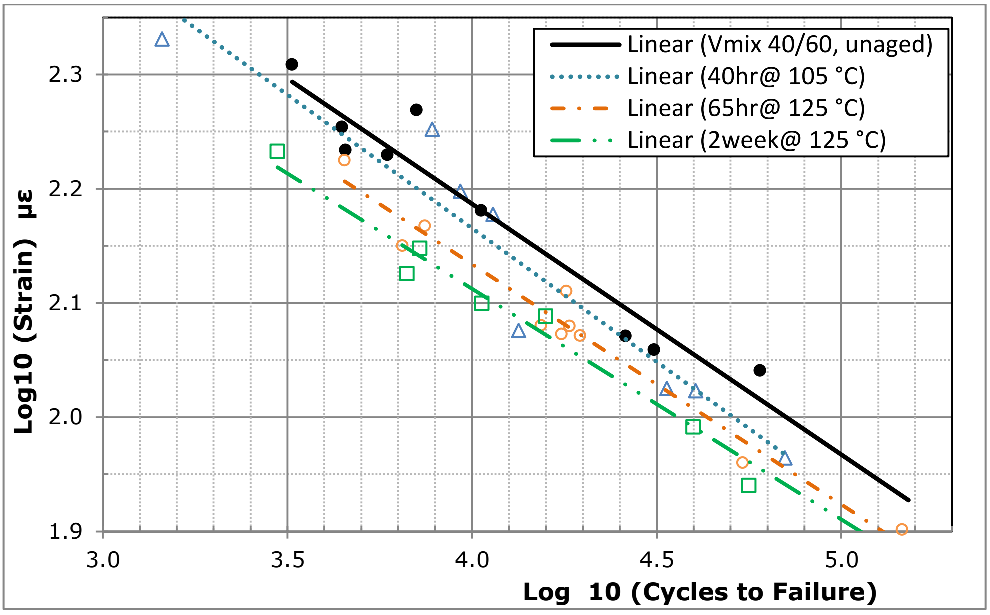


Figure 4-3 Fatigue lines of aged and non-aged virgin samples

4.1.3 DSR results of virgin and recovered binders from RAPs

The master curves of complex modulus and phase angle of the virgin bitumen and recovered binder from RAPs are displayed in Figure 4-4 and Figure 4-5 respectively. Table 23 presents description for the recovered binders from RAPs. The trend from the two figures indicates the massive impact of temperature on behaviour of virgin and recovered bitumens. Figure 4-4 shows that all binders, regardless of their grade, tend to reach a plateau region at high frequencies/low temperature. However, at low frequencies/high temperature, the behaviour varied widely. The highly aged binder (10-2546) was not affected much by test temperature compared to virgin or the others aged binders.

Figure 4-5 indicates that all binders, except the highly aged (10-2546), behaved almost like pure viscous material at high temperature/low frequency as phase angles δ approached 90°. At low temperature/high frequency, they demonstrated relatively pure elasticity as δ approached low values. The Penetration Index PI of binder (10-2546) was 3.48 (Table 19), which complies with the findings of Figure 4-4 and Figure 4-5 in that, highly aged binders are less susceptible to temperature than less aged. In general, bitumens acquired more elasticity and stiffening as they were aged more.

Table 23 Description of the recovered binders from virgin samples

Bitumen ID	Description	Ageing protocol
10-1512	Recovered from non-aged virgin samples	No ageing
10-1631	Recovered from aged virgin samples	40hrs@105 °C
10-1844		65hrs@125 °C
10-2546		2weeks@125 °C

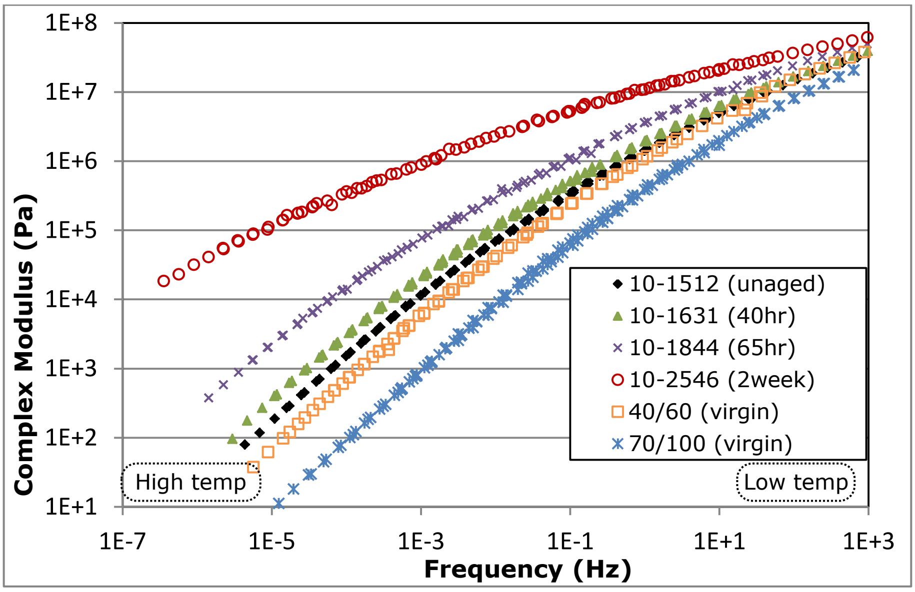


Figure 4-4 Complex modulus master curves of virgin and recovered binders from RAP (reference temperature =20 °C)

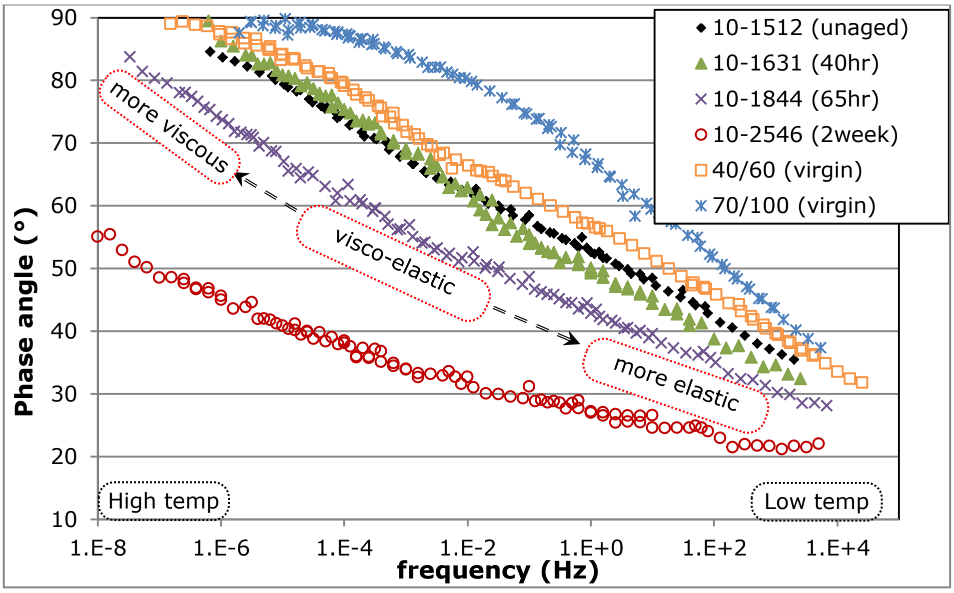


Figure 4-5 Phase angle Master Curves of virgin and recovered binders from RAP (reference temperature =20 °C)

4.2 Results analysis of first round of recycling

4.2.1 Stiffness Results

Figure 4-6 shows the variation of stiffness moduli with air voids for the virgin and recycled mixtures after the first recycling run. It is clear that the control mix (V-mix 40/60) achieved the highest stiffness values amongst all mixes. Also, averages of air voids were 3.6% and 4.0% for the control and recycled mixes respectively, meaning that the compaction of the V-mix (40/60), hence its strength, was relatively better. In order to compare between stiffness moduli of all mixtures, the values were normalized at the designed 5.0% air voids. The normalized stiffness moduli are displayed in Figure 4-7.

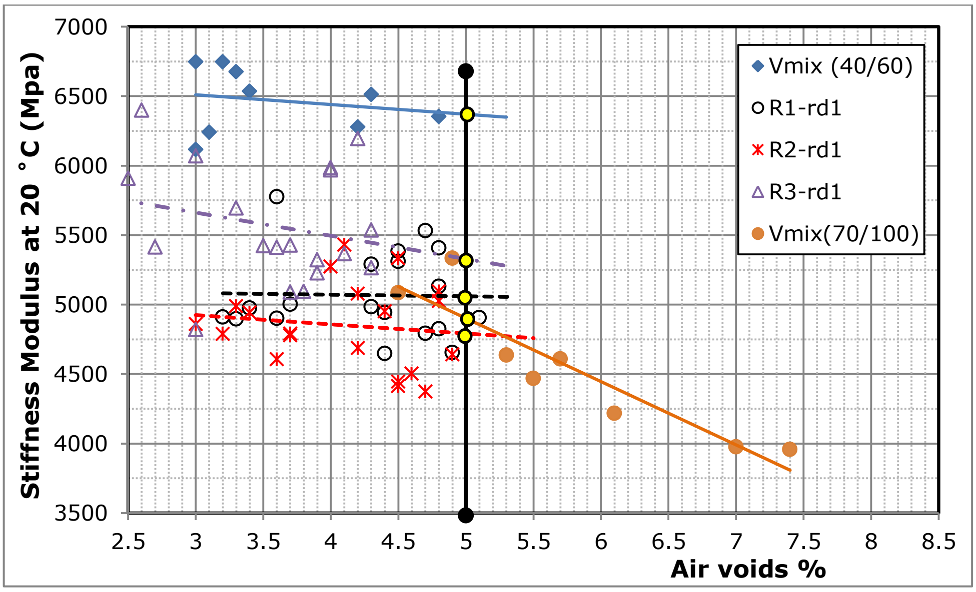


Figure 4-6 Stiffness modulus vs air voids after the 1st round

Many findings can be drawn from Figure 4-7 as follows:

1. The mixtures containing RAP tend to have lower stiffness moduli than mixture without RAP, V-mix (40/60). The difference in stiffness values between the recycled and the V-mix (40/60) lies between (20% - 22%).
2. All stiffness moduli of the R-mixes are close to stiffness modulus of virgin mix made from bitumen 70/100 (V-mix 70/100). The difference in stiffness values ranges from 0.4% to 4.0%.

3. The recycled mix of the third kind of RAP (R3) attained the highest stiffness modulus amongst other R-mixes, although the differences were not considerable.
4. Stiffness moduli of the different types of R-mixes -regardless RAP content- are situated in a range less than 4%, indicating that the percentage of RAP might have no significant effect on stiffness modulus of recycled mixes included in the study.

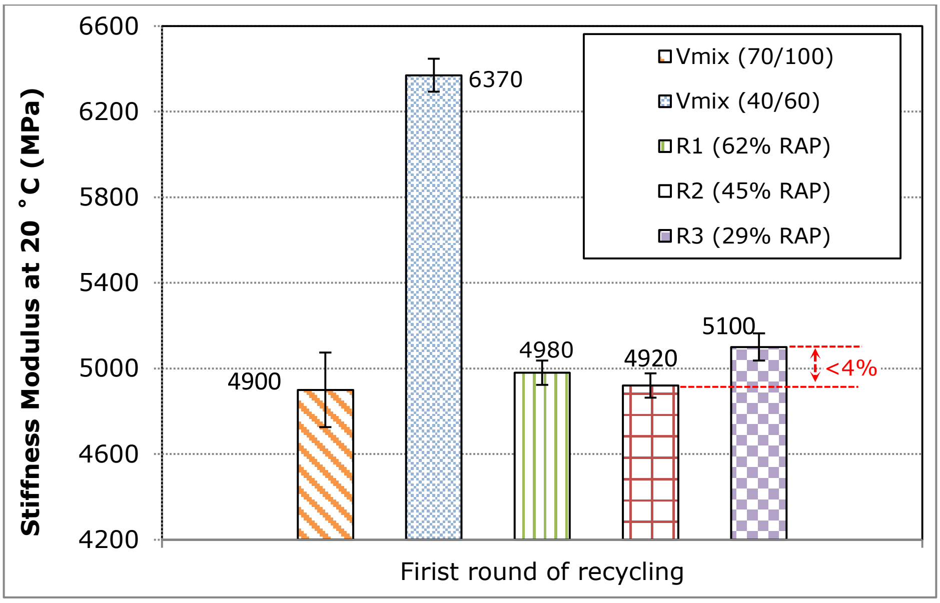


Figure 4-7 Stiffness moduli after first round of recycling

Interpretations and discussions about previous findings are provided below in detail.

<u>Interpretation of the first finding</u>

This finding seems to contradict the common belief in that the presence of RAP causes brittleness of mixture, thus increases stiffness modulus (Al-Rousan et al., 2008, Huang et al., 2005, Sargious and Mushule, 1991, McDaniel and Shah, 2003, Huang et al., 2004). However, similar results were reported by (Widyatmoko, 2008, Oliver, 2001). This contradiction might possibly be interpreted as follows:

- For researchers adopting the common belief, it seems that the RAP binder was not taken into account as a contributor in the mixing process. In other words, perhaps, there were no changes either in content of the virgin bitumen (by reducing its amount) or even its grade (by choosing softer bitumen). This in turn made the RAP materials contribute with an extra amount of aged RAP binder, which was not taken into consideration in advance during the design process. Therefore, this leads to increased stiffness of the binder within the recycled mix, and ultimately increases its stiffness modulus.

- For researchers contradicting the common belief, they attribute the reduction in stiffness to use of softer bitumen and/or rejuvenating agents. Also, the reduction in bitumen content by the same amount, in accounting for the RAP binder, might have an effect on this decrease.

The reasons that make the recycled mixtures have lower stiffness than that of fresh mixtures are varied and numerous. However, in general, they can be grouped into two main categories; factors related to design procedure and others related to production process. Both categories are explained and discussed below in detail.

Design procedure-related factors

Design methods for recycled Hot-Mix Asphalt (HMA), as it is known, are based on two main hypotheses. The first assumes separation of all RAP agglomerations into their initial components, representing the same gradation of the recovered aggregate from RAP, but this is not true in reality (Al-Qadi et al., 2007, McDaniel and Anderson, 2001). The second hypothesis assumes a state of complete blending between the virgin and aged RAP binders, which is also not found in practice. Consequently, the dissimilarity between the hypothetical and real situation, to a large extent, controls the performance of these kinds of mixtures.

Regarding the first hypothesis, Figure 4-8 exhibits the significant difference between two grading lines; RAP lumps and RAP aggregate. The former grading line indicates coarser grading, while the latter shows finer. Design methods of recycled HMA use the finer grading (line 3) in design process in order to combine with the virgin aggregate to achieve the desired gradation shown in Figure 3-3.

However, the coarser grading (line 5) is the one represents the introduced RAP in the real mixing process. Therefore, the theory underlying the design procedure assumes and expects that, at mixing stage, the coarser grading converts to the finer. However, if the RAP lumps do not completely break down, the overall mixture gradation will be coarser than expected. Accordingly, the total surface area of aggregates decreases, resulting in thicker binder film thickness and increment of the VMA, which in turn affect stiffness negatively (Kandhal et al., 1998, Tran and Hassan, 2011).

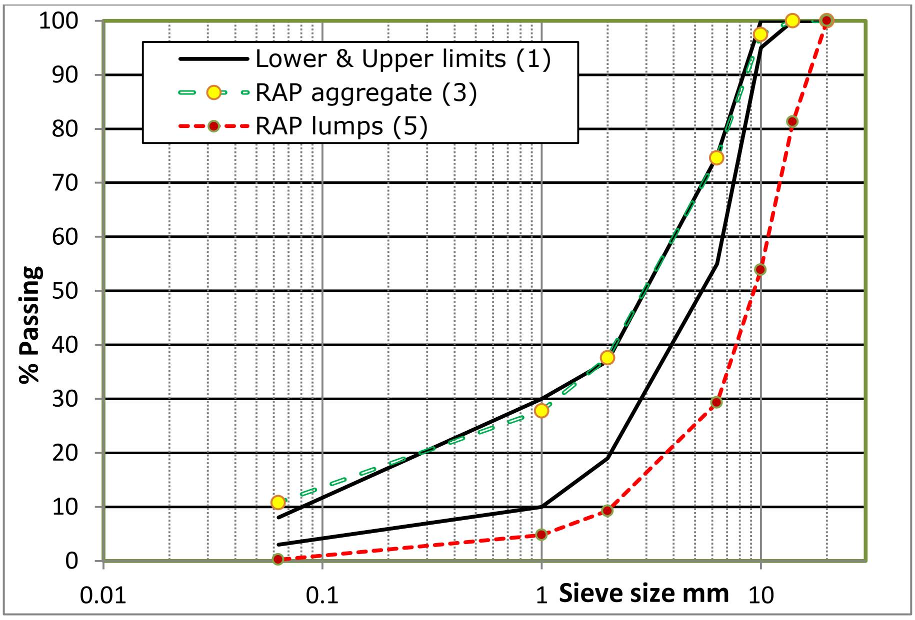


Figure 4-8 Gradation of RAP aggregate before and after recovery

Also, Figure 4-8 shows that RAP lumps contains almost no filler materials (passing sieve No. 0.063) in its initial state. But these filler exist in shapes of small size lumps. At the same time, the design method assumes that the RAP lumps disintegrate into their initial components and contributes with the fillers they have. However, in practice upon mixing, typically, RAP lumps (line5) do not crumble in a way resembling the RAP aggregate (line 3). Accordingly, they cannot provide the mixture with the expected ratio of effective mineral fillers. Despite of the presence of these fillers in small size lumps, they do not fulfil their main role in filling voids between coarse aggregate, providing the desired interlocking. Therefore, the recycled mixes are produced with small amount of filler materials, which come only from virgin aggregates. Consequently, the massive loss of these filler would change the design gradation of recycled mixes, which in turn would affect stiffness property.

In light of the above discussion, the design methods for recycled mixes should pay attention to this problem, and use another gradation located between the two grading lines. In addition, tools to predict the effective grading line of RAP aggregate, at mixing, should be developed. An approximate method to predict this new grading line of RAP aggregate is introduced in Appendix 4.

Regarding the second hypothesis, which assumes that RAP contribute their whole binder, i.e. all RAP binder leaves RAP lumps surface entering the mixing medium to interact with virgin binder. However, this in fact does not occur (Al-Qadi et al., 2007), where the aged binder tends to stick to the RAP lumps (Huang et al., 2005). Moreover, this aged layer does not leave lumps surface even after warming the RAP at high temperature; see Figure 4-9 which displays RAP particles after heating at 100 °C. Consequently, the amount of aged binder existing in the mixing medium would be less than that expected from the design procedure, causing two significant problems, especially with high proportion of RAP.

1) The loss in the contributed binder from RAP increases with high RAP content, resulting in a decrease in the effective bitumen content. Therefore, the covering and binding issue for recycled mixture are not the same as in virgin mixture. The next example indicates the effect of RAP ratio on the amount of loss in bitumen content.

- If the RAP materials participate with 70% of their aged binder, so the loss ratio is 30%.
- By assuming RAP contains 5.0% binder, then
- the loss in bitumen content for 10% and 60% RAP equals:
- (0.3 * 0.1 * 5 = 0.15%) & (0.3 * 0.6 * 5 = 0.9%) respectively.

2) According to the shortage in the contributed RAP binder, the percentage of soft virgin bitumen (in the total bitumen content)

increases. Figure 4-10 shows the movement of point R to the right side, to R*, as the percentage of the new bitumen increases. Therefore, it makes the resultant binder within the recycled mixture softer than desired, resulting in soft recycled mixture.

Figure 4-9 RAP particles after warming for 2 hours at 100 °C

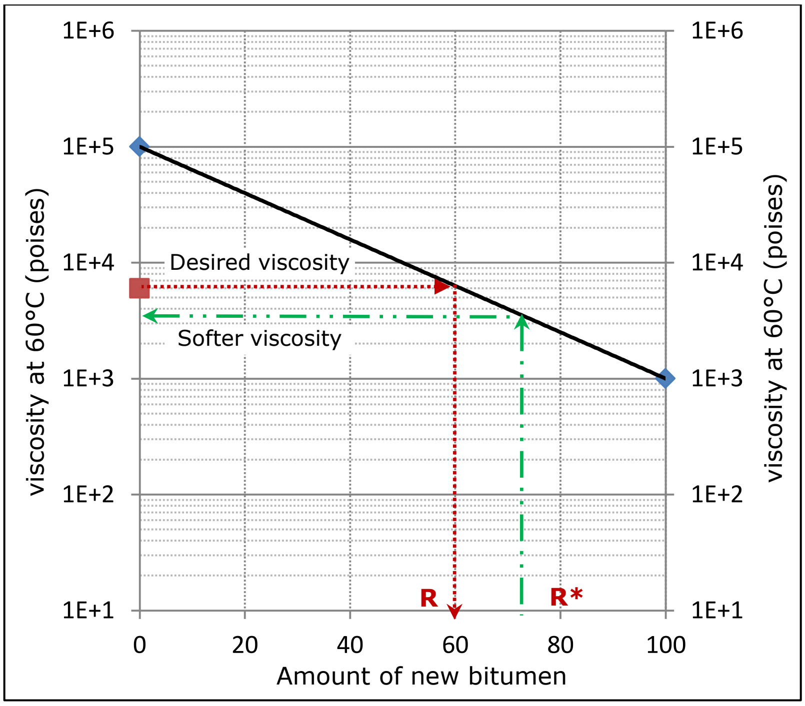


Figure 4-10 Effect of increasing the proportion of new bitumen on the resultant binder of recycled mixture

Accordingly, as concluded from the above two points, the recycled mixture should be compensated by an additional amount of new bitumen that has similar properties to the RAP binder. The following example illustrates this point.

- <u>For mixture R2-rd1:</u> **P_b=5.2%,** **P_{nb}= 3.0%**
- ∴ RAP is expected to contribute with 2.2% of the aged binder 20/30 dmm (RAP binder for this mix had Pen of 23 dmm)
- If RAP participates with 70% of its binder, then the effective binder $P_b = P_{nb} + 0.7 * (P_b - P_{nb})$ =3.0 +0.7 * (5.2 - 3.0) = 4.5%

∴ 0.7% of aged binder 20/30 needs to be added

∴ Final P_{nb} = (**3.0**% of binder 70/100 + **0.7%** of binder 20/30)

P_b: Total bitumen content **P_{nb}**: proportion of new bitumen

Production process - related factors

The greatest problem in producing recycled mixtures with good properties for the resistance of fatigue and rutting is the extent by which the virgin binder interacts with aged RAP binder, hence restoring its properties. Most of this interaction occurs in the production and construction process. Later interaction occurs via long-term diffusion, which needs more time to take place. Preheating RAP, dry mixing time between RAP and superheated virgin aggregate, size of RAP particles, mixing and compaction temperature… etc., are all factors leading to greater interaction between aged and virgin binder.

Preheating RAP and its effect on mixing level between the aged and virgin binders was investigated by (Stephens et al., 2001, Daniel and Lachance, 2005). Stephens et al. (2001) revealed that preheating time had profound impact on strength of mixes, indicating that more blending does occur between the aged and virgin binders. Daniel and Lachance (2005) mentioned that the blending between the virgin and RAP binder does not occur to the desired extent if RAP are not sufficiently heated. They also reported that there is an optimum preheating time for the RAP to allow its particles to soften, break down, and blend with the virgin materials.

(Nguyen, 2009) studied the effect of RAP particle size and dry mixing time (between the superheated aggregate and RAP) on the homogeneity and strength of recycled mixes. The results showed improvement in both stiffness and homogeneity with small size of RAP particles, as well as through extending dry mixing time. Similar findings to Nguyen's results were obtained and presented in this research, Sec 4.6 and chapter 6. Mixing and compaction temperature seems to have a significant effect on motivating the interaction between the aged RAP binder and the soft virgin one. Results on mixing temperature effect are displayed elsewhere in this chapter, Sec 4.7.

All the previous factors help in enhancing the interaction between the aged and virgin binder. However, the question remains "why does complete blending fail to occur?" A number of hypotheses were proposed by researchers (Carpenter and Wolosick, 1980, Huang et al., 2005, Oliver, 2001) to address this issue.

Carpenter and Wolosick (1980) outlined the mechanism by which the rejuvenator penetrates and softens the aged RAP binder. The authors proposed that the rejuvenator do not instantaneously combine with the old binder during the mixing process, but that this takes time. Oliver proposed that the virgin binder forms a "shell" around the aged binder-coated RAP aggregate particles, creating low viscosity regions, which affect the mechanical properties of the recycled mixture. This phenomenon occurs, because it is hard for the virgin binder to penetrate RAP agglomerations of aggregate/binder or filler/binder. A third hypothesis was suggested by Huang, where it is proposed that only a small portion of the aged RAP binder actually participated in the re-mixing process, while other portions formed a stiff coating around RAP aggregates and RAP functionally acted as "composite black rock".

The conclusion of the above discussion indicates that complete blending between the aged and virgin binder does not occur, unless attention has been given to the factors that promote and help the interaction between the aged and virgin binder during the production and construction process.

Interpretation of the second finding

Interpretation of the first finding provided some facts, including: first, RAP materials did not participate with all their binder, which results in an effective increase in new bitumen percentage. Second, incomplete interaction between the aged and new binder led to regions of low and high viscosity, which affected the homogeneity of the recycled mix. These two facts influenced the mechanical properties of recycled mixes which made them more sensitive to the properties of the new bitumen 70/100, which finally led to produce recycled mixtures with stiffness values similar to those of the virgin mix made of bitumen 70/100.

Interpretation of third and fourth findings

The R3-mix achieved the highest stiffness modulus amongst the recycled mixes, although the differences were small, as they were less than 4%. The underlying cause is likely the amount of RAP used, which was 29% for this mix and 45% and 62% for the R2-mix and R1-mix respectively. Also, percentages of dust (Table 20) were 18%, 6%, 0% for R3, R2, and R1 respectively, demonstrating that the minimum loss in mineral fillers was for the R3-mix. Therefore, its strength was not affected as much as the other two recycled mixes.

4.2.2 Fatigue results

Fatigue lines of the V-mixes and R-mixes after the 1st round of recycling are shown in Figure 4-11. Comparing the fatigue behaviour of the V-mixes, it appears that V-mix 40/60 possessed longer fatigue life than V-mix 70/100. This finding conforms with other researchers' findings (Copper and Pell, 1974, Oke, 2011) in that the mixes with stiffest bitumen have more resistance to fatigue. Also, one should point here to the considerable difference in stiffness (not due to ageing of binder) between these two mixes.

The main observation from the graph is that all the recycled mixes had shorter fatigue lives compared to the control mix. Moreover, fatigue lines of virgin mixes stand as two extremes surrounding the fatigue lines of R-mixes. The most likely reason for this was the incomplete blending between aged and virgin binders, which led to formation of some regions of low and high viscosity, where the virgin and aged binders dominate respectively (Oliver, 2001). This separation in the structural configuration resulted in lowering the fatigue resistance compared to the control mix (V-mix 40/60), where it was more consistent in its structural configuration. Also, the significant difference in stiffness between these R-mixes and the control mix had a primary role in controlling fatigue behaviour, see Figure 4-7.

Figure 4-11 also shows that all the recycled mixes behaved approximately in a similar way, regardless of their RAP content. It might be expected that the fatigue life would be much shorter for mixes with high RAP content because RAP contain hard binder which in turn lowers the flexibility of recycled mix, hence decrease its fatigue resistance. However, it seems that more bleeding occurred during the process of warming RAP (Chen et al., 2007, Daniel and Lachance, 2005, Soleymani et al., 2000). This bleeding caused the availability of more aged binder, which motivated more interaction with the virgin binder. Consequently, the homogeneity of recycled mixes was improved, which led to an increase in fatigue resistance (Nguyen, 2009). It should be stated that the warming RAP temperature was 85°C for the R1-rd1 compared to 40°C and 20°C for the R2-rd1 and R3-rd1 respectively.

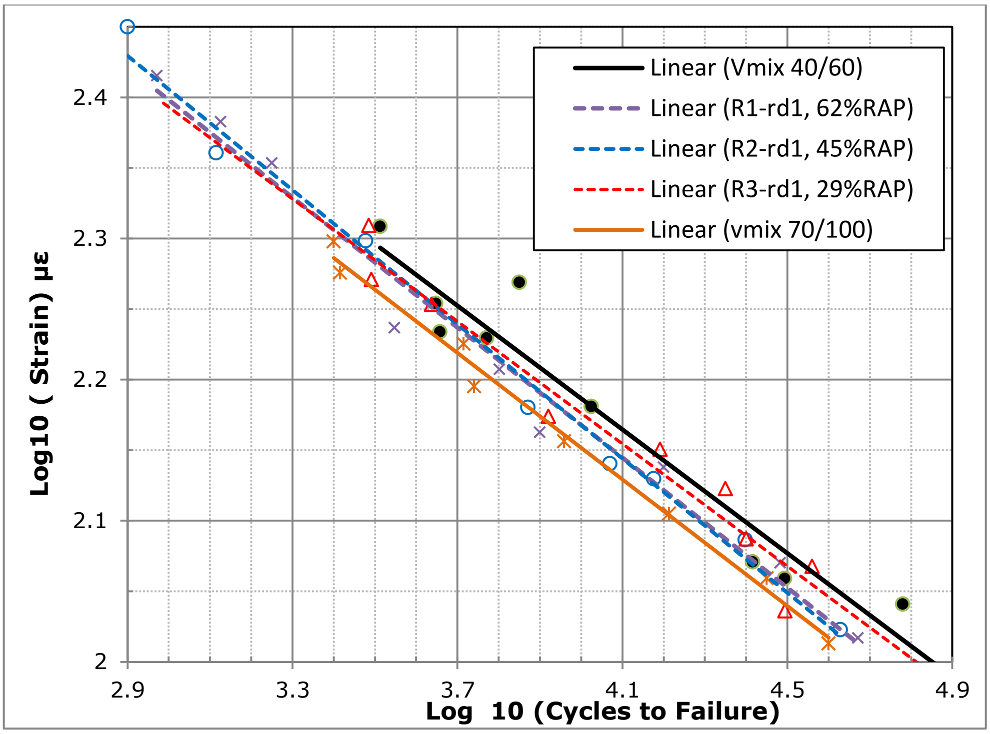


Figure 4-11 Fatigue lines of R-mixes of first round of recycling

4.3 Results analysis of second recycling round

4.3.1 Stiffness results

It was anticipated that as voids of samples increase, there would be a reduction in stiffness modulus. Figure 4-12 depicts stiffness moduli of the virgin and recycled mixtures after the second round of recycling. It is obvious from Figure 4-13 that the recycled mixes of second round attained more average air voids than others in the first round, typically 5.5% compared to 4.0%. It appears from Figure 4-14, which shows number of gyrations for producing samples of each mix, that the recycled mixes of 1st cycle achieved their target thickness after less number of gyrations than those of the 2nd cycle. It means that their workability was better. The reason behind this might be because part of RAP particles used in producing the recycled mixes of the 2nd cycle were aged twice, hence their RAP binder became harder. This issue may make the settlement of RAP and virgin binder in the mould not like the case of the virgin mix or the recycled mixes of the 1st cycle.

