Effects of Laboratory Mixing Methods and RAP Materials on Performance of Hot Recycled Asphalt Mixtures

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Abstract

The primary work reported in this thesis is concerned mainly with the effects of different mixing methods and RAP materials on homogeneity and mechanical properties of hot recycled asphalt mixtures. The recycled asphalt mixture conforms to the requirement of BS 4987-1 (2005) for dense bitumen macadam size 10 mm (DBM 10 mm). The proportion of RAP in the recycled mixture is 40%. RAP materials are artificially aged and processed in the laboratory to prevent the variability of RAP gradation, bitumen content, and the origin. Laboratory RAP is also used to assure that every single RAP particle is an agglomerate of RAP aggregate and binder.

The mixing procedures include Black Rock (BR), Complete Blending (CB), the SHRP procedure, and a newly developed field simulation method (FS). The primary difference between these methods is the mixing mechanism. The BR case implies the situation in which there is completely no interaction between RAP and virgin binder. On the contrary, RAP and virgin binder are fully interacted in the CB case. The mixing procedures for BR and CB cases conform to those for conventional asphalt mixtures. However, the bitumen for BR case is pure virgin bitumen. In addition, the bitumen for CB is the blend between RAP and virgin binder. The RAP/virgin binder proportion is 4/6. In the SHRP method, RAP is preheated at 110^{o}C for two hours before being mixed with virgin aggregate and binder for 2 minutes at 130^{o}C. In the FS method on the contrary, the mixing procedure duplicates what occurs in the asphalt mixing plant. RAP is mixed with superheated virgin aggregate (215^{o}C) for different durations before this combination is blended with virgin bitumen for 2 minutes at 130^{o}C. The RAP/superheated virgin aggregate mixing duration starts from short mixing time where RAP still exists at approximately original size and gradually increases until the change in RAP lump size is insignificant. Depending on the size of RAP used, RAP/superheated virgin aggregate mixing duration varies from 1 to 8 minutes.

The homogeneity of hot recycled asphalt mixture is examined by using virgin binder with a different colour from that of RAP binder. The colour of virgin binder is obtained by mixing clear binder (Shell Mexphalt C 160/220 Pen) with iron oxide pigment. The proportion of pigment is 10% by weight of the binder making this binder red. The use of virgin binder

with different colour from that of RAP binder helps to clearly differentiate the locations of RAP and virgin materials. Surfaces of slices cut from compacted recycled specimens are photographed by digital camera. The analysis of these surfaces in vertical order allows the locations of RAP material to be qualitatively identified in a 3D manner.

Stiffness modulus values of samples for homogeneity assessment are also determined by indirect tensile stiffness test. The stiffness test is carried out in four directions along the circumference of each specimen with 45^{o} angular increments. The experimental results show that the stiffness measurement in four directions can indicate the heterogeneity of recycled mixture. The variation in stiffness values in different measured directions will be substantial for heterogeneous mixtures and minor in the case where recycled mixtures are homogeneous. The results indicate there are mutual relations between mixing effort, homogeneity, and stiffness values of recycled asphalt mixtures. The longer mixing time will enhance the homogeneity and reduce the variation in stiffness values of recycled mixture. In addition, as more RAP and virgin binder are incorporated, the stiffness values of recycled mixture generally increase once the mixing time is extended.

As the clear binder is dyed red by 10% by weight of iron oxide, the proportion of the pigment certainly alters the flow characteristic of binder. This might affect the mixing process and rejuvenating effect between virgin and aged binder. Therefore, the effects of mixing methods and RAP sizes on mechanical performance of hot recycled asphalt mixtures are further investigated using normal straight run bitumen 160/220 Pen as virgin binder. The assessment indicators include stiffness modulus, resistance to fatigue damage, and resistance to permanent deformation.

The experimental results indicate that the conventional laboratory mixing method (SHRP) tends to overestimate the mechanical properties of recycled asphalt mixture. The long RAP preheating time that never exists in the industry coincidentally enhances the reaction between RAP and virgin binder. The long RAP preheating time also slightly alters the properties of RAP binder.

For the FS method, the increase in mixing duration significantly improves the homogeneity level of recycled mixtures. The homogeneity level is also substantially affected by the size of RAP material. For the same mixing effort, the mixtures comprised of small RAP are

generally more homogeneous than those made from larger RAP. The more homogeneous the mixture, the more interaction between RAP and virgin binder. Therefore, recycled mixtures become stiffer and have better resistance to permanent deformation and fatigue failure. A slightly linear increase in stiffness can result in an exponential increase in fatigue life of the recycled mixture.

The mechanical properties including stiffness modulus, resistance to fatigue damage, and resistance to permanent deformation of hot recycled asphalt mixtures are not similar to those of the BR or CB mixtures, even at the favourable condition where RAP is preheated for 2 hours at 110^{o}C in the SHRP method and 8 minutes mixing duration in the FS method. This implies that RAP does not act as Black Rock. In addition, the assumption that RAP and virgin binder are fully blended also never exists in the recycled asphalt production process.

Keywords: Reclaimed asphalt pavement (RAP), recycled, asphalt, mixtures, mechanical properties, homogeneity

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Declaration

The work described in this thesis was carried out at the Nottingham Transportation Engineering Centre, Department of Civil Engineering, The University of Nottingham between April 2006 and April 2009. The thesis is the result of my own work, except the work from others that has been specifically referenced. No part of this thesis has been, or currently is, submitted for any degree, diploma, or other qualifications.

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Glossary

Actual blending: or "Actual Practice" is the case when RAP is preheated before being blended with virgin aggregate and rejuvenator

Aggregate: inert materials, for instance, sand, gravel, crushed stone, and slag for asphalt concrete production

Asphalt mixture: the combination of aggregate and bitumen

Batch Plant: or Batch facility, is equipment designed to produce hot asphalt concrete in batch

Bitumen: the residual product of fractional distillation process of crude oil, used as binder in asphalt mixture

Black Rock: the situation when RAP is inert in the recycled mixture

Counter flow drum mixer: the drum mixer with the direction of flame counter to the movement direction of aggregate

Diffusion: is the process when rejuvenator covers, incorporates with RAP binder and recovers the properties of RAP binder

Double Barrel: a trademark of Astec Industry for a unique counter flow drum mixer

Drum mixer: or Drum facility, is a combination of drum dryer and mixer for hot asphalt mixture production

Mechanical mixing: the effort of using mechanical effect to produce homogeneous mixture of different ingredients

Parallel drum mixer: drum mixer with the direction of the flame is similar to that of aggregate movement

RAP aggregate: the aggregate extracted from RAP

RAP binder: the aged bitumen extracted from RAP

RAP: acronym for reclaimed asphalt pavement or recycled asphalt pavement, the material is crushed, milled from deteriorated pavement for recycling

Recycled mixture: the asphalt mixture that used RAP material, virgin aggregate and rejuvenator

Rejuvenator: the materials which include modifiers, reclaiming, recycling, modifying, softening agents, recycling modifiers, rejuvenators, fluxing oils, extender oils, aromatic oils, and virgin binder which will be used to recover the properties of RAP binder

Segregation: the non-homogeneity of the mixture, or the locally high concentration of certain type of material in the whole mixture. Segregation can be divided into size

segregation, and chemical segregation in term of recycling when the complete blending status between RAP binder and rejuvenator has not been reached

Total blending: or “complete blending”, is the case when RAP binder is extracted from RAP, being mixed with rejuvenator. The blend of RAP and rejuvenator is then mixed with RAP and virgin aggregate to produce the recycled mixture

Virgin binder: bitumen not previously used

Virgin aggregate: aggregate not previously used

1 Introduction

1.1 Background

Recycling pavements has been used for many years as a rehabilitation technique in the highway industry. The first recorded asphalt pavement recycling project was in 1915 (Epps et al., 1980). Since that moment, there has been a wide range of recycling methods regarding the equipment and procedures. There is also a variety of materials used as rejuvenator, for instance, soft bitumen, bitumen fractions, and also commercial recycling agents. Karlsson and Isacsson (2003d) summarised the methods for recycling asphalt pavement as follows:

In-plant asphalt recycling

In this method, reclaimed asphalt pavement (RAP) is mixed with new materials in the mixing plant. Depending on the processing temperatures, in-plant recycling is divided into hot recycling (above 120^{o}C), warm recycling (70-120^{o}C) and cold recycling (below 70^{o}C).

In-place or In-situ asphalt recycling

The difference of in-place from in-plant asphalt recycling is that all the work is carried out in the field. In-place recycling is divided into four sub-categories (Karlsson and Isacsson, 2003d):

- Remixing is a process in which approximately 30-50 mm thick of the deteriorated asphalt surface is milled and scarified. The reclaimed material is mixed with new materials before being paved and compacted.
- Repaving process is almost the same as remixing except no fresh asphalt is added to the reclaimed material. The deteriorated pavement is heated and milled before being spread over again on the road surface. If rejuvenator is used, the reclaimed material is mixed with rejuvenator before repaved. In addition, a new thin asphalt layer is put on top and two layers are compacted together.
- Cold in-place recycling is a process in which bitumen emulsion, foamed bitumen, or extremely soft bitumen is used as rejuvenator. The application of this method is favourably used in the climatic regions with temperature below 10^{o}C.

- Full depth reclamation is a process that allows the reconstruction of the whole pavement structure using existing pavement materials.

In some aspects, pavement recycling philosophy has certain advantages compared to conventional pavement construction. These benefits of recycling pavements can be summarized as follows (Kandhal and Mallick, 1997):

- Reduce costs of new construction and rehabilitation projects
- Being consistent with environmental sustainable development in terms of conservation of energy, mineral aggregates, and bitumen binder
- Preservation of road geometry
- Reduce the construction time delay

Due to the benefits brought to society by pavement recycling techniques, up to this moment 80% of the asphalt pavements removed each year from widening and resurfacing projects are put back on roads, roadbeds, shoulders and embankments. In the US, almost all the States allow reuse of RAP in the surface course with percentage of RAP from between 10 and 30% (United States Department of Transportation, 2007). The popularity of recycling asphalt pavements has made RAP the most recycled material in the US in terms of both percentage and tonnage. Mike Acott, president of the National Asphalt Pavement Association, reported that approximately 73 million tons of RAP were reused every year (NAPA, 2004).

1.2 Problem statement

The quality of an asphalt mixture is primarily affected by the design method, materials and production process. The design step will determine the type and proportion of materials in the mixture. The production process assures the mixture has the level of homogeneity as required in the design step by using proper mixing methods such as mixing temperature and duration. However, recycled mixture is different from conventional asphalt mixture as the input materials include RAP, which is a combination of aged binder and aggregate. Hence, the problems encountered in the recycling asphalt industry include not only those found in conventional asphalt but also issues associated with RAP sizes, mixing methods and diffusion mechanisms.

In the design process, the proportion of RAP binder, type and amount of rejuvenator are selected based on the viscosity mixing equations. The fundamental philosophy of these

equations is that RAP binder and rejuvenator binders are completely blended. In addition, the output and input of these viscosity mixing equations rely primarily on just the viscosity values and proportions of each bitumen constituents. The other issue is whether the results of these viscosity mixing equations are reliable, especially when two bitumen binders with complicated chemical composition are mixed together.

Even when the results of these viscosity mixing equations are accurate, the other problem is whether the complete blending between RAP binder and rejuvenator assumed in these equations actually occurs in recycled asphalt mixture. In the laboratory, RAP binder is extracted and recovered before being deliberately blended with rejuvenator without any interventions. On the contrary, the mixing process between RAP binder and rejuvenator in the asphalt mixing plants is affected by many factors such as the presence of aggregate, filler, existence of RAP materials as agglomerates, mixing temperature, and efficiency of the mixer.

The methods of preparing the recycled mixtures in the laboratory also indicate a shortcoming as these methods could not represent the mixing mechanism in the field. In the laboratory, RAP material is conventionally preheated for a long time before being mixed with virgin aggregate and rejuvenator. The long preheating time might coincidently soften RAP and enhance the mixing between RAP and virgin materials. On the contrary, RAP material at ambient temperature is mixed with superheated virgin aggregate in the plant mixer for a really short time. The question here is whether the short mixing duration in the plant mixer can produce the recycled mixture with the level of homogeneity similar to that of the laboratory procedure product. If the complete blending cannot occur in the industry but only in the laboratory, the laboratory procedure has overestimated the properties of the recycled mixture.

Size of RAP is also a problem as the bigger the size of RAP, the longer the time for the heat to penetrate and break the RAP materials into separated pieces. Although there is a wide range of RAP sizes handled in the asphalt pavement recycling industry, for instance, the maximum RAP size is 50 mm, and even 75 mm is allowed in asphalt hot recycling process (United States Department of Transportation, 2007), up to this moment, there is a lack of research to investigate the effect of RAP sizes on the properties of recycled mixtures.

1.3 Research objectives

The objectives of this research are as following:

- To better understand the hot recycling asphalt technique.
- To develop a protocol to prepare the hot recycled mixture in the laboratory that duplicates the production mechanism in the industrial asphalt mixing plant.
- To investigate the effects of mixing methods and RAP materials on homogeneity of hot recycled asphalt mixtures.
- To investigate the effect of mixing methods and RAP materials on mechanical properties of recycled mixture including stiffness modulus, resistance to permanent deformation, and resistance to fatigue damage.
- To correlate the homogeneity and mechanical properties of hot recycled asphalt mixture.

1.4 Research methodology

To study the effects of mixing process on the properties including homogeneity and mechanical performance, recycled asphalt mixtures are manufactured by different mixing procedures. The mixing procedures include black rock (BR), complete blending (CB), the SHRP procedure, and a newly developed field simulation method (FS). The primary difference between these methods is the mixing mechanism.

The BR case implies the situation in which there is no interaction between RAP and virgin binder. On the contrary, RAP and virgin binder are fully interacted in CB case. The mixing procedures for BR and CB methods conform to those of conventional asphalt mixtures. However, the binder for BR case is pure virgin bitumen. On the contrary, the binder for CB case is the blend between RAP and virgin binder. The RAP/virgin binder proportion is 4/6. In the SHRP method, RAP is preheated at 110^{o}C for two hours before being mixed with virgin aggregate and binder. In FS method on the contrary, the mixing procedure duplicates what occurs in the asphalt mixing plant. RAP is mixed with superheated virgin aggregate (215^{o}C) for different durations before this combination is blended with virgin bitumen. The RAP/superheated virgin aggregate mixing duration starts from short mixing time where RAP still exists at approximately original size and gradually increases until the change in RAP lump size is insignificant.

In addition, two RAP sizes are used to study the effects of RAP materials on properties of hot recycled asphalt mixture. RAP material is artificially aged and processed in the laboratory. This is to prevent the variability of RAP aggregate gradation, binder content and origin. In addition, the use of artificial RAP is used to assure that every single RAP particle is an agglomerate of RAP aggregate and binder.

The homogeneous level of hot recycled asphalt mixture is examined by positioning the locations of RAP and virgin materials. The use of virgin binder with a different colour from that of RAP binder helps to clearly differentiate the locations of RAP and virgin materials. Surfaces of slices cut from compacted recycled specimens are photographed by digital camera. The analysis of these surfaces in vertical order allows qualitative identifying of the locations of RAP material in a 3D manner. The virgin binder is obtained by mixing clear binder (Shell Mexphalt C 160/220 Pen) with iron oxide pigment. The proportion of pigment is 10% by weight of the binder making this binder red. Stiffness modulus values of samples for homogeneity assessment are also determined by indirect tensile stiffness test. This is aimed to correlate the homogeneous level and mechanical properties of recycled hot asphalt mixtures.

As the clear binder is dyed red by 10% by weight of iron ioxide, the proportion of the pigment alters the flow characteristic of the binder. This might affect the mixing process and rejuvenation between virgin and aged binder. Therefore, the effects of mixing methods and RAP sizes on mechanical performance of hot recycled asphalt mixtures are further investigated using normal straight run bitumen 160/220 Pen as virgin binder. The assessment indicators include stiffness modulus, resistance to fatigue damage, and resistance to permanent deformation.

1.5 Scope of work

The scope of work in this thesis includes:

Chapter 1: Introduction

The content of this chapter briefly demonstrates current problems of asphalt recycling technique that leads to the research objectives.

Chapter 2: Literature review

This chapter contains up-to-date knowledge on hot asphalt recycling

techniques and related issues.

Chapter 3: Laboratory RAP production

This chapter presents the purposes and procedure for laboratory RAP production.

Chapter 4: Zero shear viscosity and the accuracy of viscosity mixing equations

This chapter contains the evaluation of different viscosity mixing equations using zero shear viscosity.

Chapter 5: Effect of laboratory mixing methods on homogeneity of recycled asphalt mixtures

This chapter presents the effects of different RAP/superheated virgin aggregate mixing durations and RAP sizes on homogeneity of hot recycled asphalt mixture. The homogeneity of recycled mixtures is studied by using virgin binder with different colour from that of RAP binder. The red colour of virgin binder is obtained by mixing clear binder with iron oxide pigment. The proportion of pigment is 10% by weight of the binder making this binder red. The content of this chapter also includes the correlation between homogeneity and stiffness distribution of hot recycled asphalt mixtures.

Chapter 6: Effect of mixing process and RAP materials on stiffness of recycled asphalt mixtures

The proportion of the pigment certainly alters the flow characteristic of red virgin binder (Chapter 5). This might affect the mixing process and rejuvenation between virgin and aged binder. Therefore, the effects of mixing methods and RAP sizes on mechanical performance of hot recycled asphalt mixtures are further investigated using normal straight run bitumen 160/220 Pen as virgin binder. The data and analysis on the effect of mixing method and RAP materials on stiffness modulus, resistance to fatigue damage and resistance to permanent deformation of hot recycled asphalt mixtures are presented in Chapters 6,7, and 8.

Chapter 7: Effects of mixing methods and RAP materials on fatigue life of recycled asphalt mixtures

Chapter 8: Effect of mixing methods on permanent deformation resistance of hot recycled asphalt mixtures

Chapter 9: Conclusions and Recommendations

2 Literature review

2.1 Asphalt mixture

2.1.1 Definition of asphalt mixture

Asphalt or bituminous mixture is a combination of bitumen and mineral aggregate. This kind of mixture is normally used for construction of highway pavement layers, parking areas, and pedestrian streets. Once asphalt mixture is compacted to required air void content, mineral aggregate with different size fractions plays a role as skeleton to provide the strength. Bitumen, a residual fraction of fractional distillation process of crude oil, will act as an adhesive, to bond aggregate particles together and improve the performance of the mixture (Read and Whiteoak, 2003).

2.1.2 Classification of asphalt mixture

Depending on the proportion and particle size distribution, asphalt mixtures are divided into two main categories, gap-graded and continuous-graded mixtures. In gap-graded, the particle size distribution is not continuous (Figure 1). Normally, there is one single size of coarse aggregate. The high void content due to single size of coarse aggregate will be filled with sand, filler and bitumen. The structural strength of gap-graded mixtures is built by the mortar of sand, bitumen and filler. Depending on the required aggregate gradation and binder content, gap-graded mixture is classified into mastic asphalt (BS-EN:13108-6, 2006), hot rolled asphalt (BS-EN:13108-4, 2006), stone mastic asphalt (BS-EN:13108-5, 2006), and porous asphalt (BS-EN:13108-7, 2006).

Different from gap-graded, there normally exist many different aggregate size fractions in continuous-graded mixtures with the hypothesis that the smaller particles will fill up the voids generated by the bigger particles (Roberts et al., 1991). Hence, the strength of aggregate skeleton is based on the interlock among aggregate particles. This makes the continuous-graded mixture better at deformation resistance than gap-graded one. However, as the required amount of binder content in gap-graded mixture is higher due to using fine aggregate as sand and filler, this type of mixture has better fatigue resistance (Read, 1996).

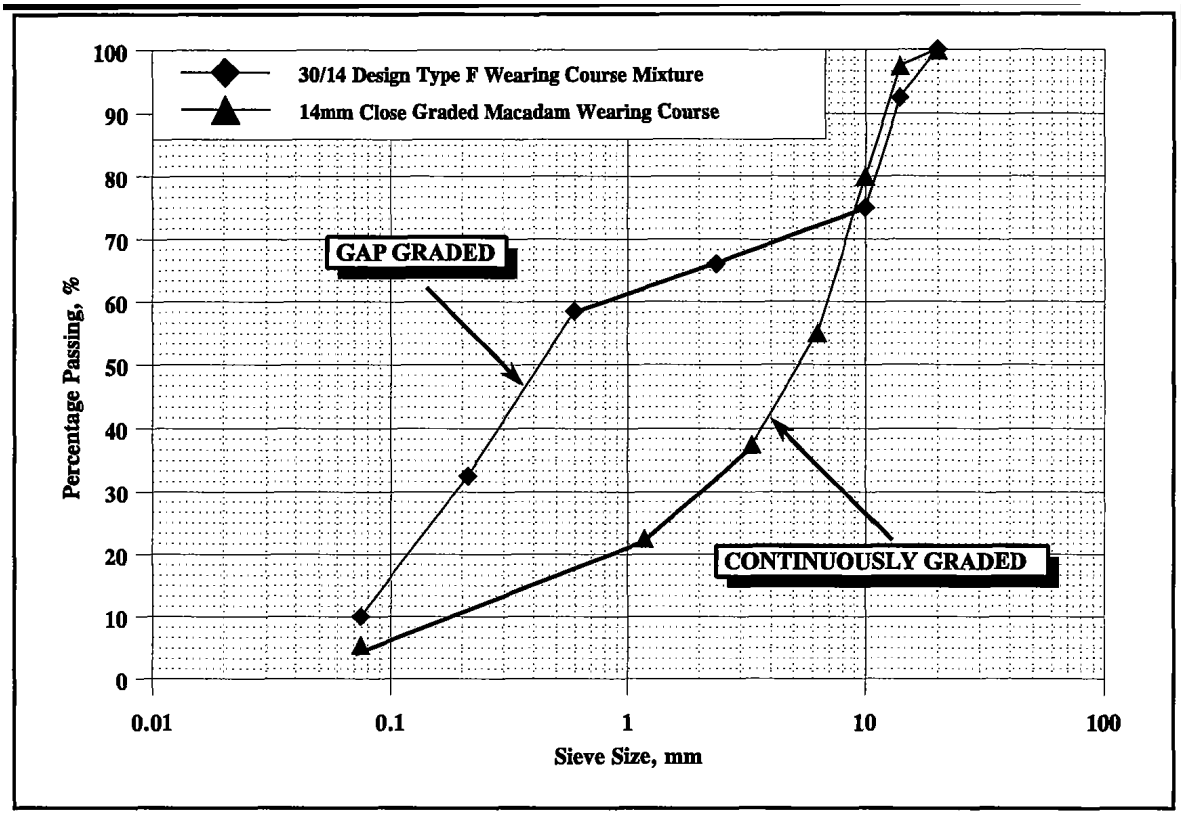


Figure 1: Comparison on gradation of gap-graded and continuous-graded asphalt mixture (Read, 1996)

2.1.3 Properties of asphalt mixture

Stiffness modulus

Stiffness is the resistance to deformation under applied stress conditions. As asphalt mixture is a visco-elastic material, the stiffness of asphalt mixture normally includes elastic and viscous components. The proportions of each component rely primarily on the temperature and the loading time. Under low temperature and short loading time, the asphalt mixture will behave elastically. On the contrary, the relation between stress and strain will follow viscous manner under high temperature and long loading time (Read and Whiteoak, 2003).

The stiffness of asphalt mixture can be determined by the following equation:

$$E = \frac{\sigma}{\varepsilon} \qquad (1)$$

Where:

E : stiffness modulus

σ : applied stress

ε : strain caused by applied stress

Permanent deformation

Permanent deformation is the phenomenon that unrecoverable strain is accumulated after the load is released in each loading cycle. Figure 2 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 characteristic of asphalt mixture, cannot recover (Perl et al., 1983). Although this viscous and plastic deformation is really small after each loading cycle, the accumulation will become large after millions of loads (Figure 3). This will cause rutting phenomenon in the pavement structure.

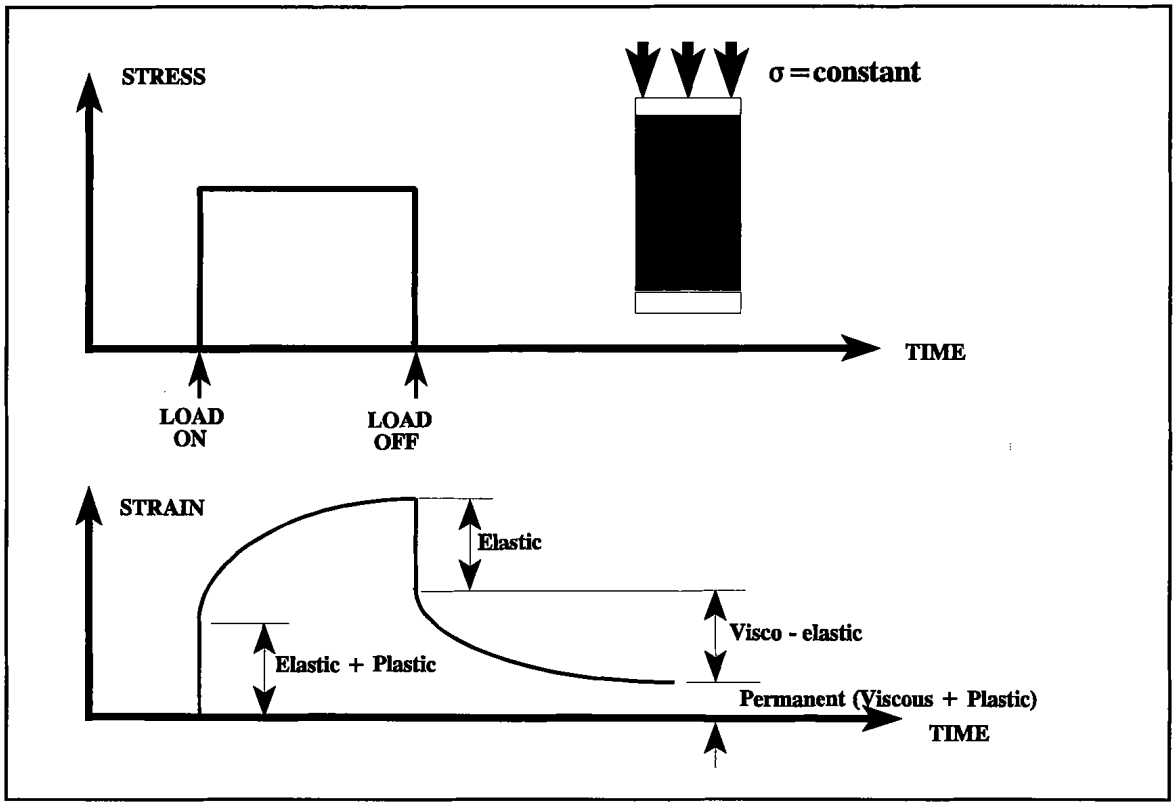


Figure 2: Strain response due to applied stress of Visco-Elasto-Plastic Constitutive model (Perl et al., 1983)

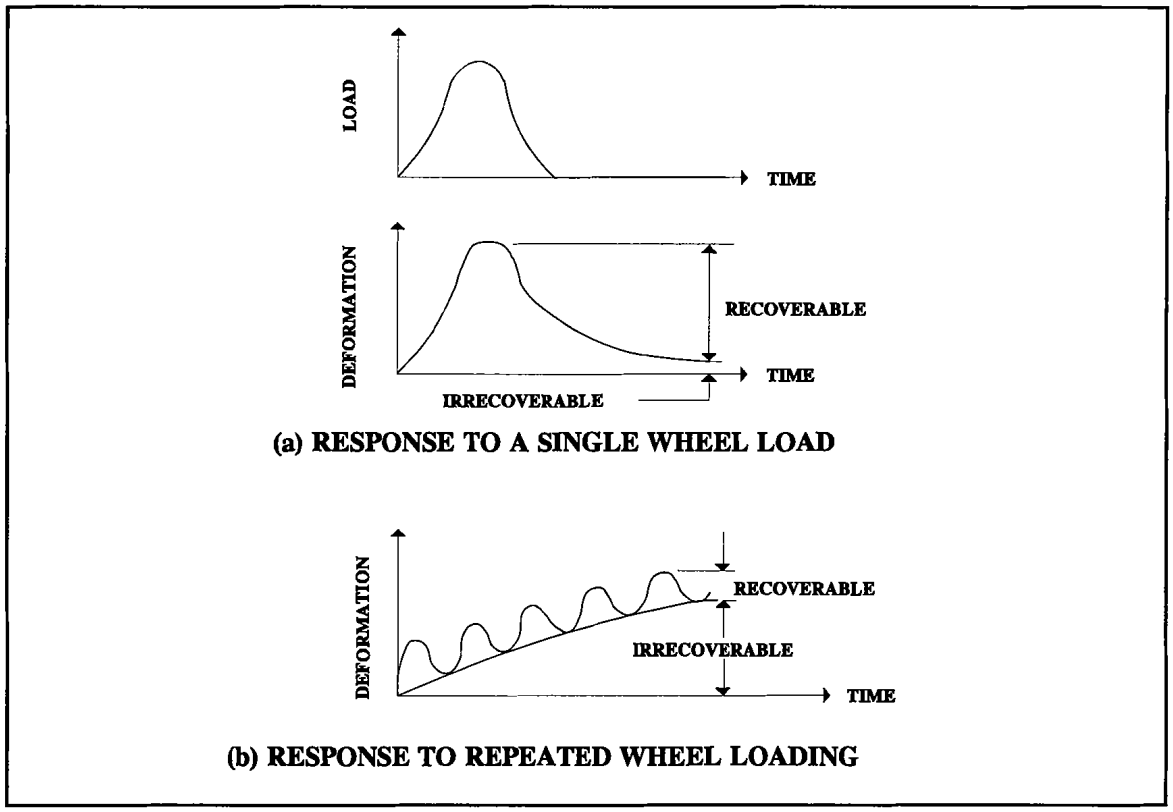


Figure 3: Visco-elastic response to millions of load application (Read, 1996)

Fatigue characteristic of asphalt mixture

Fatigue can be defined as: "The phenomenon of fracture under repeated or fluctuating stress having a maximum value generally less than the tensile strength of the materials" (Pell, 1988). However, tensile stress induced in the pavement is not only due to traffic loading but also the effect of surrounding environment, for instance, the fluctuation of surrounding temperature. Read (1996) also defined the fatigue as: "Fatigue in bituminous pavement is 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". The empirical data shows that the tensile range from 30 to 200 microstrain is the condition that fatigue damage might possibly occur (Brown, 2000).

The relationship defining the fatigue life of bituminous mixture based on crack initiation is as follows (Brown, 2000):

$$N_f = c\left(\frac{1}{\varepsilon_f}\right)^m \qquad \textbf{(2)}$$

Where

N_f : number of applications of load to initiate a fatigue crack

ε_t : initial value of tensile strain

c, m : factors depending on the composition and properties of the mixture

2.2 Durability of asphalt mixture

2.2.1 Definition of durability

Asphalt pavement in general has to carry the traffic under certain climatic conditions. In order to satisfy the performance demand, a pavement must have the ability to withstand any damage during the whole service life. Therefore, the durability of asphalt pavement is defined as follows (as cited in Scholz, 1995):

> *"Durability as it applies to bituminous paving mixtures is defined as the ability of the materials comprising the mixture to resist the effects of water, aging and temperature variations, in the context of a given amount of traffic loading, without significant deterioration for an extended period".*

2.2.2 Mechanism of ageing in asphalt mixture

As asphalt mixture is a combination of bituminous binder and a skeleton of mineral aggregate, the ageing mechanism of asphalt mixture is understood as that of the bitumen. Traxler (1963) studied the causes of ageing or hardening phenomenon in asphalt binder and concluded there were 15 factors which might cause ageing in bitumen (Table 1). However, some of the causes were just listed but not verified by experimental data. Petersen (1984) suggested the fundamental factors caused hardening in asphalt materials, which were:

1. Loss of oily components of bitumen by volatility or absorption by mineral aggregate.
2. Changes in chemical composition as chemical molecules of bitumen react with oxygen (oxidation).
3. Molecular structuring causing thixotropic effects (steric hardening).

Oxidation is the phenomenon when chemical molecules in bitumen are oxidised by oxygen in the atmosphere and form polar groups containing oxygen, for instance, hydroxyl, carbonyl and carboxylic groups (Read and Whiteoak, 2003). The polar molecules own unevenly distributed electrical charges and tend to interact with the others. Depending on

the strength of the bond, these polar molecules will from a network and comprise a wide range of molecular types and sizes (John, 1993).

Rostler and White (1962) studied the compositional change of 85/100 penetration grade bitumen. Bitumen composition was divided into asphaltene (A), nitrogen base (N), first accidaffin (A_1), second accidaffin (A_2), and paraffins (P) fractions. Each fraction had its particular function. Nitrogen base has the function of peptizing inert asphaltene. The accidaffin group will keep the peptized asphaltene solvated. This solution will be gelled by paraffins. Due to ageing, the proportion of nitrogen base and first accidaffin change greatly, first accidaffin changes to nitrogen base, and nitrogen base turns to asphaltene. The resulting proportion of each fraction in bitumen would cause incompatibility (or sysneresis) and substantially affect the durability of bitumen.

Noureldin (1995) also studied the ageing effect of bitumen and reported that bitumen is a combination of asphaltene, resin, and oil. The viscosity of bitumen is mainly attributed to the asphaltene component. During the ageing process, the oil will convert to resin, and the resin will turn to asphaltene. The increasing proportion of asphaltene plus the fact that the maltene phase necessary to disperse asphaltene is insufficient will increase the viscosity of bitumen.

Ageing is also due to the loss of volatiles in bitumen. Oily proportion of bitumen primarily volatizes due to high temperature. In addition, the loss of volatiles is also attributed to long term exposure of asphalt to the environment. In addition, depending on the mineralogy of aggregate, oily component is also absorbed by porosity when bitumen is in contact with aggregate. However, the hardening due to these phenomenon is not considerable compared to ageing by oxidation (Read and Whiteoak, 2003).

Effects	Influence by					Occurs		Ways to Retard
	Time	Heat	Oxygen	Sunlight	B&G Rays	At Surface	In Mass	In General, Selected Source and Process
1. Oxidation (in dark)	X	X	X	-	-	X	-	1) Inert atmosphere 2) Free radical inhibitors
2. Photooxidation (direct light)	X	X	X	X	-	X	-	1) Protection from light 2) Inert atmosphere 3) Free radical inhibitors
3. Volatilization	X	X	-	-	-	X	X	Protection from heat
4. Photooxidation (reflected light)	X	X	X	X	-	X	-	1) Proection from light 2) Inert atmosphere 3) Free radical inhibitors
5. Photo chemical (direct light)	X	X	-	X	-	X	-	1) Protection from light 2) Additives?
6. Photo chemical (reflected light)	X	X	-	X	-	X	X	1) Protection from light 2) Additives?
7. Polymerization	X	X	-	-	-	X	X	Free radical inhibitors
8. Development of an internal structure (aging) (Thixotropy)	X	-	-	-	-	X	X	1) Add dispering agents 2) Change source and processing of asphalt
9. Exudation of oil (Syneresis)	X	X	-	-	-	X	-	Reduce paraffinic content
10. Changes by nuclear energy	X	X	-	-	X	X	X	----------
11. Action of water	X	X	X	X	-	X	-	Change source and processing
12. Absorption by solid	X	X	-	-	-	X	X	Improve dispersion of asphalt
13. Adsorption of components at solid surface	X	X	-	-	-	X	-	----------
14. Chemical reactions or catalytic effects at interface	X	X	-	-	-	X	X	----------
15. Microbiological deterioration	X	X	X	-	-	X	X	Add fungistatic and bacteriostatic agents

Table 1: Mechanism of bitumen aging (Traxler, 1963)

2.2.3 Factors affecting ageing mechanism

Chemical composition of bitumen binder

White et al. (1970) studied the effects of chemical composition on durability of bitumen. Four bitumen binders from different origins, California, Venezuela, Arkansas, and Alberta were fractioned into five basic components, asphaltene (A), nitrogen base (N), first accidaffin (A_1), second accidaffin (A_2), and paraffins (P). Bitumen blends were produced by blending different components in various proportions. Each blend was subjected to syneresis analysis. The homogeneity of each blend was studied by microscope. The compatibility of each blend was also evaluated by filter paper test under ultraviolet light. The aim of filter paper test was to identify the separation of oil phase. White et al. (1970) claimed that compatibility of bitumen relied primarily in the proportion of Nitrogen bases and Paraffins, expressed as ratio N/P, or syneresis parameter. This ratio should be greater than 1 for the bitumen to be free of syneresis.

Durability of each blend was also studied by Pellet abrasion test before and after aging. The pellet was made by compressing a mixture of Ottawa sand and bitumen. The mixture was produced by mixing Ottawa sand and bitumen at 160^{o}C for 6 minutes. The bitumen content of the mixture was 2% by weight of the sand. During ageing process, the mixture was conditioned under infrared light of 7 days at 60^{o}C. The test was carried out by shaking 2 gram pellet in a square bottle. The loss in milligrams after 500 revolutions of the pellet was recorded. The test results showed that durable bitumen must have the compositional parameter, expressed as $(N+A_1)/(P+A_2)$, above 0.4.

Temperature

Temperature seriously affects the ageing or hardening rate of bitumen. The higher the temperature bitumen is exposed to, the more bitumen ages. Especially in the condition of above 100^{o}C, Read and Whiteoak (2003) stated that the oxidation rate increases twofold for each increment of 10^{o}C. Temperature extremely affects the properties of bitumen. Data in Figure 4 illustrates that for 30s mixing time, a raise of 5.5^{o}C in mixing temperature will elevate the softening point by 1^{o}C.