All stiffness moduli were calculated at the designed air voids of 5.0%, and are presented in Figure 4-15.

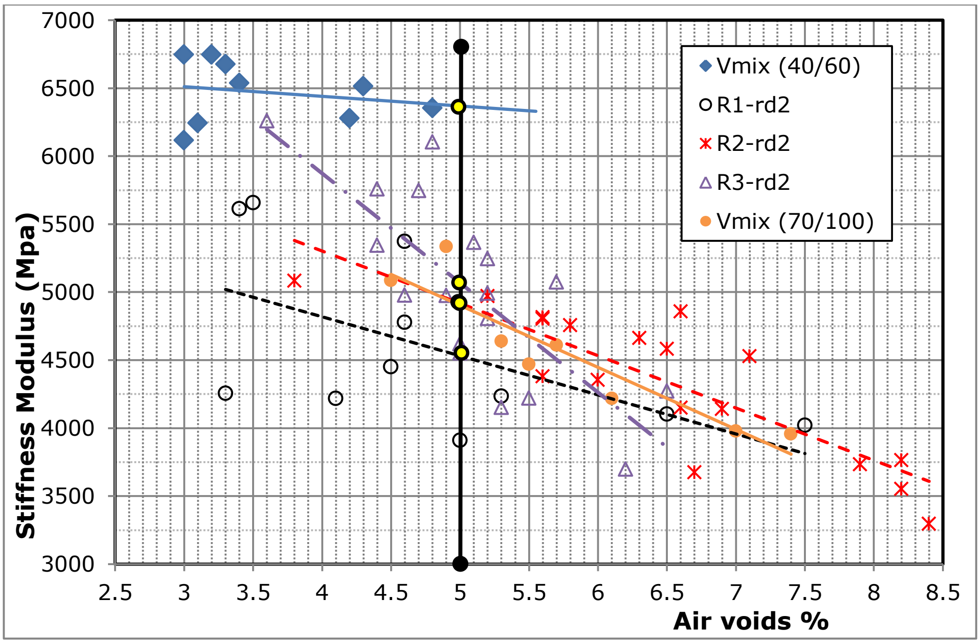


Figure 4-12 Stiffness moduli against air voids after 2nd recycling round

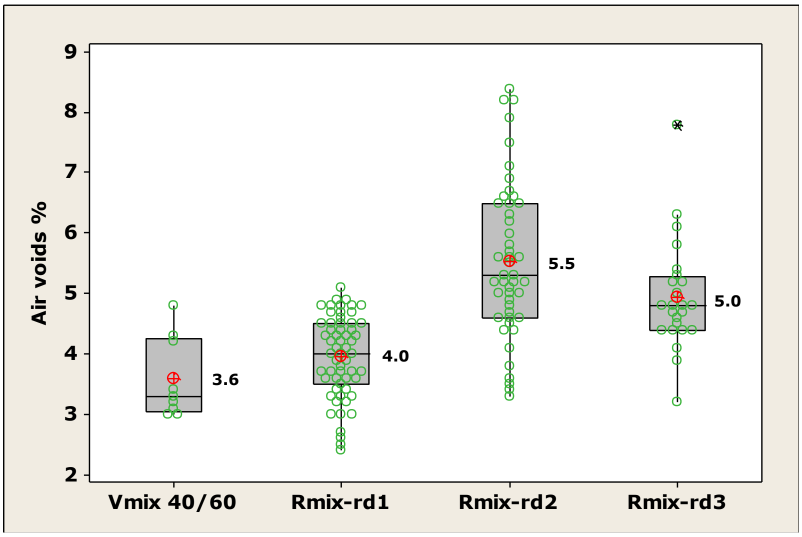


Figure 4-13 Averages of voids contents of all mixes

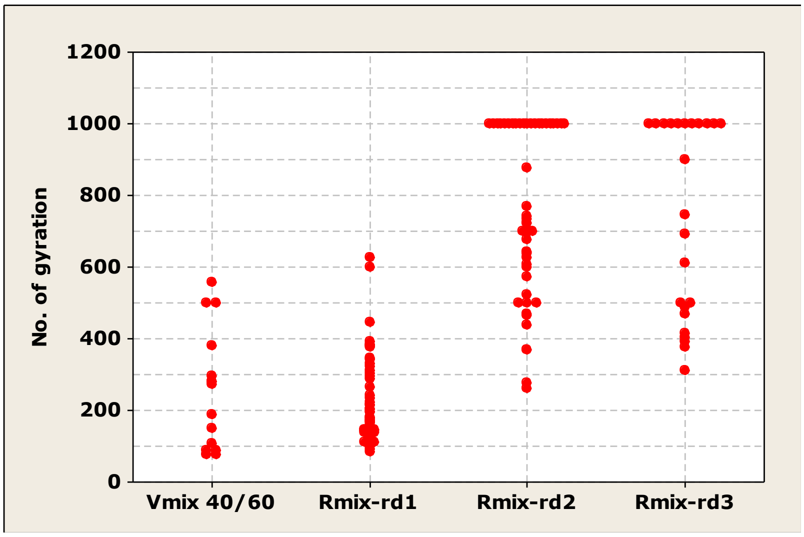


Figure 4-14 Number of gyrations of all mixes

It is clear from Figure 4-15 that there are no significant differences in stiffness values between the recycled mixes of the first and second rounds, except for R1-rd1 and R1-rd2, where the difference was 9%. Even though this difference is not significant, yet it can be interpreted in light of design the R1-rd2 mix. Table 20 indicates that the initial RAP content for the R1-rd2 mix was 78%, but thereafter it was modified to 65% to fulfil the requirements of aggregate gradation. As a result, the virgin bitumen content was increased by 13%. As (Kandhal et al., 1995) pointed out, the properties of recycled mixtures are influenced by the amount of RAP. Thus, this reduction in RAP content (or increment of new bitumen content) probably led to an increase in the flexibility of the mix, and at the same time, the stiffness decreased. Substantially, it can be said that the second round of recycling had significant influence on changing the stiffness of recycled mixes.

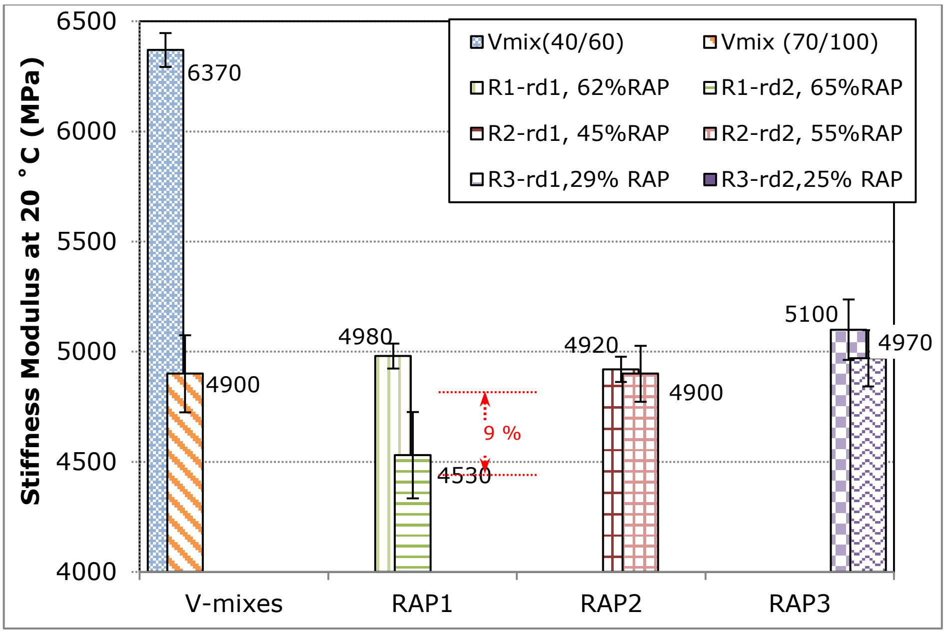


Figure 4-15 Stiffness moduli values after second round of recycling

4.3.2 Fatigue results

Figure 4-16 depicts the fatigue behaviour of the recycled mixes after the second round of recycling. The clear and interesting observation in this graph is that the R1-rd2 mix achieved the longest fatigue life, even better than the control mix. Again as introduced earlier in the explanation of the stiffness results, this mixture had an excess amount of the softer bitumen 70/100. This increment is thought to be responsible for this improvement in fatigue resistance by providing more flexibility for this mix at the expenses of its stiffness, see Figure 4-15. It is worth mentioning that this improvement did not result from the complete blending case, but from the extra flexibility provided by the soft bitumen. The other two recycled mixes (R2-rd2 and R3-rd2) exhibited a similar trend to those of the first round.

In general and apart from the R1-rd2 mix, it can be revealed that the second round of recycling has no great effect on fatigue resistance or stiffness.

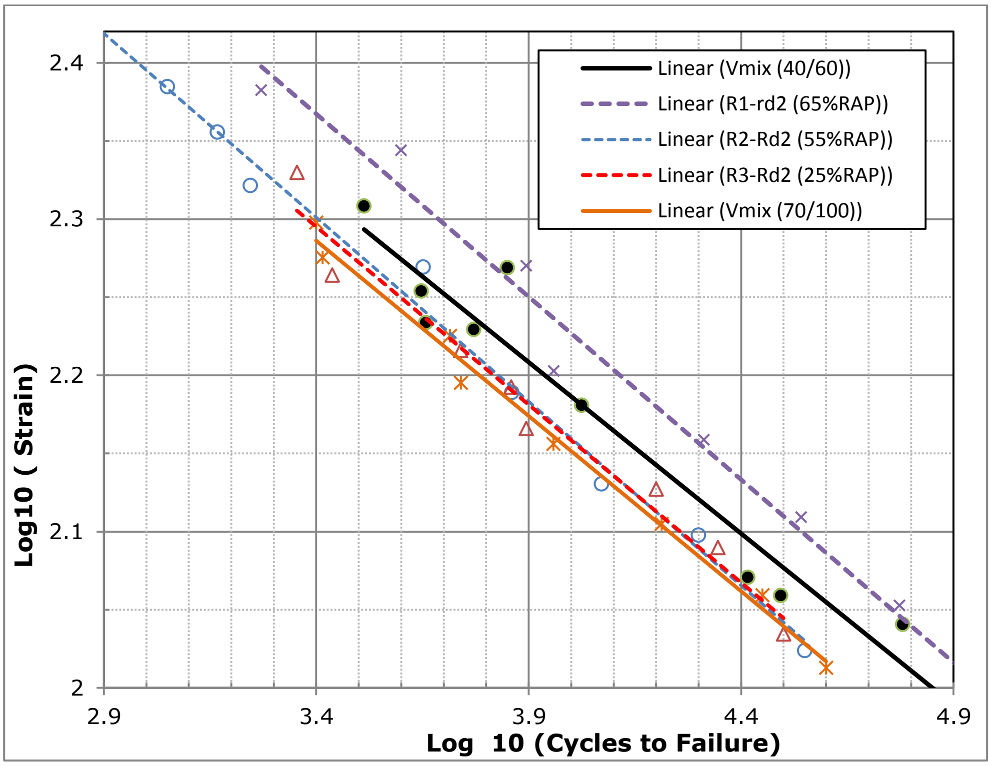


Figure 4-16 Fatigue lines of R-mixes after second round of recycling

4.4 Results analysis of last round of recycling

4.4.1 Stiffness and fatigue results

The laboratory results of stiffness and fatigue for the recycled mixtures after the last round of recycling are presented in Figure 4-17 and Figure 4-18 respectively. The results demonstrated that no substantial differences in fatigue and stiffness behaviour of the recycled mixtures of this round, and those of previous rounds. The variation in stiffness values between all recycled mixes – regardless of RAP content – was about 10%, see Figure 4-17, which suggests that the percentage of RAP might not have a significant effect on the stiffness of recycled mixes. This finding is in agreement with finding of Perez at al. (Perez et al., 2004). Moreover, it is obvious from the graph that all the recycled mixes had stiffness values lower than that of the control mix with differences ranging between (20 - 30%. Also, the stiffness values of the recycled mixes fluctuated around the stiffness of V-mix 70/100 by +4.0% and -8.0%.

Overall, after three rounds of recycling, there is no clear trend in increasing or degradation of stiffness. Indeed, it could increase as R-mixes of RAP2, or decrease as R-mixes of RAP3, or fluctuate as R-mixes of RAP1, see Figure 4-17.

Figure 4-18 exhibits the fatigue behaviour of the recycled mixes after the third round of recycling. Also Figure 4-19 shows the fatigue behaviour of the three types of recycled mixes after each cycle. It is clear that the performance of recycled mixes in this cycle was not significantly different from those in previous cycles. Analyzing the results of fatigue in all rounds of recycling indicated that, apart from the R2-rd2 mix, all the different recycled mixes behaved similarly. This finding is in agreement with that derived from the analysis of stiffness, in that repeated recycling has no significant effect on the mechanical properties of the recycled mixtures.

Moreover, these mechanical properties can be highly improved by paying attention to the production techniques, such as increasing the mixing and compaction temperature and decreasing the size of

RAP agglomerations, as discussed earlier. It is imperative to state that the significance of the results obtained may be limited to the materials used and tests applied.

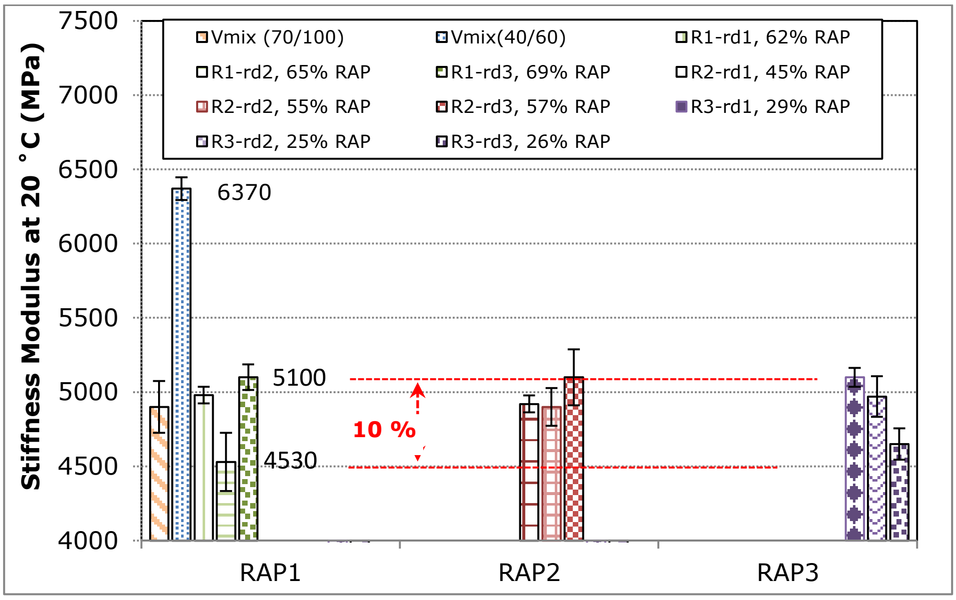


Figure 4-17 Stiffness moduli values after third round of recycling

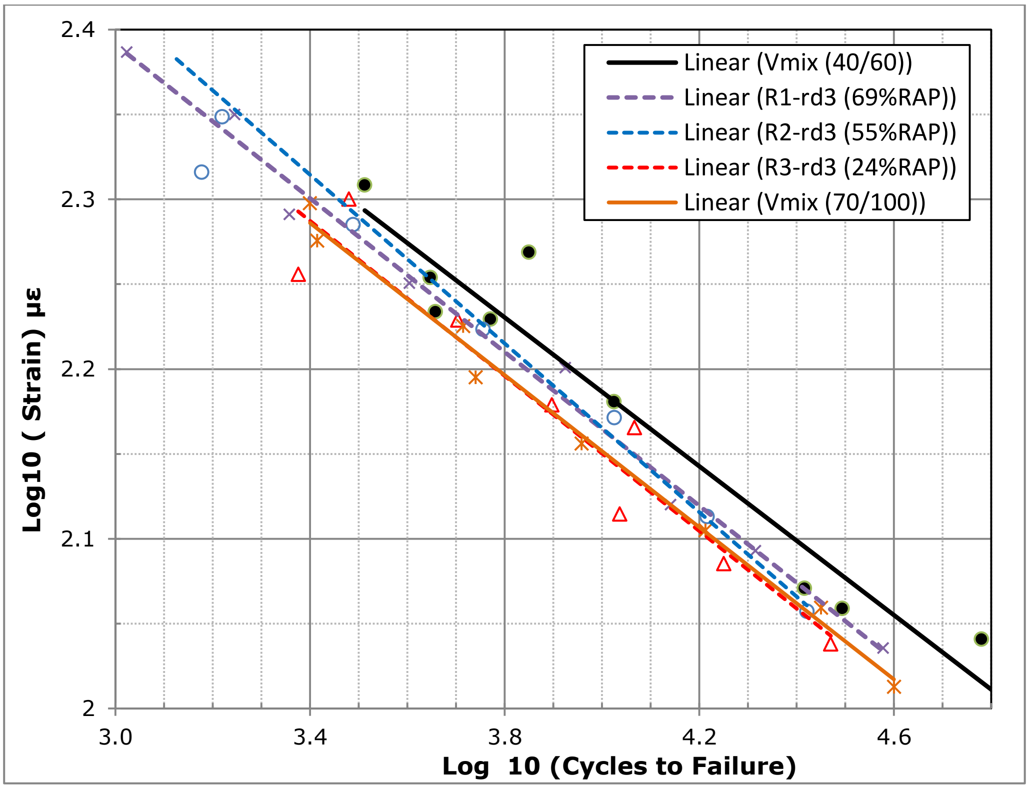


Figure 4-18 Fatigue lines of R-mixes after third round of recycling

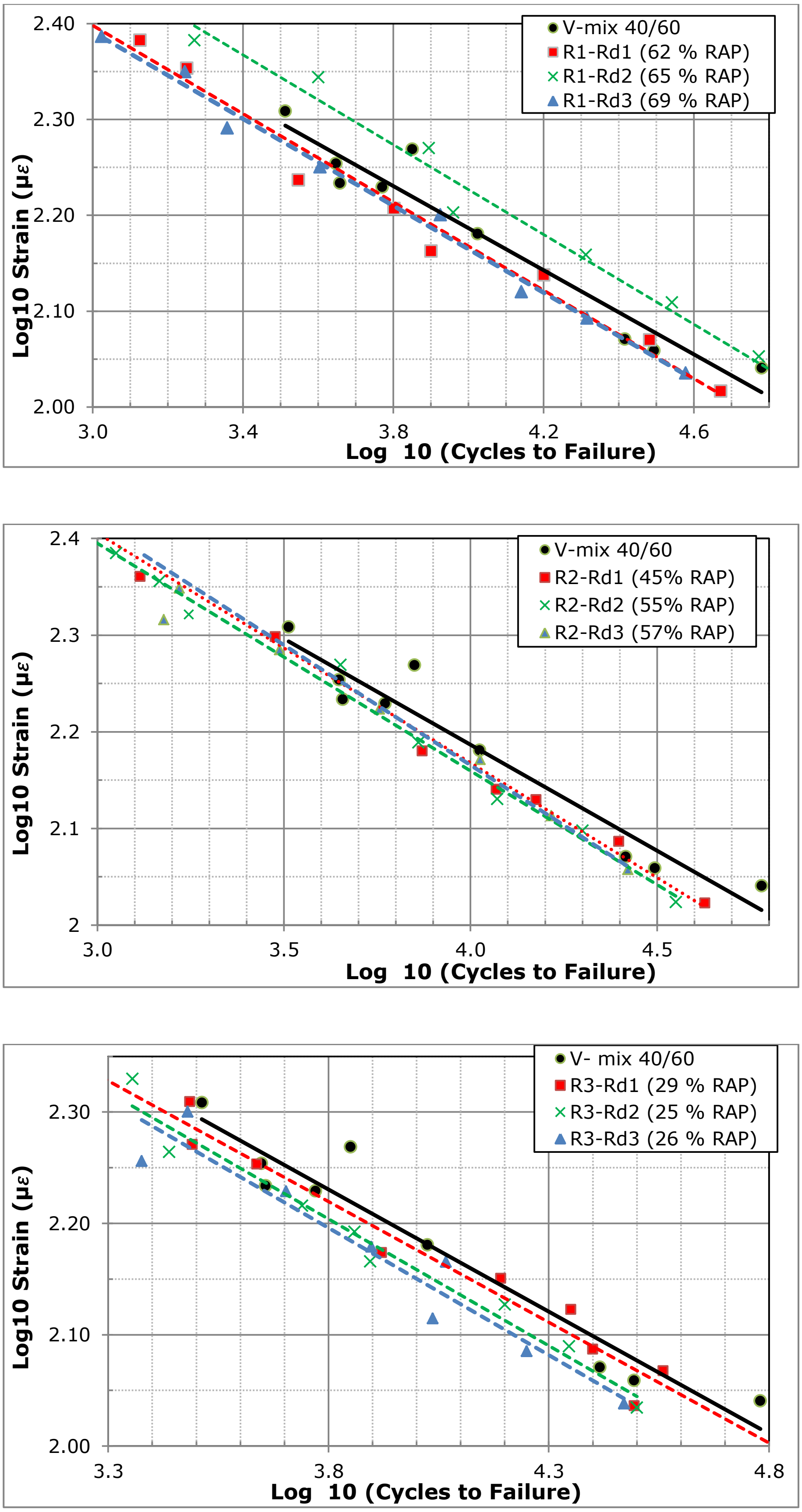


Figure 4-19 fatigue behaviour of each R-mix after each cycle of recycling

4.5 Comparison between the total blending and standard practice mixtures

In order to gain in-depth understanding of the effect of recycling on the mechanical behaviour of the recycled mixtures, an experiment was designed to compare between the recycled mixtures produced, according to two different blending states, namely total blending and standard practice. Total blending involves blending the new bitumen with the recovered RAP binder, then adding this admixture to the virgin aggregate to produce the recycled mixture. In standard practice, the new bitumen is added to virgin aggregate and RAP materials, then blending them all together at the same time.

In the total blending case, the aged bitumen needs to be recovered from RAP before blending with new bitumen. However, in laboratory work, only a small amount of aged bitumen can be recovered from a large amount of RAP. Also, the recovery process is time-consuming and expensive. Hence, the aged bitumen used in the total blending case was produced using RTFOT (Rolling Thin-Film Oven Test) so that it had the same properties as binder recovered from RAP. One recycled mix was produced according to total blending to resemble the recycled mix R2-rd1 (made from RAP2 in the 1st round). This recycled mix was named as R2-total, and had the same gradation, and bitumen content as R2-rd1. The two mixes were subjected to the ITSM and ITFT tests to compare their mechanical properties.

4.5.1 Ageing of standard practice and total blending

The ageing in the standard practice case was done by exposing the cores to heat in a force draft oven for 65hrs @ 125 °C. Penetration of the recovered bitumen, after ageing, was 23 dmm. Thus, the objective of ageing in the total blending case is to use the RTFOT to produce an aged bitumen with the same penetration of 23dmm (BS EN 12607-1, 2007). In order to determine the required ageing time in the RTFOT, aimed at reducing the penetration of the virgin binder 40/60 from 48 to 23 dmm, three groups of virgin bitumen (40/60 Pen) were aged by the RTFOT for 30, 75 and 120 minutes respectively. The penetration test was then applied to these aged bitumen samples. The ageing time can be estimated from the results shown in Figure 4-20; and was found to be 160 min. In order to validate the estimated ageing time, a sample of bitumen 40/60 pen was aged by the RTFOT for 160 min, and its penetration measured. This was found to be 23 dmm, which confirms the acceptability of this ageing time.

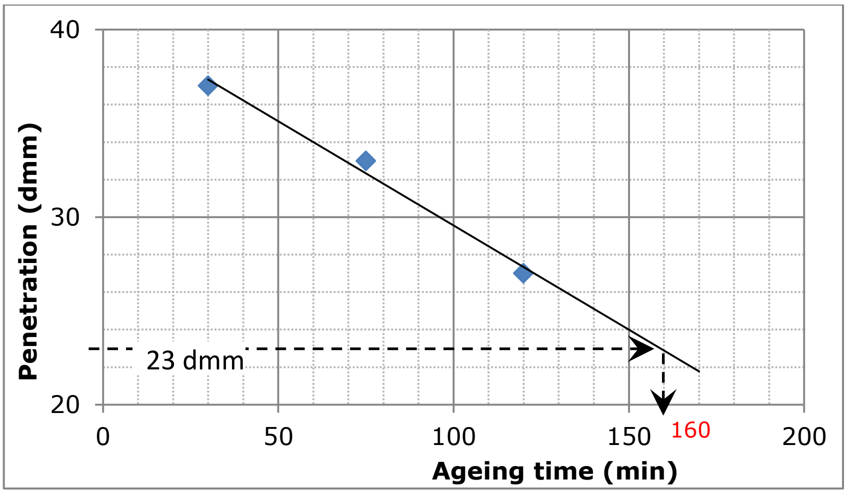


Figure 4-20 RTFOT ageing time vs penetration

4.5.2 Design and producing the R2-total

The ZSV of the binder aged by the RTFOT was determined from DSR data, and equals 72200 poises. By using the blending chart and bitumen 70/100 with viscosity 1630 poises as new bitumen, and by knowing the target viscosity of 7600 poises, the percentage of new bitumen was determined as 55%, as indicated in Figure 4-21.

4.5.3 DSR results

The DSR test was applied on the recovered binder from RAP2, as well as bitumen aged via the RTFOT. The complex modulus and phase angle master curves were established as shown in Figure 4-22 and Figure 4-23. The reference temperature was 25 °C. The graphs clearly show the great similarity in complex modulus and phase angle over a wide range of frequencies, although there are slight differences at low frequencies. This means that for bitumens from the same origin, the aged bitumen produced by the RTFOT can be considered the same as the aged bitumen recovered from RAP, if they have the same penetration.

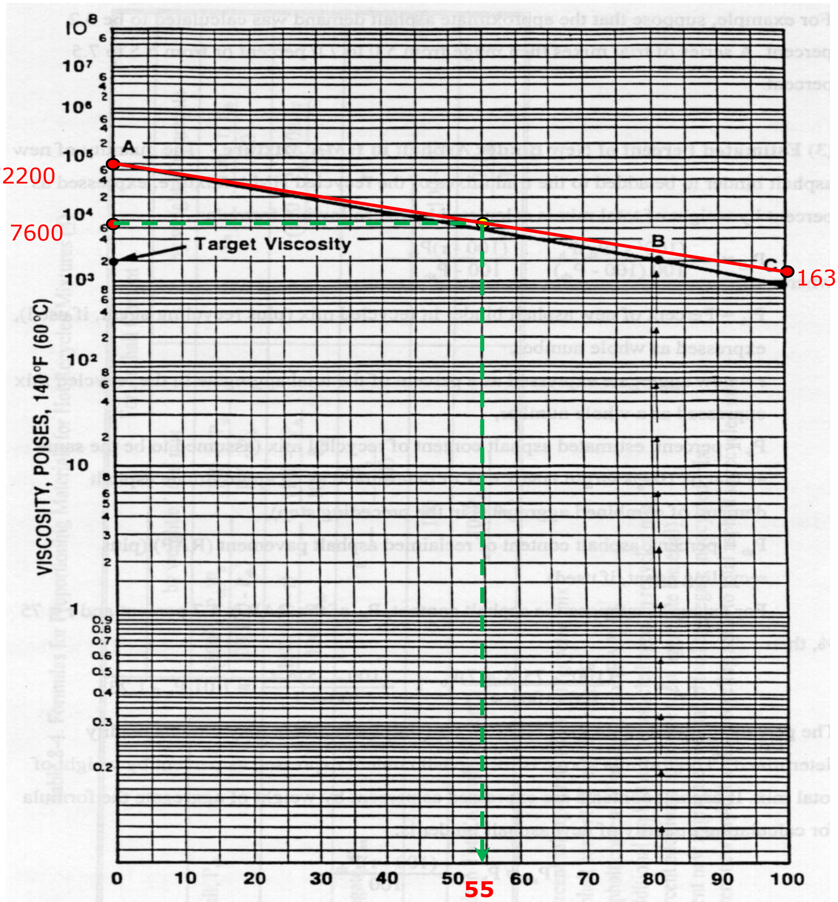


Figure 4-21 New bitumen content of Total Blending case

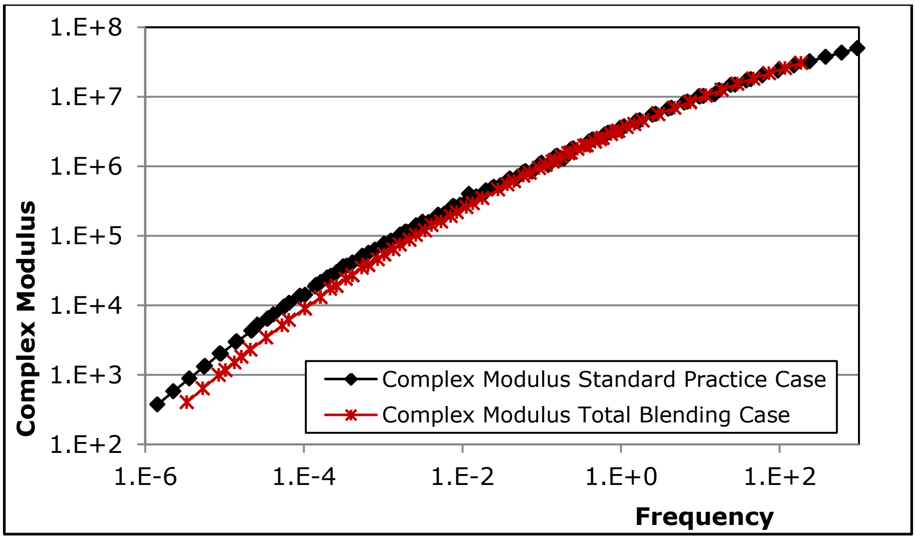


Figure 4-22 Complex Modulus master curves of aged bitumens (reference temperature =20 ˚C)

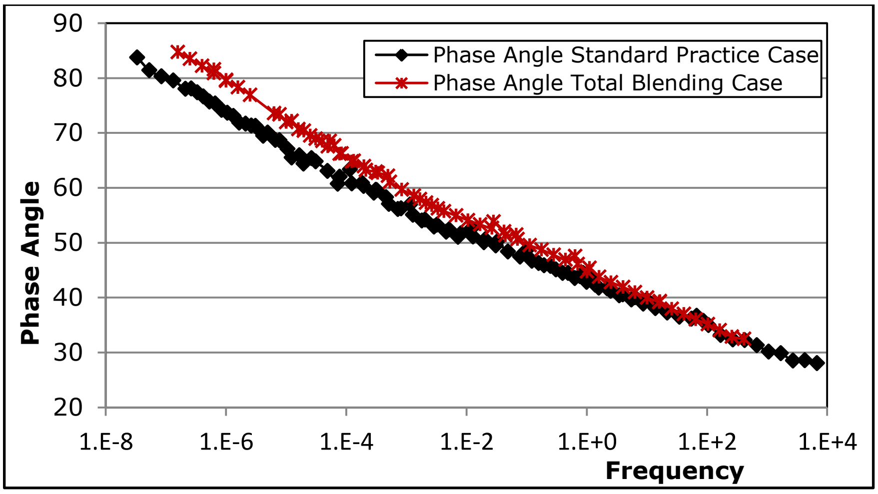


Figure 4-23 Phase Angle master curves of aged bitumens (reference temperature =20 °C)

4.5.4 Results of the ITSM and ITFT Tests

Figure 4-24 displays the stiffness modulus of two virgin mixes (V-mix 40/60 and V-mix 70/100) and two recycled mixes (R2-total and R2-rd1). Obviously, the stiffness modulus of R2-total is quite close to that of V-mix 40/60, as the difference is only 6.6%. However, the difference of 19.5% is considerable between R2-total and R2-rd1. Fatigue lines of the virgin and recycled mixes are plotted in Figure 4-25. The figure clearly shows that R2-total is similar to the control mix (V-mix 40/60) and better than the R2-rd1 mix, in terms of fatigue performance. The findings of this experiment indicate no substantial differences in mechanical properties between the recycled mix of the total blending case and the control mix. Consequently, this emphasizes the significant effect of the blending process on improving the performance of recycled mixtures, in terms of stiffness and fatigue.

Table 24 Indicates physical properties and asphaltenes content of the recovered binder from V-mix 40/60, R2-total, and R2-rd1 mixes. It is clear that properties of the recovered binder of total blending case resemble, to great extent, those of the recovered binder from V-mix 40/60, while recovered binder from standard practice case is much softer. This finding demonstrates that the blending between the new bitumen and RAP binder, in standard practice case, was not complete or perfect as was the case in the other two mixes.

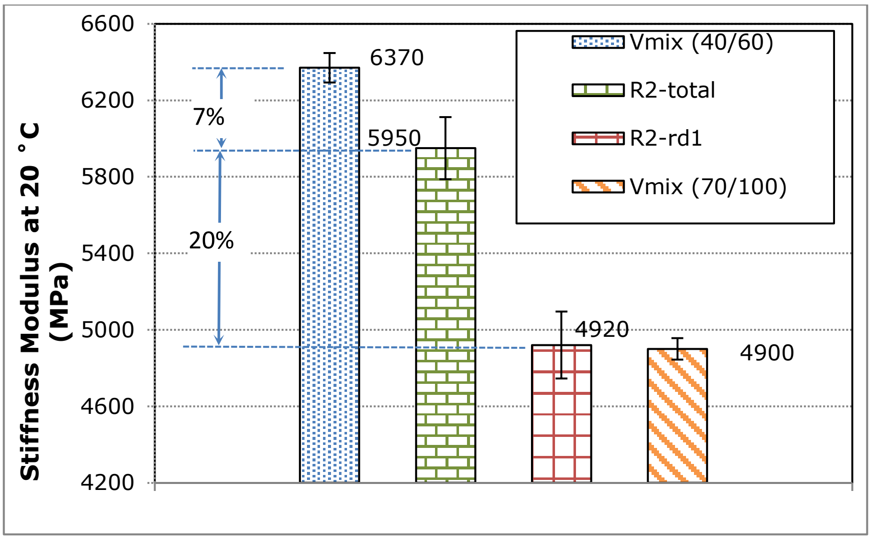


Figure 4-24 Stiffness Modulus Results

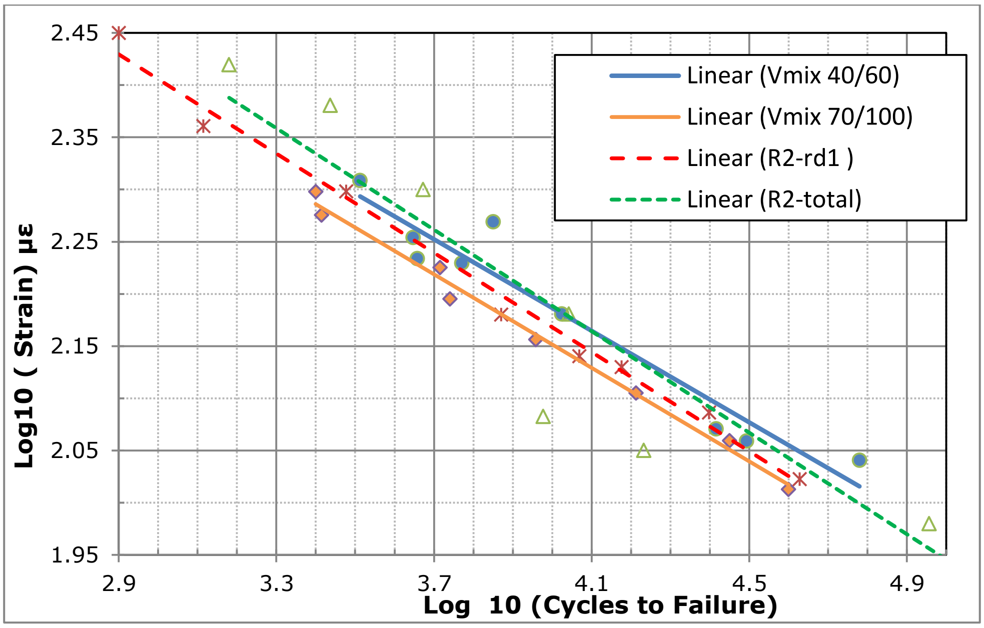


Figure 4-25 Fatigue Lines for all cases

Table 24 properties of recovered binders from V-mix 40/60, R2-rd1, R2-total mixes

	Penetration (dmm)	Softening point (°C)	Asphaltenes content %
Recovered bitumen from virgin mixtures	37	59.4	16.8
Recovered bitumen R2-total mix	37	56.8	17
Recovered bitumen from R2-rd1 mix	56	58.8	15.5

4.6 Effect of RAP size on strength and fatigue properties of recycled mixtures

This sub-investigation aims to look at the effect of RAP size on the behaviour of the recycled mixes in terms of rutting and fatigue resistance. Three recycled mixes were produced with the same design parameters and production procedure of the R-mixes in the second recycling round. The only difference was the size of RAP particles: 13mm maximum nominal size instead of 20 mm. The recycled mixes of 13 mm RAP size were tested via the ITSM and ITFT tests, and then compared with the 20 mm R-mixes. Stiffness modulus results of the 13mm and 20mm R-mixes are displayed in Figure 4-26, while Figure 4-27,Figure 4-28, and Figure 4-29 show the fatigue behaviour.

4.6.1 Stiffness results

Figure 4-26 clearly shows the large increment in stiffness values for the different mixes of 13mm RAP size. These increases were considerable for the recycled mixes with high RAP content (R1-rd2 and R2-rd2) where the stiffness values were increased by circa 13% and 18% respectively. For the R3-rd2, there was also improvement in stiffness, although less significant. The reason behind these improvements can be explained as follows.

When large RAP agglomerations disintegrate into small sizes, the surface area of aggregate particles is increased, which allows more surface for interaction between the aged and new bitumen. The presence of RAP warming (warming temperatures were 95 °C and 70°C for R1-rd2 and R2-rd2) as well as large surface areas, led to liberating more aged binder, in what is known as bleeding (Chen et al., 2007, Soleymani et al., 2000). This in turn produced more blending between the virgin and aged binder. Logically, as the blending comes closer to the total blending case, the properties of the recycled mix improve.

For R3-rd2, RAP was not warmed, hence bleeding was not as substantial as for the other two mixes, and consequently, the improvement was not the same. In general, it can be concluded that the stiffness modulus of the recycled mixes can be significantly improved. The improvement can be achieved by adding simple techniques to the production process, such as processing of the RAP to small size and warming of RAP to sufficient temperature and time; otherwise, there would be more ageing of RAP binder. (Daniel and Lachance, 2005) reported that there is an optimal preheating time for RAP to allow for the greatest degree of blending between the virgin and RAP materials.

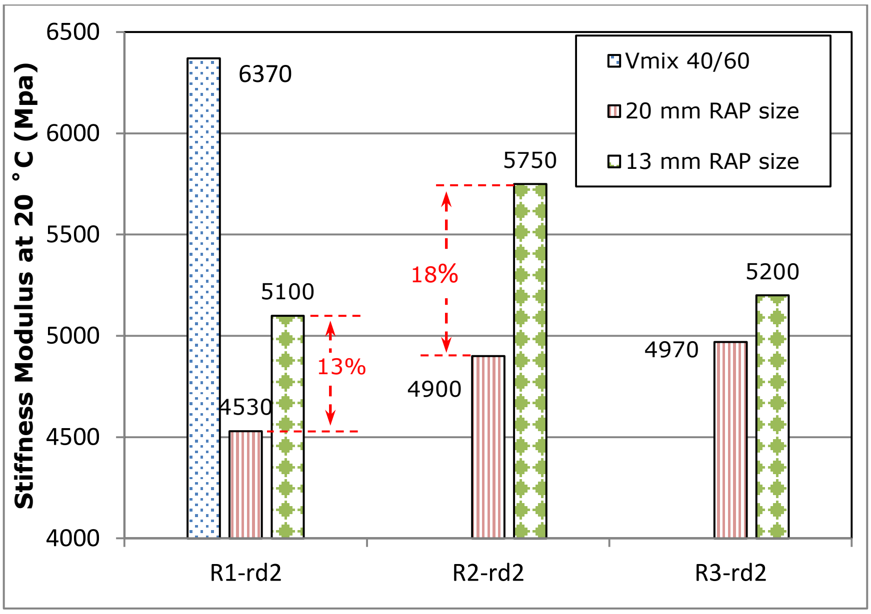


Figure 4-26 Stiffness of the 13mm & 20mm recycled mixture

4.6.2 Fatigue results

Comparisons between the 13mm and 20 mm recycled mixtures are displayed in Figure 4-27, Figure 4-28, and Figure 4-29. For mix R1-rd2 (Figure 4-27), the 13 mm R-mix had shorter fatigue life than the 20 mm R-mix. As mentioned in sec 4.3.2, the 20 mm R-mix had an extra amount of soft bitumen 70/100 pen, which provided more flexibility, thus its fatigue behaviour was improved. Also, as mentioned previously, this improvement in fatigue performance might not result from any significant further blending between the aged and virgin bitumen. However, when the small RAP size was utilized in the 13 mm R-mix, more bleeding occurred in the presence of preheating. Accordingly, more aged binder became available to interact with the soft bitumen in the mixing medium. This further blending lowers mixture flexibility, which resulted in reduced fatigue resistance. The fatigue lines of these two mixes are considered an indication of the additional interaction between the aged and soft bitumen, in the 13 mm R-mix, as a result of using small RAP agglomerations.

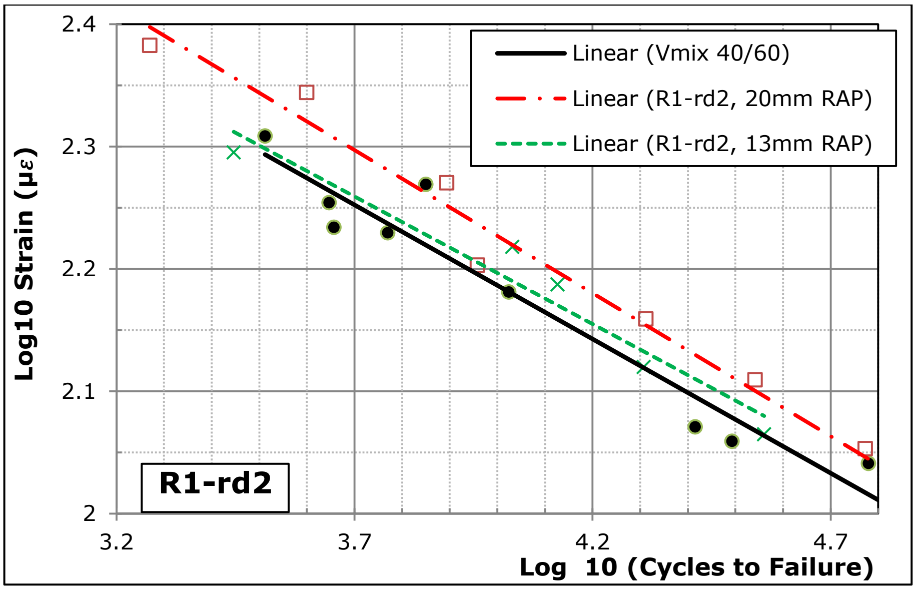


Figure 4-27 Fatigue lines of the 13mm & 20mm R1-rd2

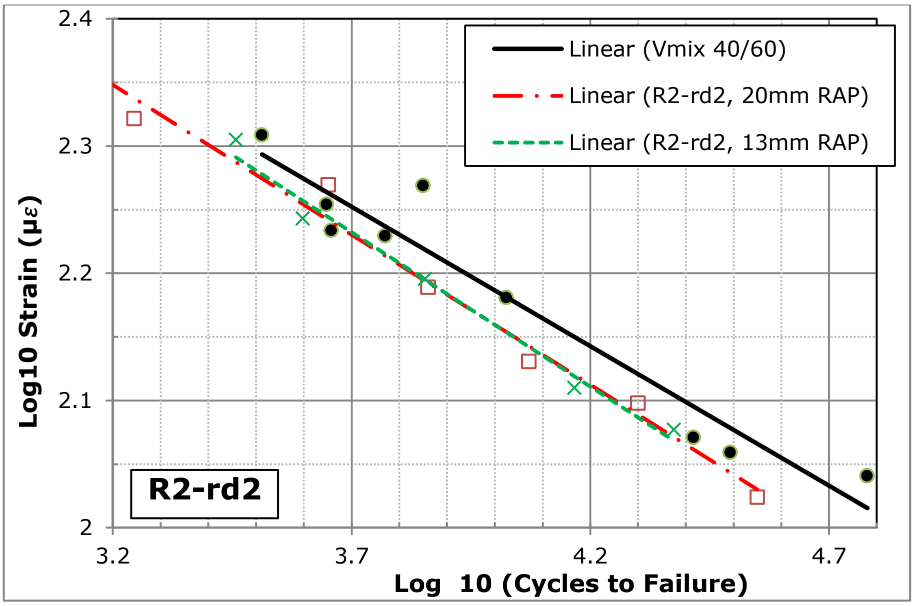


Figure 4-28 Fatigue lines of the 13mm & 20mm R2-rd2

For the other two types of mixtures, R2-rd2 and R3-rd2, it is clear from Figure 4-28 and Figure 4-29 that using small RAP size did not affect the fatigue behaviour, regardless of any improvements in their stiffness. In summary, it can be revealed that using small size RAP agglomerations has a crucial impact in improving stiffness of the recycled mixtures with high RAP content, especially with warming of RAP particles. At the same time, the fatigue behaviour might not be affected by small RAP size.

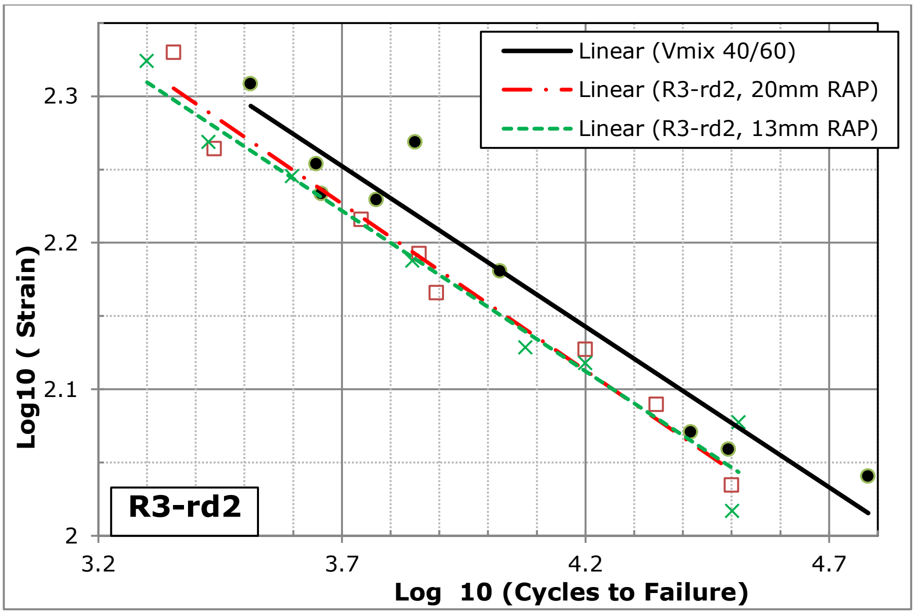


Figure 4-29 Fatigue lines of the 13mm & 20mm R3-rd2

4.7 Effect of mixing and compaction temperature on behaviour of recycled mixtures

4.7.1 Stiffness results

In a trial to look into the factors by which the mechanical properties of the recycled mixtures can be improved, the effect of the mixing and compaction temperatures was considered. This investigation began by producing another recycled mix using the same design parameters as for the R3-rd3 mix made from the third highly aged type of RAP which had penetration of 12 dmm. The only difference was in the mixing and compaction temperatures. For simplicity, the second mix with high mixing and compaction temperature is prefixed as R3-rd3-comp. The mixing and compaction temperatures for the first R-mix were both 135 °C, while they were 160 °C and 155 °C respectively for the R3-rd3-comp. After manufacturing, both mixes were subjected to the ITSM and ITFT tests, then the results were compared with those of the control mixture. The results were in the form of stiffness moduli normalized at 5.0% air voids and fatigue lines, as displayed in Figure 4-30 andFigure 4-32.

Figure 4-30 shows the huge increment in stiffness of R3-rd3-comp by about 24% over R3-rd3. This important finding emphasizes the significant impact of the mixing and compaction temperatures on improving the stiffness of the recycled HMA. Moreover, this improvement is a clue that an additional blending has taken place between the highly aged and soft binders. This great increment in stiffness demonstrates that the highly aged RAP does not act as black rock, especially when it is mixed and compacted at a high, safe temperature. It has been reported that RAP binder should have a minimum penetration value of 15 dmm; i.e. RAP would behave as black rock if its binder has a penetration < 15 dmm (Highways Agency, 1998). However the finding from Figure 4-30 might open the door for using these types of RAP. It is worth mentioning that the R3-rd3-comp mix was produced with no preheating of RAP, only 8 minutes of dry mixing with superheated aggregate.

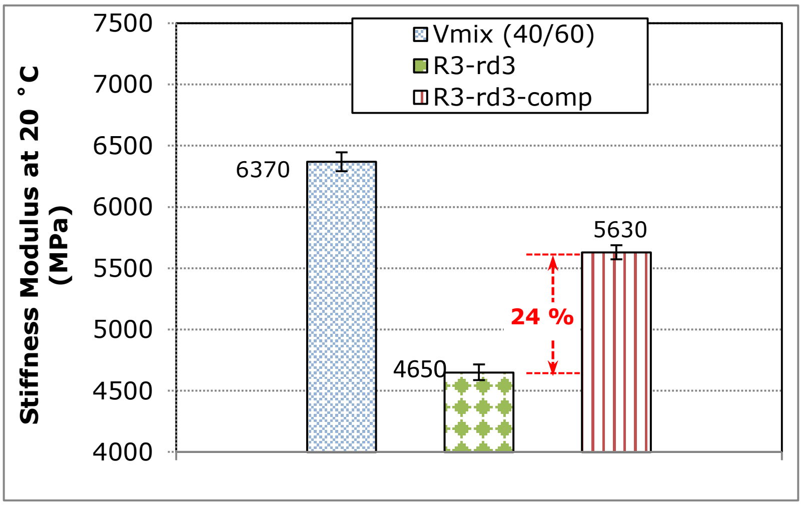


Figure 4-30 Mixing and compaction temperature effect on stiffness

The photographs in Figure 4-31 show no bleeding had occurred after the dry mixing process. Again, it proves that almost all the additional blending happened during mixing and compaction processes with the help of heat. Comparing the number of gyrations and voids content of both mixes (Table 25), it can be concluded that the workability of the R3-rd3-comp mix was better, which improved homogeneity of the recycled mix, providing more positive effect on the stiffness.

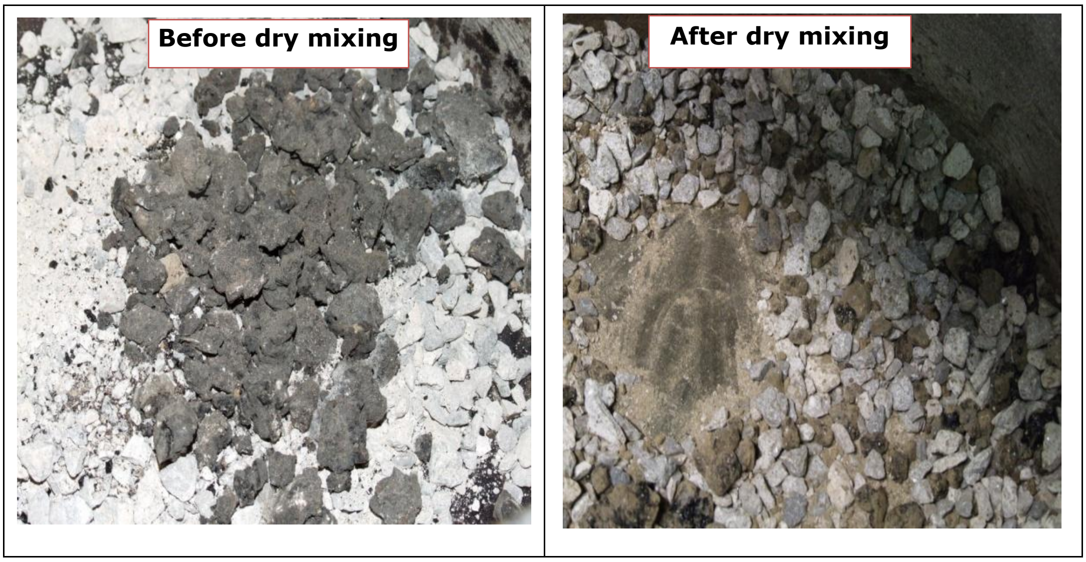


Figure 4-31 Highly aged RAP before and after dry mixing with superheated aggregates

Table 25 Voids and number of gyrations of the R3-rd3 and R3-rd3-comp mixes

	R3-rd3	R3-rd3-comp
No. of gyration	939	602
Average air voids	5.1	3.7

4.7.2 Fatigue results

Figure 4-32 displays the resistance of the two previous mixes as well the control mix to fatigue. It is shown that the R3-rd3-comp mix achieved longer fatigue life than the R3-rd3 mix, even better than the control mix. Increasing the mixing and compaction temperatures by 25°C and 20°C respectively provided more blending between the aged and virgin binders which in turn improved fatigue resistance of for the R3-rd3-comp mix. In general, findings of this investigation emphasize the significant effect of the mixing and compaction temperatures, not only on stiffness property, but also on fatigue characteristics.

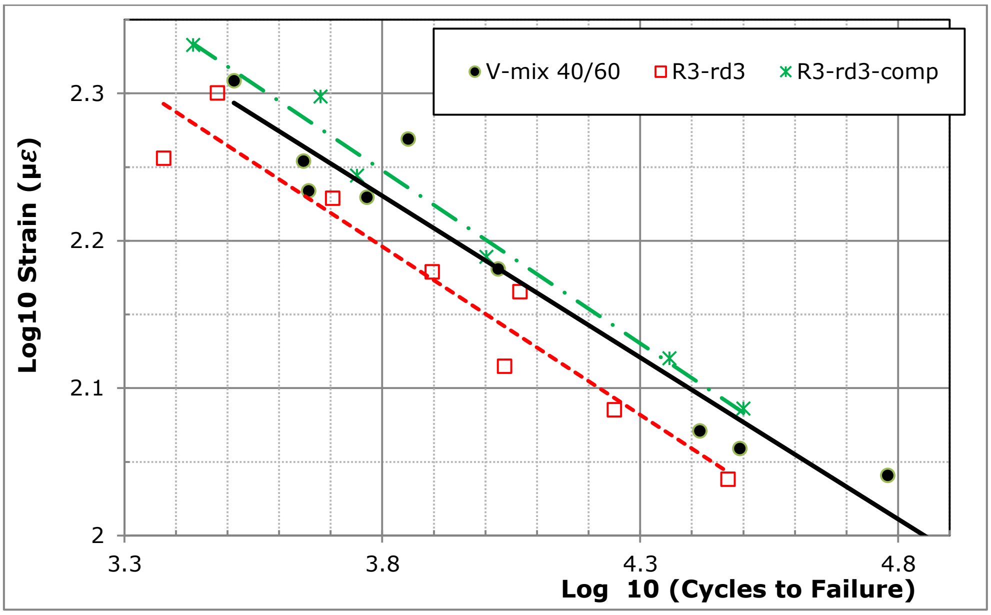


Figure 4-32 Mixing and compaction temperature effect on fatigue behaviour

4.8 Effect of ageing on stiffness and fatigue characteristics of virgin and recycled mixes

To study the effect of ageing on the mechanical properties of recycled and virgin HMA, specimens of each mix were tested before and after ageing to identify stiffness and fatigue properties via the ITSM and ITFT tests. These tests were conducted on V-mixes and R-mixes after the 1st and 2nd cycles. Because the effect of ageing on the R-mixes for both cycles was almost similar, results of 2nd cycle are presented here, and Appendix 9 contains results of 1st cycle.

As was expected there was an increase in stiffness of V-mixes with ageing. These increments were 33, 27, and 50% when they were aged for 40hrs@105 °C, 65hrs@125 °C, and 2weeks@125 °C respectively. However, when the corresponding R-mixes were aged for the same ageing protocol, the increases in stiffness were higher; 50, 42, and 130% for R1-rd2, R2-rd2, and R3-rd2 respectively, see Figure 4-33. This finding demonstrates that the responses of the effective binders of V-mixes and R-mixes for ageing were not similar and did not have the same properties.

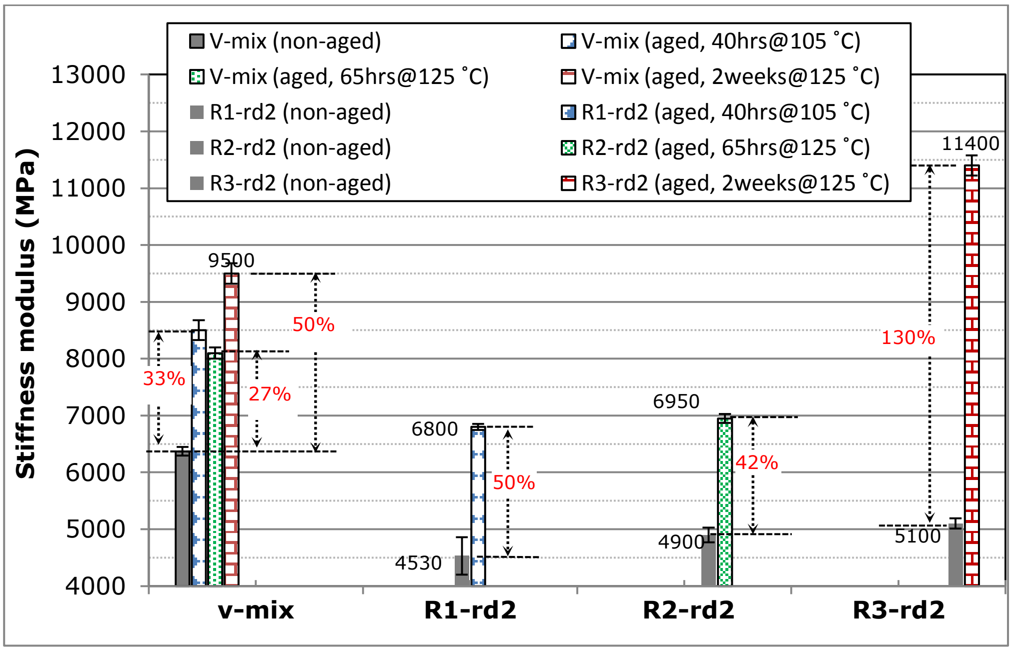


Figure 4-33 Effect of ageing on stiffness of V-mixes and R-mixes of 2nd cycle of recycling

It has been reported that the soft binders are more sensitive to ageing than hard binders (Malan, 1989). Accordingly, the effective binders of R-mixes were softer than those of V-mixes. This occurred because RAP binder was not fully rejuvenated as a consequence of non-complete blending within R-mixes. However, these high increases in stiffness of the aged R-mixes -especially at sever conditions of ageing- indicate that they would be more durable than V-mixes. But what about the R-mixes behaviour in resisting fatigue?