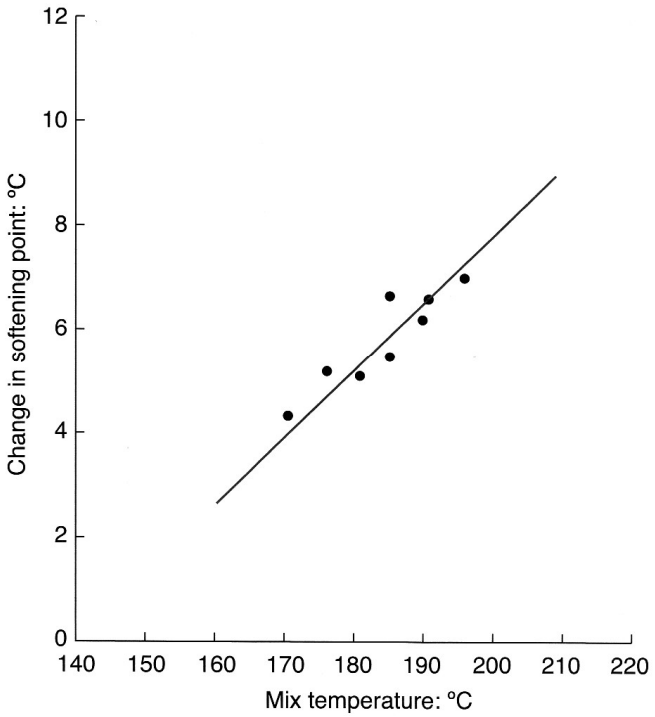


Figure 4: Relationship between the temperature of the mixture and change in softening point (Read and Whiteoak, 2003)

Air void content in total mixture

The air void contents after compaction presents highway engineers with a paradox. Although low air void content reduces the ageing rate, it might increase rutting phenomenon. Vice versa, if the air void content is increased, the asphalt binder coating aggregate can be oxidized faster. The stiff oxidized bitumen will easily rupture. Water can get in and destroy the bond between bitumen film and aggregate and reduce the tensile strength of the mixture. Most highway agencies prefer the range of air voids after compaction from 3 to 5% (Roberts et al., 1991). However, if the compaction quality is not well controlled, the high air void content will cause faster ageing speed. Figure 5 shows the ageing of pavement made of bitumen that has penetration of 100 dmm at 25^{o}C. The penetration after mixing is 70 dmm. If the air void content is less than 5%, the penetration of bitumen after five years in service is almost the same as the initial value. On the contrary, if the void content is higher than 9%, the pavement is extremely aged as the penetration reduces from 70 to 20 (Read and Whiteoak, 2003)

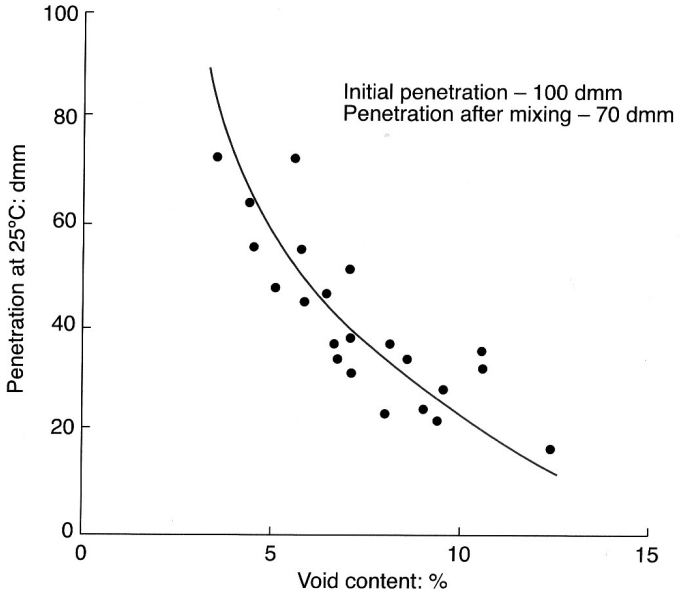


Figure 5: The effect of void content on the hardening of bitumen on the road (Read and Whiteoak, 2003)

Bitumen film thickness

During the mixing process, the bitumen is exposed to extremely high temperature in condition of very thin layer approximately 5 to 15µm thick. Bitumen will be extremely aged due to oxidation and loss of volatiles. The loss of bitumen penetration during mixing is approximately 30% (Read and Whiteoak, 2003). Another study by Kandhal and Chakraborty (1996) also showed that the thicker the bitumen film, the less viscosity of bitumen increase after short and long term ageing (Figures 6 and 7).

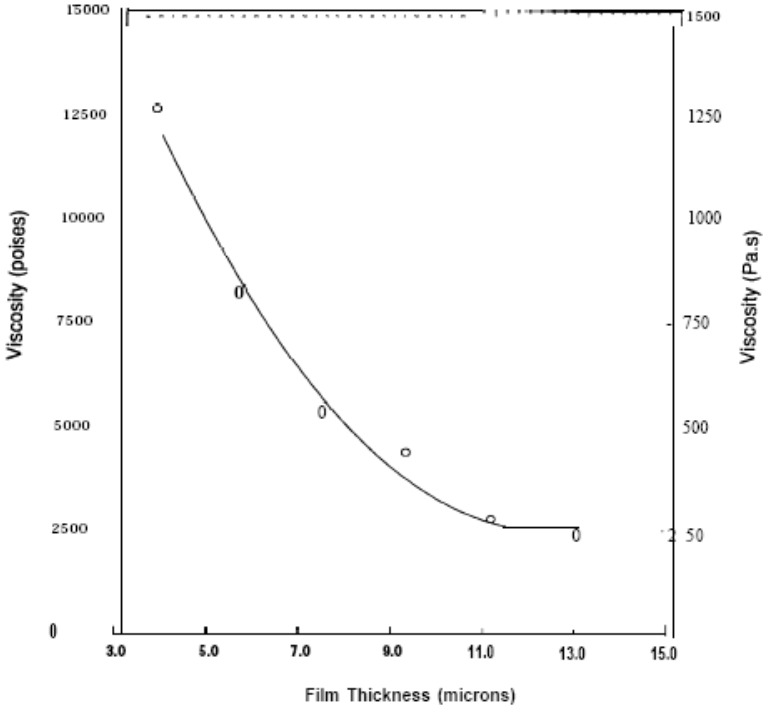


Figure 6: Asphalt film thickness vs viscosity after short term ageing (Kandhal and Chakraborty, 1996)

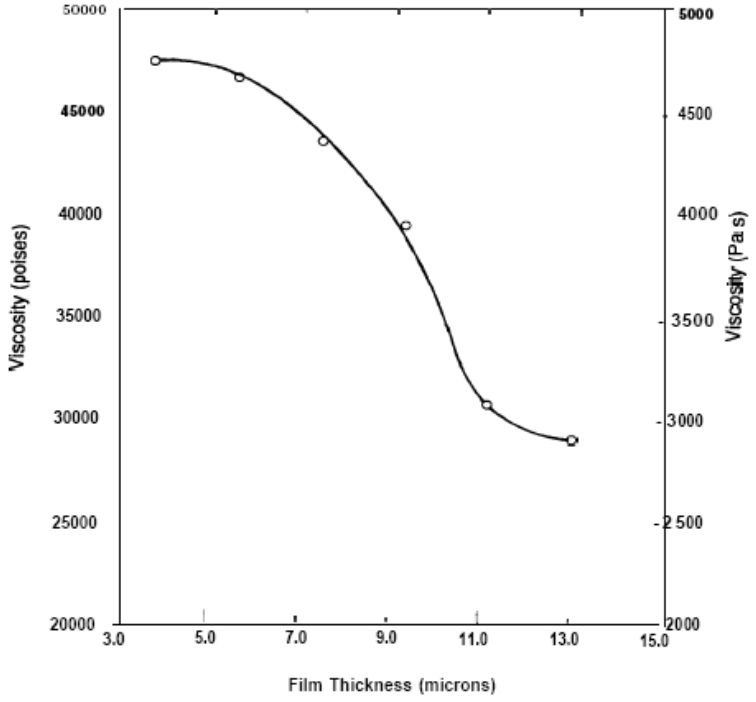


Figure 7: Asphalt film thickness versus viscosity after long term ageing (Kandhal and Chakraborty, 1996)

2.2.4 Consequences of ageing in bituminous mixture

The compositional changes in bitumen due to ageing will result in the increase of bitumen viscosity. Kandhal and Koehler (1984) carried out a study on durability of dense-grade

pavements using different types and sources of bitumen in Pennsylvania, US. The data measured from 1961 to 1976 (Figure 8) shows that the longer time the pavement is exposed to environment, the higher the pavement viscosity.

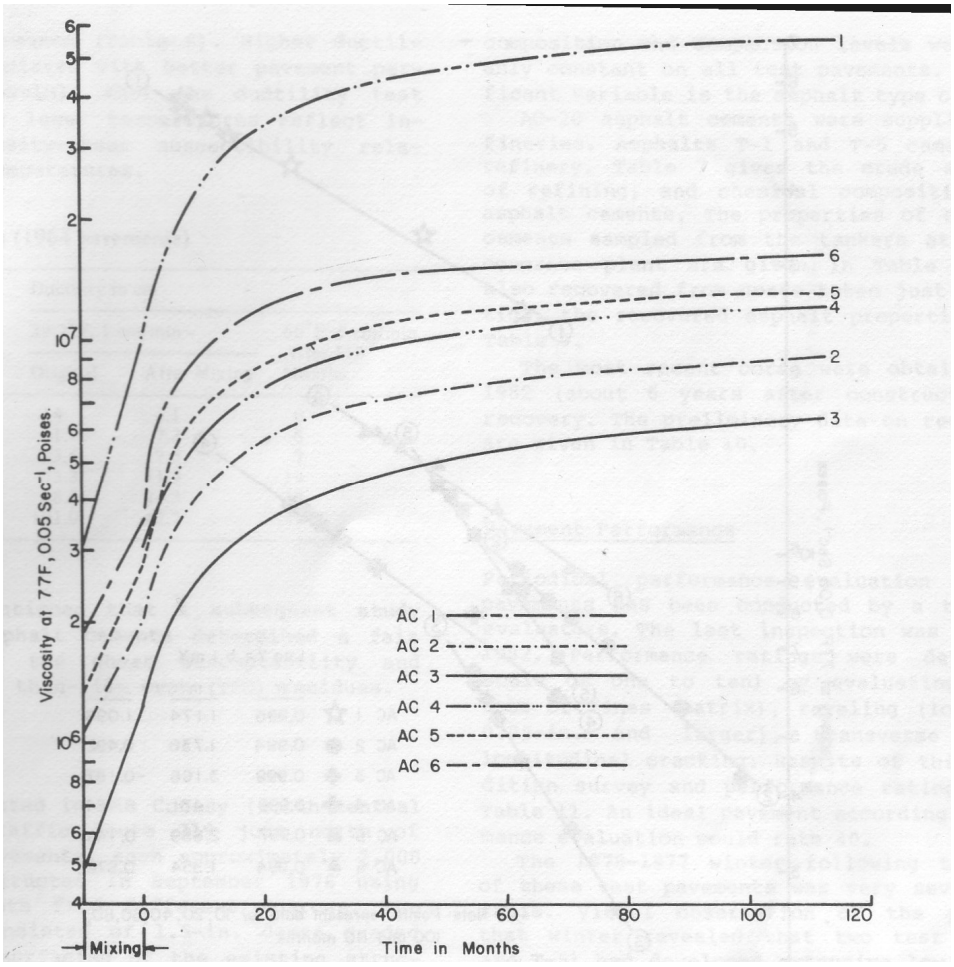


Figure 8: Effect of ageing time on bitumen viscosity extracted from pavements (Kandhal and Koehler, 1984)

Ageing will also change the visco-elastic properties of bitumen. Research by Daniel et al. (1998) shows that the longer the ageing time, the lower the phase angle of bitumen (Figure 9). In fact, the decrease of loss modulus plus the increase of viscosity of bitumen due to ageing will result in the pavement being more prone to cracking at low temperature. Kliewer et al. (1996) studied the effect of ageing on fracture temperature. The experimental results (Figure 10) demonstrated that the increase of ageing time would result in the increase of fracture temperature. In fact, the more aged the pavement, the more prone to cracking.

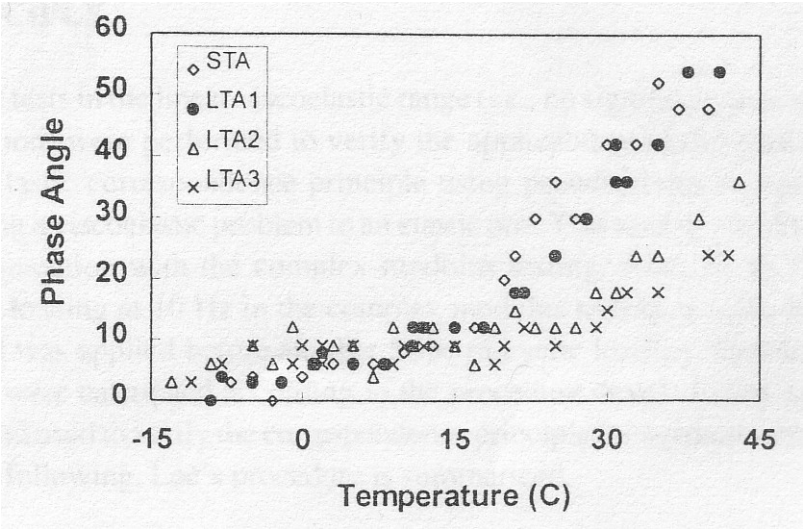


Figure 9: Phase angle versus ageing levels (Daniel et al., 1998)

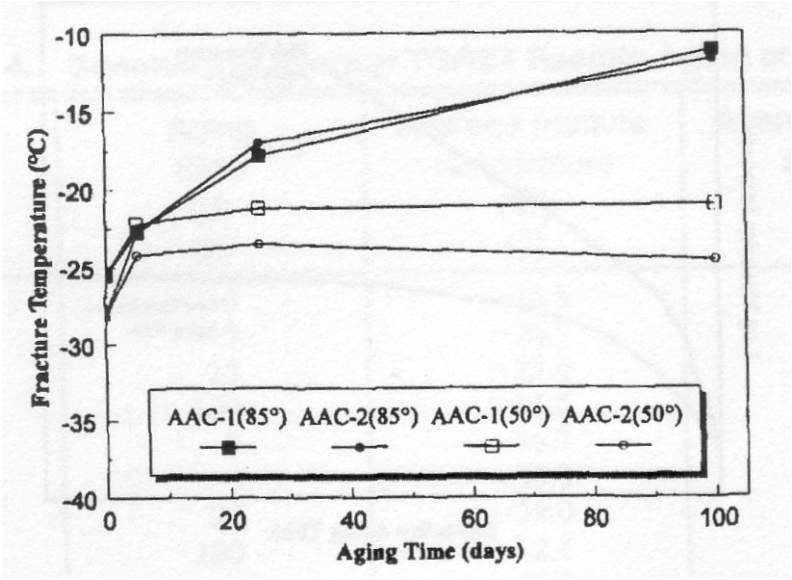


Figure 10:Fracture temperature versus ageing time (Kliewer et al., 1996)

2.2.5 Laboratory tests simulating field ageing

Plancher et al. (1976), studied the effect of lime on durability of bitumen by comparing the resilient modulus of cylindrical specimens with diameter of 4 cm and thickness of 2.5 cm before and after ageing procedure. Both normal and lime treated bitumen were used in this research. The results showed that mixtures using lime treated bitumen had better resistance to ageing. The ageing procedure included:

- pressing the mixture of sand and bitumen in specified dimension mould at 150^{o}C under pressure of 27.6 MPa.
- conditioning in the oven 150^{o}C for 1 hour.

- cooling at 25^{o}C for 72 hours then testing the resilient modulus for un-aged specimen.
- storing at 150^{o}C for 5 hours.
- cooling at 25^{o}C for 72 hours then testing the resilient modulus for aged specimen.

Hugo and Kenedy (1985) implemented the accelerated ageing procedure in both dry and moist conditions. Both types required the slab with thickness of 4 cm to be conditioned under temperature of 100^{o}C for 4 to 7 days. An open reservoir is put in the oven in order to maintain the relative humidity higher than 80% in moisturised condition. After ageing, the bitumen was recovered and subjected to Shell plate viscosity testing at different temperatures. The ageing effect was obtained by comparing the viscosity of recovered bitumen with that of original bitumen. Although it is advantageous to study the ageing in moisturised condition, the affect of different void content and temperature on hardening is not mentioned in this research.

These mentioned scholars studied the ageing of bitumen in compacted mixtures. However, the ageing during production process has been ignored. Von Quintas in 1988 simulated the hardening of bitumen during production, or short term ageing, by conditioning the loose mixture at 135^{o}C in a force draft oven for 8, 16, 24, and 36 hours. The laboratory data, although scattered, generally showed approximately the same ageing level as in the field. Not only short term, long term ageing was also studied by conditioning specimens for 2 days at 60^{o}C followed by 3 days at 107^{o}C (Airey, 2003).

The most comprehensive study on ageing of aggregate mixture is the project A-003A by Bell et al. (1994a) under the Strategic Highway Research Program (SHRP). In this research, many factors affecting the ageing mechanism were considered, for instance, air void content, temperature, and production. Short term ageing, presenting the hardening of bitumen during production process, is simulated by conditioning loose mixture at 135 or 163^{o}C during 1, 6, and 15 hours (STOA). The aged mixture is then compacted to 4 and 8 percent air void after STOA. For long term ageing, the compacted specimens are conditioned in force draft oven for 2 or 7 days at constant temperature of 107^{o}C. Before LTOA, compacted specimens are preconditioned for 2 days at 40 or 60^{o}C to assure the stability of specimens. Characteristics before and after ageing are determined by resilient modulus and indirect tensile tests. The results from the tests showed that in some mixtures,

the resilient modulus is 4 times higher than the initial value after STOA and 6 times for LTOA. Hence, the accelerated ageing procedure is recommended as follows:

- STOA: loose mixture is conditioned at 135^{o}C for 4 hours.
- LTOA: compacted mixture is conditioned at 85^{o}C for 5 days or 100^{o}C for 2 days.

The recommended accelerated ageing procedures were then verified by field practice. After this field validation, Bell et al. (1994b) concluded that:

- STOA: is the simulation of bitumen hardening in pavement during production and construction plus less than two year performance.
- LTOA (8 days at 85^{o}C): is the simulation of bitumen hardening in pavement for 18 years performance in the condition of wet-no-freeze climate, or 9 years in dry-freeze climate.

Airey (2003) suggested the condition of 4 days at 85^{o}C to simulate LTOA in pavement for 15 years performance in the condition of wet-no-freeze climate, or 7 years in dry-freeze climate. However, in AASHTO PP2 (1994), it is demonstrated that this condition is equal to LTOA during 5 days at 85^{o}C.

2.3 Design methodology for recycling of bituminous pavements

2.3.1 Objectives and design procedure of pavement recycling

There are different objectives depending on the organizations in charge or related to the pavement recycling job. For instance, the contractors want to recycle the pavements as the costs of construction are cheaper due to the reuse of existing materials (RAP). The government is also interested due to the saved money from construction hence the problem of constrained budgets for highway maintenance can be solved. In term of highway engineers, the overall objective of recycling pavement is, to restore the properties of existing deteriorated pavements materials, to such a level that can satisfy the service requirements.

The bitumen, due to the chemical changes during service life of asphalt pavement, cannot be used without any modifications. Any materials that can alter the properties of RAP binder are defined as modifiers. This wide definition includes reclaiming, recycling, modifying, softening agents, recycling modifiers, rejuvenators, fluxing oils, extender oils, and aromatic oils (Karlsson and Isacsson, 2003d). The purpose of asphalt pavement recycling (Epps et al., 1980) is to choose proper modifiers to:

- Restore the consistency of aged bitumen.
- Restore the chemical composition of aged bitumen for durability.
- Provide sufficient binder to coat the new aggregate added and satisfy the stability requirement of the mixture.

To obtain the overall objective of recycling bituminous pavements, (Davidson et al., 1977), recommended the design procedure for asphalt pavement recycling includes:

- Determine the properties of existing pavement (RAP) including bitumen content, consistency of bitumen, bitumen demand for aggregate, aggregate gradation.
- Select the reclaiming agent. The reclaim agent must reduce the viscosity of aged binder to the desired level and improve the durability.
- Analyse and use data for design.

2.3.2 Methods for recycling bituminous pavements

The concept of recycling or reusing the existing pavement material in new construction or rehabilitation project has lasted for many years. The first recycling pavement project recorded was in 1915 (Epps et al., 1980). Since that moment, there has been a wide variety of pavement recycling techniques. These approaches are normally classified based on the materials to be recycled for instance, bituminous or portland cement pavement, the structural layers which will benefit from recycling as surface, base or sub base, and the procedure as well as equipment for recycling purpose.

Generally, recycling techniques are categorized into two main types, in-plant and in-situ recycling. Regarding in-plant recycling, the reclaimed pavements are transported to asphalt production plant, ripped, milled, and crushed into required sizes before being blended with virgin bitumen and aggregate in the mixing plant. Depending on the mixing temperatures required of the recycled mixture, in-plant recycling is further divided into cold, warm, and hot recycling (Karlsson and Isacsson, 2003d). Apart from the other in-plant recycling methods, hot recycling proves to be the most advantageous due to the ability to correct most of the pavement surface defects, deformation and cracking. In addition, hot recycled mixture with 10 to 30% of RAP can have the same performance compared to virgin mixture (Kandhal and Mallick, 1997).

Different from in-plant recycling, in-situ methods are processed on site. In-situ recycling is also divided into hot in-situ recycling which includes remixing and repaving and cold in-

situ recycling or full depth reclamation. In remixing method, existing pavement is milled, mixed with new materials before being laid and compacted. The procedure in repaving method is almost the same except no new materials are added. However, a new layer is laid on top of the recycled pavement to increase structural strength of the pavements. In full depth reclamation, all the surface and a part of base course is milled, scarified, and mixed with bitumen emulsion, foamed bitumen or soft bitumen to produce a stabilized base. A new surface is then laid and compacted on the new recycled base (Kandhal and Mallick, 1997).

2.3.3 Selection of rejuvenators

Davison et al. (1977) studied the recycling aspect with a wide range of 6 aged binders and 12 reclaiming agents. The percentages of aged bitumen for each combination were in turn 0, 5, 25, 50%. In addition, the effect of asphaltene origin was also investigated by using one reclaiming agent with different asphaltenes. The consistencies as well as the chemical fractions of recycled mixture before and after ageing were compared. It was suggested that the compositional parameter of reclaiming agent should be in the range of 0.4 to 1, preferably 0.4 to 0.8, and the syneresis parameter (Section 2.2.3) should be higher than 1 to assure the durability improvement of aged bitumen binders. Dunning and Mendenhall (1978) suggested that the flash point of modifier should be enough to produce the blend with flash point of 205^{o}C. In addition, the viscosity at 60^{o}C of modifier should be in range of 90 to 300 cP.

The origin where bitumen came from also affects the durability of recycled materials. In the study by White et al. (1970), four bitumens from different sources, California, Venezuela, Arkansas, and Alberta, were used. All bitumen binders were fractionated into five basic fractions. The different asphatene fractions with the same proportion were in turn mixed with different maltene phases. When the asphaltene and maltene from California and Alberta were cross blended, there were segregations with all the blends with asphaltene coming from Alberta. The other blends with California asphaltene showed no sign of heterogeneity or syneresis.

White et al. (1970) also concluded that the properties of bitumen were governed predominantly by the composition of the maltene phase. This is actually the ability to peptize asphaltenes by mean of the maltenes phase. The molecular weight of asphaltenes

also affected the viscosity of the blend. His experimental data indicated that the blends with higher molecular weight asphaltenes had higher viscosity than blends with lower molecular weight asphaltene.

The durability of recycled bitumen was also studied by Chaffin et al. (1997) by assessing the potential of some rejuvenators for asphalt pavement recycling. In this study, industrial supercritical fractions (ISCF-A, ISCF-B, ISCF-C), commercial recycling agents (CRA-A, CRA-B, CRA-C) as well as bitumen fractions were appraised. Bitumen fractions are fractions F3 extracted from SHRP bitumen (YBF, AAF, ABM) in a supercritical pilot plant at Texas A&M University at a temperature of 221^{o}C and pressure of 49.3 Bar (Bullin et al., 1995). The SHRP bitumens come from different crude sources. YBF is the popular AC-20 and there is no clear origin recorded for this bitumen. Meanwhile, AAF and ABM in turn originated from West Texas Sour and California Valley (Mortazavi and Moulthrop, 1993). The aged bitumen was artificially produced from SHRP bitumen ABF in an air bubbling apparatus (denoted as ABF-AB1). The properties of recycling agents are illustrated in (Table 2).

	Viscosity (dPa.s)	Saturate (wt%)	Asphaltene (wt%)	Aromatic (wt%)
ISCF A	17.6	20.4	0.3	79.3
ISCF B	58.0	30.8	0.7	68.5
ISCF C	434.0	11.4	3.4	85.2
CRA A	2.4	8.7	0.7	90.6
CRA B	1.2	12.4	0.9	86.7
CRA C	1.0	28.0	0.5	71.5

Table 2: Industrial supercritical fractions and commercial rejuvenating agent properties (Chaffin et al., 1997)

The blends were produced by mixing aged ABF-AB1 with different rejuvenating agents. The amount of aged bitumen was determined by ASTM 4887 (2003) so the final viscosities of the blends were approximately the same as that value of SHRP AAF-1 (approximately 2000 P at 60^{o}C). All the blends as well as AAF-1 were subjected to TFOT and PAV ageing to determine the ageing index. The aging index was the ratio between viscosities before and after artificial aging by TFOT and PAV method. The results (Table 3) indicated that the blends with bitumen fractions had lowest ageing index, followed by the blends with

industrial supercritical fractions and commercial rejuvenating agents. The SHRP AAF-1 had the highest ageing index.

	Composition Asphalt/agent	Viscosity (dPa.s)	TOFT AI	PAV AI
SHRP AAF-1	N/A	1890	2.80	12.42
AAF-AB1/ISCF A	72/28	1900	1.68	4.21
AAF-AB1/ISCF B	61/39	2140	N/A	N/A
AAF-AB1/ISCF C	43/57	2080	1.67	3.89
AAF-AB1/CRA A	81/19	1840	1.85	4.30
AAF-AB1/CRA B	83/17	1850	1.70	4.46
AAF-AB1/CRA C	83/17	1900	1.96	5.53
AAF-AB1/YBF F3	61/39	2000	1.50	3.00
AAF-AB1/AAF F3	67/33	2090	1.67	3.85
AAF-AB1/ABM F3	44/56	1670	1.59	2.93

Table 3: Ageing index (AI) after TFOT and PAV ageing of recycled blend with different rejuvenators (Chaffin et al., 1997)

2.3.4 Estimation of the consistency of the aged bitumen – modifier blend

A crucial phase of the design procedure for recycling asphalt pavement is to predict the viscosity of recycled bitumen binder. The design viscosity of the recycled binder is usually obtained by blending different proportions of aged binder and modifier until the desired viscosity is obtained (Epps et al., 1980). This process is time consuming due to many blending trials and complicated chemical constituents of bitumen. Bitumen is a compound of many different chemical substances, and consistency of each is far different from the others.

Davidson et al. (1977) built a viscosity blending chart to simplify the viscosity estimation process (Figure 11). The construction of this nomograph was based on the trial blending data of 6 aged binders and 12 reclaiming agents. Figure 11 is an illustration of how to use the viscosity blending chart. The first step is to draw a line that connects the viscosity values of aged and virgin binder (points 3 and 5). To determine the proportion of virgin binder in the blend, the next step is to draw a horizontal line at desired viscosity value of the blend on Y-axis. Final step is to draw the vertical line from the point that the first two lines cross each other (point 2). The point that this vertical line crosses the X-axis is the proportion of virgin binder. The viscosity blending chart can also be used to determine the viscosity of recycled blend or for the selection of rejuvenators.

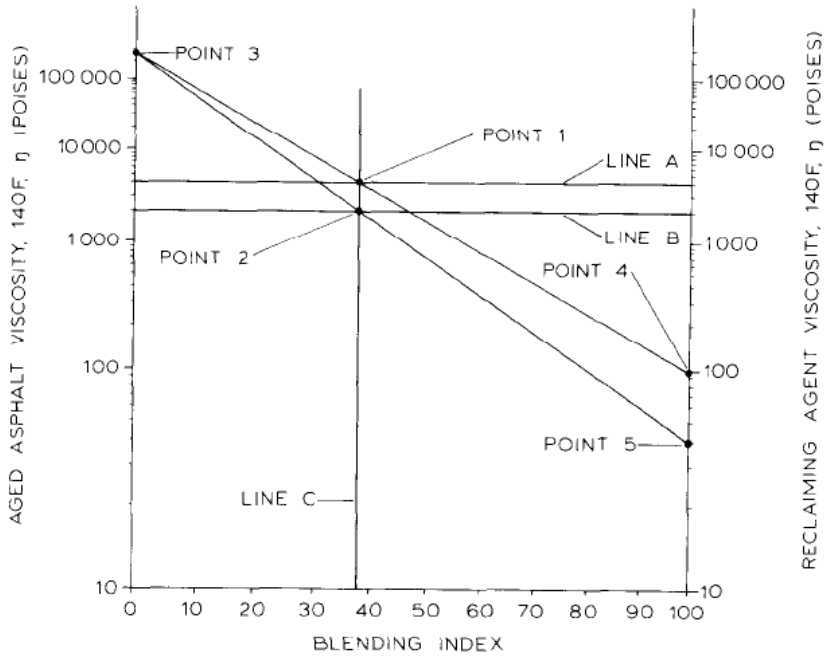


Figure 11: Nomograph for predicting 60°C viscosity of recycled asphalt (Davidson et al., 1977)

Viscosity of bitumen blend between aged and virgin binders can also be predicted using viscosity mixing equations. In these equations, aged and virgin bitumen binders are considered as liquids and the viscosity of the bitumen blend can be estimated approximately by mixing theory for binary liquids (Chaffin et al., 1995). Arrhenius (1887) suggested the following equation. This equation was then developed to ASTM D4887 (2003), one of the most popular tools to predict the viscosity of recycled binder (Karlsson and Isacsson, 2003d).

$$\ln(\eta_{mix}) = x_1 \ln(\eta_1) + x_2 \ln(\eta_2) \quad \textbf{(3)}$$

Where:

η_{mix} : viscosity of the mixture of two binary liquids

η_1, η_2 : viscosity of both liquids

x_1, x_2 : volume percentages of both liquids

The Arrhenius equation, due to its simplicity, could not express the interaction between two liquids in the blend. However, the interaction between two liquids, whether in chemical or physical form, may alter the characteristic of the blend. This is due to the complicated chemical composition of bitumen itself and especially in case of recycled binder which is a mixture of at least two bituminous materials coming from different crude oil sources. The

difference in origin might lead to the fact that although two rejuvenators have the same viscosity, after mixing with aged binder, the viscosities of recycled blends are still different (White et al., 1970).

Grunberg and Nissan (1949) also introduced an equation to estimate the viscosity of binary liquids. One advantage of this viscosity mixing rule over Arrhenius equation is the interaction between two liquids in the blend. The viscosity of binary liquid mixture is expressed as follows:

$$\ln(\eta_{mix}) = x_1 \ln(\eta_1) + x_2 \ln(\eta_2) + x_1 x_2 G_{12} \quad \textbf{(4)}$$

Where:

G_{12} : is a characteristic of the system of two binary liquids or interaction parameter

Epps et al. (1980) also introduced an equation to estimate the viscosity of a mixture between two liquids. The viscosity of binary liquid is based on the log log relationship with the log log viscosity of each individual liquid and the mass percentage in the whole mixture. This equation is expressed as follows:

$$\ln(\ln(\eta_{mix})) = x_1 \ln(\ln(\eta_1)) + x_2 \ln(\ln(\eta_2)) \quad \textbf{(5)}$$

Actually, the Arrhenius equation is a special case of Grunberg and Nissan viscosity mixing rule where G_{12} is equal to zero. A study by Irving (1977) concluded that generally, Grunberg and Nissan equation was the best equation to estimate the viscosity of binary liquids. Irving (1977) also claimed that if constant parameter G_{12} was used universally, the predicted viscosity could be less than 30% difference from actual value.

Chaffin et al. (1995) carried out a study to verify the effectiveness of different viscosity mixing equations. In this research, three SHRP bitumens, AAA-1, AAF-1, and ABM-1 were used to produce aged bitumen by using pressurised oxygen vessel and air bubbled reaction apparatus. A wide range of softening agents was used, for instance, low viscosity bitumen binders, commercial recycling agent, and supercritical fractions. Low viscosity bitumen included AC-3, AC-5 from Diamond Shamrock (DS) in Duma, Texas, AC-5 from Shell in Deerpark, Texas, and AAV, ABH from SHRP. Commercial recycling agents were Sun Hydrolene 125, Witco Cyclogen, Exxon Nuso 95 and Mobil Mobisol 120. Supercritical fractions were extracted from AC-20 (YBF), AAA-1, ABM-1, and AAF-1. Viscosities of aged bitumens, softening agents are illustrated in Table 4. The consistencies of aged

bitumens and softening agents were measured by rheological apparatus at 60°C and frequency of 1.6Hz.

Aged bitumens were blended with low viscosity bitumen, softening agents including commercial agents and supercritical fractions at increments of 20%. Viscosity values estimated by different viscosity mixing equations were then compared to experiment data. Using Grunberg and Nissan equation, interaction parameter G_{12} for each pair of aged bitumen/softening agent was calculated. The results of G_{12} for the whole experiment (Table 5) showed that the interaction parameters G_{12} of each pair of aged bitumen/softening agent varied considerably. The finding of Chaffin et al. (1995) is also in agreement with Irving (1977). In fact, using a constant value of G_{12} would result in considerable errors in viscosity estimation.

Material	60°C Viscosity (dPa·s)[a]
POV AAA-1	22,500
AAA-AB7	22,900[b]
AAA-AB8	36,600
AAF-AB1	52,500
AAF-AB2	20,900
Oven Coastal	100,000
POV ABM-1	47,200
NUSO 95	1.3
Mobil 120	1.8
Sun 125	3.0
Cyclogen	8.9
AAF F2	12
AAA F2	13
YBF F2	38
YBF F5	47
AAF F3	70
AAA F3	79
ABM F2	98
ABM F5	100
YBF F3	138
Shell F3	165
ABM F3	650
DS AC-3	310
DS AC-5	500
Shell AC-5	575
SHRP AAV	630
SHRP ABH	900

[a] 1 dPa·s = 1 Poise
[b] Initial value

Table 4: Viscosity at 60°C of aged bitumen and softening agents (Chaffin et al., 1995)

Asphalt	Agent	G_{12}	Asphalt	Agent	G_{12}
POV AAA-1	Sun 125	-5.80	AAA-AB7	Sun 125	-6.31
AAA-AB7	Cyclogen	-6.28	AAA-AB7	YBF F2	-5.42
AAA-AB7	YBF F5	-4.28	AAA-AB7	ABM F2	-4.63
AAA-AB7	YBF F3	-3.45	AAA-AB7	ABM F3	-4.10
AAA-AB7	SHRP ABH	0.03			
AAA-AB8	Cyclogen	-6.33	AAA-AB8	AAA F2	-5.47
AAA-AB8	YBF F5	-4.03	AAA-AB8	AAA F3	-4.77
AAA-AB8	AAF F3	-4.52	AAA-AB8	DS AC-3	--- [a]
AAA-AB8	DS AC-3 Maltene	--- [a]	AAA-AB8	Shell AC-5	1.14
AAA-AB8	SHRP AAV	-0.46	AAA-AB8	NUSO 95	-6.23
AAF-AB1	NUSO 95	-8.42	AAF-AB1	AAF F2	-5.88
AAF-AB1	ABM F2	-4.88	AAF-AB1	AAA F3	-4.56
AAF-AB1	Shell F3	-3.64	AAF-AB1	ABM F5	-4.90
AAF-AB1	DS AC-5	2.57	AAF-AB1	SHRP ABH	0.08
AAF-AB1	DS AC-3	2.18	AAF-AB1	ABM F3	-3.99
AAF-AB1	Mobil 120	-7.69			
AAF-AB2	Sun 125	-6.24	AAF-AB2	Mobil 120	-7.50
AAF-AB2	AAA F2	-4.83	AAF-AB2	AAF F2	-5.26
AAF-AB2	ABM F5	-3.95	AAF-AB2	YBF F3	-3.39
AAF-AB2	AAF F3	-3.81	AAF-AB2	Shell F3	-3.12
AAF-AB2	Shell AC-5	-0.37	AAF-AB2	SHRP AAV	-0.88
AAF-AB2	DS AC-5	1.82			
Oven Coastal	Sun 125	-10.71	Oven Coastal	Cyclogen	-9.28
Oven Coastal	YBF F3	-6.54	Oven Coastal	YBF F5	-6.90
POV ABM-1	ABM F3	-1.48	POV ABM-1	ABM F2	-3.39

[a] --- Data not applicable

Table 5: Aged bitumen - softening agent Grunberg interaction parameter G_{12} (Chaffin et al., 1995)

The variation of G_{12} was attributed to the viscosity difference between softening agents and aged bitumen. The larger the difference in viscosity between aged bitumen and rejuvenator, the greater the absolute value of interaction parameter G_{12}. To eliminate the viscosity effects, Chaffin et al. (1995) introduced the dimensionless log viscosity (DLV). Using DLV, Grunberd and Nissan equation is mathematically transformed as follows:

$$DLV = \frac{\ln(\eta_m / \eta_1)}{\ln(\eta_2 / \eta_1)} = \left(1 + \frac{G_{12}}{\ln(\eta_2 / \eta_1)}\right)x_2 + \left(\frac{-G_{12}}{\ln(\eta_2 / \eta_1)}\right)x_2^2 \qquad \textbf{(6)}$$

Where:

η_m, η_1, η_2 Viscosity of mixture, rejuvenator and aged binder

x_2 Proportion of aged binder in the mixture

Based on experimental data, Chaffin et al. (1995) came up with the following equation to estimate the viscosity of bitumen blend:

$$DLV = 0.01 + 0.26x_{as} + 0.73x_{as}^2 \quad \textbf{(7)}$$

Where:

x_{as} : the proportion of aged binder in the blend

In Grunberg and Nissan method, the viscosity of the blend has a second order polynomial relationship with the proportion of aged binder. Meanwhile, the viscosity mixing equation by Chaffin et al. (1995) expressed the second polynomial relationship between DLV and proportion of aged binder. Although the ways to find the solutions are mathematically different, both methods have the same philosophy, to use one constant interaction parameter universally. This will lead to the fact that the method performs well with some types of blend and not with others. Chaffin et al. (1995) compared the predicted viscosity values using different method to the experimental data. The result indicated DLV method performed well when supercritical and commercial recycling agents were used. On the other hand, the deviation is considerably larger than those obtained by the other mixing rules when soft asphalt was used as recycling agent. In this case, Arrhenius or ASTM 4887 is the best to estimate viscosity of the blend.