Figure 4-34, Figure 4-35, and Figure 4-36 show the fatigue lines of virgin and recycled mixes before and after ageing. It is clear that aged samples had shorter fatigue lives than non-aged ones, as was expected. Also, as shown from Figure 4-34 and Figure 4-35 that the differences between the fatigues lines before and after ageing, for both virgin and recycled mixes, are nearly similar. This indicates that the first two ageing levels (40hrs@105 °C and 65hrs@125 °C) had no great impact on fatigue life of the virgin or recycled HMA. In other words the two mixtures would behave similarly under mild ageing levels. On the contrary, for the third level of ageing (2weeks@125 °C), as shown in Figure 4-36, the differences between fatigue lines of both mixes is significant, which means that at severe ageing conditions, the degradation in fatigue life of the recycled mixes would be faster than that of the virgin mixes.

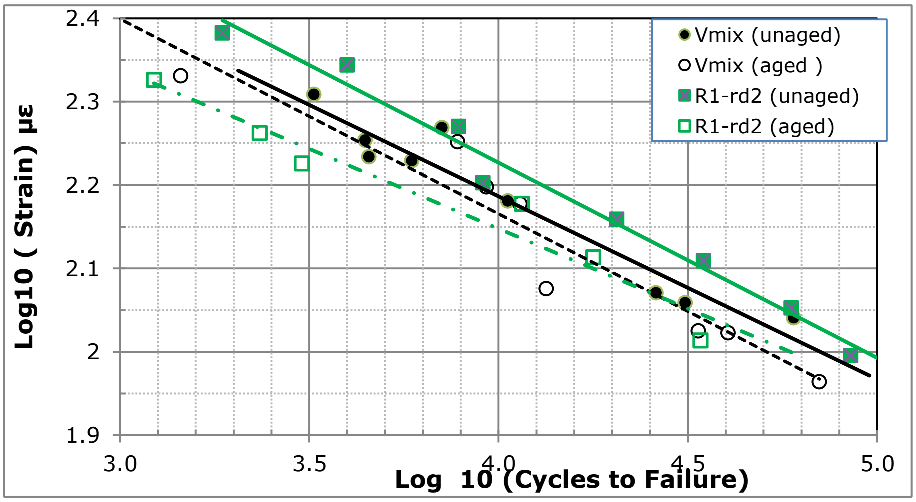


Figure 4-34 Effect of ageing of 40hrs@105 °C on fatigue behaviour of V-mix and R1-rd2

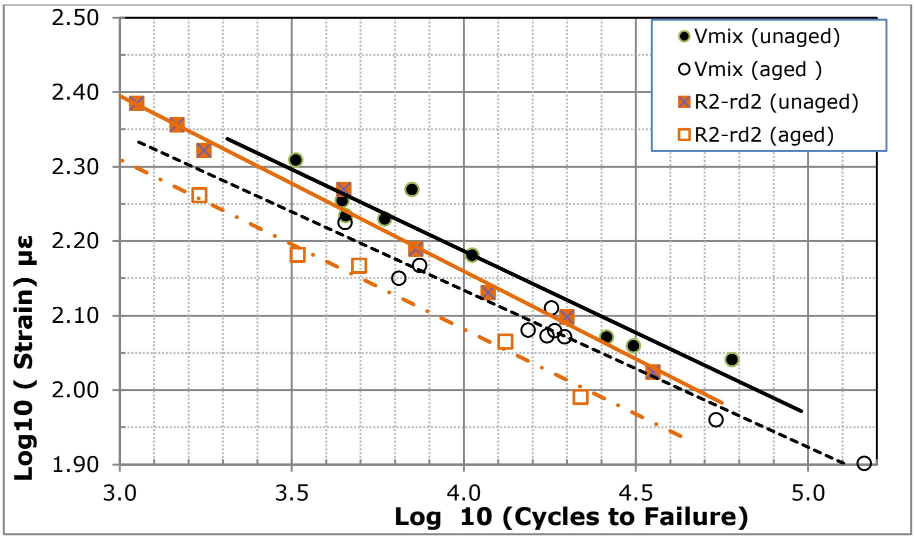


Figure 4-35 Effect of ageing of 65hrs@125 °C on fatigue behaviour of V-mix and R2-rd2

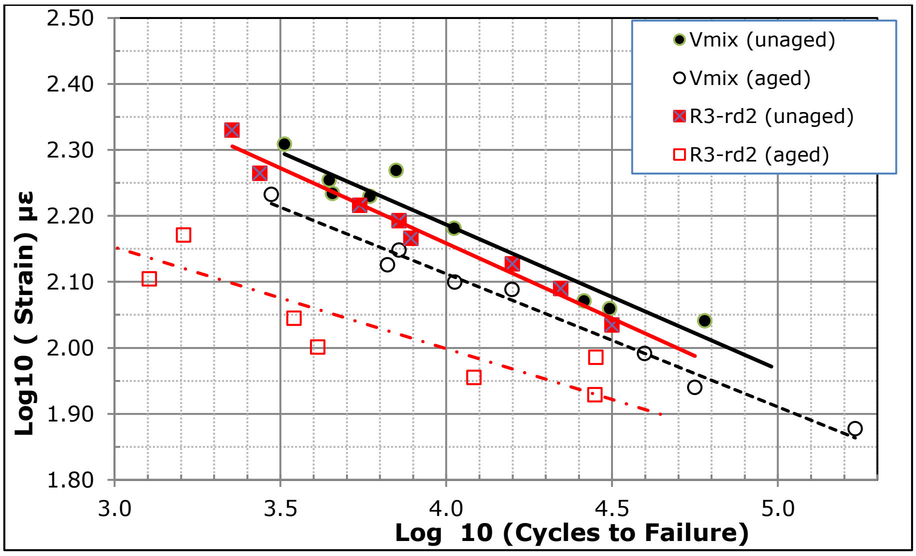


Figure 4-36 Effect of ageing of 2weeks@125 °C on fatigue behaviour of V-mix and R3-rd2

4.9 Summary

The aim of the research is to evaluate the effect of the repeated recycling on the mechanical properties of the hot asphalt mixtures. In view of that, the repeated recycling has been conducted over three rounds and the recycled samples were tested after each round for their stiffness and resistance to fatigue. The results showed that:

- After the first cycle of recycling, there was some degradation in performance of recycled asphalt (in terms of stiffness and fatigue resistance). However, repeated recycling has no further effect on deterioration of recycled asphalt after the second or even the third round.

- Regardless the percentage of RAP, the variation in stiffness as well resistance to fatigue was insignificant between all recycled mixes, indicating that no significant differences between the mixes of common (≥25%) and high (≥50%) RAP content.

The incomplete blending between the aged and virgin binders within the recycled mixtures seems to be the main factor for this degradation of their properties. In order to investigate this issue, another recycled mix was produced according to “total blending” technique, and then was tested and its mechanical properties were compared to the virgin mix. It was revealed that:

- The behaviour of both mixes, in stiffness and fatigue, were similar. Consequently, this finding highlights the substantial influence of the blending process on improving the performance of recycled mixtures.

In an attempt to explore the factors by which the blending between RAP binder and virgin bitumen can be enhanced, size of RAP particles and mixing and compaction temperatures were considered. The results confirmed that:

- The mixing temperature had the greatest impact on enhancing the blending process between the binders, which resulted in producing recycled mixes similar to the conventional mix.
- The size of RAP had also significant effect on improving the stiffness property.

5 Using Hirsch model to predict the dynamic complex modulus |E*| of HMA

5.1 Review

The dynamic complex modulus, universally denoted as |E*|, is one of the major properties of the visco-elastic materials, such as HMA, which influences the structural response of flexible pavements. It can be defined as the ratio of the amplitude of sinusoidal stress (at any given time or frequency) and sinusoidal strain (at the same time or frequency). The |E*| defines the ability of the viscoelastic material to resist the compressive and tensile strains as it is subjected to cyclic loading. Several tests can be employed to evaluate the dynamic complex modulus for asphalt mixes. However, as the complex modulus test is relatively complex, time-consuming and requires expensive apparatus, numerous attempts have been made to evolve predictive models to calculate the dynamic modulus from the conventional properties of the binder and mixture (Li et al., 2012, Li, 2011, Garcia and Thompson, 2007).

There are many models, currently employed, with sufficient accuracy to predict the dynamic modulus |E*| of HMA, such as the Hirsch Model, Shook and Kallas Regression (SKR) Model, Witczak Model, Picado-Santos and Capitao (PSC) Model. The most common easy and accurate model used to estimate |E*| of HMA is the modified Hirsch model (Christensen Jr et al., 2003). Originally, the Hirsch model was generated to estimate the modulus of elasticity of Portland cement concrete based on empirical constants, aggregate and cement mastic moduli and their volumetric proportions (Hirsch, 1961). Later, the model was modified and adapted to predict $|E^*|$ of bituminous mixture from the complex shear modulus $|G^*|$ of the recovered binder, voids in the mineral aggregate (VMA) and voids filled with bitumen (VFB) (Christensen Jr et al., 2003). Equation 18 and Equation 19 show the mathematical form of the Hirsch model for estimating the dynamic modulus of HMA, as proposed by Christensen et al. (2003).

$$|E^*|_{mix} = P_c\left[4.2 \times 10^6\left(1-\frac{VMA}{100}\right) + 3|G^*|_b\left(\frac{VMA \cdot VFB}{10{,}000}\right)\right] + (1-P_c)\left[\frac{1-\frac{VMA}{100}}{4.2 \times 10^6} + \frac{VMA}{3 \cdot VFB \cdot |G^*|_b}\right]^{-1} \quad \text{Equation 18}$$

$$P_c = \frac{\left(20 + \frac{3 \cdot VFB \cdot |G^*|_b}{VMA}\right)^{0.58}}{650 + \left(\frac{3 \cdot VFB \cdot |G^*|_b}{VMA}\right)^{0.58}} \quad \text{Equation 19}$$

Where

$|\boldsymbol{E}^*|_{\boldsymbol{mix}}$: Dynamic modulus of mix, psi
$|\boldsymbol{G}^*|_{\boldsymbol{b}}$: Complex shear modulus of binder, psi
VMA : voids in the mineral aggregate, %
VFB : voids filled with bitumen, %
$\boldsymbol{P_c}$: Aggregate contact factor

The complex shear modulus of binder $|\boldsymbol{G}^*|_{\boldsymbol{b}}$ can be measured experimentally via the DSR test. The Hirsch model was chosen, in this research, to predict the dynamic complex modulus of asphalt HMA, because of its simplicity and the small number of parameters it needs. Moreover, it has been used by many researchers, and the results showed good and accurate estimation, more so than many other models (Li et al., 2012, Li, 2011, Zofka et al., 2004).

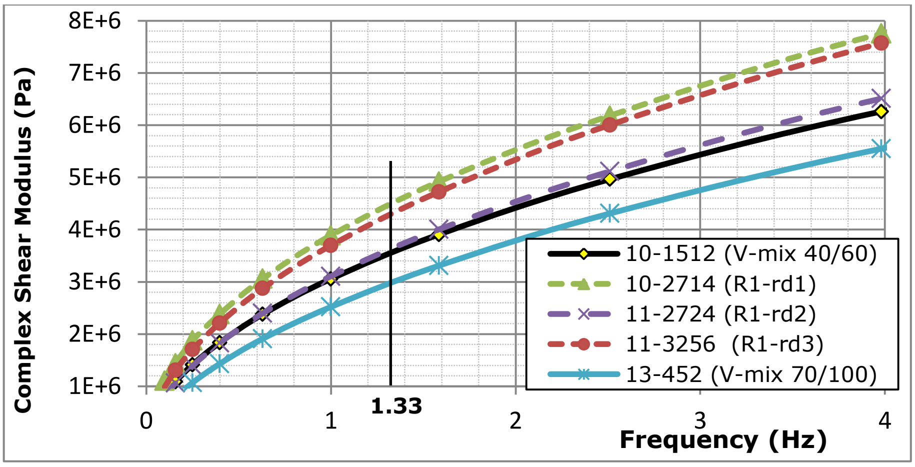
Li et al. (2012) compared the results of dynamic modulus tests for 20 different dense graded HMA samples, collected from Northeast US region, with the predicted |E*| values from the Witczak and Hirsch models. It was found that both models achieved high goodness of fit, where the Witczak model consistently underestimated the measured |E*| values by numerical value of 2, with greater underestimation with numerical value of 6 by the Hirsch model. The factors influencing the measured |E*| values and prediction errors were also evaluated. It was concluded that binder properties, air voids, and presence of RAP affect the |E*| values significantly. In addition, Nominal Maximum Aggregate Size (NMAS) and RAP notably affected the prediction errors of the Hirsch and Witczak models (Li et al., 2012).

5.2 Using the Hirsch model in calculating |E*| of virgin and recycled HMA

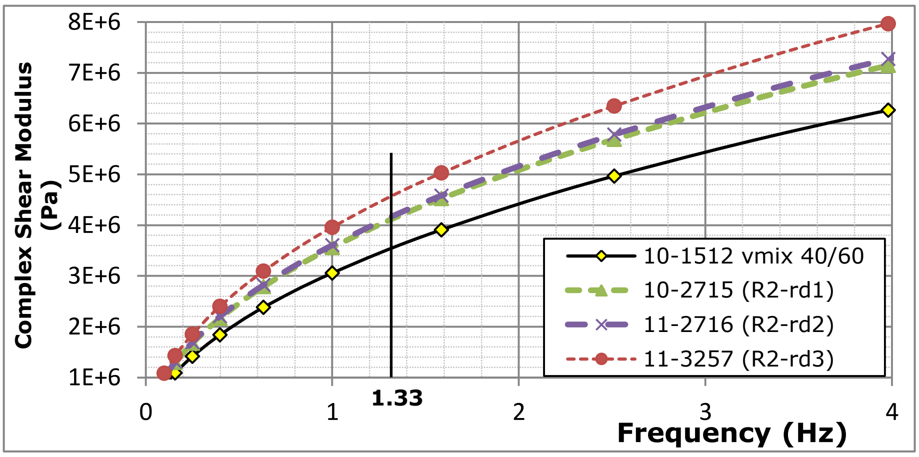
The predicted $|E^*|$ were calculated by the Hirsch model for V-mixes and R-mixes. The parameters of Equation 18 are V_a, VMA, VFB, and G* of the recovered binder. In order to compare the estimated $|E^*|$ with the stiffness modulus values measured by the ITSM test at 20 °C, the G* at 20 °C should be included in results of the DSR test. Also, because the rise time in the ITSM test is 124±4 ms (1.33 Hz) (Read and Whiteoak, 2003), therefore all the G* values should be calculated at this frequency. Figure 5-1 shows the G* for recovered binders from all virgin and recycled mixes used in this study at 20 °C and over wide range of frequencies.

The estimated $|E^*|$ values were calculated for all mixes at V_a =5.0% (because the stiffness moduli were normalized at 5.0%). Figure 5-2 shows that the predicted $|E^*|$ of V-mix 40/60 and V-mix 70/100 are roughly 75% and 90% of stiffness moduli measured by ITSM respectively. Because the V-mix contains no RAP, i.e. no RAP binder, thus the blending is supposed to be complete. Therefore, the G* master curve truly represents the binder of these mixes. Accordingly, the difference between the predicted and measured values could be referred to the accuracy of the model, let us say. Consequently, it has been assumed that the Hirsch model underestimates the $|E^*|$ values by error factor of 25% or 10% (as shown in Figure 5-2). However, because the stiffness moduli of all recycled mixes were closer to that of V-mix 70/100 than V-mix 40/60, the 10% error factor was considered in all later calculations. Therefore, it was expected that the model would underestimate the $|E^*|$ for all R-mixes by the same error factor. However, as clear from Figure 5-2, the model overestimated the $|E^*|$ for all R-mixes except for R3-rd1.

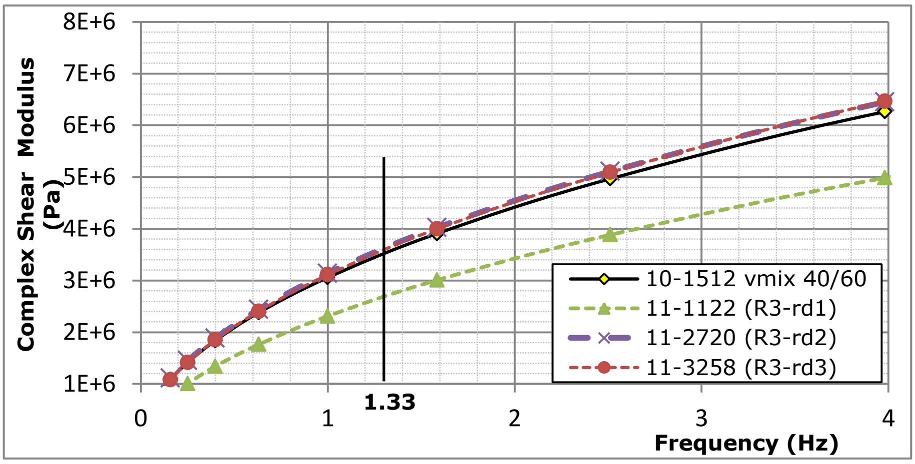
The inability of the Hirsch model, to predict the $|E^*|$ for the recycled mixes, could be attributed to two main reasons. The first relates to the error in measuring the G* of R-mixes, while the second relates to the error of assuming a participation ratio of RAP binder (R) in calculating the VMA and VFB, see Appendix 8. These two reasons are discussed below in more detail.



a) G* at 20 °C for recycled mix made of RAP1



b) G* at 20 °C for recycled mix made of RAP2



c) G* at 20 °C for recycled mix made of RAP3

Figure 5-1 Complex shear modulus at 20 °C for all mixes

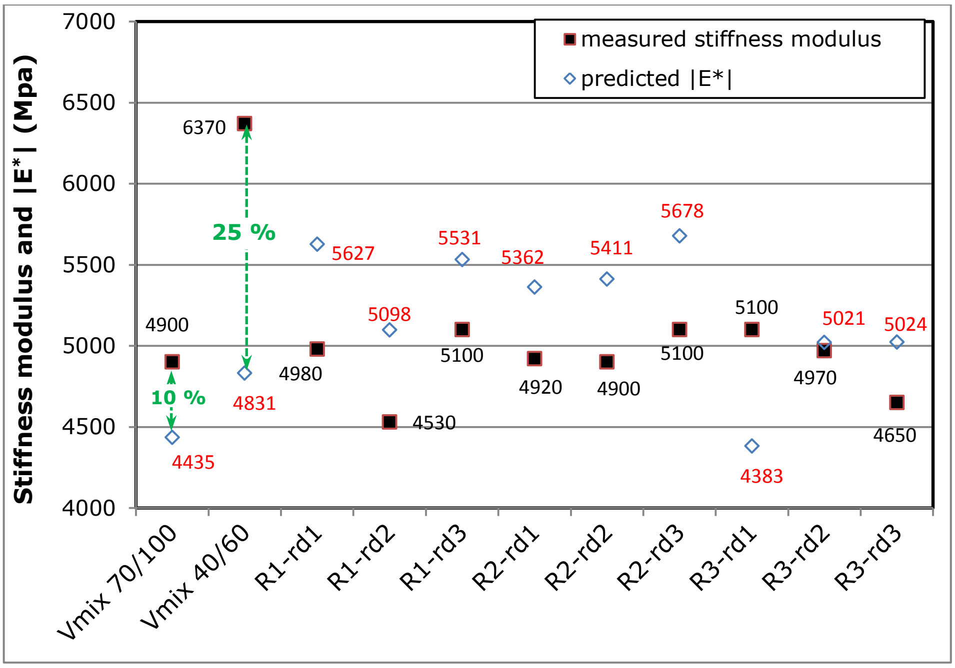


Figure 5-2 Estimated and measured |E*| for V-mix and R-mixes

<u>1) The error in calculating the G* value</u>

As concluded earlier in last chapters, the total blending case did not occur between the aged and new binder during the mixing and compaction stage for the R-mixes. On account of this, the resultant binder inside the R-mix differs from the aged and new (soft) bitumen 70/100 dmm. Accordingly, the recovered binder from these R-mixes cannot ideally represent their effective binder. Through the recovery and extraction process, additional blending would have occurred, especially in the centrifugal apparatus, where the rapid rotation totally blends all the solvent (Oliver, 2001). Consequently, the complex shear modulus curve G* of the recovered binder does not express the actual curve of the existing binder in the R-mix.

Figure 5-3 exhibits the G* master curves of recovered binders from some recycled and virgin mixes. The graph demonstrates that the G* master curves of the recovered binders of the R-mixes, to a great extent, conform to that of the V-mix. This similarity between the master curves occurred, because complete blending took place between binders, not during production of the R-mixes, but through the recovery and extraction process.

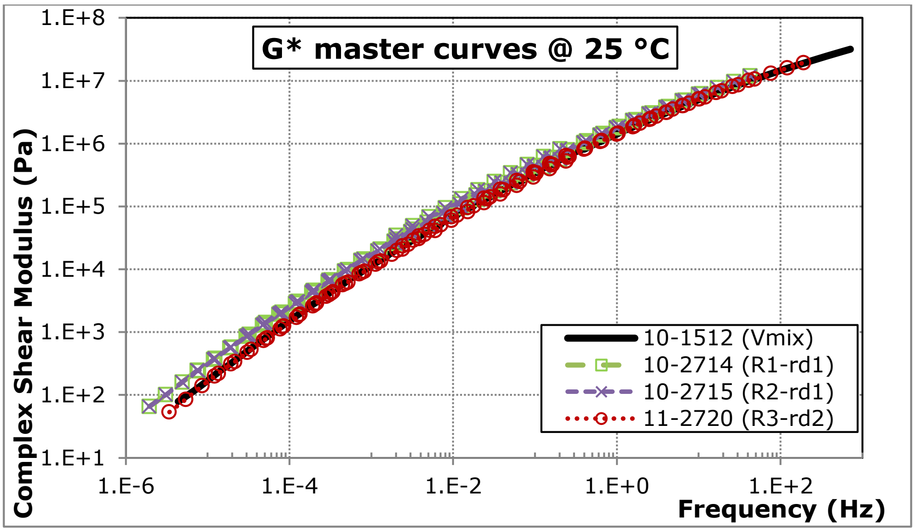


Figure 5-3 Complex shear modulus master curve of recovered binders from recycled and virgin mixtures

As reported by many researchers (Al-Qadi et al., 2007, McDaniel et al., 2000, Oliver, 2001, Roberts et al., 1996, Huang et al., 2005), the contribution of the RAP binder is probably substantially lower than the usually assumed 100%. Hence, there would be a shortage in the amount of aged binder, which leads, upon blending with the new bitumen, to failure to rejuvenate the whole amount of RAP binder. At the same time, an amount of the new bitumen would not be used in the rejuvenation process. The result is that the effective binder in the recycled mixture is softer than desired. Thus, the G* master curves of that effective binder should be located between the G* master curve of the desired one (recovered from Vmix) and the new soft bitumen 70/100, as illustrated in Figure 5-4. It is worth mentioning that getting the effective binder to approach the desired one depends mainly on the efficiency of the rejuvenating process. Also, there is no experimental tool to measure the actual rheological properties of the effective binder in the R-mix.

<u>2) The error due to assumption of RAP binder participation ratio, R in calculating VMA and VFB</u>

Assuming the participation ratio of RAP binder by 100% for the recycled mixes in the Hirsch model is inaccurate, because it means that all RAP binder is fully available in the mixture and would effectively contribute to the blend, but this is not the case in reality.

How close the efficiency of blending (between the aged and new bitumen) to the complete blending case is basically relies on the participation ratio of RAP with its aged binder to the blend.

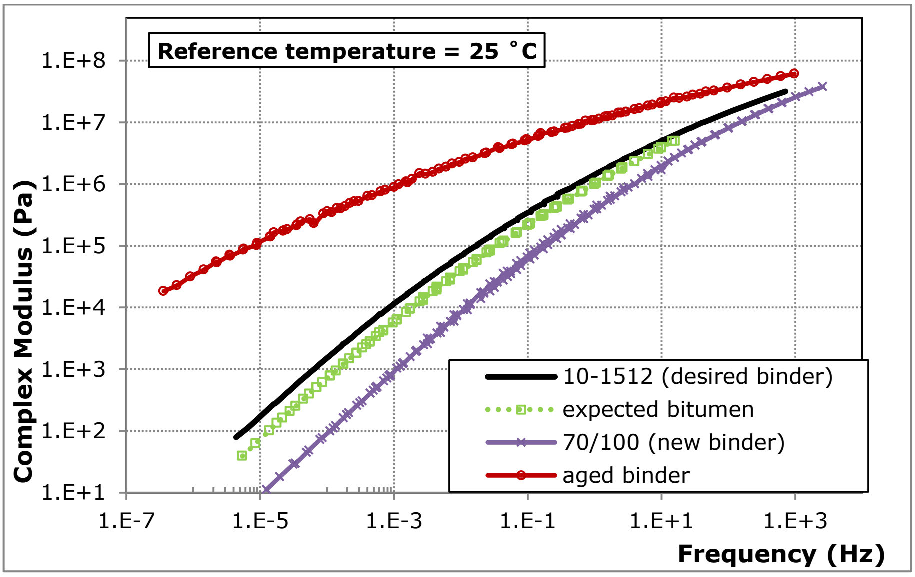


Figure 5-4 The expected rejuvenating process explained by G* master curves

For example, in the R1-rd1 mix

By considering the participation ratio is 70%, then the effective bitumen content can be calculated from Equation 20 as:

(2.2 + 0.7 *[5.2 – 2.2]) = 4.3% instead of 5.2% as for V-mix.

$$P_{beff} = P_{bnew} + R\,(P_{bt} - P_{bnew}) \qquad \text{Equation 20}$$

Where

P_{beff} : effective bitumen content inside the recycled mix

P_{bnew} : new bitumen content, from design

R : participation ratio, assumed

P_{bt} : total bitumen content of the Rmix, from design

Figure 5-5 shows the estimated values of |E*|, according to the change in the participation ratio (R) from 60% to 100% in 10% increments. It is quite clear that the change in the |E*| values is very small (<4%). This means the Hirsch model is not affected by the participation ratio (R) compared to the complex shear modulus (G*).

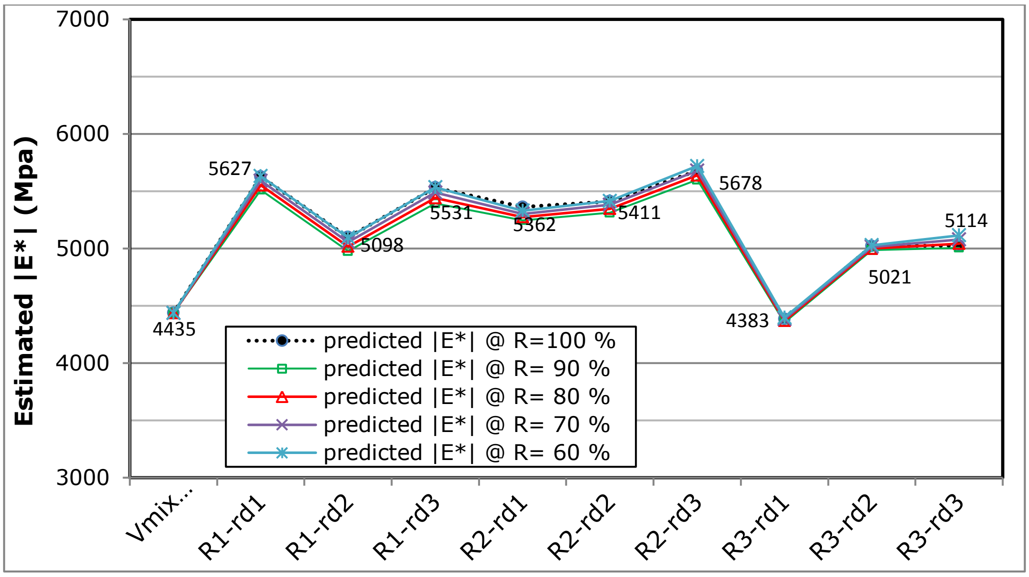


Figure 5-5 Estimated |E*| due to changing participation ratio (R) of RAP binder

5.3 Using the Hirsch model in back calculating G* for recovered binder of R-mixes

As discussed above, the G* for the recovered binders of R-mixes, in reality, does not represent effective binders with in the mixes. Also, because there is no experimental tool to determine the actual properties of the effective binder of the recycled mixture, the Hirsch model was used in an attempt to estimate an approximate and acceptable value of G* for these effective binders. The advantage of this method is that it can be used to predict the properties of the effective binders in recycled mixtures. The R1-rd1 mix was taken as an example to illustrate this technique as indicated below:

- For the V-mix 70/100, the ratio between the estimated |E*| and the measured stiffness equals (4435 / 6370) ≃ 90%, see Figure 5-2.
- The Hirsch model is assumed to underestimate the measured stiffness values by 10% for all R-mixes; thus, the predicted |E*| of the R1-rd1 mix would be (4980 * 0.90) = 4482 MPa.
- By assuming the participation ratio of RAP binder R = 70%, then VMA and VFB equals 15.38 % and 67.5 % respectively, see Appendix 8.
- Equation 18 can be used to back calculate the G* value, which was found to be 2.75 MPa.

Point C, Figure 5-6, could express the G* value of the effective binder much better and more realistically than point A. In addition, dividing the value of point C by that at B, gives (2.75/ 3.6) ≃ 76%, which could be described as the efficiency of the rejuvenating process, based on the G*. Table 26 presents the back calculated values of G* for effective binders of all R-mixes.

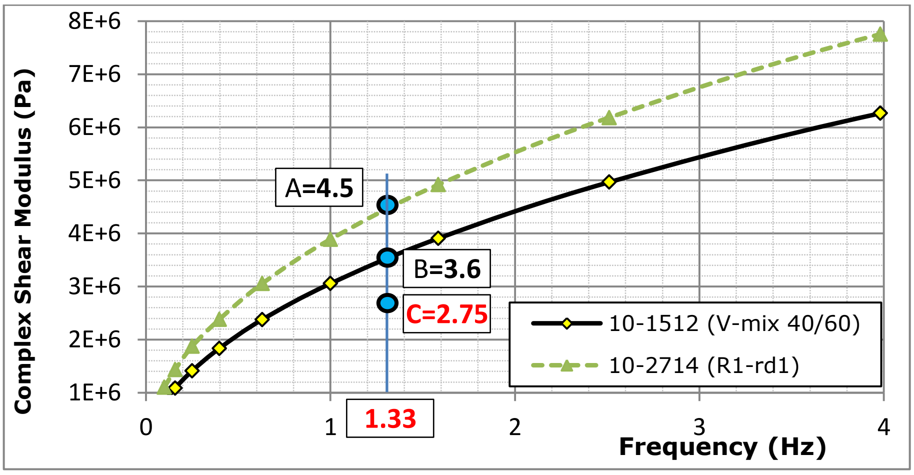


Figure 5-6 Illustrative example of back calculation of the G* of effective binder of the R1-rd1 mix

Table 26 Back calculated and measured complex shear modulus, G*

Recycled mixes	Back calculated G*	Measured G*	Rejuvenating efficiency%
R1-Rd1	2.75	4.50	76.5
R1-Rd2	1.73	3.61	48.1
R1-Rd3	2.12	4.30	61.5
R2-Rd1	2.05	4.10	57.0
R2-Rd2	2.04	4.15	56.6
R2-Rd3	2.21	4.60	61.5
R3-Rd1	2.21	2.70	61.5
R3-Rd2	2.01	3.61	58.2
R3-Rd3	1.83	3.61	50.8

In order to assure that the previous technique is effective, the G* of the R1-rd1 mix was calculated from the G* values of its component binders; 10-1631 (recovered from RAP 1) and 70/100 new bitumen, see Figure 5-7.

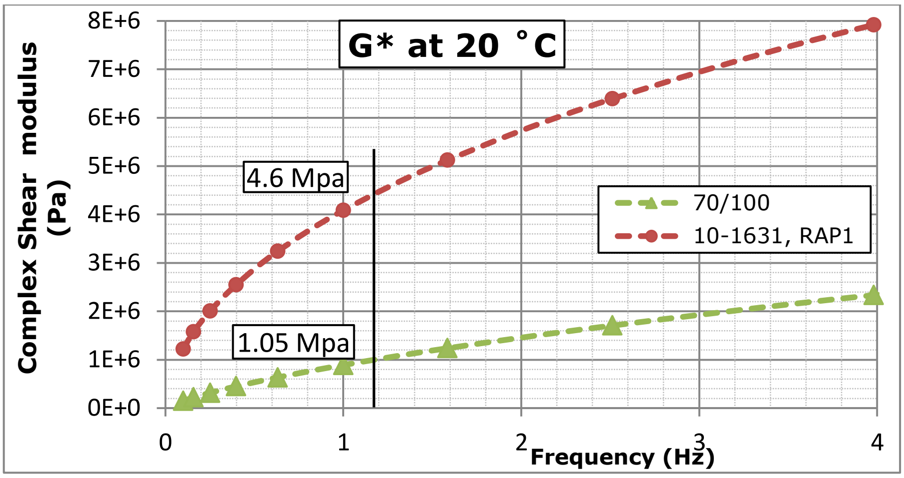
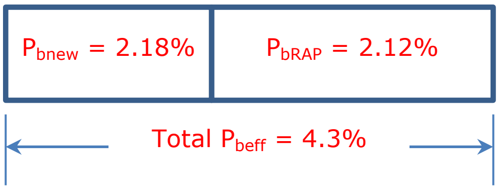


Figure 5-7 Complex shear modulus of new bitumen and recovered binder from RAP1 at 20 ˚C



∴ Compound G* $= \frac{2.18}{4.3}(1.05) + \frac{2.12}{4.3}(4.6) = 2.80$ **Mpa**

It is clear that the compound G* is closer to the predicted G* from the Hirsch model (2.75 MPa) than the measured G* (4.5 MPa).

5.4 Summary

Because there is no experimental tool to measure the properties of the effective binders within the recycled mixtures, the Hirsch model was applied to estimate the complex shear modulus (G*) of those effective binders from the available data of mixture volumetrics and the ITSM test.

The model manifested itself as a possible tool to estimate an approximate and acceptable values of the G* for these effective binders, but only at one frequency. Moreover, the degree of rejuvenation process of the aged binder can be approximately specified.

6 Effect of blending efficiency on the properties of recycled HMA

The findings of the previous chapter indicated that the recycled mixtures had inferior stiffness and fatigue properties compared to the virgin mix. The reasons responsible for this were discussed earlier, but the primary cause is the incomplete blending between the aged and virgin binders. The experimental results also showed that the properties of the R-mixes can be improved by paying attention to efficiency of the blending process. Size of RAP agglomerations, mixing and compaction temperatures, as investigated in chapter 4, are examples of the factors affecting blending efficiency. Doyle and Howard (2010) reported that the level of blending depends on several parameters such as mixing duration and temperature, fundamental properties of the RAP materials (e.g. bitumen viscosity, absorbed bitumen, total bitumen content), level of compactive effort, and additives (Doyle and Howard, 2010). In the light of these findings, an objective has been put in place to investigate the factors by which mixing efficiency can be improved.

Durability of bituminous mixtures relates to how these mixes behave over time. Moisture damage is one of the main factors affecting the durability of an asphalt pavement. Consequently, evaluation of water sensitivity is essential when studying the recycled asphalt mixtures, as this property is directly related to the performance and durability of these materials during the road pavement’s life. Therefore, another objective in this chapter is to assess the resistance of the recycled mixtures to damage by moisture. Deterioration was measured and assessed via the water sensitivity test.

6.1 Improving the blending efficiency of hot recycled asphalt mixture

Some of the factors which are believed to have an impact on the blending efficiency of recycled HMA were investigated in this experimental work. These factors were the warming temperature of RAP, dry mixing time (between the warmed RAP and superheated aggregate), and mechanism of mixing (from horizontal to inclined blending). Mixing mechanism was investigated by using two different types of mixers: a normal and an inclined mixer. Figure 6-1 shows photos of both mixers, while Figure 6-2 depicts schematic diagrams for both mixers to illustrate how they work.

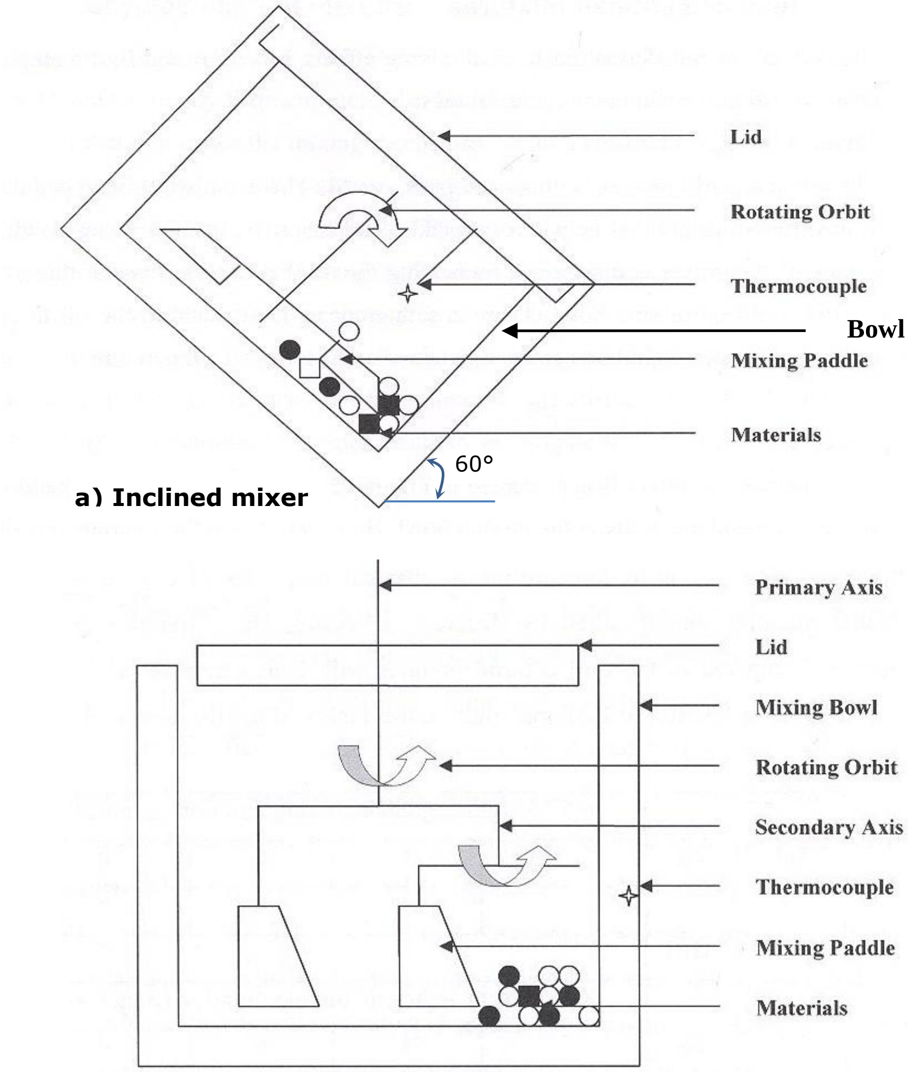
Figure 6-1 Inclined and horizontal mixer

Inclined mixer

Figure 6-2 a) illustrates how the inclined mixer works. Four mixing paddles are used to steer and blend the admixture inside the bowl. Since the rotating axis of the mixer is not vertical, but inclined with 60° (compared to ground plane), the collision between the materials within the mixing bowl consists of not only horizontal but also vertical movement. Moreover, the mixer allows reverse rotation. The heat supplied to the mixer is controlled by a thermocouple that measures the temperature of air inside the mixer.

Normal mixer

The normal or horizontal mixer is sketched in Figure 6-2-b. There are two mixing paddles moving with different orbits that help to drive and blend materials in the mixing bowl. Providing heat to the mixer is done by heating the oil which moves between the external and internal walls of the mixing bowl. There is a thermocouple in the oil to control the heat supply; hence the mixer can be maintained at the required temperature.



b) Normal (horizontal) mixer

Figure 6-2 Schematic of mixers

6.1.1 Methodology

The procedures below describe the steps to fulfil the experimental program.

1- Prepare RAP materials made from crushing virgin samples aged at 125 °C for 65 hrs.
2- Fabricate recycled specimens with the same design parameters as the recycled mix R2-rd1 (RAP =45%, new bitumen content 70/100= 3%, and 10 mm DBM grading).

3- Produce four recycled gyratory samples with different RAP warming temperatures, dry mixing times, and types of mixers, see Table 27.
4- The wet mixing duration between the virgin aggregates, RAP materials and new bitumen is fixed at 3min.
5- Compact the loose samples in the gyratory compactor to achieve 5% target air voids.
6- Trim 5.0 mm from each side of the cylindrical samples to achieve level surfaces and a thickness of 40±2 mm.
7- Test all the samples in the NAT machine to measure their stiffness using the ITSM test.

Table 27 Specimen sets produced

Mixer type	Dry mixing time (min)	Warming RAP temperature		
		20 °C	40 °C	80 °C
Inclined	2	****	****	****
	8	****	*****	***
	16	****	****	****
Normal	8		****	

* Number of samples

6.1.2 Results of stiffness modulus test

Figure 6-3 displays the relationship between air voids (calculated according to (BS EN 12697-6, 2003))and stiffness modulus at 20 °C test temperature for all recycled samples. It is clear from the best fit line that stiffness modulus is inversely proportional to air voids. Despite this, a few specimens with high voids content show high stiffness modulus such as those in circles. The reason behind this might be to the presence of holes on the side surface. These holes, which were taken into account in calculating the voids content, do not have as significant an effect on decreasing the strength of the sample as if they were inside its body. Figure 6-4 shows a photograph of holes on the side surface of one of the samples circled in Figure 6-3. This observation might explain why some specimens with high air voids have stiffness more than others with low voids.

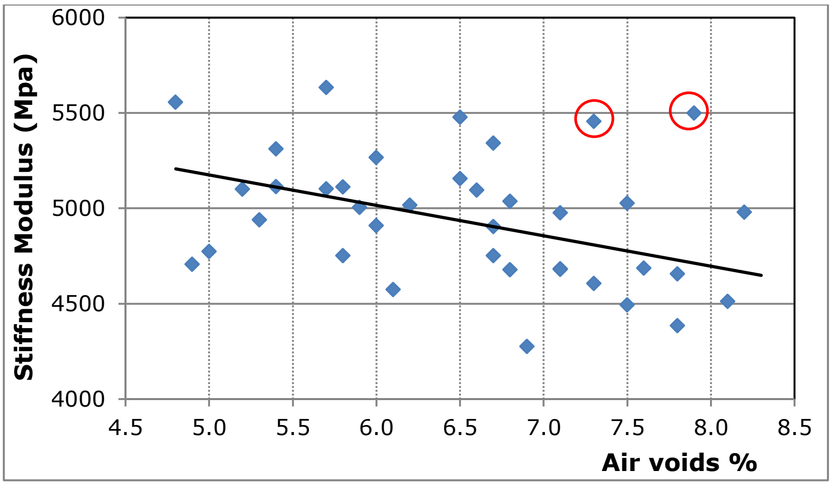


Figure 6-3 Stiffness modulus against air voids for recycled samples

Figure 6-4 Distribution of voids on side surface of samples

Figure 6-5 shows the stiffness modulus against air voids for each group separately. Because the number of samples in each group was only four, and bearing in mind the problem of side surface holes for some samples, some of the trend lines may not accurately represent the stiffness modulus of the group. Therefore, comparison between different groups was done based on the average stiffness moduli, not the normalized stiffness at 5% air voids as used in the last chapter. Figure 6-6 shows the average stiffness moduli at 20 °C test temperature for all groups at different warming RAP temperatures and dry mixing times. Full data are presented in Appendix 5. Many findings can be revealed from the graph as follows. For simplicity, warming RAP temperature will be shortened to WRT.

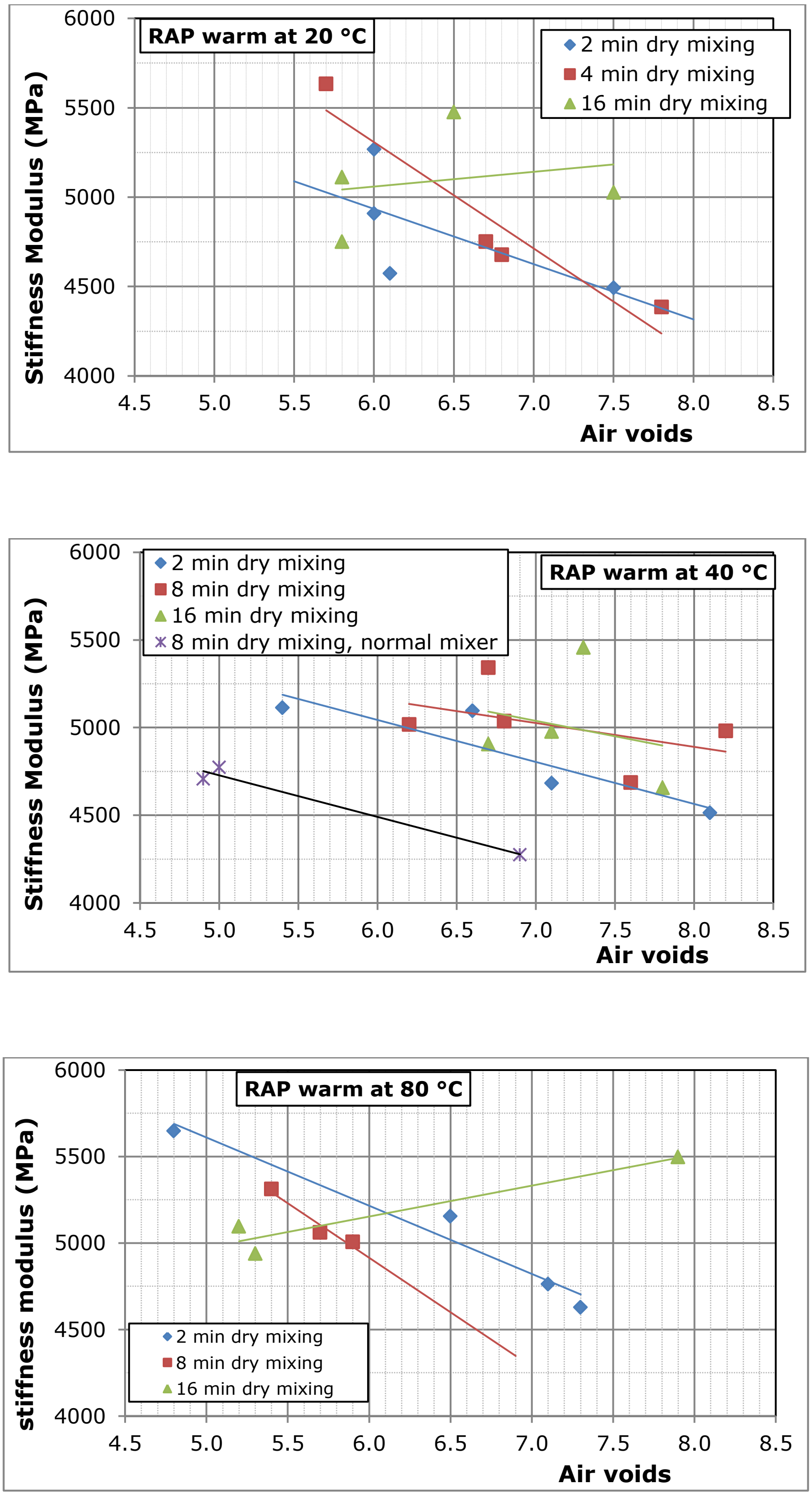


Figure 6-5 Stiffness moduli vs air voids of each group at 20°C

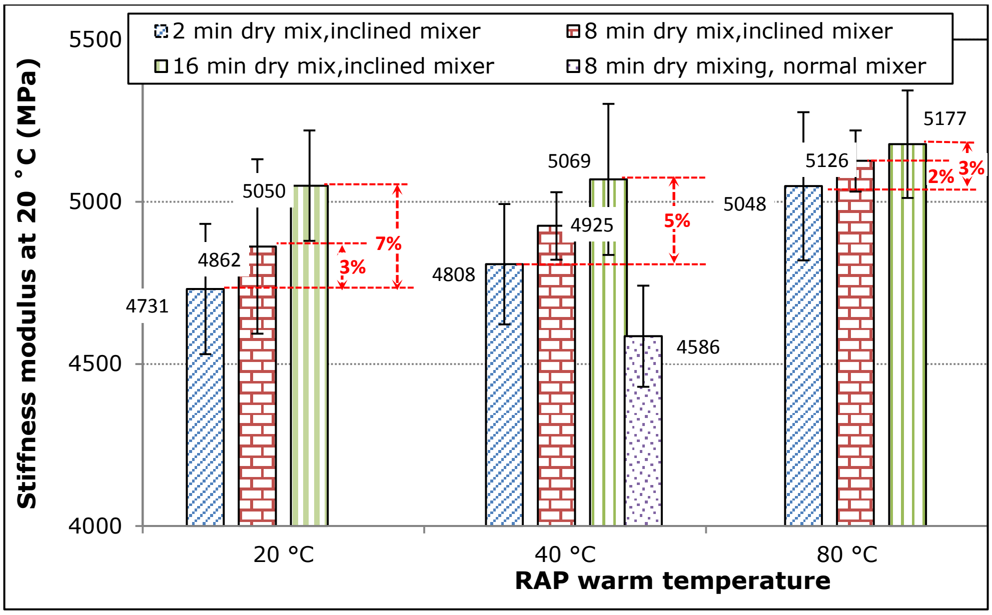


Figure 6-6 Averages stiffness moduli at 20 °C of all groups

6.1.2.1 Effect of mixer type

1- All mixes produced by the inclined mixer presented an increase in stiffness moduli compared to those produced by the normal mixer. Some of these increases are significant as they are more than 10% while others are not, see Table 28. The reason behind these increases is that the mixing efficiency of the inclined mixer is much better than that of the normal mixer due to two reasons:

- The inclined rotating axis of the mixer allows horizontal and vertical movements of mixes components. Hence, collisions between the bulky sized RAP agglomerations become more, which helps to break down these blocks of RAP. However, the impact of this feature was not clearly visible in this experiment because the weight of the batch was small (around 1.0 kg). Probably, the impact of this feature would have been considerable when dealing with larger quantities. The greater the amount of material in the mixer, the more collisions between particles and disintegration of RAP lumps occur. Separation of RAP lumps plays substantial s role in homogeneity of the recycled mix. Nguyen (2009) studied the effect of the same two mixers on homogeneity of the recycled HMA. It was found that the mixes produced by the inclined mixer were more homogeneous than those produced by the normal one.

- Practically, measuring the temperature of the loose mix during the blending process in the inclined mixer is achieved without stopping the mixer and opening the outer cover –which is the case for the normal mixer- resulting in losing some of the heat.

Table 28 Increments in stiffness of mixes of the inclined mixer compared to mixes of the normal mixer

Dry mixing time	Increment in stiffness %		
	Warming RAP temperature, WRT		
	20 °C	**40 °C**	**80 °C**
2 min	3%*	5%	10%
8 min	6%	7%	12%
16 min	10%	11%	13%

* 100 × (4731-4586)/4586 = 3 %, see Figure 6-6

2- Table 28 indicates that five mixes out of nine achieved significant increase in stiffness. From these five, all the mixes produced after warming RAP at 80°C attained an increase ≥ 10%. Also, the mix produced by the inclined mixer at (8min dry mix and 40°C WRT) achieved an increase of only 7% over the mix produced by the normal mix at same mixing conditions (8min dry mix and 40°C WRT). However, significant increase of 10% was achieved for the mix produced by the inclined mixer at (2min dry mixing and 80°C WRT). This indicates the significant effect of warming RAP and that using mixers with greater efficiency can improve the stiffness property of recycled HMA, even at short dry mixing times.

6.1.2.2 Effect of warming RAP temperature (WRT)

3- For mixes with different dry mixing times (2, 8, 16 min), the stiffness modulus increased with increasing the WRT. Although, these increments were small (less than 10%, see Figure 6-6), they could be more significant when dealing with larger and more efficient mixers such as drum or batch mixers. This conclusion is in agreement with findings of Daniel and Lachance (2005) in that preheating RAP has a profound impact on motivating the blending between the aged and virgin binder (Daniel and Lachance, 2005).

4- The recycled mix produced with only (2min dry mixing and 80°C WRT) was similar to, or even, better than those produced at (16 and 8min dry mixing without warming of RAP i.e. at 20°C). This means that considerable time can be saved by warming the RAP before starting the mixing process. This saving in time, definitely, increases the productivity of the asphalt mixing plant.

6.1.2.3 Effect of dry mixing time

5- Figure 6-6 exhibits that the stiffness moduli increase with increasing the dry mixing time at all groups of WRT. This indicates that the heating up and softening of RAP agglomerations occur more as the RAP materials are mixed with the superheated aggregates for a longer time. Similar results were revealed by (Nguyen, 2009) where improvements in stiffness and homogeneity of the mixture were observed.

6- From Figure 6-6, the most impact of dry mixing time on increasing stiffness occurred at 20°C WRT (7% increase when dry mixing was increased from 2-16 min). On the other hand, the least effect of dry mixing time was at 80°C WRT. This means that when the WRT is not sufficient to separate RAP lumps and soften the RAP binder (i.e. at 20°C), the dry mixing will strongly contribute to softening the bonds of RAP lumps. However, when RWT is enough to deactivate the bonds in RAP lumps (i.e. at 80°C), the effect of dry mixing can only heat the RAP up to the mixing temperature and distribute RAP particles all over the mixture. A similar finding was reported by (Nguyen, 2009).

6.2 Effect of moisture damage on recycled HMA

6.2.1 Water sensitivity test

One of the major factors affecting the durability of bituminous asphalt mixtures is moisture damage. Generally, damage by moisture is demonstrated as loss in cohesion of the mix and/or loss of adhesion between bitumen and aggregate interface. The water sensitivity test is a protocol used to determine susceptibility of asphalt mixture to water by measuring the loss in stiffness after conditioning in water. Typically the test contains two phases, conditioning and evaluation. The conditioning process aims to simulate field exposure conditions. By applying the test, it can be concluded how the mixture behaves under conditions of moisture.

The test procedures start, firstly, by measuring the unconditioned stiffness ITSMU of the samples according to (BS EN 12697-26, 2004). The samples are then placed in vacuum desiccators covered with distilled water at 20±1°C (minimum 20mm above the upper surface of the specimens) and are subjected to vacuum of 510±25 mm Hg (680±33 mbar) for 30±1 min. The first cycle begins straight away by placing the samples in a hot water bath at 60±1 °C for 6±1 hrs followed by a cold water bath at 5±1 °C for 16±1 hrs. The last step is determining the conditioning stiffness ITSMc1 of the samples via the ITSM test at 20±1 °C after conditioning the specimens in a water bath at 20±1 °C for 2 hrs. It is worth mentioning that the ITSM test has to be performed within 1 min after the sample has been taken out of the conditioning water. By repeating the 2nd and 3rd conditioned cycles, the conditioned stiffness ITSMc2 and ITSMc3 can be measured and the stiffness ratio for each cycle can easily be calculated from the following equation (BBA, 2008).

$$ITSM_{ratio,\ Ci} = ITSM_{Ci} \ / \ ITSM_{U} \qquad \text{Equation 21}$$

Ci: Conditioning cycle i=1, 2, 3

$ITSM_{Ci}$: Conditioned stiffness after conditioning cycle ci

$ITSM_{U}$: Unconditioned stiffness

6.2.2 Water sensitivity results

Responses of the virgin and recycled mixes to moisture damage were evaluated by the water sensitivity test. The test results are displayed in Table 29 and full data are presented in Appendix 6. Each value of the recycled and virgin mix represents a set of 36 and 4 samples respectively. Table 29 indicates that the behaviour of both recycled and virgin mixes was similar in that there was initial increase in stiffness modulus after the 1st conditioning cycle; the deterioration then began to take place. The statistical analysis of the results illustrates an acceptable level of dispersion of results around the mean value, with maximum coefficient of variation COV (equal standard deviation divided by the mean) of 6.1% and 3.7% for R-mix and V-mix respectively.

The laboratory results showed that the retained stiffness ratios, after three cycles of conditioning, were 1.09 and 1.0 for the R-mix and V-mix respectively. A threshold value of retained ''strength'' of 0.7 has been proposed for considering a mix sensitive to water, by (Lottman, 1982) for tensile strength and stiffness tests, by (Terrel and Al-Swailmi, 1994) for triaxial resilient modulus tests, and by (Scholz, 1995) for indirect tensile stiffness modulus tests. Accordingly, as presented in

Table 29, neither the recycled nor the virgin mix was susceptible moisture damage. Moreover, even after four cycles of conditioning, the recycled specimens have better resistance to moisture damage than virgin samples. Similar findings were reported by (Widyatmoko, 2008, Kiggundu and Newman, 1987, Al-Rousan et al., 2008, Oliveira et al., 2011).

Table 29 Responses of virgin and recycled mixes to moisture damage

	Cycle 1			Cycle 2			Cycle 3			Cycle 4		
	$ITSM_r$	SD	COV	$ITSM_r$	SD	COV	$ITSM_r$	SD	COV	$ITSM_r$	SD	COV
R-mix	**1.18**	0.07	6.1	**1.12**	0.05	4.9	**1.09**	0.06	5.3	**1.06**	0.07	6.1
V-mix	**1.06**	0.01	0.8	**1.02**	0.02	1.9	**1.00**	0.04	3.7	**0.97**	0.03	3.1

Proposed explanation why the recycled mix has better resistance to moisture damage than virgin mix

As introduced earlier in the literature, the common moisture damage mechanism occurs by infiltration of moisture, in either liquid or vapour state, through binder or mastic film. The moisture, then, reaches the aggregate-binder interface and displaces the binder from the aggregate surface. This leads to reduction of the adhesive bond between the aggregate and binder, or breakage of the bond in severe conditions. Consequently, separation of aggregate particles is prone to take place, referred to as "stripping" (Caro et al., 2008).

Figure 6-7 illustrates for an aggregate coated with mastic subjected to two possible moisture damage mechanisms. Because RAP is a material which had already been exposed to ageing, thus RAP binder becomes more elastic and stiffer. Therefore, the bond between the aggregate and RAP binder becomes stronger (the clue for this can be revealed by looking at the remains of binder on the aggregate surface after washing by the solvents, such as trichloroethylene, during the recovery process). This strong bond makes the intrusion of moisture too difficult to reach the aggregate-binder interface.

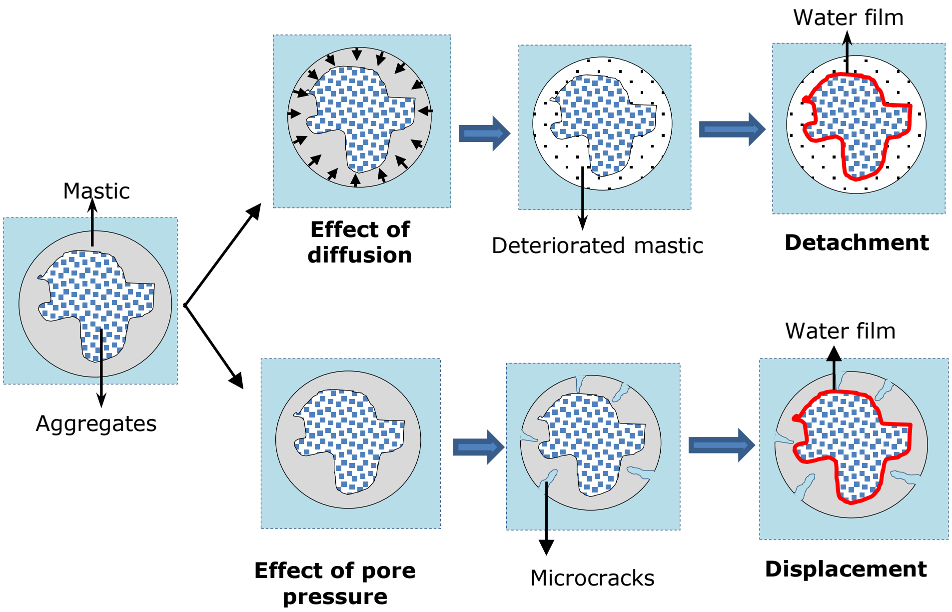


Figure 6-7 Illustration of two possible moisture damage mechanisms (Caro et al., 2008)

It has been reported that the aged binder tends to stick and coats the RAP aggregates. This in turn reduces water absorption when using RAP materials (Guthrie et al., 2007, Gregory and Tuncer, 2009, Huang et al., 2005, Karlsson and Isacsson, 2006). For this reason, the resistance of recycled mixtures to water sensitivity increases.