Mixing rule is also expressed in BS EN 13108 part 1 (2006). In this document, the penetration and softening point of the mixture is estimated by those of individual bitumen comprising the mixture and the mass proportions. The penetration of the mixture is estimated by the following equation:

$$\log(pen_{mix}) = a\log(pen_1) + b\log(pen_2) \quad \textbf{(8)}$$

Where:

pen_{mix} : calculated penetration of the mixture

pen_1, pen_2 : penetrations of both binders comprising mixture

a, b : mass proportions of each bitumen in the mixture ($a + b = 1$)

The softening point of the mixture is estimated by the following equation:

$$T_{mix} = aT_1 + bT_2 \quad \textbf{(9)}$$

Where:

T_{mix} : calculated softening point of the mixture.

T_1, T_2 : softening point of each individual binder in the mixture.

2.4 Hot recycled mixture production

The conventional plants for producing hot asphalt mixture are batch plant and drum plant. With existence of RAP, some modified features should be made to the conventional mixing plant to incorporate RAP materials to produce the hot recycled asphalt mixtures (Roberts et al., 1991). The way RAP is processed is different with different modified mixing plants.

2.4.1 Batch plant

The schematic of a batch mixing plant is illustrated in Figure 12. For conventional asphalt mixture, each component has its own function. The burner is in charge of drying aggregate to remove the moisture content and preheat aggregate to the temperature required for mixing. After drying process, the heated aggregate is conveyed to the screening deck to determine the quantities necessary and stored in the hot bin. Bitumen is also preheated and weighed before sprayed and mixed with heated aggregate in the pugmill.

However, there are problems using conventional method to produce hot recycled asphalt mixture. The materials for recycled mix are not just virgin aggregate and bitumen but also RAP. If the RAP material is dried the same way as the virgin aggregate, there will be environmental problems as the RAP bitumen is burned directly by the flame in the burner causing blue smoke (Hughes, 1978). Hence, the conventional method is modified to prevent the “blue smoke” phenomenon. RAP is stored separately before being introduced to virgin aggregate in the hot bin. Virgin aggregate is superheated and the excessive thermal energy will be used to heat up RAP material from ambient to required mixing temperature and remove the RAP moisture content. After storing in hot bin, the combination of RAP and virgin aggregate will be mixed with virgin bitumen to produce the recycled mixture.

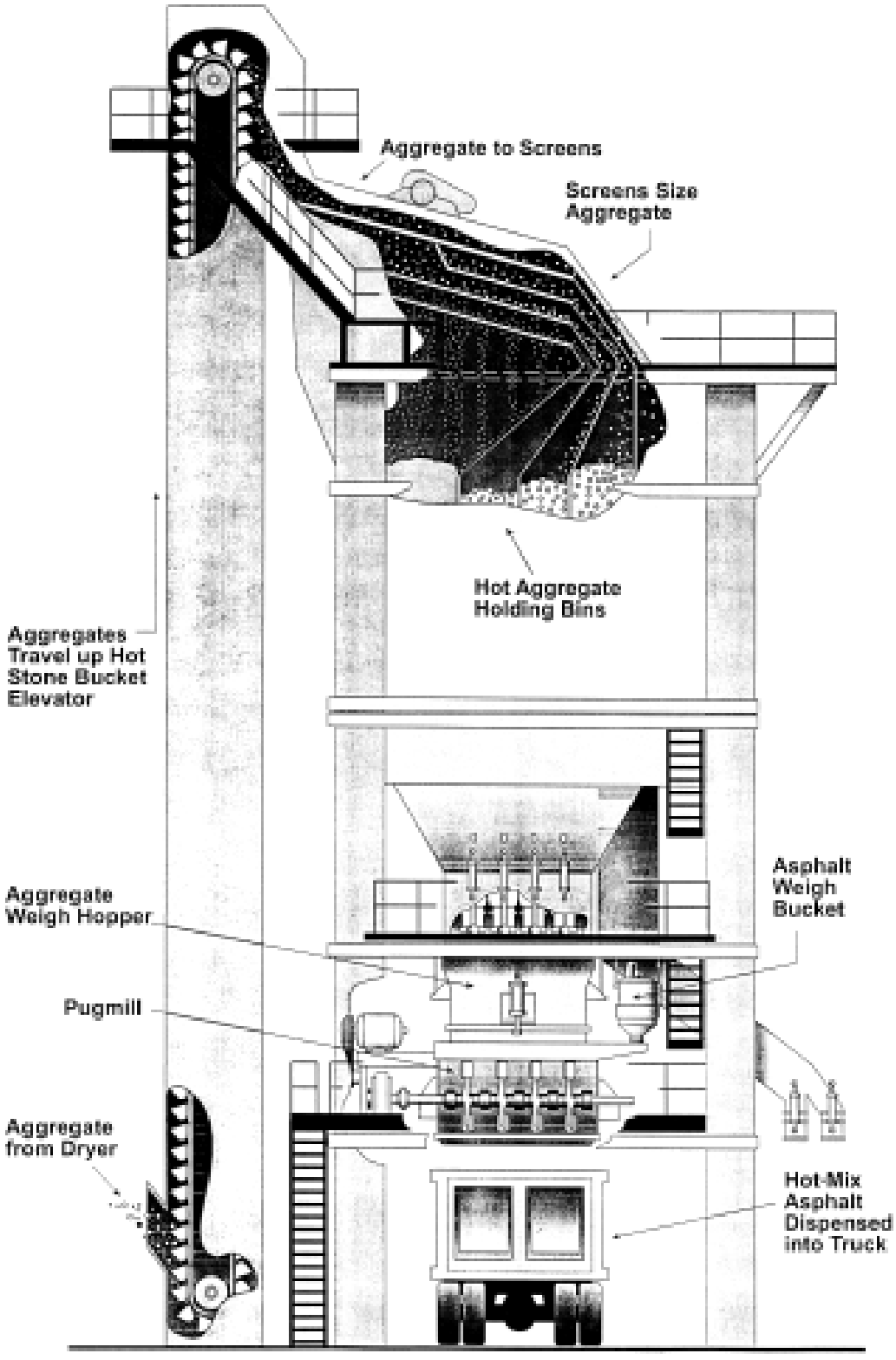


Figure 12: Batch Plant (MAPH-2, 2000)

There are different methods of introducing RAP to the superheated virgin aggregate (Brock and Richmond, 2005):

- Method 1: RAP is mixed with superheated virgin aggregate before being screened, weighed, and stored.
- Method 2: RAP is weighed and screened before introduced and stored with superheated virgin aggregate in hot bin
- Method 3: RAP is dried separately and then mixed with heated virgin aggregate and bitumen.

In the first method; it is really difficult to control the gradation of the recycled mixture as the size of RAP and the size of RAP aggregate are not similar, sometimes considerably different. Two RAP particles have the same size, for example, ½ inch (12.5 mm). However, one might be made of only one ½ inch (12.5 mm) aggregate; the other might be combined of many 1 mm particles. In addition, the bottom deck screen, especially sizes smaller than 6.4 mm will be blind due to the RAP binder filling up those tiny holes of the screens. In addition, bigger RAP size cannot be used in this process as the bigger size, for instance, size 2 inches (50 mm), cannot pass the screen decks.

In the second method, as the RAP is introduced to superheated virgin aggregate and stored in the hot bin, the blend is not well mixed. Hence, the heat from superheated virgin aggregate is not well transferred to the RAP materials to remove all the moisture content and heat up RAP.

The only problem with the third method is the production rate and the cost. RAP materials do not have the same characteristics as virgin aggregate as RAP is a combination of aged bitumen and aggregate. With bitumen, if the drying temperature is higher than 100^{o}C, it will increase the ageing speed of RAP bitumen (Shell bitumen handbook). On the other hand, if low drying temperature is employed, the time for heating will be longer and might seriously affect the production rate as well as the cost of asphalt production.

As RAP is mixed with virgin aggregate at extremely high temperatures, the properties of RAP binder might change. The ageing process might also be affected by the steam generated due to RAP moisture content during the mixing process in the pugmill.

2.4.2 Drum facility (Drum mixer)

The schematic of drum mixer for producing hot asphalt mixture is demonstrated in Figure 13. The procedure in the drum facility is quite different from batch plant. In batch plant, the process of drying and heating aggregate is separate from the mixing aggregate with bitumen. Drying and heating aggregate are processed in the burner. The mixing between aggregate is implemented in the pugmill. However, with conventional drum facility, aggregate is heated and mixed with bitumen in the same drum. The drying and heating time of aggregate is twice as long as the mixing time between aggregate and bitumen. Mixing time of aggregate with bitumen is normally 30 seconds (Read and Whiteoak, 2003). Bitumen is introduced and mixed with heated aggregate at the two third point of the overall time.

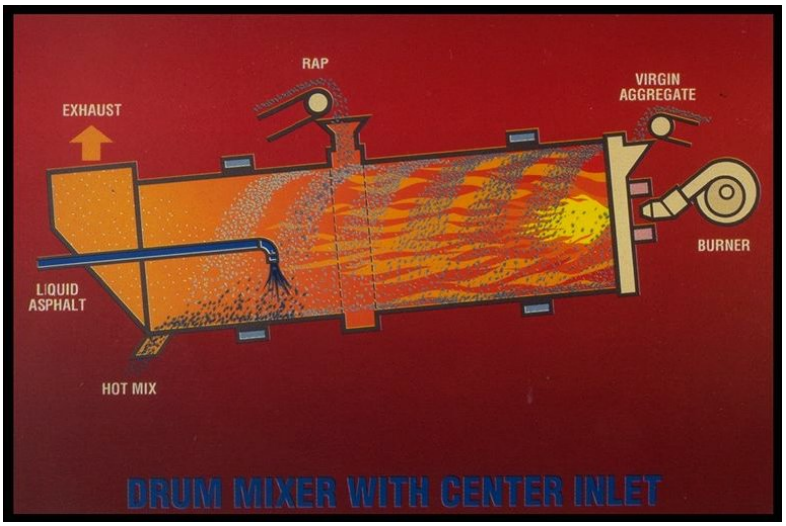


Figure 13: Drum mixer with RAP centre inlet (Brock and Richmond, 2005)

There are two main types of drum facility, parallel and counter drum mixer. Both types are different regarding the way that materials are introduced into the mixer. In parallel mixer, materials go in the same direction with the flame. Vice versa, the movement of materials is opposed to the direction of the flame in counter drum mixer (Brock and Richmond, 2005).

In order to intake RAP materials, the conventional drum facility must be modified for hot recycled asphalt production. Depending on what type of drum mixer, the modifications are different. The first version of parallel drum mixer has a centre RAP inlet (Figure 13). In this facility, RAP is mixed with superheated virgin aggregate before being mixed with virgin

binder. The design of kicker flight in the middle of the drum mixer is aimed to form a dam of virgin aggregate so that the direct exposure of RAP to the flame is prevented.

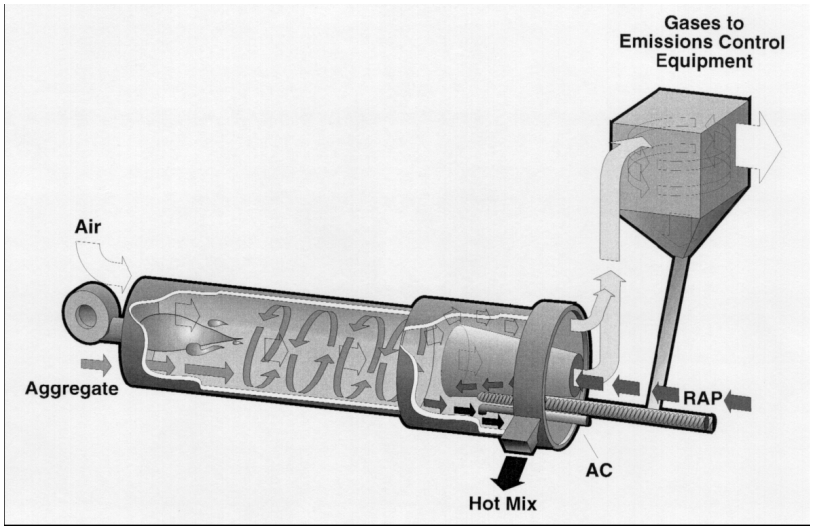


Figure 14: RAP in parallel drum mixer with isolated area (Brock and Richmond, 2005)

In parallel type, there is also a drum mixer with separated mixing area (Figure 14). In this facility, RAP is introduced with superheated virgin aggregate before entering isolated mixing area where the blend is mixed with virgin binder. Sometimes, the mixer is designed separately and called added continuous mixer (Figure 15).

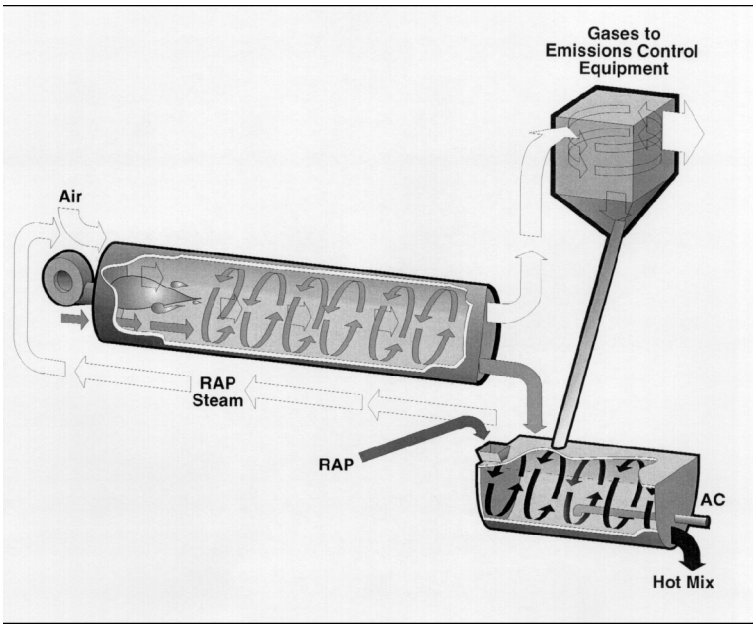


Figure 15: RAP in parallel drum facility with added continuous mixer (Brock and Richmond, 2005)

The latest type of drum facility is called double barrel mixer. In this facility, the shell of the drum is used as a shaft of the coater (Figure 16). As drying and mixing compartment are separated by the shell of the drum, the exposure of RAP to direct flame of the burner is absolutely prevented.

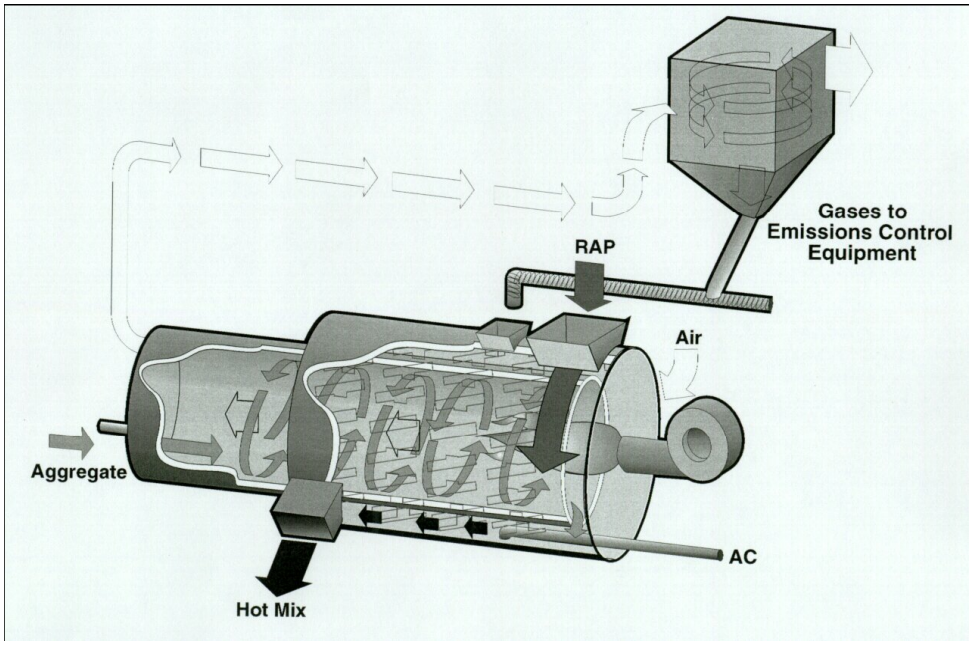


Figure 16: Double Barrel Drum facility (Brock and Richmond, 2005)

Except for the parallel drum facility with isolated area in which, the water steam is removed considerably from mixing area, RAP material, virgin aggregate and virgin bitumen are mixed in the condition of high temperature and steam. An example of preheating temperature for RAP in drum mixer is illustrated in Table 6. Hence, the characteristics of RAP binder might be changed, for instance, the ageing after mixing with superheated aggregate due to the direct exposure to high temperature and steam condition. An advantage of drum mixer is big sizes of RAP can be processed as the RAP is incorporated directly into the mixer.

Generally, in both types of mixing plant, RAP material at ambient temperature is introduced with superheated virgin aggregate. The heat transferred from superheated virgin aggregate will help to remove the RAP moisture content. In addition, the energy RAP absorbs from superheated virgin aggregate also increases RAP temperature and weakens the bitumen bonds between RAP aggregate particles. Under the mechanical mixing, RAP materials are separated and mixed with virgin aggregate. The combination of RAP and

virgin aggregate is then mixed with virgin binder. The total duration for a production cycle in batch plant is about 60 seconds (Read and Whiteoak, 2003). In drum mixer, the production cycle is approximately the same except for double barrel mixer at about 90 seconds (MAPH-2, 2000).

RAP Content (%)	RAP Moisture Content (%)	Superheat Temperature Required (^{o}C)			
		116 ^{o}C Mix	127 ^{o}C Mix	138 ^{o}C Mix	149 ^{o}C Mix
10	0	132	144	156	168
	1	134	147	159	171
	2	137	149	162	174
	3	140	152	164	177
	4	143	155	167	179
	5	146	158	170	182
20	0	144	158	172	186
	1	151	164	178	192
	2	157	171	184	198
	3	163	177	191	204
	4	169	183	197	211
	5	175	189	203	217
30	0	162	178	166	209
	1	173	188	315	219
	2	183	199	214	230
	3	194	209	225	241
	4	204	220	236	251
	5	215	231	246	262
40	0	186	203	221	239
	1	218	219	237	256
	2	234	235	253	272
	3	250	251	269	288
	4	266	267	286	304
	5	282	283	302	320
50	0	216	238	260	282
	1	240	262	284	309
	2	264	287	309	331
	3	289	311	333	356
	4	313	336	358	380
	5	338	360	382	404

Table 6: RAP preheating temperature required in Drum Mixer (Brock and Richmond, 2005)

2.4.3 RAP sizes used for production of recycled mixture

There is a variety of RAP sizes used for production of RAP in recycled mixtures regarding the equipment used for recycling and the percentages of RAP in the mixture. Table 7 illustrates the maximum sizes of RAP allowed for batch and drum mixing plants in relation

to RAP proportion of some States in America. The maximum size of RAP used is normally less than 2 inches (50 mm). However, there are some States, for instance, Arkansas, and Minnesota which use up to 3 inches (75 mm) RAP sizes (United States Department of Transportation, 2007).