Interpretation for the initial increase in stiffness moduli after the first conditioning cycle

The crucial benefit of running the ITSM test after each conditioning cycle is that it gives more details about behaviour of the tested specimens after each conditioning cycle, permitting more evaluation and assessing for what is happening inside the specimen. By looking at the retained stiffness ratio after the 1st conditioning cycle in Table 29, it can be noticed that a significant increase of 18% took place for R-mix, while only 6% occurred for V-mix. The initial increasing of the virgin mix is most probably due to additional ageing of binder after immersing in the hot water bath at 60°C for 6 hrs. As for the recycled mix, the increase was triple. This significant increment addresses another factor, along with further ageing, responsible for this increase. This factor could possibly be attributed to an extra reaction having been promoted between the aged and new binders during immersion the recycled samples in the hot water bath for the first time. It seems that the temperature of the hot water might have accelerated the diffusion of the new bitumen through the aged binder, leading to more blending between the binders.

Similar results of an initial increase in stiffness modulus after the 1st cycle of conditioning were obtained by (Widyatmoko, 2008, Scholz, 1995). Figure 6-8 shows the response of two types of the recycled and virgin mixes to moisture damage. The types of tested mixtures were Asphaltic Concrete Wearing course (ACWC), Asphaltic Concrete Base course (ACBC), and Hot Rolled Asphalt (HRA) wearing course. In general, it can be said that the first conditioning cycle might act as a curing period for the recycled mixture in the same way as in cement concrete.

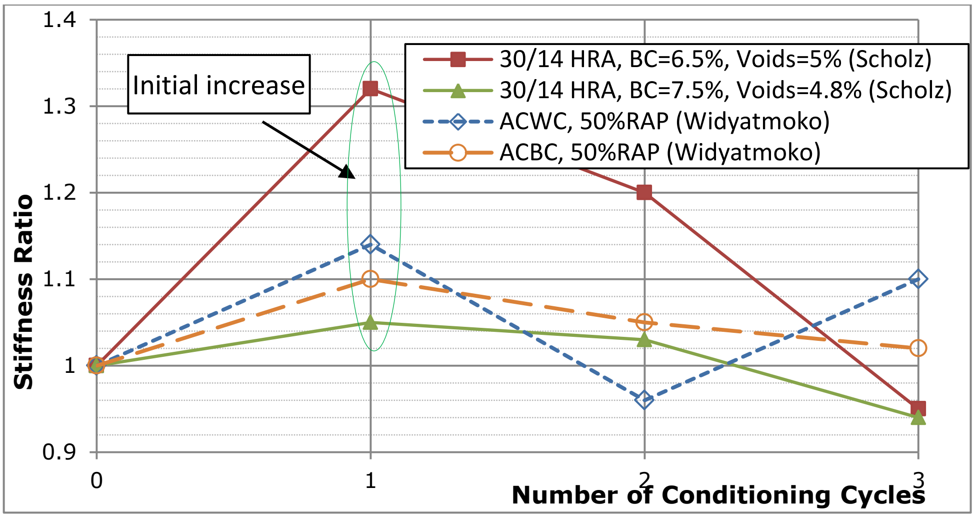


Figure 6-8 Responses of recycled mixes to moisture damage

6.2.3 Effect of dry mixing time and the WRT on performance of the R-mixes under conditions of moisture

Figure 6-9 shows the results of water sensitivity test of different R-mixes made at various dry mixing times (2, 8, and 16 min) and WRT (20, 40, and 80 °C). It is observed that significant increases occurred after 1st conditioning cycle. The highest increase of 27% was achieved by R-mix-16min@80°C, while the lowest increase of 13% was for R-mix-2min@20°C. The R-mix-8min@80°C was the second highest (22%). This finding indicates that the initial growth of stiffness increases with increasing the dry mixing time and WRT, which reinforces the importance of these two factors in improving durability of recycled HMA.

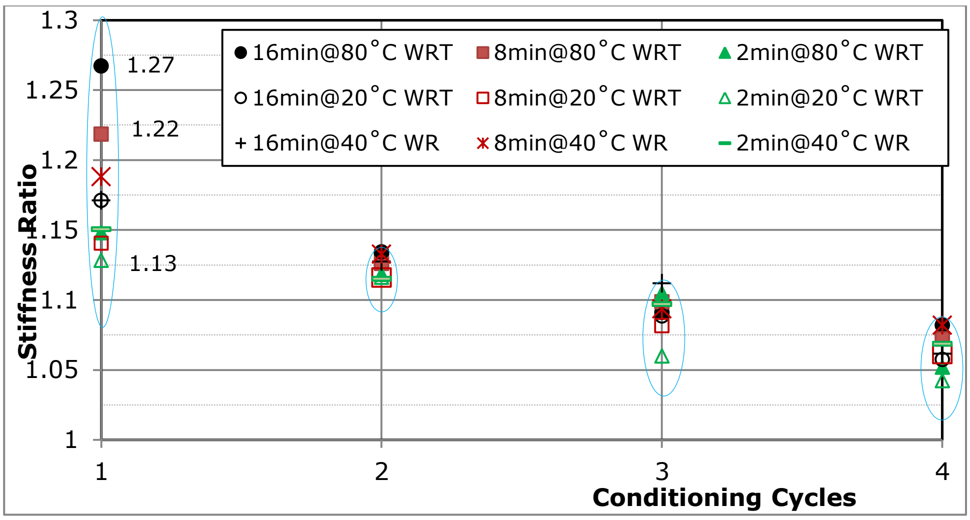


Figure 6-9 Dry mixing time and WRT effect on resisting water sensitivity

6.3 Summary

Certain factors such as dry mixing time, warming RAP temperature, and mechanism of blending that are believed to improve the efficiency of blending have been investigated. In addition, the behaviour of recycled and virgin mixtures under moisture conditions was evaluated via the water sensitivity test.

The experimental results clarified that the effectiveness of the length of dry mixing time increases in cases with no warming of RAP, while its impact is reduced with raised warming temperature. Accordingly, considerable saving in dry mixing times and significant improvements are feasible when using short dry mixing times with increased warming RAP temperature (compare mixes of 2min@80 °C and 16 min@20 °C).

The results of water sensitivity tests indicated insensitivity of both the recycled and virgin mixes to moisture damage. In addition, the recycled mixture demonstrated more resistance to damage by water than the virgin mix.

Linking these findings with what is happening in reality in Asphalt Production Plants, it can be said that using a short time of dry mixing in an inclined rotating mixer such as a drum mixer is likely to help in improving the efficiency of blending between the new bitumen and aged RAP binder in recycled HMA resulting in a considerable increase in stiffness.

7 Effect of storage time on increase in the stiffness of recycled and virgin HMA

Because the properties of HMA are affected by time and/or temperature, most tests require conditioning period for specimens before testing. In the ITSM test, standards specifically require conditioning of samples at 20 °C for 7 hrs at least. However, sometimes the asphaltic samples are stored for a long time before testing. The question that can arise here is "does storage period and storage temperature greatly affect the test results particularly for recycled samples?" Therefore, one of the objectives of this study is to explore the impact of long storage period on stiffness of asphaltic samples.

Recycled mixes were manufactured by mixing the virgin aggregate and RAP with soft bitumen 70/100 dmm. In addition, the design procedure of recycled mixes presumes full availability of RAP binder in the mix and would effectively contribute in the blend. However, how much RAP binder would actually participate in the blend depends mainly on the extent the old bitumen leaves the surface of RAP aggregate and interacts with the new bitumen. During mixing process, the new bitumen interacts with RAP binder, but possibly not to the extent expected from the design assumption. The issue here is whether the interaction between the old and the new bitumen will continue after mixing stage or stop?

(Noureldin and Wood, 1987) studied the diffusion of certain types of rejuvenator through the old layers of RAP binder during mixing process. They concluded that the rejuvenators could diffuse efficiently through the hard film of old binder. (O'Sullivan, 2011) investigated the impact of long-term diffusion (diffusion after production stage) on the properties of recycled mixes with high RAP content (90 and 80%) prepared with different percentages of the industrial rejuvenator Renoil (1736). To eliminate the effect of ageing by oxidation, one of recycled mixes was put in an inert gas oven. O'Sullivan found that there was an increase in dynamic modulus value of recycled mix of inert gas oven over time. The researcher referred this increment to the continuing interaction between RAP binder and the rejuvenator over time.

The diffusion process could last for a while after mixing and production stage, leading to further interaction between the aged and new binders. This in turn enhances the binding property inside recycled mix resulting in more strength. Diffusion within recycled mixes can be manifested in forms of increasing of stiffness over time. Therefore, the main objective of this sub-study is to investigate any increase in stiffness modulus over time, assuming that this increase can reflects the degree of mixing and diffusion between the binders The influence of storage temperature on accelerating the long-term diffusion process was also examined.

7.1 Methodology

To achieve the objectives of this plan, an experimental programme has been carried out, as shown in the flow chart in Figure 7-1. The experimental program includes manufacturing of two groups of 15 virgin and recycled samples. Each group was divided into three sets of 5 samples which were stored in cabinets at different storage temperature: 5°C, 20°C and 30°C. All samples were tested according to the ITSM test at one month intervals. Before carrying out the ITSM test, the samples had been conditioned at 20 °C for a minimum of 7 hrs.

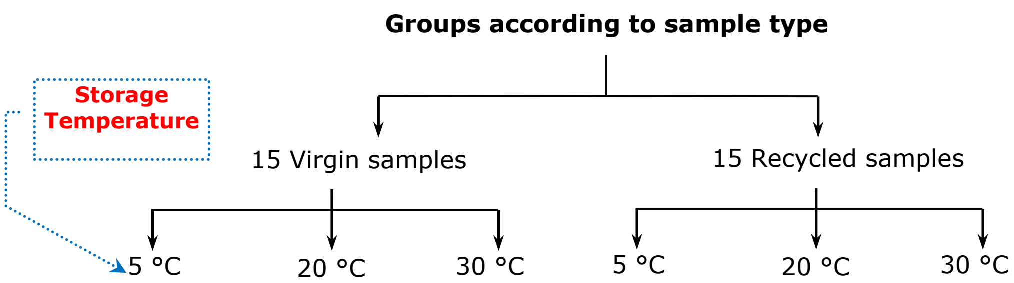


Figure 7-1 Schematic diagram of storage time plan

7.1.1 Material preparation and mixing procedure

The virgin samples for this plan were produced with the same features as the control mix (V-mix 40/60) in the repeated recycling plan. Design of the recycled mix was the same as the R2-rd1 mix (45% RAP and 3.0% bitumen content of 70/100 dmm). The RAP used to produce the recycled samples was the second type of repeated recycling plan (produced from crushing the aged virgin samples for 65hrs@125 °C). Table 30 introduces the proportion material for making one recycled sample. Mixing temperature for virgin samples was 160±5 °C while it was 140±5 °C for the recycled ones. The mixing procedures for the virgin and recycled samples were the same as for V-mix 40/60 and R2-rd1 in the repeated recycling plan respectively.

Table 30 Proportion of materials for one recycled sample of R2-rd1

Target Air Voids	5 %	**Samples type: Gyros**	(100*50 mm) diameter* height
Target Density	2420 kg/m3		
Asphalt Grade	70/100	**Binder Content**	3.016%
Aggregate Size	**Mass %**	**Mass g**	
RAP[2]	45	417	
10 mm	22	204	
6.0 mm	27	250	
Dust	06	56	
Sum	100	926	
Binder mass		29	
Total Mass		955	

7.1.2 Compaction and trimming process

The loose samples were compacted straight away after 30 minutes of mixing stage, in the gyratory compacter (at 800 kPa pressure and 2.0° angle of gyration) to achieve the target air void of 5 %. Diameter of sample was 100 mm and the target height for the virgin and recycled compacted samples were 60 mm and 50 mm respectively. The compaction temperature was 150±5 °C for virgin samples and 135±5 °C for recycled ones.

After compaction, the moulds were left to cool overnight before extraction of the cores from metal forms. To eliminate defects in the surface that might result from compaction, each specimen was trimmed from both ends (10 mm for virgin samples and 5 mm for the recycled) to achieve level surfaces with height of specimen of 40±2 mm. Afterwards, the bulk specific density of each specimen was determined according to (BS EN 12697-6, 2003) to estimate the air void content (BS EN 12697-8, 2003).

7.1.3 Selecting the sets of samples for each storage scheme

All specimens were tested under the ITSM test to determine the initial stiffness moduli. Based on these stiffness moduli five specimens were chosen for each set so that their stiffness moduli were close to each other. Table 31 displays the sample ID with the corresponding air voids and stiffness values along with the selected specimens for each set.

7.2 Assessment method

The ITSM test is classified as a non-destructive test. Thus repeated testing on the same specimen produces no substantial changes in stiffness modulus values. From this standpoint, all the assessments were based on measuring the stiffness modulus of the samples (on the same axes) every month. The results were presented as stiffness index (SI), see Equation 22; hence it is easy to monitor any changes that might be taken place in stiffness values over time. Care should be taken when positioning the sample in the NAT machine since any slight movement away from the axis that was tested before would lead to changes in the test's measurements.

$$\boldsymbol{SI} = \frac{\boldsymbol{Stiff_{anytime}}}{\boldsymbol{Stiff_{initial}}} \qquad \text{Equation 22}$$

In the ITSM test, the stiffness modulus of a specimen is the mean of two values at any two perpendicular diameters with the condition that the difference between these two values should not be greater than 10 %. British Standard (BS EN 12697-26, 2004) supposes the ratio of 10 % as a significant variation that requires rejecting the test and repeating it again. Using the same concept, it was decided to consider any increment in stiffness index of 10 % or more as a significant change in stiffness value.

Table 31 Selecting samples for each storage scheme set

Virgin samples

Sample ID	Air Voids	Stiffness modulus (MPa)	storage scheme	Sample ID	Stiffness
11-1276	3.0	6739	**5 °C**	11-1285	**7046**
11-1277	3.4	7132		11-1277	**7132**
11-1278	3.2	8217		11-1289	**7249**
11-1279	6.9	6771		11-1276	**6739**
11-1280	4.4	8611		11-1279	**6771**
11-1281	3.8	9268	**20 °C**	11-1287	**7907**
11-1282	4.5	8111		11-1283	**7960**
11-1283	3.8	7959		11-1282	**8111**
11-1284	4.7	6998		11-1284	**6998**
11-1285	3.3	7046		11-1278	**8217**
11-1286	3.1	8991	**30 °C**	11-1288	**8286**
11-1287	4.6	7907		11-1290	**8399**
11-1288	4.3	8286		11-1280	**8611**
11-1289	3.9	7249		11-1286	**8991**
11-1290	4.1	8399		11-1281	**9268**
Ave	4.07				

Recycled samples

Sample ID	Air Voids	Stiffness modulus (MPa)	storage scheme	Sample ID	Stiffness modulus (MPa)
11-2506	6.4	5201	**5 °C**	11-2519	**3869**
11-2507	5.5	6082		11-2516	**3842**
11-2508	6.7	4346		11-2515	**3793**
11-2509	5.1	5862		11-2517	**3628**
11-2510	5.4	6395		11-2514	**3525**
11-2511	5.9	5779	**20 °C**	11-2510	**6395**
11-2512	5.5	5669		11-2507	**6082**
11-2513	4.9	5874		11-2511	**5779**
11-2514	8.5	3525		11-2513	**5874**
11-2515	6.7	3793		11-2509	**5862**
11-2516	6.0	3842	**30 °C**	11-2512	**5669**
11-2517	7.3	3628		11-2518	**5265**
11-2518	5.5	5265		11-2506	**5201**
11-2519	6.7	3869		11-2520	**4660**
11-2520	6.2	4660		11-2508	**4346**
		6.15			

7.3 Results and analysis

7.3.1 Relationship between stiffness and air voids

It was anticipated that as the air voids of the specimens increase there would be a decrease in stiffness modulus. Figure 7-2 shows the air voids against the stiffness moduli for all the virgin and recycled samples used in this sub-study. Even though there is some scatter in the data due to the fact that asphalt is not a homogeneous material and there is natural variation owing to the way in which the aggregate settles in the compactor, yet it is clear from the best fitting lines that stiffness is inversely proportional to air voids.

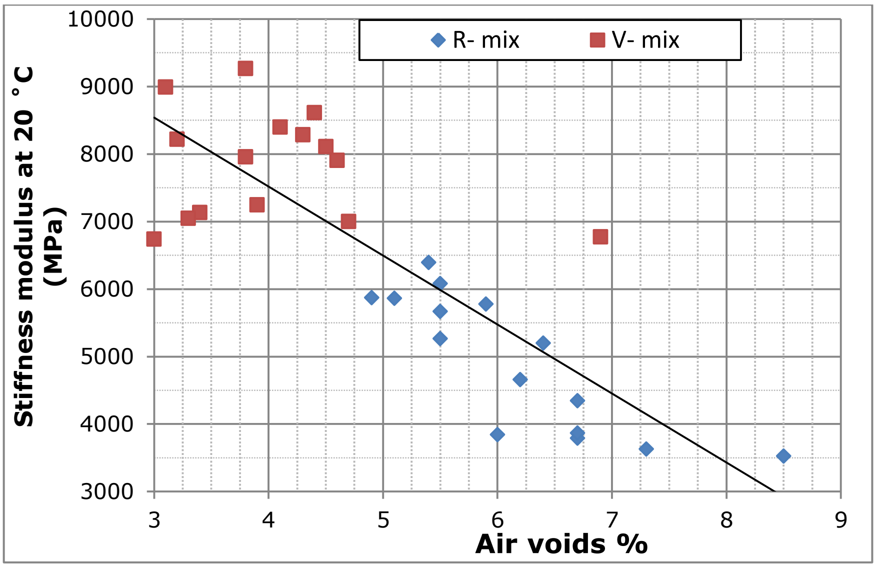


Figure 7-2 Air voids against stiffness modulus

It is clear from the plot that the stiffness moduli of recycled samples are lower than those of virgin ones. The reason for this –as revealed from chapter 4- is because the mixing between RAP and virgin binder within the R-mix was not complete in the same way as for the V-mix. The graph also indicates that the average air voids of recycled samples are higher than those of virgin samples. This might be due to insufficient compaction of the recycled samples compared to virgin samples. The difference in the compaction temperature might be the reason where it was 135±5 °C and

150±5 °C for the recycled and virgin mixtures respectively. The compaction temperature was decreased for R-mix because softer bitumen 70/100pen was used, while the bitumen 40/60 pen was used for V-mix. Also, the size of RAP lumps might be another cause for making the compaction inadequate especially when breakdown of these lumps does not occur perfectly.

7.3.2 Effect of storage time on stiffness

Assessment of the effect of storage time on stiffness modulus was conducted by measuring the stiffness index (SI) for the laboratory prepared samples periodically each month. The stiffness moduli were determined by applying the ITSM test via the NAT machine. The complete data of stiffness indices and complex modulus values for both virgin and recycled samples are presented in Table 32 and Appendix 7. Figure 7-3 displays the SI of the virgin and recycled samples over time. Each point on the graph represents the mean of 15 samples accompanied with the error bars (calculated from standard error) that show how the data disperses around the average value. The virgin samples were tested for nine months while the recycled samples were tested for seven and half.

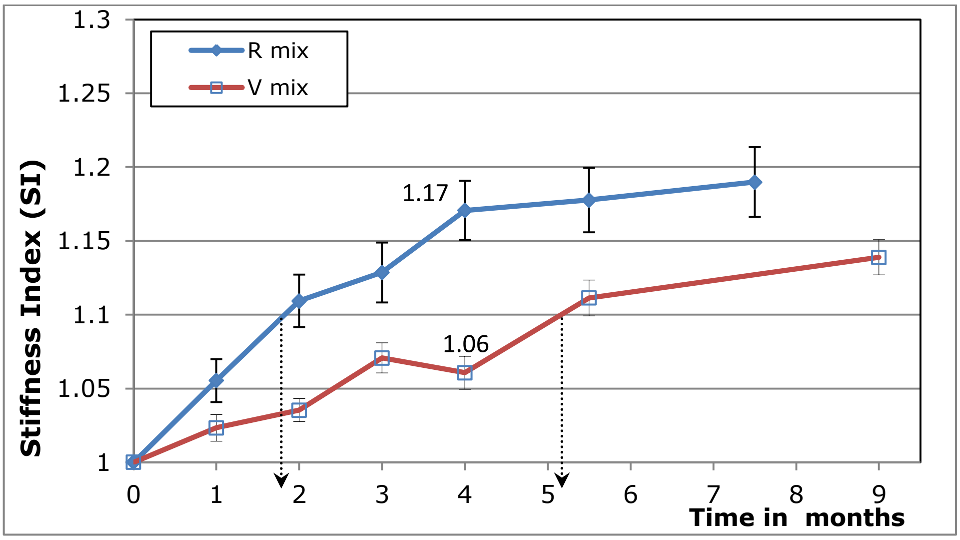


Figure 7-3 Effect of storage time on stiffness indexes of virgin and recycled mixture

Figure 7-3 shows a gradual escalating in SI over time for both mixes. However the rise in SI for R-mix is more than that of V-mix.

Furthermore, in the first four months, the increase rate of SI for R-mix was higher than that of V-mix, yet this rate seemed to be constant thereafter. Looking at the graph, it is apparent that R-mix achieved significant (i.e. 10%) increase after nearly two months, while this occurred after almost five months for V-mix. This means that after two and five months for R-mix and V-mix respectively, the mechanical properties had significantly changed. The reason for these increases in stiffness moduli could be due to ageing and continuing interaction between the old and the new binders by the effect of long-term diffusion as will be discussed below.

From above finding, it can be revealed that it is better to carry out any experiments within the first 1.5 months straight away after producing the recycled samples; otherwise major alteration would take place in their mechanical properties. As for the virgin samples, the maximum time that might guarantee no significant variation in the mechanical properties of samples is around 5.0 months.

7.3.2.1 Analysis of the data for virgin samples

By analyzing the data for the V-mix, where the binder is by definition fully blended, the increasing stiffness is likely to be due to the ageing process. This increase ascends at a nearly constant rate through the whole testing period, Figure 7-3. (Malan, 1989) reported that the ageing of binder increases the hardness of bituminous asphalt mixture. Several researchers (Airey, 2003, Lu and Isacsson, 2002, Petersen, 1984, Read and Whiteoak, 2003) identified four main contributors to ageing process: oxidation, exudation, physical hardening and loss of volatile components. However, loss of volatile components is not an issue, here, as it is restricted to the mixing stage.

Because the used aggregate was limestone, which is regarded as one of the porous aggregates, some ageing due to exudation might be expected, since some of the oily component of the bitumen would be absorbed by the adjacent aggregate. This assumption is supported by the finding observed by (Noureldin and Wood, 1987) that limestone aggregate is prone to absorb light fractions of bitum-

Table 32 Stiffness indexes of Virgin and Recycled mix over time

Storage Temp.	V mix								R mix								
	Sample ID	0	1	2	3	4	5	9	Sample ID	0	1	2	3	4	5.5	7.5	Time in months
5 °C	11-1285	1	1.05	1.08	1.1	1.07	1.14	1.17	11-2519	1	1.05	1.12	1.12	1.19	1.20	1.18	
	11-1277	1	1.00	1.02	1.08	1.04	1.11	1.12	11-2516	1	1.05	1.14	1.11	1.17	1.15	1.16	
	11-1289	1	0.97	1.01	1.05	1.03	1.08	1.10	11-2515	1	1.11	1.12	1.11	1.15	1.14	1.19	
	11-1276	1	1.06	1.07	1.17	1.16	1.18	1.22	11-2517	1	1.13	1.09	1.13	1.18	1.18	1.18	
	11-1279	1	0.95	1.02	1.06	1	1.08	1.10	11-2514	1	1.02	1.08	1.1	1.15	1.17	1.17	
20 °C	11-1287	1	1.01	1.01	1.04	0.99	1.02	1.08	11-2510	1	0.98	1.02	1.03	1.03	1.03	1.06	
	11-1283	1	1.02	1.04	1.04	1.05	1.09	1.10	11-2507	1	1.08	1.09	1.13	1.14	1.11	1.12	
	11-1282	1	1.02	1.00	1.01	1.02	1.03	1.06	11-2511	1	0.99	1.02	1.05	1.13	1.15	1.14	
	11-1284	1	1.08	1.05	1.07	1.11	1.16	1.19	11-2513	1	1.00	1.04	1.06	1.09	1.10	1.09	
	11-1278	1	1.04	1.07	1.08	1.08	1.13	1.16	11-2509	1	0.98	1.02	1.04	1.09	1.11	1.11	
30 °C	11-1288	1	1.02	1.04	1.09	1.08	1.16	1.18	11-2512	1	1.03	1.12	1.11	1.15	1.16	1.17	
	11-1290	1	1.04	1.04	1.07	1.08	1.15	1.17	11-2518	1	1.10	1.17	1.26	1.27	1.30	1.31	
	11-1280	1	1.00	0.97	1.03	1.05	1.11	1.11	11-2506	1	1.05	1.15	1.16	1.24	1.25	1.27	
	11-1286	1	1.03	1.05	1.05	1.06	1.09	1.13	11-2520	1	1.15	1.25	1.3	1.34	1.36	1.40	
	11-1281	1	1.06	1.06	1.12	1.09	1.14	1.17	11-2508	1	1.11	1.21	1.22	1.24	1.26	1.30	
Ave		**1.0**	**1.02**	**1.04**	**1.07**	**1.06**	**1.11**	**1.14**		**1.0**	**1.06**	**1.11**	**1.13**	**1.17**	**1.18**	**1.19**	

en. Regarding physical hardening, although there is no decisive evidence of its occurrence, but still can be considered as one of associator for ageing process, especially one third of samples were stored at low temperature (5 °C) which might be affected by physical hardening. Oxidation is the primary component in the ageing process and is most probably the main motivator for this increase in the SI as most of samples were exposed to the air in the cabinet all the time.

7.3.2.2 Analysis of the data for recycled samples

As shown in Figure 7-3, the trend of SI of R-mix rises progressively from one month to another with a rate higher than that of V-mix. After four months, the rate seems to be approximately the same as that of V-mix. The question, here, is why the trend line for R-mix was not the same as for V-mix? The answer to this question could be ascribed to the nature of composition and mixing of each mixture.

In V-mix, the mixing process is followed the total blending case. However, inserting the RAP as a main element of R-mix could very well change the nature of the mixing between the RAP, virgin aggregate, and new bitumen. It would have been anticipated that the properties, consequently, the behaviour of R-mix is exactly the same as V-mix, only if the blending was perfect. But insufficient interaction between the admixtures of R-mix resulted in changes to the behaviour of this mix compared to V-mix.

It was concluded from analysis of the data for virgin samples that ageing is deemed to be the only responsible cause for the increase in SI. Thus, there should be another reason for the difference in the increment between the two lines shown in Figure 7-4.

Bitumens with high penetration grade are more susceptible to temperature, hence ageing, than those of low penetration (Malan, 1989). According to Malan, the R-mix which has bitumen 70/100 pen would be more sensitive to ageing more than the V-mix made from bitumen 40/60 pen. However, since bitumen 70/100 had partially interacted with the aged RAP binder and restored some of its properties, thus the properties of resultant bitumen within R-mix should be between those of 70/100 and the desired binder (recovered from the V-mix). If the interaction was complete, the resultant binder would have the same properties of that of V-mix. It means the resultant binder is harder than bitumen 70/100 and softer than the binder of V-mix.

As is clear from Table 33, Figure 7-5 and Figure 7-6, which show the rheological and physical properties of the resultant and desired binder along with the new bitumen, the rheological and physical properties of the recovered binder from the R-mix (10-2715) are closer to those of recovered binder from V-mix (10-1512) than those of new bitumen 70/100. Consequently, the R-mix will be more susceptible to ageing than the V-mix, but not significantly. Therefore, the effect of ageing is expected to be more in the R-mix, but not enough to be the responsible for the area indicated in Figure 7-4.

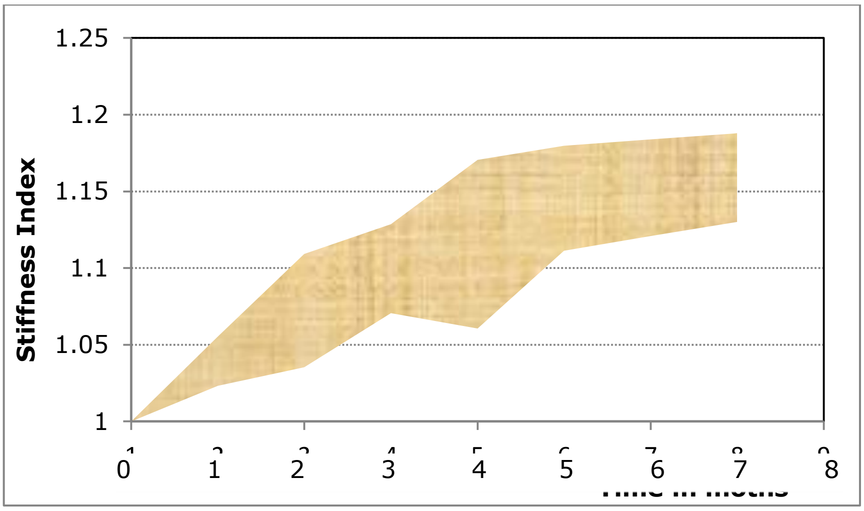


Figure 7-4 Difference in increment of SI among V-mix and R-mix

Table 33 Physical properties of bitumen 70/100 and recovered binder from V-mix and R-mix

Bitumen ID	Bitumen type	Penetration (dmm)	Softening Point °C	ZSV (Pa.s)*	Asphaltenes content %
10-1512	Desired bitumen (rec from V-mix)	37	59.4	1798	16.8
10-2715	Resultant binder (rec from R-mix)	56	58.2	1074	15.5
10-887	New bitumen 70/100	91	47	163	11.9

* Pa.s = 10 poises

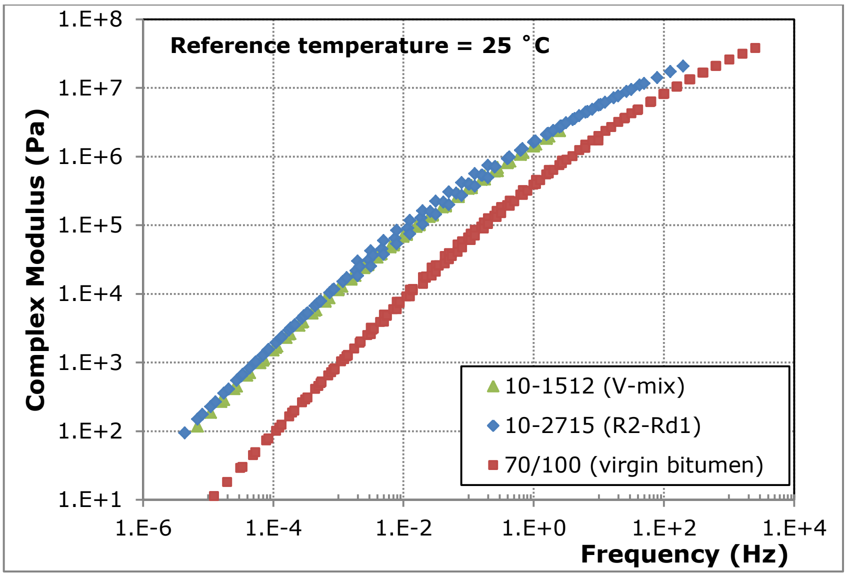


Figure 7-5 Complex modulus master curves of bitumen 70/100 and recovered binder from V-mix and R-mix

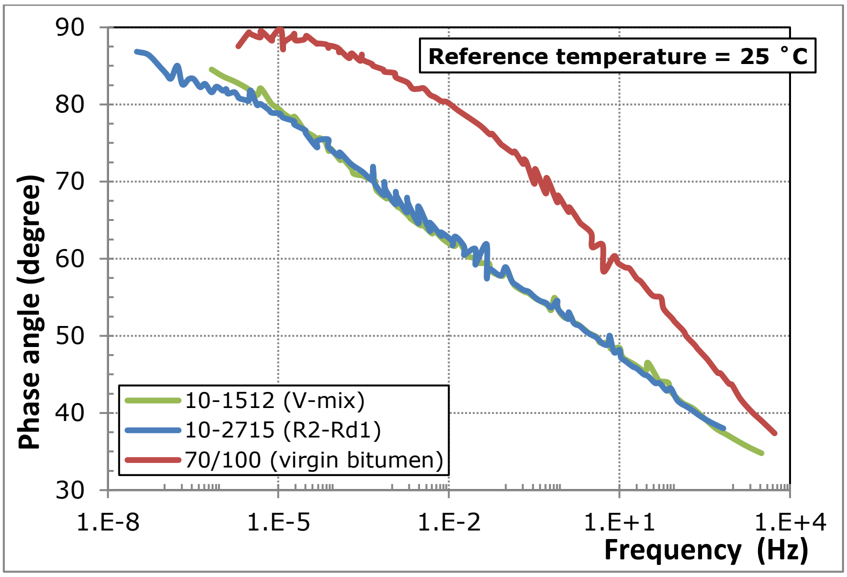


Figure 7-6 Phase angle master curves of bitumen 70/100 and recovered binder from V-mix and R-mix

So, what could be primarily responsible for the shaded area in Figure 7-4? As concluded from chapter 4, the mixing between the new bitumen and the RAP binder has not reached the total blending limit. Consequently, this reaction is most likely to continue over time as an effect of long-term diffusion between the aged and new binders. It has been reported that full rejuvenation is usually achieved within about 3–6 months after mixing stage (AAPA, 1997). This process could occur by diffusing the molecules of new bitumen

(70/100) through the aged film of binder attached to the RAP aggregate surface, softening and restoring some of its properties.

The way in which the rejuvenator diffuses into the aged binder was outlined by (Carpenter and Wolosick, 1980). They reported that penetration of the rejuvenator into the aged layer of binder continues till it approaches equilibrium. The equilibrium here occurs when there are no more molecules of the new bitumen of low viscosity to penetrate the aged layer of binder. That is because the viscosity of the outer medium, which surrounds the aged binder layer, is gradually elevated as some of the aged binder molecules begin to be softened. The diffusion takes place over the majority of the aged layer of binder except at the aggregate-binder interface. This further interaction between the binders via diffusion led to existence of more active binder instead of the inert aged binder. Hence, the binding properties between the aggregates and bitumens increased resulting in an increase in stiffness of the recycled mixture. The proof for occurrence of long-term diffusion can be observed from Figure 7-4 as the SI of the R-mix increases with a rate higher than that of V-mix over the first four months and after that the rate for both mixes seems to be the same, suggesting that the diffusion process might almost be completed or it has no obvious effect after four months. The further increase in stiffness is only due to the ageing process.

From the above discussion, it can be revealed that long-term diffusion occurs between the old and new bitumen in the recycled mix and continues till reaching equilibrium. During this process, improvements in stiffness property of R-mix happen.

7.3.3 Statistical analysis of the results

The error bars shown in Figure 7-3 indicate tight distribution/small error bars for virgin specimens and loose distribution/large error bars for recycled samples, meaning that V-mix demonstrates more consistency than R-mix. This finding can also be observed from the slopes of fitted lines in Figure 7-2 as the slope of V-mix line is less than that of R-mix. Also it is possible to monitor the significant changes between the sequential points if the upper error bar of a point does not overlap the range of the error bar of the next point. So it appears from Figure 7-3 that there is an important variation in the first two months, for R-mix, and then the significant change begins to decrease.

7.3.3.1 Compare the means between V-mix and R-mix

In order to evaluate if there is a significant variation among means of stiffness indices of both mixes (V-mix & R-mix), SPSS 17 (statistical analysis software) was used. Firstly, it is important to know whether the data are following the normal distribution or not so as to determine the correct type of test, either parametric or non-parametric. The normality test was used for this purpose and the outputs are displayed in Table 34. The table contains two tests for normality, the Kolmogorov-Smirnov test and the Shapiro-Wilk test. The most important parts of this table are the columns headed Sig (i.e. significance). As with any statistical test, it is necessary to keep in mind the null hypothesis when interpreting the results. In this case, the null hypothesis would be that there is no difference between the distribution of the data for stiffness index (SI) and a normal distribution. Conventionally, a P value (or Sig value) of less than 0.05 indicates rejection of the null hypothesis and the data do not follow the normal distribution.

Table 34 Normality test for V-mix and R-mix

Tests of Normality

	Group	*Kolmogorov-Smirnov*			*Shapiro-Wilk*		
		Statistic	*df*	*Sig.*	*Statistic*	*df*	*Sig.*
Stiffness index	*R-mix*	*.088*	*90*	*.079*	*.970*	*90*	*.035*
	V-mix	*.099*	*90*	*.030*	*.972*	*90*	*.051*

As seen from the table, the Kolmogorov-Smirnov test indicates normality of the R-mix (as sig > 0.05) and non-normality of the V-mix data (as sig < 0.05). However, the inverse occurs with the Shapiro-Wilk test. And as is well known, the parametric tests are more accurate, simple and preferable to the non-parametric tests, and they need the data to follow normality. Therefore the data of both mixtures were considered follow normality, especially as shown from frequency histograms, Figure 7-7, that the data could be approximately regarded as normally distributed for both mixes.

The Independent sample t-test was selected to compare means of the virgin and recycled mixtures. The outputs of the test are presented in Table 35. The null hypothesis would be that there is no difference in the average SI of the R-mix and that of the V-mix. As is clear from the highlighted cell in Table 35 where sig < 0.05, the null hypothesis is rejected, or in other words, there is a significant variation between the averages SI for V-mix and R-mix.

This finding means that the increase in SI of the R-mix due to ageing and long-term diffusion is considerable compared to the increment in SI of the V-mix according to ageing only. Hence it could be revealed that the long-term diffusion has an effective and significant role in improving the mechanical properties of the recycled mixtures.

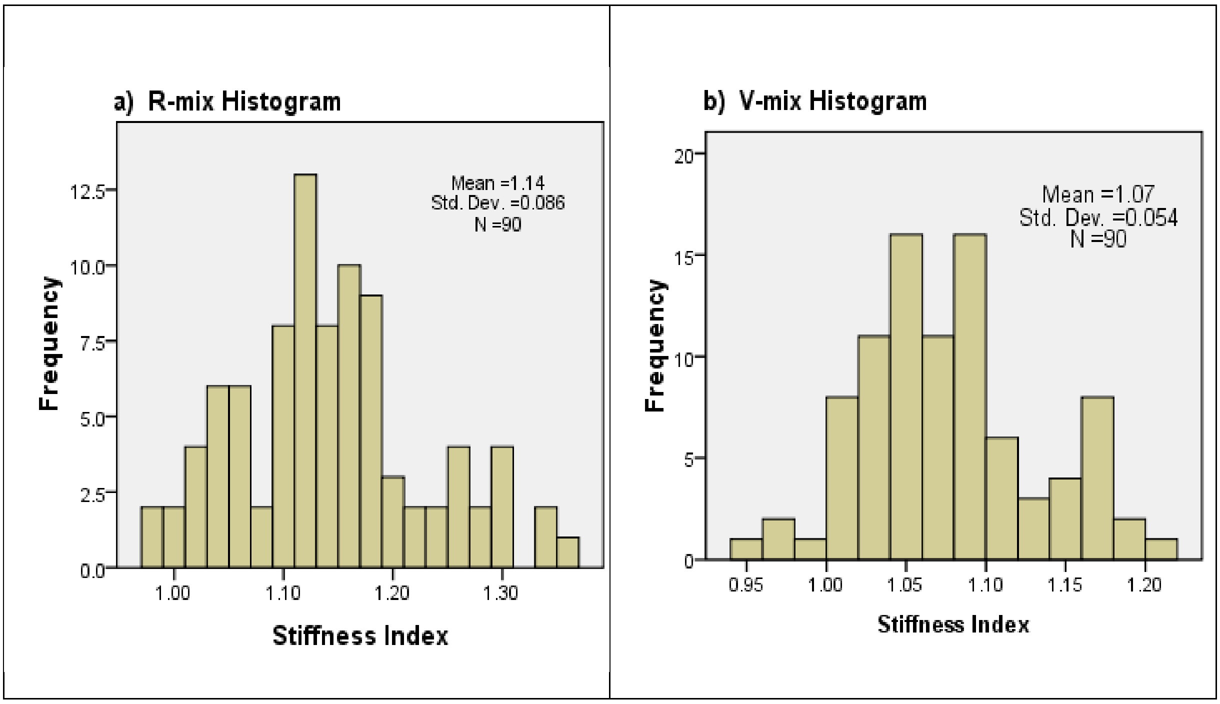


Figure 7-7 Histogram of frequency a) R-mix and b) V-mix

Table 35 Independent sample t-test output for V-mix and R-mix

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
									Lower	Upper
Stiffness index	Equal variances assumed	12.474	.001	6.179	178	.000	.06622	.01072	.04507	.08737
	Equal variances not assumed			6.179	150.416	.000	.06622	.01072	.04505	.08740

7.3.4 Effect of storage temperature on stiffness of hot asphalt mixture

As revealed from the literature, short-term diffusion process is generally affected by the temperature. Increasing temperature provides the molecules extra energy which in turn motivates and accelerates the process of diffusion. Moreover, increasing mixing and compaction temperature, at mixing stage, has a considerable effect on improving the mechanical properties of hot recycled mixtures (as concluded in chapter 4, sec 4.7). As discussed earlier in this chapter, the storage time has significant impact on increasing the stiffness of the recycled mixtures. However, does storage temperature, also, have an effect on the long-term diffusion process?

Figure 7-8 and Figure 7-9 display the increment in SI values over time for the recycled and virgin samples respectively, at different storage temperatures. It is observed from Figure 7-8 that the specimens stored at 30 °C achieved the highest increase in SI through the whole period of the experiment. The next in rank to the R-mix @30 °C samples are the R-mix @5 °C samples, while the samples of R-mix @20 °C had the lowest increase. The same trend occurred with the virgin specimens, but with the exception that the SI-increment-lines overlapped in some test intervals and are limited to a narrow range of 14 % over nine months. However, the SI-increment-lines of recycled samples diverged from each other over the whole seven and half months.

As discussed in section 7.3.2.2, the reasons for the improvements in SI of the R-mix are mainly the ageing process and long-term diffusion. On the other hand, the only cause for any increment in SI of the V-mix is the ageing process. The SI-increment-line of R-mix @ 20 °C will be considered as a datum for purposes of comparison. It can be noticed, from Figure 7-9, that raising the storage temperature from 20 °C to 30 °C led to slight rise in the SI. This slight increase occurred as a result of ageing process due to rising the storage temperature by 10 °C (from 20°C to 30°C). As is well known, increase in temperature results in increase in ageing process.

However, Figure 7-8 shows the significant divergence between the SI-increment-lines of @20 °C and 30 °C. This significant increase in SI indicates the substantial effect of temperature on accelerating the diffusion process. It should state here that process of ageing has a small sharing for this increment.

The conclusion that can be drawn from the above discussion is that storage temperature has substantial effect on motivating the interaction between the aged and new binders, even after production of recycled mixture, via long-term diffusion.

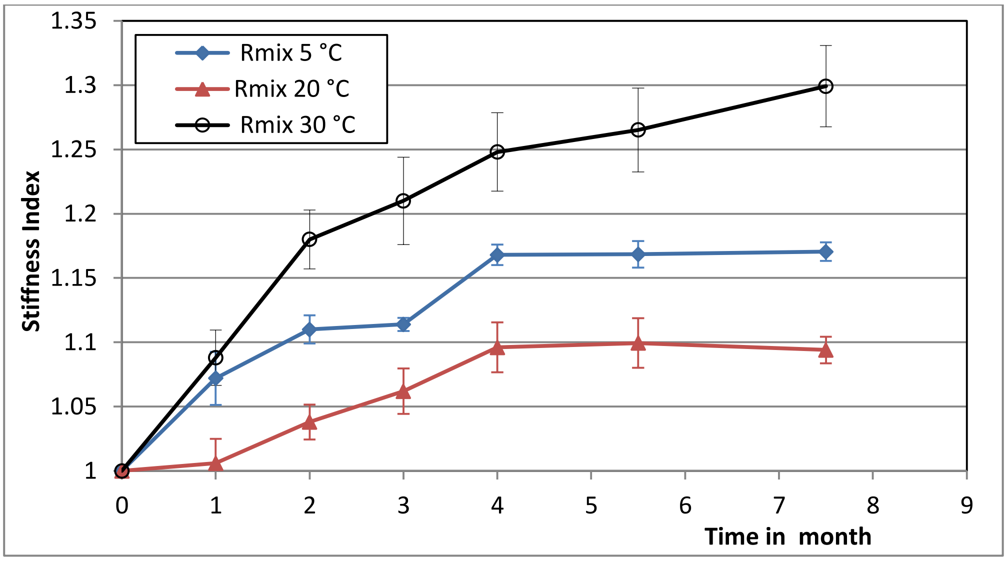


Figure 7-8 Effect of storage temperature on stiffness of hot recycled asphalt mixture

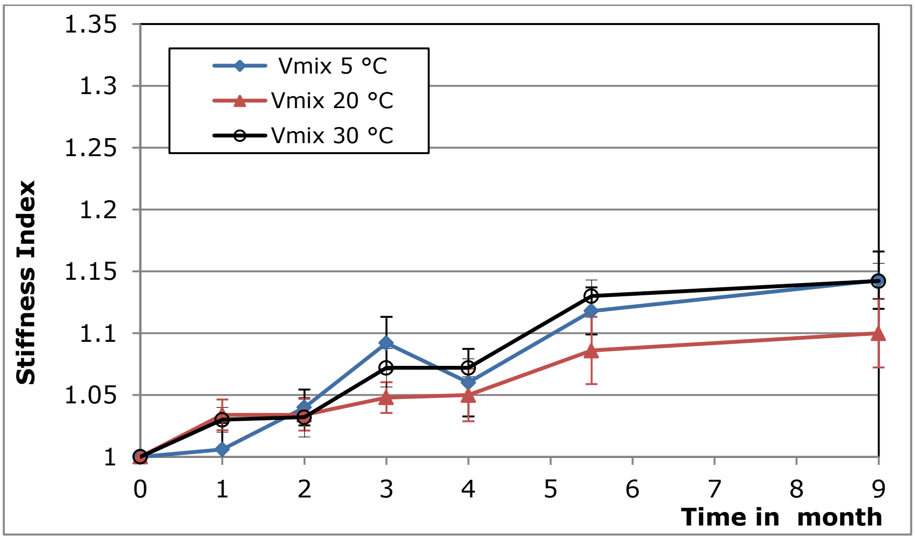


Figure 7-9 Effect of storage temperature on stiffness of hot virgin asphalt mixture

It was expected that the SI-increment-line of R-mix-5 °C would hold the last position between the three groups as the temperature declined from 20 °C to 5 °C, but as shown in Figure 7-8 it comes second to R-mix-30 °C. Almost the same trend exists among the virgin samples, see Figure 7-9. Even though, there is no specified reason for this observation in light of existing data, but the stored specimens at low temperature (5 °C) may have gained further ageing via low-temperature physical hardening.

To prove whether physical hardening is responsible for this observation or not, an experimental program and different techniques would have to be followed. But because this is outside the scope of this research, it is highly recommended to study this point in detail in future work. However, an interpretation will be given and discussed in the context of the following paragraphs in view of the available results as well as previous studies.

The significant effect of physical hardening on bitumen properties at low temperature is well reported. Physical hardening (aging) is a process that occurs at low temperature in asphalt binders as a consequence of cooling or quenching amorphous (non-crystalline) materials from melting temperatures to below the glass transition temperature (Bahia and Anderson, 1993, Anderson and Marasteanu, 1999, Struik, 1977). Read and Whiteoak (2003) mentioned that this process could occur at ambient (room) temperature if bitumen is left isothermally for a long time. The glass transition temperature (Tg) of amorphous materials like bitumen is the critical temperature at which the material changes its behaviour from being glassy (hard and brittle) to being rubbery (elastic and flexible). Physical hardening phenomenon is thermo-reversible in that all the properties affected by physical hardening can be recovered when the binder is heated to room temperature or above.

Unfortunately, low temperature physical hardening has only been reported in asphalt binders and not in asphalt mixtures. Very few investigations have been performed to evaluate physical hardening effect of asphalt mixture behaviour at low temperature. Thus, the effect of low temperature physical hardening on asphalt mixture properties and pavement performance is still not clear enough.

Romero et al. (1999) utilized the thermal stress restrained specimen test (TSRST) to investigate the effect of low-temperature physical hardening on the behaviour of hot asphalt mixtures at low temperature. An outline of Romero et al.’s work is presented in the literature review chapter. The authors revealed that the physical hardening observed in binders might not necessarily transmit into asphalt mixture properties. They also pointed out that other factors such as mineral filler, aggregate, and air voids may have impact on mixture properties more than physical hardening (Romero et al., 1999).

In another study (Cannone Falchetto and Marasteanu, 2011) to investigate the effect of physical hardening on asphalt mixture creep behaviour at low temperatures, Bending Beam Rheometer (BBR) creep tests were applied on prepared beams of asphalt binders as well asphalt mixtures. It was concluded that creep stiffness of all binders increased significantly with conditioning time. However, the results showed that the rise in mixture creep stiffness was much less than that observed in asphalt binder. In addition, only 5% of changes observed in binders as a result of physical hardening were reflected in the composite asphalt mixture, implying that the aggregate might have an important role in transferring these changes from binder to mixtures. The authors recommended using acoustic emission techniques in future research in combination with tests of mixture physical hardening to quantify micro cracking activity that may explain the aggregate components’ role inside the asphalt mixture.

In view of the last discussion, it can be concluded that physical hardening could affect asphalt binder and mixture as well but not equally. A small percentage of the changes that occur in binder due to low-temperature physical hardening might be transmitted to asphalt mixture in terms of increasing stiffness. Moreover, the presence of aggregates beside bitumen within a composite asphalt mixture appears to play a vital role in reducing or increasing the proportion of changes converted to the mixture from binder.

Referring to Figure 7-8, the issue of R-mix-5 °C stiffening more than R-mix-20 °C can be explained as this mixture attained extra stiffness due to physical hardening when stored at low temperature. In addition, the acquired ageing in hot-recycled asphalt mixture seems to be non-reversible, unlike bitumen. The clue for this is because the samples of R-mix-5 °C were conditioned for 7 hrs at 20 °C before applying the ITSM test, and if this process is reversible for mixtures as it is in bitumen, the R-mix-5 °C would not have achieved the position shown in Figure 7-8 and Figure 7-9.

7.4 Summary

It is well known that the properties of hot asphalt mixtures are affected by time due to ageing. However, it is not known whether the recycled asphalt mixtures are affected to the same extent as the virgin asphalt mixtures due to the factor of time, or whether there are other factors that would lead to significant variation in their mechanical properties. To investigate whether there is another factor or not, a group of virgin and recycled laboratory samples were prepared and tested periodically every month via the ITSM test to measure the stiffness modulus and monitor any increase in the stiffness value over time. The principal conclusions that can be drawn from this chapter are:

- ❖ It is advisable for the recycled asphalt specimens to be tested within the first 1.5 months directly after production otherwise a major alteration would happen in their mechanical properties.
- ❖ The maximum time that guarantees no significant variation in the mechanical properties of the virgin asphalt samples is around 5.0 months.

- Since the total blending hypothesis applies to the virgin mixture, the ageing process is the reason for any further increment in stiffness over time.
- In recycled mixtures, long-term diffusion between the old and new binders occurs and continues till reaching an equilibrium stage. During this process, along with the effect of high temperature, the improvement in mechanical properties of the R-mix could be significant.
- Virgin mix demonstrates more consistency than recycled mixture.
- The increase in SI of the R-mix due to ageing and long-term diffusion is statistically significant compared to the increment in SI of the V-mix according to ageing only. Hence long-term diffusion has an effective and important role in improving the mechanical behaviour of recycled mixtures.
- Increasing the storage temperature of the recycled samples has substantial effect on accelerating the interaction between the aged and new binders via long-term diffusion process.
- As revealed from literature, asphalt mixture can be affected by physical hardening but not to the same extent as binder. Also existence of aggregates in the composite asphalt mixture seems to have a basic role in determining the proportion of changes transmitted from binder to mixture.
- The further ageing in hot-recycled asphalt mixture due to low-temperature physical hardening might not be reversible as is the case in bitumen.

8 Conclusions and recommendations for future work

8.1 Conclusions

This research presents a new piece of work in asphalt hot recycling topic which can benefit highway agencies, contractors, and pavement designers as well. As revealed from past researches, properties of recycled mixes differ from those of virgin mixes (Al-Rousan et al., 2008, Oliver, 2001, Tabakovic et al., 2006, Tran and Hassan, 2011, Widyatmoko, 2008, Al-Qadi et al., 2007). The reason behind this is because they have RAP materials as a main element of their constituents. In addition, the binder of RAP is hard (due to ageing) and needs to be rejuvenated via blending with a recycling agent in order to restore its properties. However, full rejuvenation of RAP binder is not exist in real world, because not all the RAP binder leaves RAP lumps and contributes in blending process with the recycling agent. Therefore, the mechanical properties and durability of recycled mixes differ from virgin ones.

Since the hot recycling of pavement is not a new technology, there are current roads constructed by using recycled mixtures. Now the question is if these roads are going to be recycled for second or third time, will the performance of resultant recycled mix after second or third cycle significantly differ from that produced after first cycle? In another words, what is the effect of repeated recycling on the properties of recycled HMA? The answer for this question was the main challenge of this research.

The main findings from literature include:

A- The hypothesis of current methods for design the recycled HMA (such as Asphalt Institute Design Method) assumes the complete blending between the virgin and RAP binder. In practice, the complete blending does not exist (Al-Qadi et al., 2007, McDaniel and Anderson, 2001) because the soft new bitumen cannot penetrate all layers of the aged binder around RAP particles (Huang et al., 2004, Oliver, 2001).

B- Also the current recycled mix designs presume 100% contribution of working binder from RAP materials when added to the recycled HMA. This means all RAP binder leaves surfaces of RAP particles to the mixing medium in order to interact with the new bitumen (Al-Qadi et al., 2007). However, it is unclear if the previous assumption is correct and whether some of the binder acts as black rock and not contributing in the mixing process. In addition, this assumption is hardly to be true especially when high percentage of sever aged RAP is employed. (Doyle and Howard, 2010) reported that around 67% to 87% of the total RAP binder can be reusable and that as the RAP materials are more aged, the amounts of reusable bitumen decline.

C- Common hypotheses that explain why complete blending does not occur between aged and virgin binder are:

- (Carpenter and Wolosick, 1980) proposed that the recycling agents do not promptly combine with the aged binder during the mixing process, but this interaction takes time.
- (Oliver, 2001) assumed forming a "shell" from the soft virgin binder around the aged binder, creating regions of low viscosity which in turn control the performance of recycled HMA.
- A third hypothesis was put forward by (Huang et al., 2005) in that, the RAP functionally acts as "composite black rock" because some portions of the aged RAP binder form a stiff coating around RAP aggregates, while other portions actually participate in the mixing process.

D- The results from past researchers that have investigated and evaluated the performance of HMA incorporating RAP have been mixed and no definitive conclusion can be drawn from past research projects.

- At the time that some researchers have revealed that use of RAP improves stiffness property of recycled HMA (Al-Rousan et al., 2008, Huang et al., 2005, Huang et al., 2004, McDaniel and Shah, 2003, Sargious and Mushule, 1991), others have reported the opposite (Oliver, 2001, Widyatmoko, 2008).

- While some researchers have found that recycled HMA provide inferior fatigue and thermal performance compared to virgin mixes (Tam et al., 1992, McDaniel et al., 2000), others have observed improvements in fatigue resistance (Widyatmoko, 2008, Oliver, 2001).

The principal conclusions from the laboratory results of the repeated recycling investigation are:

1. Repeated recycling has no significant effect on degradation of the mechanical properties of the recycled HMA in terms of stiffness and fatigue.
2. Mixtures containing various percentages of RAP contents (25% up to 70%) tended to have lower stiffness than the control V-mix 40/60; the difference in stiffness ranged from 20% to 30%.
3. Stiffness moduli of all tested recycled mixes are located in a range with differences less than 10 %, indicating no significant differences between the mixes with high (≥50%) and common (≥25%) RAP content. Hence, from a laboratory point of view, the RAP content can be increased without affecting performance of the recycled mixes, only if warming of RAP is applied.
4. Complete blending, which is assumed in the design process, between the RAP and virgin binders would never exist in practise. This problem makes the recycled mixes have inferior mechanical properties compared to those of completely blended mixtures. Accordingly, the design methods for recycled mixtures tend to overestimate their performance.
5. All tested recycled mixes had stiffness moduli close to V-mix 70/100; differences in stiffness values fluctuated between +4.0% to -8.0%. This indicates that the mechanical properties of the recycled mixtures were relatively dominated by the property of the new bitumen.
6. All recycled mixes, except the R2-rd2, behaved similarly in fatigue regardless of their RAP content. It seems that warming of RAP helped to minimize the effect of RAP content. Therefore,

acceptable mechanical properties of recycled mixes containing high RAP content are achievable by preheating the RAP.

7. The recycled mixtures composed of small sizes of RAP particles generally have more stiffness than those made from large sizes. Using small sizes of RAP leads to an increase in surface area, which with the presence of warming results in liberating (bleeding) more RAP binder into the mixing medium. This in turn provides more interaction between the aged and virgin binders.
8. There are no significant differences in mechanical properties (stiffness and fatigue behaviour) between the recycled mix in the total blending case and the virgin mix. Consequently, this emphasizes the significant effect of the blending process on improving the performance of recycled mixtures.
9. Mixing and compaction temperature had the greatest impact on improving stiffness and fatigue resistance of the recycled mixes. Moreover, the highly aged RAP does not act as black rock only when it is heated and/or mixed at high, safe temperature.
10. There is no experimental tool to determine the actual properties of the effective binder of the recycled mixture. However, the Hirsch model was used in an attempt to predict the complex shear modulus (G*) of the effective binder within the recycled mixture from the ITSM data. The model showed itself to be a possible tool to estimate approximate and acceptable values of G* for these effective binders.

The main findings from investigating the factors affecting the efficiency of blending, and from water sensitivity test are

11. The recycled mixes produced by the rotating inclined mixer, after warming the RAP at 80°C, exhibited considerable improvements in stiffness compared to the mix produced by the normal, horizontal mixer. This indicates that using rotating inclined mixers such as drum mixers can improve the efficiency of blending, especially when RAP materials are warmed.
12. Stiffness modulus of the R-mix produced at only 2min dry mixing with 80°C WRT was at least similar to or better than

those produced at 16min and 8min dry mixing with no warming of RAP. It means that considerable time can be saved by warming RAP before the mixing process. These savings in time increase the productivity of the asphalt mixing plant.

13. When warming of RAP is not sufficient to soften the bond between aggregate agglomerations, dry mixing with superheated aggregates will strongly contribute to separate the lumps of RAP. However, when warming of RAP is enough to deactivate the bonds in RAP lumps, the effect of dry mixing will only heat the RAP up to the mixing temperature and distribute its particles all over the mixture.
14. The behaviour of recycled and virgin mixtures under the water sensitivity test was similar in that there was an initial increase in stiffness, after the first conditioning cycle, and then the deterioration began. Both mixes were demonstrated to be non-susceptible to damage by moisture, but the recycled specimens manifested better resistance.

The concluded outcomes from investigating the effect of storage time on stiffness modulus of the recycled HMA are:

15. It is advisable for the recycled specimens to be tested within 1.5 months after production; otherwise major alterations would happen in their mechanical properties due to long-term diffusion and ageing. However, 5.0 months is the maximum period for the virgin samples to be tested without significant changes in their properties as a result of ageing.
16. Increasing the storage temperature of the recycled samples has substantial effect on accelerating the interaction between the aged and new binders via the long-term diffusion process.