State	Max. RAP % - Batch Plants			Max. RAP % - Drum Plants			Top Size for RAP
	Base	Binder	Surface	Base	Binder	Surface	
Alabama	40	40	15	50	50	15	2 in
Alaska	-	-	-	-	-	-	-
Arizona	30	30	30	30	30	30	1.5 in
Arkansas	70	70	70	70	70	70	3 in
California	50	50	50	50	50	50	2 in
Colorado	15	15	15	15	15	15	1.5
Connecticut	40	40	40	40	40	40	2 in
Delaware	35	35	25	50	50	30	2 in
Florida	60	50	None	60	50	None	Specs
Georgia	25	25	25	40	40	40	2 in
Hawaii	30	None	None	40	None	None	1.5 in
Idaho	Open	Open	Open	Open	Open	Open	2 in
Illinois	50	25	15	50	25	15	Specs
Indiana	50	50	20	50	50	20	2 in
Iowa	Open	Open	Open	Open	Open	Open	1.5 in
Kansas	50	50	50	50	50	50	2 in
Kentucky	30	30	30	30	30	30	Specs
Louisiana	30	30	None	30	30	None	2 in
Maine	40	40	None	40	40	None	1 in
Maryland	Open	Open	Limit	Open	Open	Limit	Specs
Massachusetts	20	20	10	40	40	10	0.75 in
Michigan	50	50	50	50	50	50	Specs
Minnesota	59	50	30	50	50	30	3 in
Mississippi	30	30	15	30	30	15	2 in
Missouri	50	50	50	50	50	50	1.5 in
Montana	50	50	10	50	50	10	2 in
Nebraska	Not Used	Not Used	Not Used	Open	Open	Open	2 in
Nevada	50	50	15	50	50	15	1.5 in
New Hampshire	35	35	15	50	50	15	Specs
New Jersey	25	25	10	25	25	10	2 in

Table 7: State DOT specification requirements for the use of reclaimed asphalt pavement (RAP) in hot asphalt paving mixtures (United States Department of Transportation, 2007)

2.5 Mixing mechanism

2.5.1 Mechanical mixing

There are many aspects that scientists have to cope with in the mixing industry, for instance, mixing of solid particles, liquids, gases and liquids, and cohesive powders. Generally, the aim of a mixing procedure is to reduce the scale and intensity of segregation,

for example, size segregation, making the most homogeneity of mixing ingredients (Harnby et al., 2001). The ideal mixture with homogeneity is illustrated in Figure 17. In this research, just the aspect of mixing cohesive powders is considered as asphalt mixtures (due to bitumen having a liquid state at high mixing temperature causing interparticulate forces among aggregate particles) possess relatively comparable characteristics to those of cohesive powders.

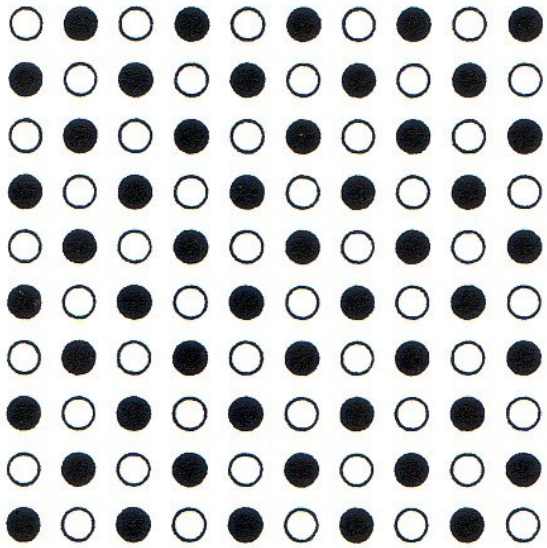


Figure 17: Ideal mixture with homogeneity (Harnby et al., 2001)

In order to obtain the most homogeneity of the mixture, the external forces, for instance, rotational, vibrating effects must be satisfied to break any bonds that exist between particles and relocate these particles in the mixture. Otherwise, segregation will occur and cause adverse effects to the quality of the mixture. There are many factors affecting the mixing process that lead to segregation, for instance, type of particles, interparticulate forces, type of mixing machine, and mixing time.

In term of interparticulate forces among particles, there are electrostatic bonding, van der Waal's forces, and liquid bridge bonding. If these particulate forces are not deactivated during mixing process, there will be movements of small free flowing agglomerates of aggregate particles (Figure 18). Particle types also attribute to the magnitude of liquid bridge bonding. For instance, if the surfaces of particles are not smooth, the surface roughness will reduce the contact areas hence reduce the bonding forces. In addition, different sizes of particle also cause segregation as these particles will have different velocities during mixing process (Harnby et al., 2001).

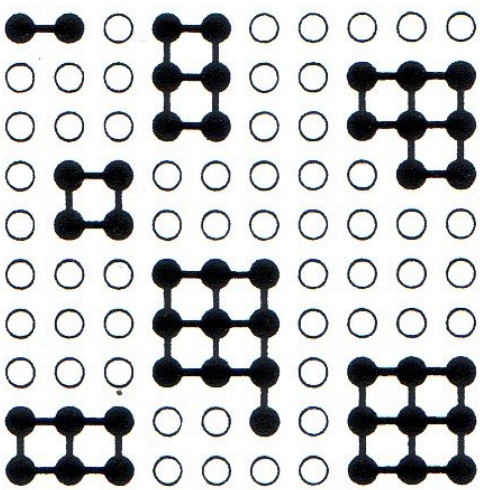


Figure 18: Mixture with "self-loving" particles (Harnby et al., 2001)

Production of conventional asphalt mixture comprises weighing, heating aggregate, and blending hot virgin aggregate with bitumen binder. During the whole process, all the materials are rolled centrifugally in a mixing vessel. The heating time of aggregate is aimed to dry the material. In addition, heating and the rotational effects on aggregate create aggregate movement, breaking up all the bonds between aggregate particles, due to moisture, electrostatic charging, van der Waal's forces. This is to make a homogeneous blend of different particle sizes of aggregate. In addition, the drying process also separates all the particles, even filler, before mixing with bitumen so binder can cover each particle surface to improve the bonding between particles in the final mixture.

However, as the size of most aggregate particles is larger than 75μm, the flow of every single aggregate particle is considered free due to the fact that electrostatic charging and van der Waal's forces among particles bigger than 75μm are inconsiderable and can be ignored (Harnby et al., 2001). In addition, as the cohesion among particles due to existence of water is not considerable compared to that of bitumen, hence just the bitumen contributes to the bond among aggregate particles. If the mixing machine and procedure cannot overcome these issues, for instance, breaking the bond between aggregate particles, relocating all the particles so the mixture can reach the homogeneous status, segregation will occur.

The mixing mechanism of recycled asphalt mixture is quite different from that of conventional asphalt mixture. Both types of asphalt mixtures are finally, the combinations

of the same type of materials, bitumen binder and aggregate. However, conventional asphalt mixture is a combination of virgin aggregate and bitumen binder while in recycled mixture, the aggregate is not just virgin aggregate but also RAP, a blend of aged bitumen and aggregate as well. In fact, this ultimate difference between two types of mixture makes the production, in fact, mixing mechanism quite different.

The production of recycled asphalt includes the following steps:

- superheating virgin aggregate
- blending with RAP
- mixing the blend of virgin aggregate and RAP with virgin bitumen

"Black rock" concept

The ultimate characteristic distinguishing RAP (reclaimed asphalt pavement) from virgin materials is the content of aged bitumen. This proportion of aged bitumen makes RAP not conform to any requirements of normal design methods for virgin mixture, for instance, Hveem, Marshall, or Superpave. Although the RAP aggregate covered by aged binder is considered stiff, inert as black rock at ambient temperature, the level that a proportion of aged bitumen might be incorporated with virgin binder during the mixing process and through service life of pavement has still been ambiguously identified.

Research has been carried out to investigate whether RAP material acts as black rocks once accommodated in the recycled mixture (McDaniel et al., 2000). In this study, three types of RAP, low stiffness RAP from Florida (FL), medium stiffness RAP from Connecticut (CT), and high stiffened RAP from Arizona (AZ) were used. All the RAP materials were processed to less than ½ inch (12.5 mm) size. Viscosity of RAP binder is showed in Table 8. Two soft virgin binders, PG 52-43 and PG 64-22 were used as rejuvenators (Table 9). The proportions of RAP in the recycled mixture were 10, and 40%.

RAP Source	Viscosity at 60^{o}C, Poise
FL	23760
CT	65191
AZ	124975

Table 8: Viscosity at 60^{o}C (Poise) of RAP binder (McDaniel et al., 2000)

		Virgin Binders		Recovered RAP Binders (Unaged)		
Aging	Property	PG 52-34	PG 64-22	FL	CT	AZ
Original	High Temp. Stiffness	53.9	67.8	82.2	82.4	89
RTFO	High Temp. Stiffness	54.6	66.6	75.4	75.8	85.3
PAV	Intermediate Temp. Stiffness	11.5	21.7	19.3	25.1	33.8
	BBR S	-23.7	-18.1	-15.9	-15.1	-5.6
	BBR m-value	-25.9	-16.2	-16.4	-14.4	-7.1
PG	Actual (Critical Temperature)	PG 53-33	PG 66-26	PG 82-25	PG 82-24	PG 89-15
	MP1 (Performance Grade)	PG 52-28	PG 64-22	PG 82-22	PG 82-22	PG 88-10

Table 9: Critical temperature and performance grades of virgin and recovered RAP binders

Test samples are designed to simulate three possible cases with different levels of blending, total blending, actual blending, and black rock. In the total blending, the aged bitumen is extracted and recovered from the RAP before being mixed with RAP and virgin aggregate. This total blending simulates what occurs during the design process. In case of actual practice, RAP and virgin aggregate are mixed directly before being blended with virgin bitumen. For the black rock case, just RAP aggregate is extracted and mixed up with virgin aggregate and binder.

To prepare for the samples, all the virgin aggregate, and RAP aggregate in case of black rock condition, are heated overnight at 150^{o}C. RAP material is also preheated at 110^{o}C for the duration of 2 hours before mixing. Preheated temperatures of virgin binder rely on the performance grade: 155-160^{o}C for PG 64-22 and 135-140^{o}C for PG 52-34. After mixing, the loose mixture is held in the oven at 135^{o}C for 4 hours successfully to simulate the short term ageing. In terms of long term ageing, the compacted sample is stored in condition of 85^{o}C for five days continuously. All the specimens are compacted by Superpave gyratory compactor at different temperatures, 143-148^{o}C for PG 64-22, and 122-130^{o}C for PG 58-34.

Superpave tests including frequency sweep (SF), simple shear (SS), repeated shear at constant height (RSCH), indirect tensile creep (ITC) and indirect tensile strength (ITS) are employed to identify the differences in properties of three blending situations, total blending, actual blending, and black rock, with both 10 and 40% of RAP. These tests cover a wide range of asphalt properties, fatigue, rutting, and low temperature cracking.

Frequency sweep at constant height is used to determine the complex shear modulus and phase angle of asphalt mixture. In this test, repeated shear load is applied on the test specimen to produce a horizontal strain of 0.005%. Axial stress is also applied to keep the specimen height constant. The results at frequencies of 0.01, 10 Hz and temperatures of 20, 40^{o}C show that stiffness of the samples increases in accordance with the increase of RAP proportion for total and actual blending cases. On the contrary with the black rock situation, stiffness of samples is the same with 10 and 40% of RAP.

In simple shear at constant height test, the shear load is increased at the rate of 70kPa/sec until it reaches the specified shear load relevant with test temperatures of 4, 20, and 40^{o}C (Procedure D of AASHTO TP7-94). The load is held constant for 10 seconds before being released at a rate of 25kPa/sec. Maximum deformation results from the test indicates that with the same RAP, the maximum deformation increases if the softer virgin binder is applied. This is similar with increasing test temperature.

To evaluate rutting phenomenon of asphalt mixture, the repeated shear at constant height test is employed. Plastic shear strain of mixture is determined under given loading mode and temperature (Procedure C, AASHTO TP7-94). During the test, the stress controlled shear load is applied to specimen until the number of loading cycles, each consisting of 0.1 sec loading time and 0.6 sec for rest period, reaches 5000 or the permanent strain exceeds 5%. Test temperature is 58^{o}C for the PG 64-22 and 52^{o}C for the PG 52-34 binder. The test result also indicates that with 10% of RAP, the recycled mixture with softer virgin binder has higher plastic shear strain. With the same virgin binder, the plastic shear strain is not influenced substantially with different sources of RAP and blending situation. However, plastic shear deformation of black rock case is considerably higher than those of total blending and actual practice with 40% RAP content.

Indirect tensile test (AASHTO TP9) is used to analyze thermal susceptibility and low temperature cracking of asphalt mixture. The relation of load magnitude, deformation, and loading time was studied at three temperatures 0, -10, and -20^{o}C. Horizontal and vertical deformations of the specimen due to the static compression load applied across the diametric plane of specimen are recorded over a period of time (240 seconds) to calculate the creep compliance. On the other hand, in terms of temperature cracking, specimen is tested at -10^{o}C by applying the load with strain rate of 12.5 mm/minute until fracture

occurs. The test result shows that with 10% RAP contents, although there is not substantial variation, the stiffness of the actual practice has tendency of being between black rock and total blending cases.

Data from all the tests showed that with 10% RAP, among 66 combinations, there were 36 cases in which the test results of actual blending, total practice and black rock were approximately the same, 9 cases that actual practice and total blending were almost similar, and only 6 cases in which actual blending resembled the black rock. The overall trend indicated that the there is no considerable differences between actual blending, total practice and black rock cases.

The test results with 40% RAP showed inconsistent trend. There were 21 cases where the test results showed no considerable variations between total blending and actual practice. There are 12 cases where the results from total blending, actual practice, and black rock were different. In fact, 10 out of 12 cases occurred with PG 64-22. In addition, there were 3 cases where actual blending resembled the black rock.

Due to the results from the tests, where 6 cases actual blending resembled the black rock with 10% RAP, 3 cases with 40% of RAP, McDaniel et al. (2000) concluded that RAP did not work as "Black Rock" or inert component in the recycled mixture. Actually, RAP binders interacted with virgin binder and the mixture generally had approximately the same properties as that of complete blending case. However, the laboratory mixing procedure used in this research is quite different from that of the mixing plant. The long RAP preheating time might enhance the interaction between RAP and virgin binder. McDaniel et al. (2000) also carried out a study to compare the laboratory mixing procedure with that of an industrial mixer. The test results showed that the laboratory mixture processed the same characters as those of a mixture mixed by real mixing plant. However, the proportion of RAP was only 15%. It has been argued whether the complete blending obtained in the laboratory can actually occur in an industrial mixer, especially in the case where high proportion and larger size of RAP is used.

Laboratory procedures for recycled mixture preparation

In general, the procedures for preparing the recycled mixture include heating the RAP to a specified temperature for a certain period, and mixing with preheated rejuvenator before

compaction. For instance, Carpenter and Wolosick (1980) heated the RAP to 116^{o}C before mixing with rejuvenator. Noureldin and Wood (1987), heated the RAP at 116^{o}C for 30 minutes before mixing with preheated rejuvenator (AC 2.5, AE-150, and Mobilsol-30) at 82^{o}C. The loose mixture was then conditioned at 60^{o}C for 15 hours. McDaniel el al. (2000), heated the RAP to 110^{o}C for 2 hours mixing with rejuvenator at required mixing temperature. The requirement of heating RAP is to make the RAP workable so that it can be mixed with rejuvenator (McDaniel and Anderson, 2001). In fact, the purpose of preheating RAP is to soften the RAP binder to break RAP into separate pieces so the rejuvenator can cover the RAP for diffusion process. Preheating time was also used for preventing the effect of RAP moisture content on the properties of the recycled mixture (Stephens et al., 2001).

Effect of RAP preheating duration

Stephens et al. (2001) studied the effect of RAP preheating time on the strength of recycled mixture with the hypothesis that if RAP acted as black rock, the effect of preheating on the recycled mixture would be insignificant. Samples were prepared with the same 15% RAP content except with preheating times from 0 to 540 minutes. There were also samples with the same aggregate gradation and virgin binder for comparison. All the samples were subjected to indirect tensile and unconfined compression tests. The test results indicated that the longer the RAP preheating time, the higher the strength of the recycled mixtures (Figure 19).

Stephens et al. (2001) concluded that the increase of indirect tensile and unconfined compression strength was attributed to the long RAP preheating time, the lump of RAP was totally heated through and broken down during mixing for complete blending. This was not a firm conclusion as the increase of indirect tensile and unconfined compression strength might also be accredited to the RAP being hardened due to exposure at high temperature during the long preheating time.

However, McDaniel et al. (2000) investigated the effect of preheating time on the properties of RAP binder. Two types of RAP taken from Arizona and Florida were subjected to different preheating times and temperatures. The properties of original RAP binders were compared to those of the RAP after different preheating time. The test results (Figures 20 and 21) indicated that the complex modulus of RAP after two hours preheated

at 110 and 150°C did not change considerably. This supports the conclusion of Stephen et al. (2001) during the first two hours of preheating, the increase in indirect tensile and unconfined compression strength of the mixture is attributed to complete blending with virgin binder as the RAP lump is heated through and completely separated.