8.2 Recommendations for future work

1. It is likely that laboratory mixing cannot adequately simulate field mixing. Hence, testing of field mixes is required to provide superior overall evaluation of the expected performance.

2. The argon inert oven can possibly be a suitable tool to assess the effect of long-term diffusion on enhancing strength of the recycled HMA, where it eliminates the effect of oxidation.
3. Additional work and research is needed to understand the behaviour of recycled HMA subjected to low temperature for extended periods of time under the effect of physical hardening.
4. Using the Hirsch model to estimate the G* of the effective binder of the recycled mix from the ITSM data gives only one value of G* at a frequency of 1.33 Hz. Therefore, it is highly recommended to apply the model to the data from the complex modulus test for mixture in order to estimate the G* values over a wide range of frequencies.
5. An effective tool needs to be evolved in order to determine the actual grading line of RAP aggregate, at the mixing stage. Hence, this grading is the one that should be used in the design procedures. The idea of Los Angeles abrasion test might be applicable with procedures in Appendix 4
6. Research is needed to study the properties of aged binder at aggregate-binder interface in RAP materials. This would provide deep understanding of how the RAP binder and recycling agents interact. Using the staged extraction and recovery technique followed by SARA analysis (Saturates, Aromatic, Resins, and Asphaltenes) for the recycled samples after mixing stage as well after far intervals could be beneficial to monitor any effect of additional diffusion between the RAP binder and recycling agent.
7. Many researches have been done to investigate the blending between the aged and virgin binder of the recycled HMA (Stephens et al., 2001, Oliver, 2001, McDaniel et al., 2000). However, quantifying the participation ratio of RAP binder is not clear yet and needs to be deeply studied. The success in specifying this ratio will make the design methods more accurate instead of hypothesizing 100% contribution for RAP binder, which is not true.

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10 Appendices

Appendix 1

Calculation of the Maximum Theoretical Density of bituminous mixture

Percent of each nominal aggregate size in total aggregate content

10 mm	6 mm	Dust	
34 %	34 %	32 %	100 %

$$\rho_{mc} = \frac{100}{\frac{P_{a1}}{\rho_{a1}} + \frac{P_{a2}}{\rho_{a2}} + \cdots . + \frac{P_b}{\rho_b}}$$

Where:

ρ_{mc} is the maximum density of the mixture, kg/m^3

P_{a1} is the percentage of aggregate no.1 in the mixture

ρ_{a1} is the apparent density of aggregate no.1, kg/m^3

P_{a2} is the percentage of aggregate no.2 in the mixture

ρ_{a2} is the apparent density of aggregate no.2, kg/m^3

P_b is the percentage of binder in the mixture

ρ_b is the density of the binder, kg/m^3

$\because P_{a1} + P_{a2} + \ldots + P_b = 100$ % , $P_b = 5.2$ %

$\therefore P_{aggregate} = 100-5.2 = 94.8$ %

$\therefore P_{a1} = P_{a2} = 34*(94.8/100) = 32.2$ % , $P_{a3} = 32*(94.8/100) = 30.3$ %

$$\therefore \rho_{mc} = \frac{100}{\frac{32.23}{2851}+\frac{32.23}{2726}+\frac{30.34}{2736}+\frac{5.2}{1031}} = 2547 \text{ kg/m}^3$$

Appendix 2

Table 36 Design table of R1-rd1

Target Air Voids:	5%	**Samples type:**	(100*60) mm D * H
Maximum Density:	2547 kg/m3	**Target Density:**	2420 kg/m3
Asphalt Grade:	70/100	**Binder Content:**	2.184 %

Aggregate Size	Mass %	Mass g
RAP[1]	61.8	689
10 mm	20	223
6.0 mm	18.2	203
Dust	0.0	0.0
Sum	100	1115
Binder	2.184	25
Total Mass		1140

Table 37 Design table of R2-rd1

Target Air Voids:	5%	**Samples type:**	(100*60) mm D * H
Maximum Density:	2547 kg/m3	**Target Density:**	2420 kg/m3
Asphalt Grade:	70/100	**Binder Content:**	3.016 %

Aggregate Size	Mass %	Mass g
RAP[2]	44.7	494
10 mm	22	243
6.0 mm	27	299
Dust	6.3	70
Sum	100	1106
Binder	3.016	34
Total Mass		1140

Table 38 Design table of R3-rd1

Target Air Voids:	5%	**Samples type:**	(100*60) mm D * H
Maximum Density:	2547 kg/m3	**Target Density:**	2420 kg/m3
Asphalt Grade:	70/100	**Binder Content**:	3.85 %

Aggregate Size	Mass %	Mass g
RAP[3]	29	318
10 mm	28	307
6.0 mm	25	274
Dust	18	197
Sum	100	1096
Binder	3.85	44
Total Mass		1140

Table 39 Design table of R1-rd2

Target Air Voids: 5%		**Samples type:** (100*50) mm D * H	
Maximum Density: 2547 kg/m3		**Target Density:** 2420 kg/m3	
Asphalt Grade: 70/100		**Binder Content:** 1.96 %	
Aggregate Size	**Mass %**	**Mass g**	
RAP[1]	65.0	606	
10 mm	20.0	186	
6.0 mm	15.0	140	
Dust	0.0	0.0	
Sum	100	932	
Binder	1.96	18	
Total Mass		950	

Table 40 Design table of R2-rd2

Target Air Voids: 5%		**Samples type:** (100*50) mm D * H	
Maximum Density: 2547 kg/m3		**Target Density:** 2420 kg/m3	
Asphalt Grade: 70/100		**Binder Content:** 2.496 %	
Aggregate Size	**Mass %**	**Mass g**	
RAP[2]	55	510	
10 mm	20	185	
6.0 mm	22	204	
Dust	3	28	
Sum	100	927	
Binder	2.496	24	
Total Mass		950	

Table 41 Design table of R3-rd2

Target Air Voids: 5%		**Samples type:** (100*50) mm D * H	
Maximum Density: 2547 kg/m3		**Target Density:** 2420 kg/m3	
Asphalt Grade: 70/100		**Binder Content**: 4.0 %	
Aggregate Size	**Mass %**	**Mass g**	
RAP[3]	25	228	
10 mm	30	274	
6.0 mm	25	228	
Dust	20	182	
Sum	100	912	
Binder	4	38	
Total Mass		950	

Table 42 Design table of R1-rd3

Target Air Voids:	5%	**Samples type:**	(100*50) mm D * H
Maximum Density:	2547 kg/m3	**Target Density:**	2420 kg/m3
Asphalt Grade:	70/100	**Binder Content:**	1.612 %

Aggregate Size	Mass %	Mass g
RAP[1]	69	648
10 mm	26	244
6.0 mm	5	47
Dust	0.0	0.0
Sum	100	940
Binder	1.612	15
Total Mass		950

Table 43 Design table of R2-rd3

Target Air Voids:	5%	**Samples type:**	(100*50) mm D * H
Maximum Density:	2547 kg/m3	**Target Density:**	2420 kg/m3
Asphalt Grade:	70/100	**Binder Content:**	2.236 %

Aggregate Size	Mass %	Mass g
RAP[2]	57	530
10 mm	20	186
6.0 mm	20	186
Dust	3.0	28
Sum	100	929
Binder	2.236	21
Total Mass		950

Table 44 Design table of R3-rd3

Target Air Voids:	5%	**Samples type:**	(100*50) mm D * H
Maximum Density:	2547 kg/m3	**Target Density:**	2420 kg/m3
Asphalt Grade:	70/100	**Binder Content:**	3.9 %

Aggregate Size	Mass %	Mass g
RAP[3]	26	219
10 mm	30	275
6.0 mm	25	228
Dust	19	192
Sum	100	913
Binder	3.9	37
Total Mass		950

Appendix 3

Table 45 Stiffness moduli of non-aged and aged virgin samples

	Sample ID	H mm	D mm	% Air voids	% Air voids Ave	Density kg/m³	Stiffness Modulus MPa	Stiffness Ave	Machine type
Non-agedV-mix	10-1271	41	100	4.8	**3.7**	2547	6355	**6469**	√
	10-1272	40	100	4.2		2439	6279		√
	10-1273	39	100	3.3		2464	6677		√
	10-1275	39	100	3.2		2465	6748		√
	10-1276	40	100	3.4		2460	6537		√
	10-1277	40	100	3.1		2467	6243		√
	10-1278	40	100	3.0		2470	6748		√
	10-1279	40	100	3.0		2471	6118		√
	10-1280	40	100	4.3		2438	6514		√
Aged 40 hr @ 105 °C	10-1305	40	100	4.1	**3.7**	2443	8895	**8719**	*
	10-1306	40	100	2.9		2473	9681		*
	10-1307	40	100	3.0		2470	8917		*
	10-1308	40	100	2.6		2480	8434		*
	10-1309	40	100	3.5		2457	8901		*
	10-1310	40	100	4.4		2434	8808		*
	10-1311	40	100	3.2		2465	7983		*
	10-1313	41	100	4.3		2438	8976		*
	10-1314	40	100	4.5		2433	7874		*
Aged 65 hr @ 125 °C	10-1486	41	100	3.7	**4.0**	2452	7646	**8284**	√
	10-1487	40	100	3.2		2466	8537		√
	10-1488	41	100	5.3		2411	7783		√
	10-1489	41	100	3.4		2460	8239		√
	10-1490	41	100	2.8		2476	8302		√
	10-1491	41	100	3.7		2452	8234		√
	10-1492	41	100	4.0		2444	7968		√
	10-1493	41	100	4.0		2446	8568		√
	10-1495	41	100	3.6		2455	8855		√
	10-1496	41	100	4.3		2437	8596		√
	10-1497	40	100	3.9		2447	7309		√
	10-1269	39	100	4.9		2422	8696		√
	10-1270	40	100	3.8		2451	8590		√
Aged 2weeks @ 125 °C	10-2141	41	100	4.0	**4.0**	2445	10131	**8284**	√
	10-2143	41	100	4.6		2430	9214		√
	10-2144	41	100	3.5		2458	9890		√
	10-2145	41	100	4.9		2422	8749		√
	10-2146	41	100	3.8		2450	10775		√
	10-2147	39	100	3.6		2455	9609		√
	10-2148	41	100	5.4		2410	10150		√
	10-2149	41	100	5.1		2417	9634		√
	10-2150	41	100	3.6		2455	9362		√
	10-2151	40	100	4.4		2430	9214		√
	10-2152	41	100	3.5		2458	9890		√

* NAT E0016 √ NAT E0015

Appendix 4

Approximate method to predict the effective grading line of RAP aggregate at mixing

- Prepare representative sample of crushed RAP materials, example 2 Kg
- Apply the particle size distribution test to establish the grading line of crushed RAP
- Prepare sample of 2 Kg of virgin aggregate so that its minimum particle size is larger than the maximum size of crushed RAP agglomeration. Thus the virgin and RAP aggregates could be visually distinguished (for example if maximum RAP particle size is retained on sieve No. 14mm, the minimum virgin aggregate particle size should be retained on sieve No. 19mm)
- Heat the sample of virgin aggregate to the required superheated temperature of 215°C for at least 7 hr, as used in this study
- Warm RAP sample for 2 hrs 70 °C (temperature can be estimated from Equation 16 andEquation 17 by knowing mixing temperature of 135°C, superheated temperature of virgin aggregate, and % RAP of 50 %)
- Mix the two samples in the mixer with maintained mixing temperature of 135 °C for 8 minutes (as used in this study)
- Separate the two samples by grading, and establish final grading line for crushed RAP, then make a comparison with the initial one to see if there significant change.

The final gradation of crushed RAP would approximately represent the effective gradation upon mixing process and can be used in the design method of recycled mixtures instead of the gradation of the recovered aggregate from RAP.

Notice:

This method has been carried out and the virgin aggregate was large particles of granite. But, after finishing the dry mixing stage the distinguish between the RAP particles and granite aggregate was not clear as the mastic started to be soften and then stacked with Granite particles. Therefore, this method was not valid for dry mixing at high temperature.

However, the granite particles can be replaced by steel balls (like Los Angeles abrasion test), in addition to implementing the test without warming RAP.

Appendix 5

Table 46 Results of ITSM test at 20 °C test temperature

Mixer type	RAP warm Temp	Dry mixing time	Sample ID	voids %	ITSM (20 °C) Mpa	ITSM (20 °C) Ave
Inclined	20 °C	2 min	11-1313	7.5	4423	4731
			11-1314	6.0	5234	
			11-1315	6.1	4390	
			11-1316	6.0	4876	
		8 min	11-1325	7.8	4386	4862
			11-1326	6.8	4678	
			11-1327	6.7	4752	
			11-1328	5.7	5634	
		16 min	11-1337	5.8	5051	5050
			11-1338	6.0	5477	
			11-1339	7.5	5027	
			11-1340	5.8	4643	
	40 °C	2 min	11-1317	8.1	4338	4808
			11-1318	5.4	5113	
			11-1319	6.6	5096	
			11-1320	7.1	4684	
		8 min	11-1329	8.2	4980	4925
			11-1330	6.2	4824	
			11-1331	6.8	4925	
			11-1332	6.7	5266	
			11-1800	7.6	4632	
		16 min	11-1341	7.3	5737	5069
			11-1342	7.1	4977	
			11-1343	7.8	4657	
			11-1344	6.7	4905	
	80 °C	2 min	11-1321	7.1	4762	5069
			11-1322	7.3	4628	
			11-1323	6.5	5155	
			11-1324	4.8	5646	
		8 min	11-1333	5.9	5006	5126
			11-1334	5.7	5060	
			11-1335	5.4	5312	
		16 min	11-1346	5.2	5096	5177
			11-1347	7.9	5496	
			11-1348	5.3	4940	
Normal	40 °C	8 min	11-1350	6.9	4276	4586
			11-1351	4.9	4707	
			11-1352	5.0	4774	

Appendix 6
Table 47 Results of water sensitivity test

Mixer type	WRT	Dry mixing time	Sample ID	ITSM$_U$ Mpa	Stiffness ratio							
					Cycle 1	Ave	Cycle 2	Ave	Cycle 3	Ave	Cycle 4	Ave
Inclined	20 °C	2 min	11-1313	4563	1.09	**1.13**	1.10	**1.12**	1.01	**1.06**	1.09	**1.04**
			11-1314	5459	1.11		1.11		1.12		1.06	
			11-1315	4758	1.16		1.13		1.05		1.03	
			11-1316	4941	1.15		1.13		1.06		0.99	
		8 min	11-1325	4449	1.22	**1.14**	1.17	**1.12**	1.07	**1.08**	1.04	**1.06**
			11-1326	4736	1.09		1.08		1.04		1.02	
			11-1327	4710	1.11		1.10		1.13		1.08	
			11-1328	5464	1.14		1.11		1.09		1.1	
		16 min	11-1337	5174	1.15	**1.17**	1.13	**1.13**	1.11	**1.09**	1.03	**1.06**
			11-1338	5680	1.05		1.11		1.09		1.06	
			11-1339	5247	1.32		1.20		1.09		1.09	
			11-1340	5000	1.17		1.10		1.07		1.05	
	40 °C	2 min	11-1317	4513	1.15	**1.15**	1.05	**1.12**	1.11	**1.10**	1.06	**1.07**
			11-1318	4858	1.19		1.21		1.18		1.14	
			11-1319	5096	1.14		1.17		1.03		1.02	
			11-1320	4688	1.12		1.03		1.06		1.05	
		8 min	11-1329	4980	1.23	**1.19**	1.16	**1.13**	1.19	**1.09**	1.18	**1.08**
			11-1330	5017	1.18		1.19		1.14		1.1	
			11-1331	4925	1.16		1.12		1.12		1.07	
			11-1332	5266	1.15		1.08		1.04		1.0	
			11-1800	4742	1.22		1.11		1.05		1.05	
		16 min	11-1341	6017	1.08	**1.17**	1.04	**1.13**	1.01	**1.11**	1.01	**1.06**
			11-1342	4743	1.18		1.16		1.2		1.19	
			11-1343	4527	1.23		1.15		1.1		0.97	
			11-1344	4938	1.19		1.15		1.13		1.08	
	80 °C	2 min	11-1321	4762	1.09	**1.15**	1.10	**1.12**	1.04	**1.10**	1.01	**1.05**
			11-1322	4628	1.08		1.10		1.09		0.97	
			11-1323	4503	1.31		1.26		1.22		1.22	
			11-1324	5646	1.11		1.02		1.08		1.01	
		8 min	11-1333	5164	1.19	**1.22**	1.05	**1.13**	1	**1.10**	0.94	**1.07**
			11-1334	5145	1.31		1.19		1.2		1.16	
			11-1335	5407	1.16		1.14		1.09		1.12	
		16 min	11-1346	5096	1.26	**1.27**	1.16	**1.13**	1.08	**1.09**	1.1	**1.08**
			11-1347	5502	1.25		1.05		1.00		0.99	
			11-1348	5026	1.27		1.16		1.14		1.12	
average						**1.18**		**1.12**		**1.09**		**1.06**

			Cycle 1	Ave	Cycle 2	Ave	Cycle 3	Ave	Cycle 4	Ave
Virgin mix	11-3048	4634	1.05	**1.06**	1.02	**1.02**	0.97	**1.00**	0.96	**0.97**
	11-3049	4719	1.06		1.04		0.99		0.98	
	11-3050	5690	1.06		0.99		0.99		0.94	
	11-3051	5925	1.07		1.01		1.05		1.01	

Appendix 7

Table 48 Stiffness modulus values for virgin and recycled mixes

Storage Temp.	V mix							R mix						
	0	1	2	3	4	5	8.5	0	1	2	3	4	5.5	Time in months
5 °C	7046	7377	7584	7752	7506	8059	8255	3869	4056	4343	4320	4587	4469	
	7132	7105	7283	7731	7418	7885	7992	3842	4046	4369	4246	4478	4336	
	7249	7013	7291	7634	7500	7799	8006	3793	4216	4257	4204	4366	4333	
	6739	7158	7229	7874	7847	7985	8224	3628	4114	3955	4115	4275	4294	
	6771	6416	6878	7155	6786	7294	7431	3525	3601	3809	3881	4038	3865	
20 °C	7907	8016	7998	8218	7861	8097	8572	6395	6240	6500	6616	6613	6591	
	7960	8119	8267	8302	8324	8679	8724	6082	6544	6617	6856	6920	6735	
	8111	8260	8116	8226	8290	8315	8622	5779	5704	5877	6081	6516	6162	
	6998	7524	7370	7462	7741	8127	8349	5874	5853	6096	6231	6420	6456	
	8217	8556	8808	8851	8896	9292	9566	5862	5758	5951	6112	6382	6210	
30 °C	8286	8453	8640	8998	8917	9472	9742	5669	5818	6329	6284	6536	6491	
	8399	8701	8703	9000	9053	9683	9861	5265	5816	6151	6659	6691	6823	
	8611	8595	8346	8907	9061	9340	9577	5201	5442	5989	6040	6446	6500	
	8991	9239	9404	9410	9571	9839	10177	4660	5358	5824	6072	6229	6250	
	9268	9806	9827	10344	10096	10528	10878	4346	4821	5257	5296	5386	5372	
Ave	7846	8023	8116	8391	8324	8693	8932	4919	5159	5422	5534	5726	5659	

Appendix 8
Calculation of VMA and VFB for virgin and recycled mixes

Table 49 VMA and VFB for all virgin and recycled mixes

		10mm %	6mm %	Dust %	RAP %	G_{sb}	G_{mb}	P_{nb} %	P_{eff}** %	P_s** %	VMA %	VFB %
	G_{agg}	2.851	2.726	2.736	2.705*							
V-mix40/60		34	34	32	0	2.771		5.2	5.2	94.8	17.19	70.9
V-mix70/100		34	34	32	0	2.771		5.2	5.2	94.8	17.19	70.9
R1-rd1		20	18	0	62	2.737		2.18	4.29	95.7	15.37	67.5
R1-rd2		20	15	0	65	2.736		1.96	4.23	95.8	15.31	67.4
R1-rd3		26	5	0	69	2.743		1.6	4.12	95.9	15.22	67.1
R2-rd1		22	27	6	45	2.743	2.42	3	4.54	95.5	15.59	67.9
R2-rd2		20	22	3	55	2.739		2.51	4.39	95.6	15.46	67.7
R2-rd3		20	20	3	57	2.738		2.24	4.31	95.7	15.39	67.5
R3-rd1		28	25	18	29	2.755		3.9	4.81	95.2	15.83	68.4
R3-rd2		30	25	20	25	2.759		4	4.84	95.2	15.86	68.5
R3-rd3		30	25	19	26	2.759		3.9	4.81	95.2	15.83	68.4

** $P_{eff} = P_{nb} + R\,(P_{bt} - P_{nb})$, R=70%, P_{bt}= 5.2% $P_s = 100 - P_{eff}$

VMA and VFB for V-mix

$$G_{sb} = \frac{100}{\frac{34}{2.851} + \frac{34}{2.726} + \frac{32}{2.736}} = 2.771$$

$$VMA = 100 - \frac{G_{mb} * P_s}{G_{sb}} = 100 - \frac{2.42 * 94.8}{2.771} = 17.19\,\%$$

$$VFB = 100 * \frac{VMA - V_a}{VMA} = 100 * \frac{17.19 - 5}{17.19} = 70.9\,\%$$

* Calculating bulk specific gravity G_{sb} of RAP

$$G_{se} = \frac{100 - P_b}{\frac{100}{G_{mm}} - \frac{P_b}{G_b}} = \frac{100 - 4.9}{\frac{100}{2.508} - \frac{4.9}{1.04}} = 2.705$$

Where

G_{se} : Effective specific gravity of recycled aggregate which is used instead of G_{sb}(bulk specific gravity) in volumetric calculations

P_b : RAP binder content %

G_{mm} : Theoretical maximum specific gravity of RAP. It was determined experimentally and equals 2.508 (BS EN 12697-5, 2009)

G_b : Specific Gravity of RAP binder (assumed 1.04 for the aged binder as it had penetration less than 15 dmm)

VMA and VFB for R-mixes are the same like V-mix

Appendix 9
Ageing effect on stiffness and fatigue behaviour of the R-mixes of 1st cycle of recycling

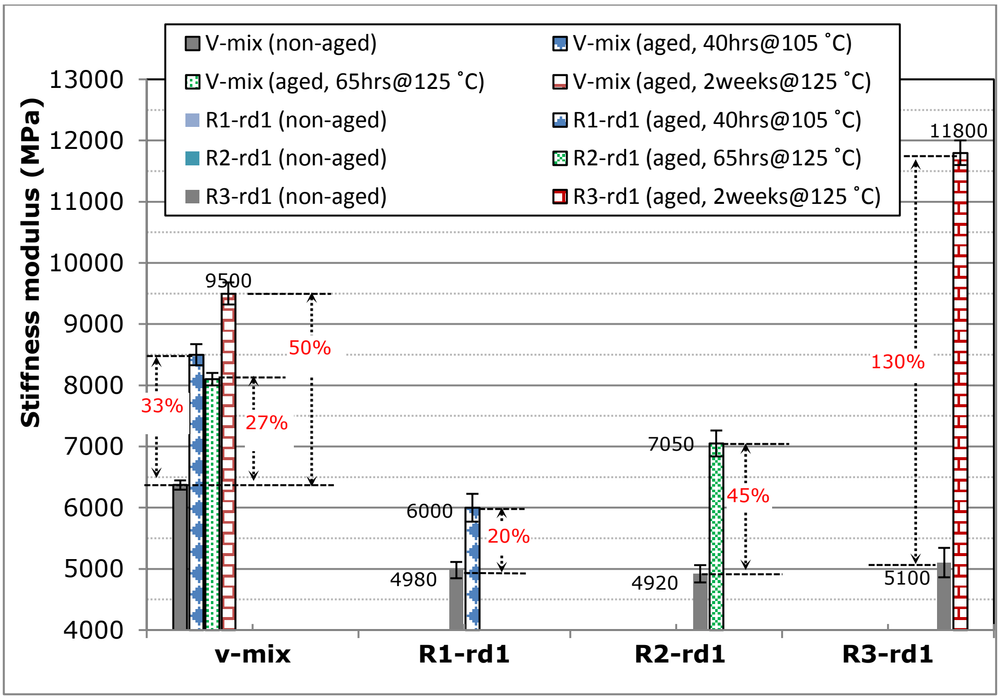

Figure 10-1 Effect of ageing on stiffness of V-mixes and R-mixes of 1st cycle of recycling

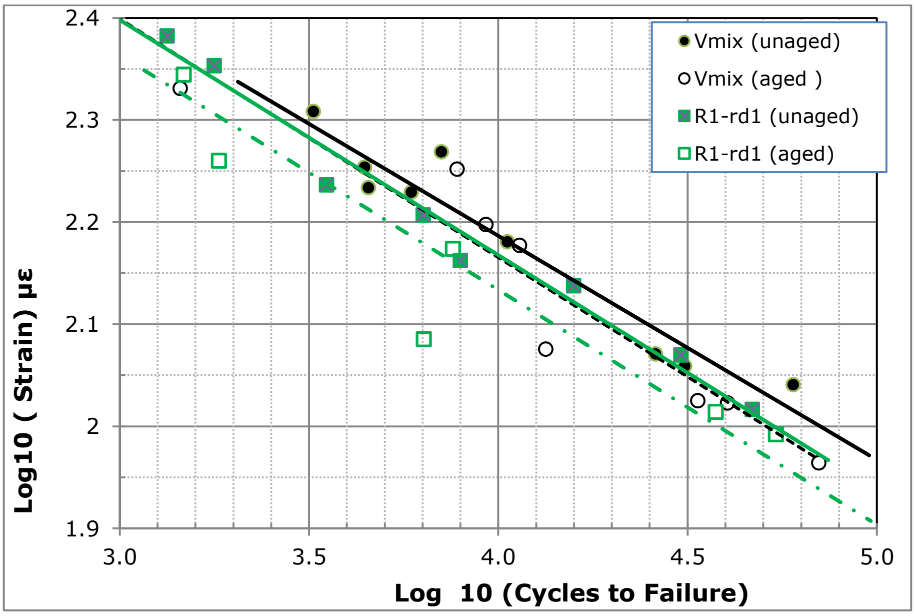

Figure 10-2 Effect of ageing of 40hrs@105 ˚C on fatigue behaviour of V-mix and R1-rd1

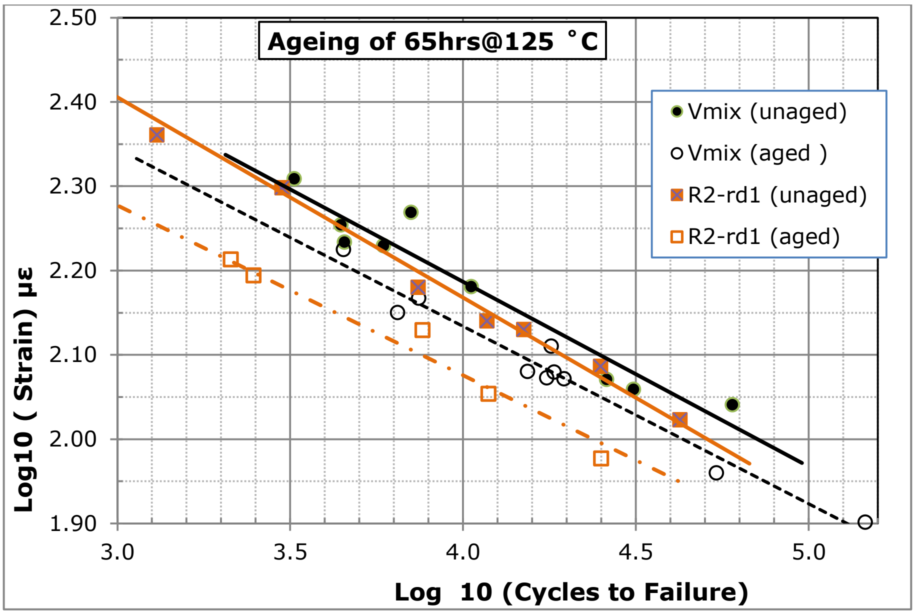

Figure 10-3 Effect of ageing of 65hrs@125 ˚C on fatigue behaviour of V-mix and R2-rd1

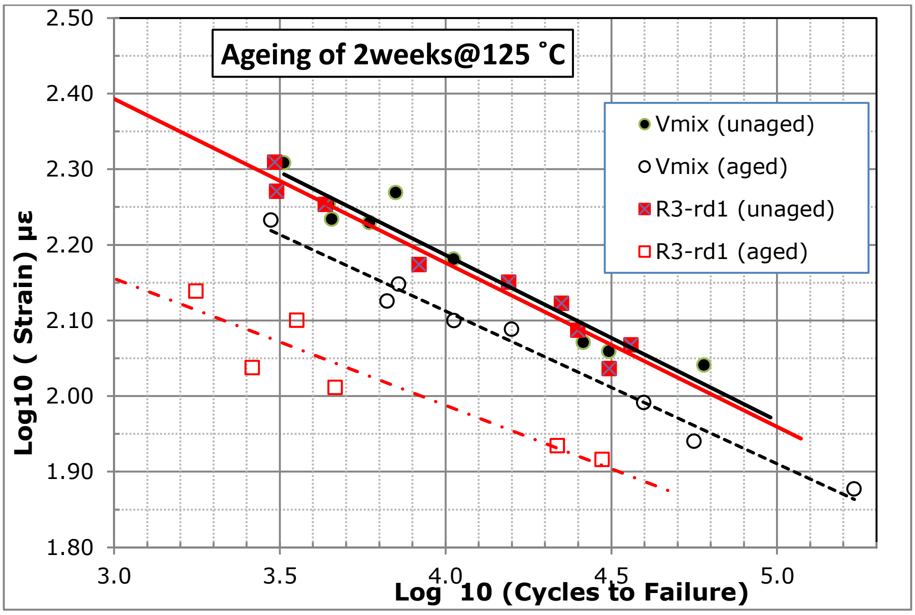

Figure 10-4 Effect of ageing of 2weeks@125 ˚C on fatigue behaviour of V-mix and R3-rd1