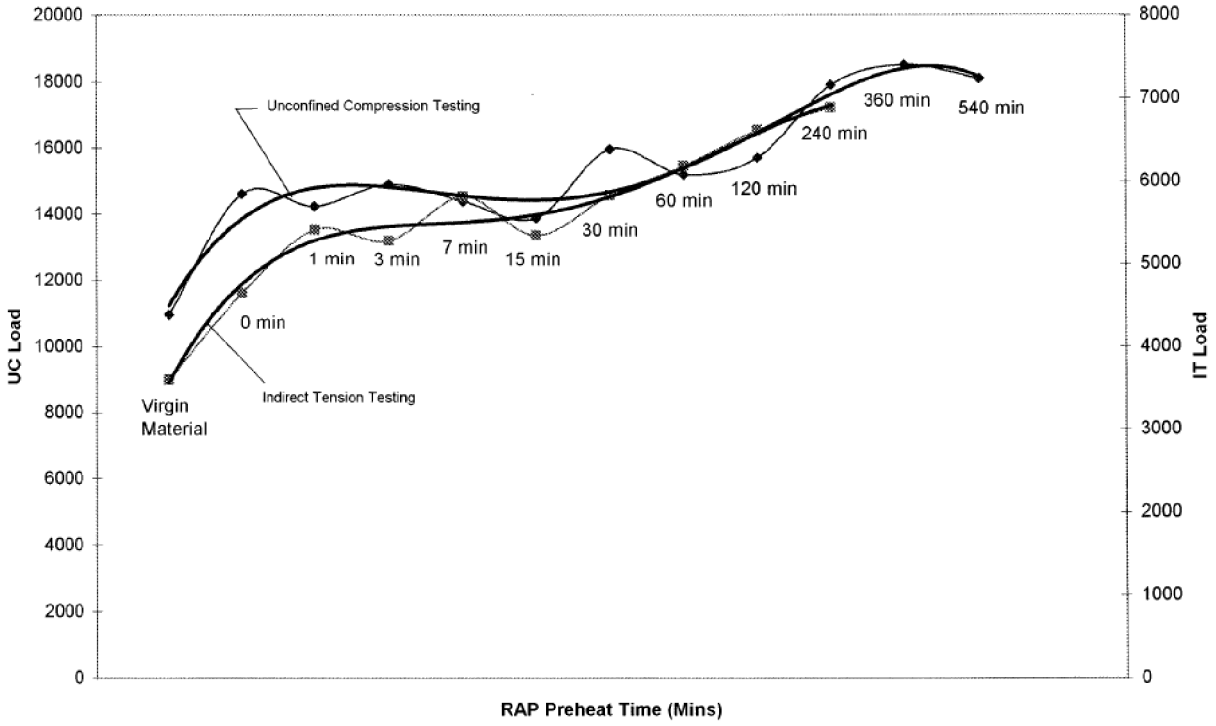


Figure 19: RAP preheating time versus indirect tensile and unconfined compression strength (Stephens et al., 2001)

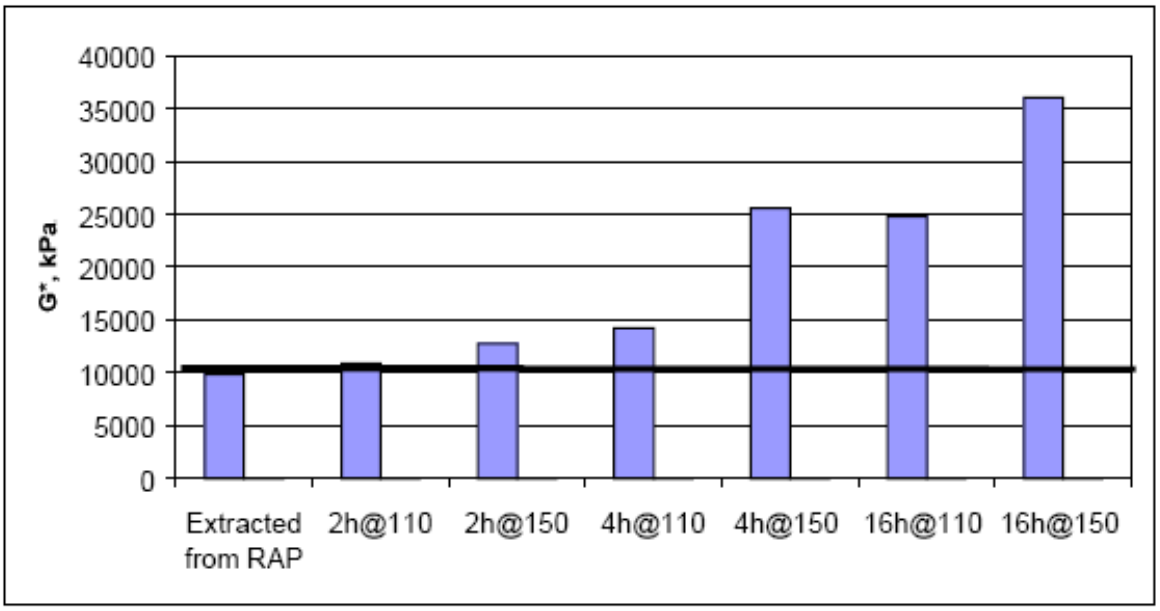


Figure 20: Arizona RAP binder complex modulus versus preheating time and temperature (McDaniel et al., 2000)

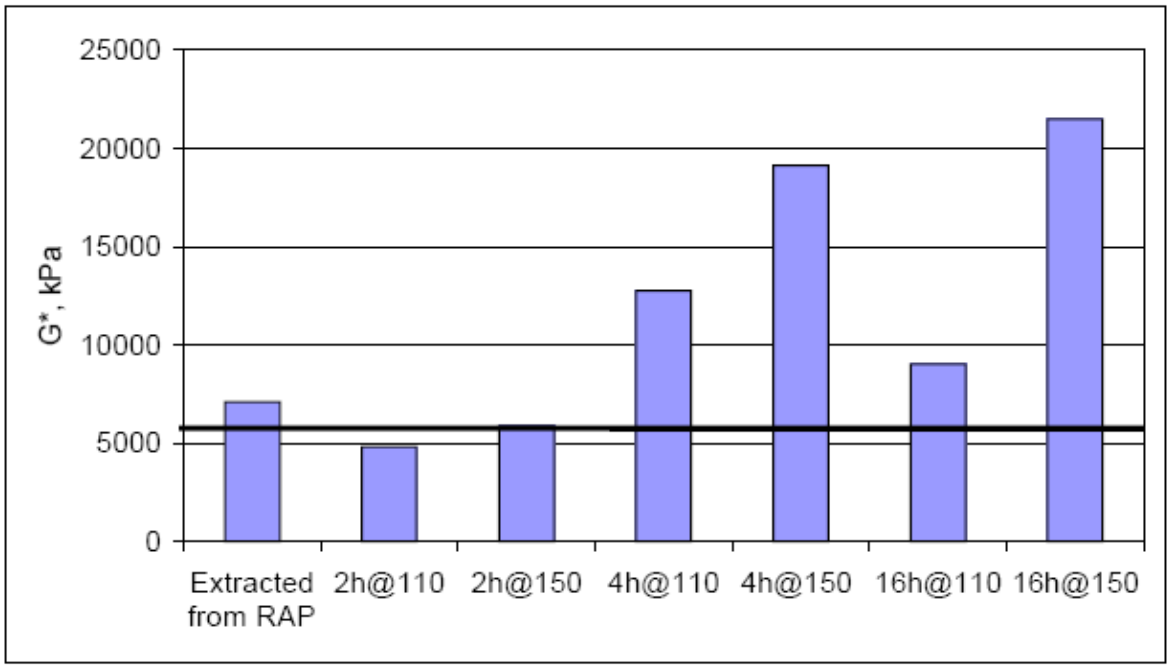


Figure 21: Florida RAP binder versus preheating time and temperature (McDaniel et al., 2000)

2.5.2 Diffusion process or chemical mixing

The performance of recycled asphalt mixtures is not only affected by the quality of mechanical mixing but also the interaction between RAP and virgin binder. The mechanical mixing only supports the fact that virgin binder can coat the particles covered by RAP bitumen. Meanwhile, the requirement of the recycling process is for the virgin binder to be well mixed and penetrate or diffuse into RAP bitumen so as to reduce the viscosity and bring back its expected requirements. However, the mechanism of diffusion is not well understood even though asphalt recycling is not a new aspect in the industry.

Diffusion mechanism

There have been some studies carried out in the past to investigate the diffusion mechanism of virgin binder into RAP bitumen. Carpenter and Wolosick (1980) undertook research to evaluate the effects of modifiers on the performance of recycled asphalt mixture. The reclaimed asphalt was taken from a city street in Champaign, Illinois in June, 1976 and crushed until passing 12.5 mm sieve. RAP bitumen was then extracted and tested. The properties of RAP bitumen and the grading of RAP aggregate are presented in Tables 10 and 11.

Properties	Value
Viscosity at 60°C (Pa.s)	4490
Penetration at 25°C (dmm)	26
Penetration at 4°C (dmm)	22
Softening point (°C)	63
Asphalt content (%)	5.3
Specific gravity (g/cm^3)	1.198

Table 10: Properties of RAP binder (Carpenter and Wolosick, 1980)

Sieves Size	Percent Passing
12.5 mm	100
9.5 mm	81
6.3 mm	78
4.75 mm	68
2.00 mm	58
850 µm	34
425 µm	23
150 µm	13
75 µm	9

Table 11: Grading of RAP aggregate (Carpenter and Wolosick, 1980)

Carpenter and Wolosick used 100% of RAP for this research and Paxole 1009, viscosity at 60°C of 234 mm^2/s (0.23 Pa.s) and specific gravity of 1.028, was employed as rejuvenator. The amount of rejuvenator was determined after trial blending with different proportions of rejuvenator over RAP binder. The result of the blending trial is a graph showing the relation between viscosity of aged bitumen, rejuvenator and % of rejuvenator. In order to get the recycled binder with target viscosity of 100 Pa.s, the amount of rejuvenator is 20% of the weight of RAP bitumen.

Resilient modulus, creep compliance, and permanent deformation tests were implemented in this research. In order to study the influence of diffusion mechanism on the properties and performance of recycled mixture, two types of samples, rejuvenated and recycled, were prepared. Both had the same material, bitumen and air void content but different methods of preparation. With rejuvenated samples, RAP bitumen was extracted and blended with

rejuvenator before being mixed with RAP aggregate. Differently in recycled sample, reclaimed materials, after being heated at 116^{o}C, was mixed directly with rejuvenator to simulate the mixing procedure in the asphalt industry. The samples then were tested at predetermined time intervals. The difference between the test results of recycled and rejuvenated mixture was studied to evaluate the influence of diffusion on the recycled samples.

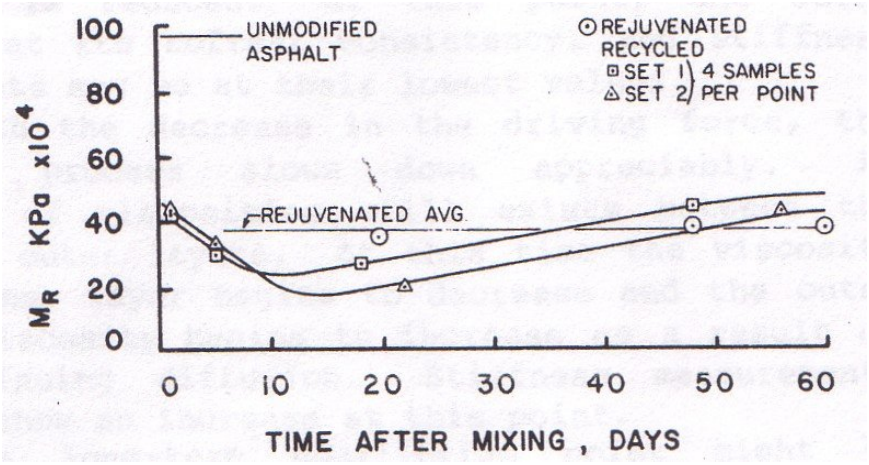


Figure 22: Effect of diffusion on resilient modulus (Carpenter and Wolosick, 1980)

The test results showed that the resilient modulus of the recycled mixture critically decreased during the first two weeks before starting to increase again (Figure 22). The phenomenon did not happen in the case of rejuvenated samples. In the rejuvenated samples, the test result is almost the same with different testing times.

Carpenter and Wolosick (1980) simply developed the diffusion model of rejuvenator into RAP bitumen. The diffusion process included the following steps:

1. the rejuvenator forms a low-viscosity layer covering the RAP particles
2. rejuvenator starts to penetrate into RAP bitumen, simultaneously softening the aged bitumen and reducing the amount of rejuvenator
3. all the rejuvenator diffused into RAP bitumen, viscosity of the aged binder coated aggregate decrease and that of outer layer (rejuvenator) increases.
4. The blend of rejuvenator and aged bitumen reaches equilibrium

In step 1, there is almost no interaction as rejuvenator just coats the RAP particles (Figure 23). Hence, the viscosity of rejuvenator and aged binder remain approximately the same. Rejuvenator then starts to diffuse into aged binder. The proportion of rejuvenator that

covers the RAP particle will gradually decrease. The mutual interaction between rejuvenator and aged binder results in the reducing viscosity of the outer layer of aged binder. Simultaneously, the viscosity of the remaining rejuvenator increases (Steps 2 and 3). The process will progress until equilibrium status where all the rejuvenator diffuses into aged binder and generates a homogeneous blend (Step 4).

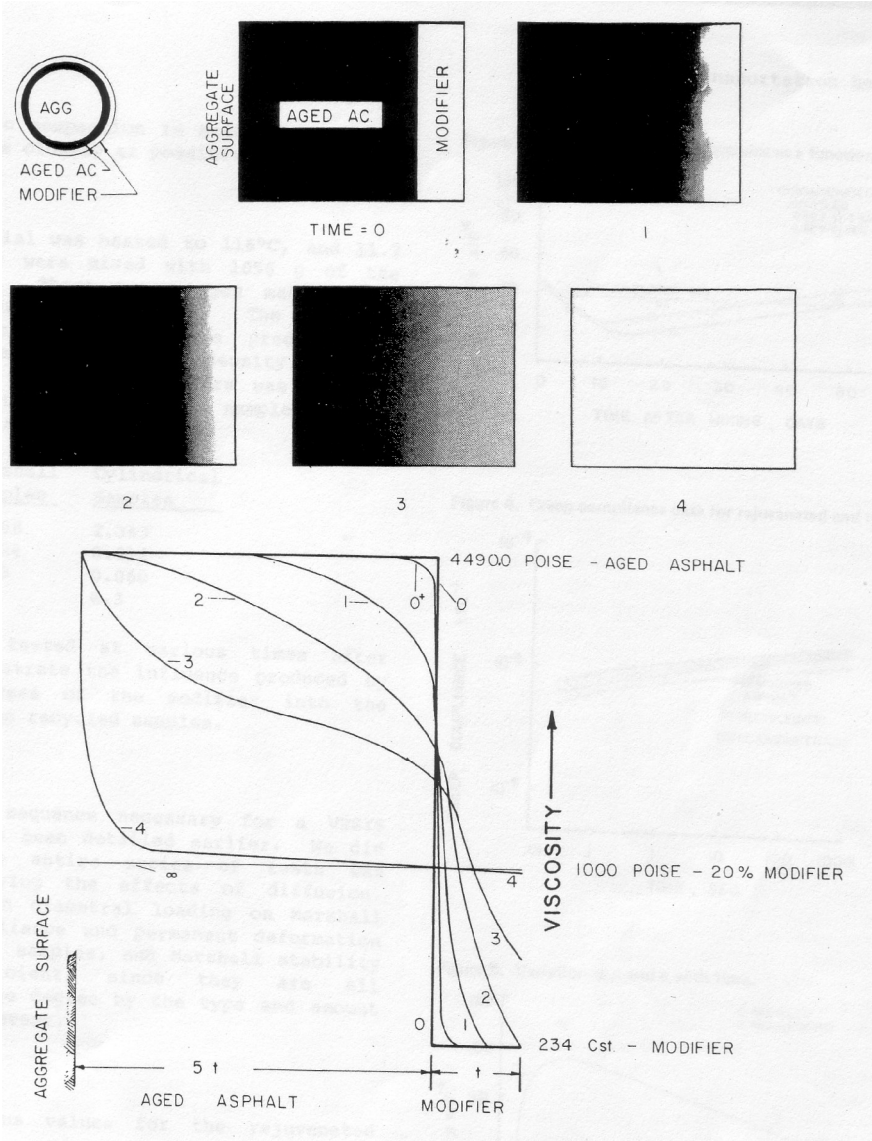


Figure 23: Schematic of modifier coating an aggregate particle during recycling process (Carpenter and Wolosick, 1980)

This simple diffusion mechanism can be used to interpret the critical duration in which the resilient modulus decreases and permanent deformation increases. Figure 24 shows after compaction, as the penetration has not started, the binding force between aggregate particles is due to the high-viscosity RAP bitumen. Actually, the rejuvenator at this moment has been located in the voids among particles. This situation leads to the fact that the

resilient modulus of recycled mixture is higher than that of rejuvenated sample. As the diffusion or penetration of rejuvenator into RAP bitumen starts, the resilient modulus decreases as the outer layer of RAP bitumen begins to be softened by rejuvenator. This phenomenon is also due to the remaining low-viscosity rejuvenator starting to bind the aggregate particles together. The resilient modulus keeps decreasing until no rejuvenator remains. At this point, the viscosity of outer layer keeps increasing until the blend between rejuvenator and RAP bitumen reaches equilibrium.

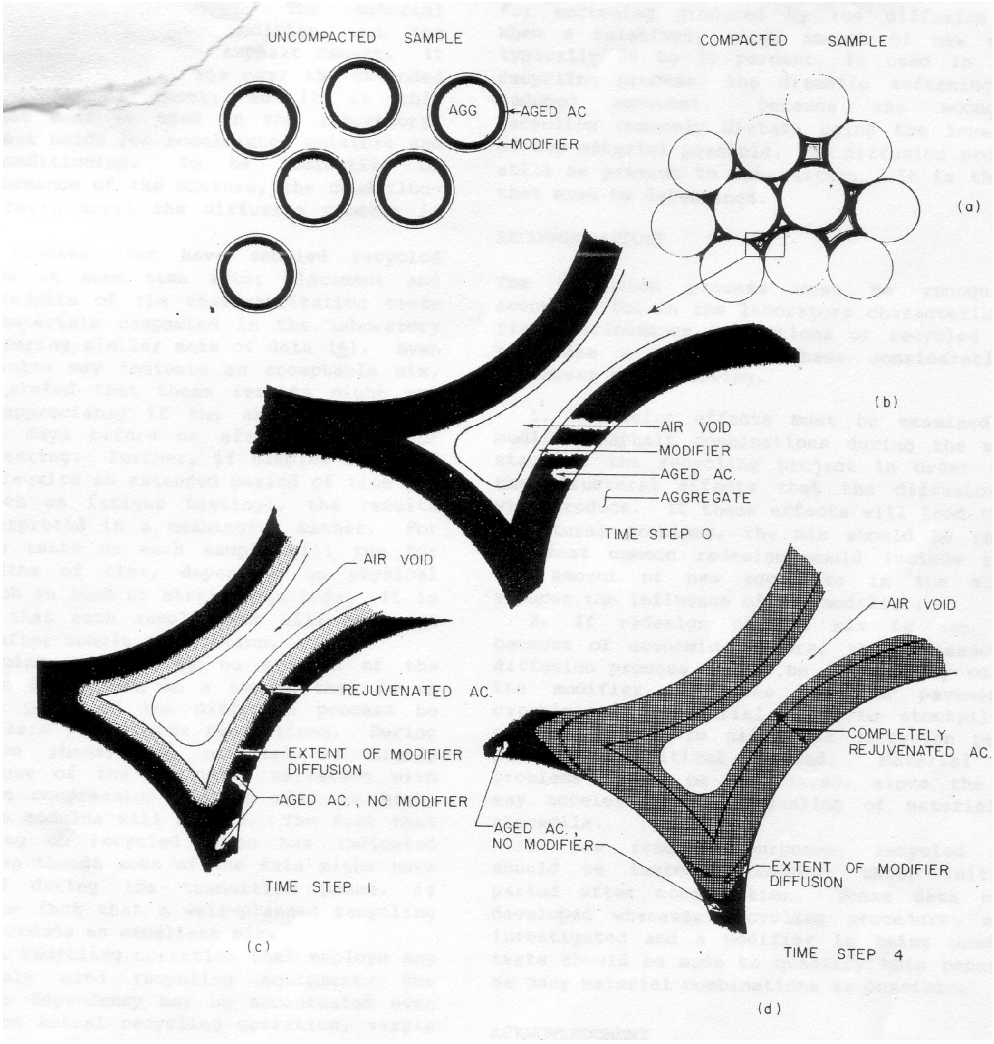


Figure 24: Diffusion model (Carpenter and Wolosick, 1980)

Staged-extraction process

Carpenter and Wolosick (1980) also carried out an extra experiment to verify the developed diffusion model. In this experiment, the binder is divided into two layers, outer layer and inner layer. If the diffusion of rejuvenator into RAP bitumen exists, the consistency of each layer will be different in relation to different testing time intervals.

The mixture is prepared with the same procedure as that for the performance tests. However, the mixture is left uncompacted. In order to divide the bitumen coat into two layers, a sample of loose mixture is immersed in trichloroethelyne for 3 minutes. The bitumen recovered by Abson method will represent the outer layer. The inner layer is achieved by washing and recovering all the bitumen. The consistency of these recovered bituminous materials will be tested. The whole procedure will be repeated at different times. The results (Figure 25) show that simultaneously, the penetration of inner layers increases and that of outer layers decreases until both penetrations are the same.

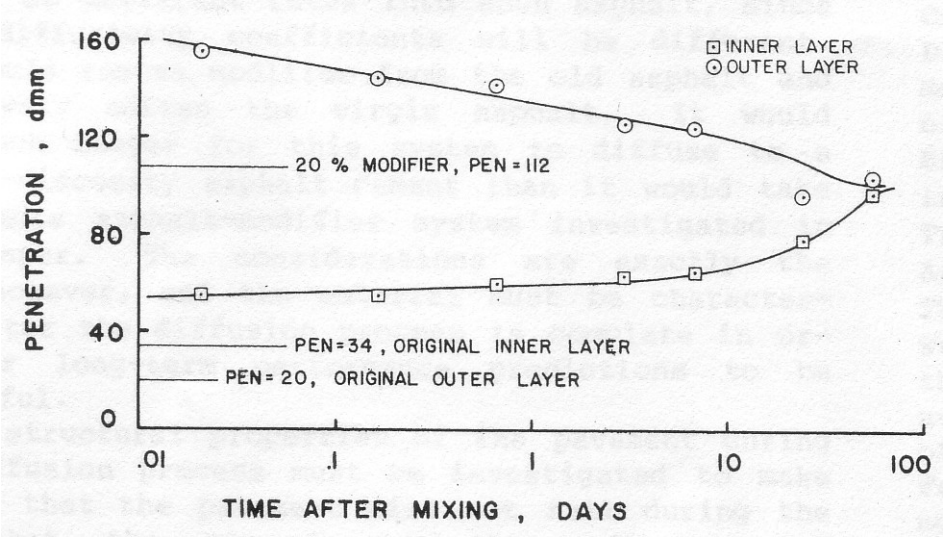


Figure 25: Penetrations of outer and inner layers as function of time (Carpenter and Wolosick, 1980)

The research carried out by Carpenter and Wolosick (1980) did not take into account the influence of virgin aggregate during mixing process. This research dealt only with the diffusion mechanism of the mixture of 100% RAP and rejuvenator. This might not represent the phenomenon that occurs in recycled mixture containing virgin aggregate. Depending on the efficiency of mixing process, there might be not only RAP particles coating by rejuvenator but also virgin aggregate particles coating by rejuvenator or blend of RAP binder and rejuvenator in recycle mixture containing virgin aggregate.

Noureldin and Wood (1987) also studied the diffusion of rejuvenator into RAP bitumen. In this research, not only the mixture of RAP and rejuvenator but also the mixture of RAP, rejuvenator and the addition of virgin aggregate were considered. The existence of virgin aggregate in the mixture aimed to simulate the real situation in the recycling asphalt industry. RAP material was milled from road US-52 in Indianapolis (Indiana). Properties of RAP binder are showed in Table 12.

Three rejuvenators, AC 2.5, Mobisol 30, and AE 150, were used. The amount of rejuvenators and percentage of RAP bitumen were estimated based on the Asphalt Institute design recycled asphalt mixture method (Arrhenius viscosity mixing equation). The target was that after being recycled by rejuvenator, the recycled bitumen must have the viscosity at 60^{o}C approximately similar to that of AC 20 (from 190 to 240 Pa.s). There were three combinations of RAP bitumen and rejuvenator, 40% RAP bitumen/60% AC 2.5, 45% RAP bitumen/55% AE 150, and 85 %RAP bitumen/15% Mobilsol 30.

Properties	Value
Penetration at 25 ^{o}C, (dmm)	28
Viscosity at 60 ^{o}C (Pa.s)	2089
Kinematic Viscosity at 135 ^{o}C (cSt)	726
Softening Point (^{o}C)	60
Bitumen content (%)	6

Table 12: Properties of RAP bitumen (Noureldin and Wood, 1987)

Noureldin and Wood (1987) also used the staged extraction method. However, different from Carpenter and Wolosick (1980), the bitumen coat was divided into four microlayers. One advantage of this method is to show the non-uniform ageing pattern of RAP material. After four microlayers extraction of RAP materials, the results (Table 13) indicated that RAP bitumen from the outer two layers were seriously hardened. On the contrary, the two inner layers close to the aggregate surface were slightly aged, the consistency were almost the same as those of the original bitumen AC 20.

Solvent increment (mL)	Binder (% by weight)	Penetration (dmm)	Viscosity at 60 ^{o}C (Pa.s)
200	55.5	24	2400
200	26.5	33	1500
300	11.2	65	250
700	6.8	57	330

Table 13: Test results on reclaimed staged-extraction of RAP (Noureldin and Wood, 1987)

To prepare for the sample, RAP was heated at 115^{o}C for 30 minutes and rejuvenator at 82^{o}C before mixing together with virgin aggregate for 2 minutes. Virgin aggregate was also

heated at 115°C for 30 minutes. The loose mixture was then preserved at 60°C for 15 hours. To obtain the bitumen of each microlayer, the sample of 1200g was in turn immersed in 200, 200, 300, and 700 mL of trichloroethylene for 5 minutes. Bitumen of each microlayer was recovered by Abson method and its consistency was determined.

In the case of mixing only RAP with rejuvenators, results from staged-extraction tests showed that all the rejuvenators could restore the consistency of the two outer microlayers. However, the other two inner microlayers showed almost unchanged tendency (Table 14). Due to the test being carried out just at one point in time, the result could not show the changing tendency of each layers consistency.

Binder	Solvent Increment (mL)	Binder (% by Weight)	Penetration at 25°C (dmm)	Viscosity at 60°C (Pa.s)
60% AC 2.5 40% RAP binder	200	67.5	67	167.4
	200	21.5	68	188.0
	300	7	59	239.4
	700	4	50	300.0
55% AE 150 45% RAP binder	200	69	75	168.3
	200	16.5	70	201.0
	300	8.5	62	229.0
	700	6	49	302.0
15% Mobilsol 30 85% RAP binder	200	71	75	186.4
	200	18	69	198.0
	300	6	63	204.0
	700	4	48	315.2

Table 14: Test results on reclaimed, staged-extraction, no virgin aggregate (Noureldin and Wood, 1987)

In the case where the recycled mixture was a combination of RAP material, rejuvenator, and virgin aggregate, the amount of aggregate was estimated so the recycled binder accounted for 6% by weight of the mixture. The grading of virgin aggregate was also selected hence the gradation of the whole mixture satisfied the requirement of Indiana specification. In accordance to 6% bitumen over total weight of the mixture, the amount of aggregate added were in turn 60, 55, and 15% in relation with mixture using rejuvenator

AC 2.5, AE 150, and Mobilsol 30. The staged-extraction test results showed that only the mixture using rejuvenator AE 150 had the same tendency as that of mixture using only RAP and rejuvenators. The other two using rejuvenators AC 2.5 and Mobilsol 30 had different trends (Table 15). The viscosities of inner layers were higher than those of outer layers.

The shortcoming of this research was that the effect of time on the diffusion process was not considered. In addition, the use of a single diffusion pattern could not fully describe the diffusion mechanism that occurs in recycled asphalt mixture. The inconsistent viscosity pattern of micro-layers compared to that of the mixture using only RAP and rejuvenator indicated the segregation of the bitumen phase in recycled mixture. This substantiates the fact that in recycled mixture, there exist RAP particles covered by rejuvenator, virgin aggregate particle covered by rejuvenator, and RAP or virgin aggregate particles covered by blend of aged binder and rejuvenator. Each situation has its own diffusion mechanism.

Binder	Solvent Increment (mL)	Binder (% by Weight)	Penetration at 25°C (dmm)	Viscosity at 60 °C (Pa.s)
60% AC 2.5 40% RAP binder	200	72	60	210.0
	200	19	51	289.2
	300	5.5	52	247.0
	700	3.5	130	80.9
55% AE 150 45% RAP binder	200	71	70	197.2
	200	19	67	173.4
	300	6	60	242.4
	700	4	50	361.6
15% Mobilsol 30 85% RAP binder	200	74	73	204.9
	200	17.5	80	166.4
	300	5.5	90	126.0
	700	3.5	100	124.0

Table 15:Tests results on reclaimed, staged-extraction, virgin aggregate used (Noureldin and Wood, 1987)

A staged-extraction process was also used by Huang et al. (2005) to investigate the effects of rejuvenator on RAP material. In this research, Huang et al. (2005) used the combination of RAP, rejuvenator, and virgin aggregate. However, just the fine RAP, containing No 4 (4.75mm) passing RAP particles was used. Limestone was used as virgin aggregate. The gradation of RAP and virgin aggregate are showed in Tables 16 and 17. However, all the particles passing size No 4 were removed before mixing with RAP. The mixing process simulates the procedure in the practical industry, 20% RAP, virgin bitumen, and aggregate were mixed together at 190^{o}C. After mixing, the rejuvenated RAP was easily separated from the whole mixture due to size difference.

Sieves Size	% Pass
No.4	100
No.8	81
No.30	46
No.50	30
No. 100	23.2
No. 200	19.3

Table 16: Properties of RAP aggregate (Huang et al., 2005)

Sieves Size	% Pass
37.5 mm	100
25.4 mm	97.6
19 mm	77.7
12.7 mm	35.3
9.5 mm	14.3
4.75 mm	1.9

Table 17: Properties of Virgin Aggregate (Huang et al., 2005)

The rejuvenated RAP was then recovered under staged-extraction process. Rejuvenated RAP was soaked in solvent trichcloethylene for 3 minute. The binder was then recovered by Abson method. The process is repeated three times for the first three microlayers. The layer in contact with aggregate surface was obtained by washing the remaining rejuvenated RAP with solvent. The recovered rejuvenated RAP bitumen is then subjected to rheological testing to identify the difference between layers. The schematic of extracted layers is illustrated in Figure 26.

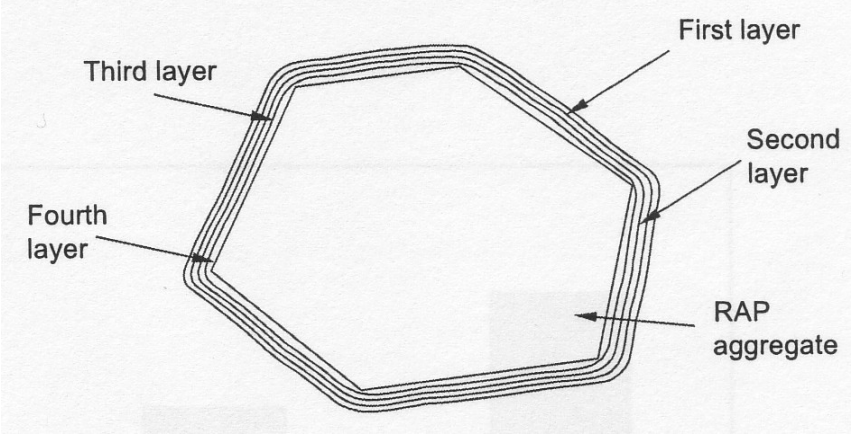


Figure 26: Layers extraction process (Huang et al., 2005)

The test results for viscosities of bitumen from extracted layers at different temperatures showed uniform tendency (Figure 27). The outer layer due to rejuvenation had lower viscosities at 135°C than those of the inners layers. The layer in contact with surface of aggregate was the stiffest. It was concluded that after mixing, about 40% of RAP binder was blended with rejuvenator. By washing all the bitumen on virgin aggregate, Huang et al. (2005) also demonstrated that during mixing process, approximately 6-6.8% of RAP binder was transferred from RAP materials to virgin aggregate.

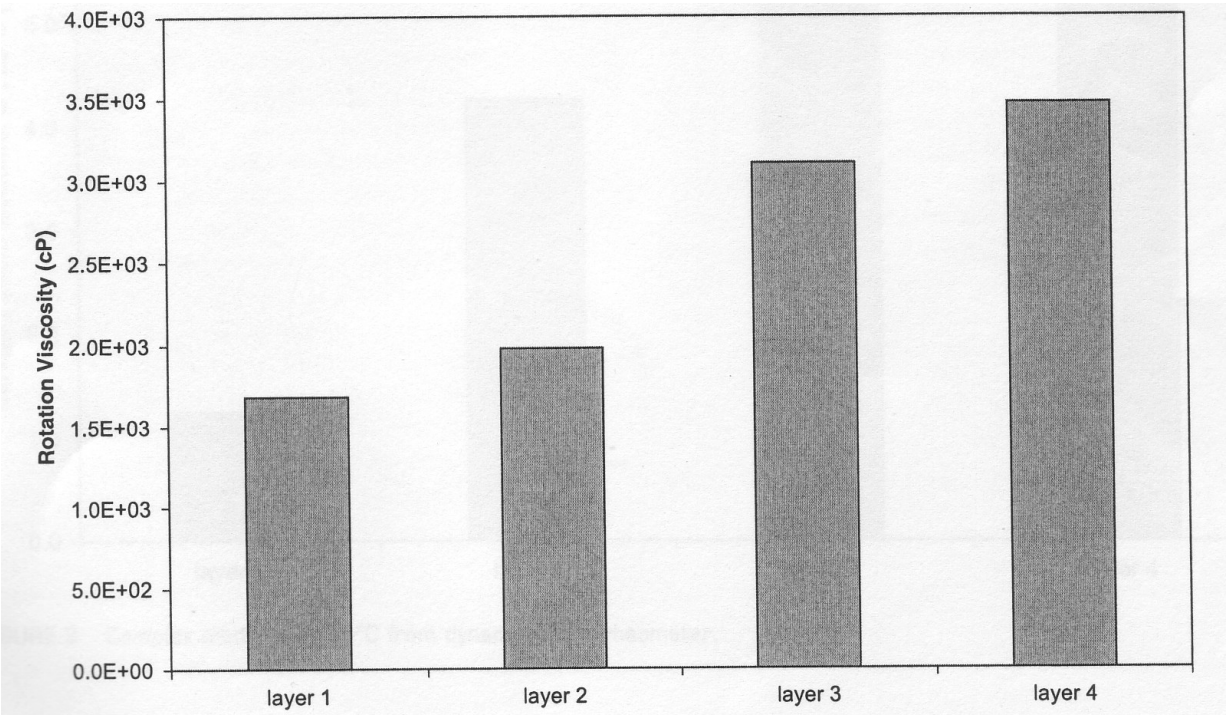


Figure 27: Viscosity at 135°C of different micro-layers coated RAP particles (Huang et al., 2005)

Investigating the diffusion mechanism using marker

Karlsson and Isacsson (2003) also carried out a study to examine the diffusion of bitumen rejuvenator. In this study, the diffusion was not characterized by accessing the consistency or rheology of rejuvenated binder microlayers. The diffusion mechanism was investigated by measuring the variations in energy absorption capability of bitumen layers over a period of time by FTIR-ATR (Fourier Transform Infrared Spectroscopy by Attenuated Total Reflectance).

A Mattson Infinity 60 AR spectrophotometer was used in this research (Karlsson and Isacsson, 2003a). This equipment includes a non-absorbing trapezoidal prism made of ZnSe (Figure 28). Two frames, with different slot width are stuck together on the surface of the prism. The thicknesses of each frame are in turn 200 and 500 µm in accordance with the thickness of top and bottom layers. To prepare for the specimen, each bitumen layer is scraped into the mould by two scrapers that fit into the frames.

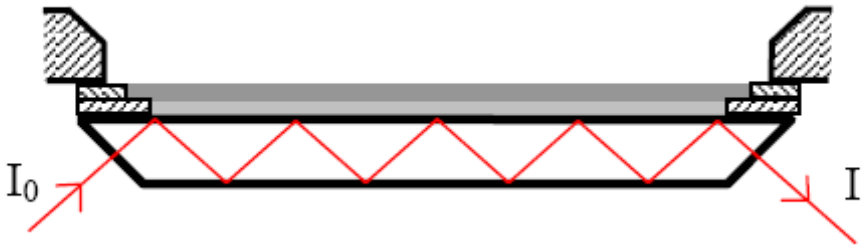


Figure 28: Schematic of FTIR – ART (Karlsson and Isacsson, 2003a)

The philosophy of this method is to measure the movement of chemical analytes through bitumen layers. As the top bitumen layer contains analyte substance, the movement of the analyte also means the penetration of that bitumen layer into the bottom one. Each analyte has particular absorption wavelength or wave number (Table 18). During 72 hours, the changes in energy absorption are scanned with a resolution of 4 cm-1 and recorded every 1 or 5 minutes. The number of scans performed during each recorded interval is in turn 64 or 256 (Karlsson and Isacsson, 2003c). The absorption value at certain time will be automatically calculated by WinFirst software using wavelength and relevant energy absorbed. Figure 29 is an example of absorbance difference versus time in relation with various wavelengths.

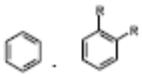
Functional group	Formula	Absorption wavenumbers (cm^{-1})
Carbonyls	C=O	1740-1690 (stretch)
Aromatic and Heteroaromatic rings		1600 (C=C ring stretch), 900-600 (fingerprint region, C-H bend)
Sulphoxides	S=O	1055-1030 (stretch)
Methyl (aliphatic)	CH_3	2962, 2872 (stretch), 1450, 1380 (bend)
Methylene (aliphatic)	CH_2	2926, 2853 (stretch), 1465, 720 (bend)

Table 18: Approximate absorption wave length of functional groups (Petersen, 1986)

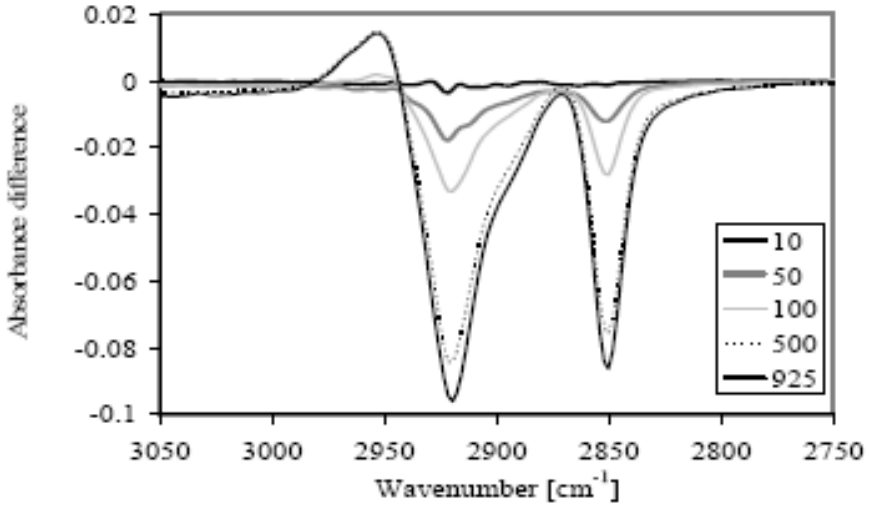


Figure 29: Spectra obtained after 10, 50, 100, 500, and 925 minutes during diffusion of rejuvenator into A-B180 at 60°C (Karlsson and Isacsson, 2003a)

Based on the calculated absorption results, the diffusion coefficient is estimated by mathematical expression of Fick's Law (Karlsson and Isacsson, 2003b). Fick's model is simply described in Figure 30. Initially, the concentration of bitumen is 0 and that of rejuvenator is c_o. Both layers have total thickness of L in which rejuvenator thickness accounts for (1- α)L. The diffusion process is assumed to occur in constant pressure and temperature.

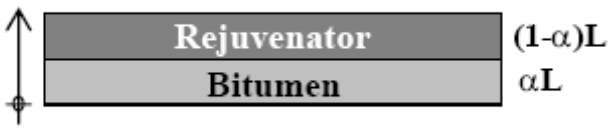
$$\frac{\partial c}{\partial t} = D.\frac{\partial^2 c}{\partial x^2} \qquad \textbf{(10)}$$

c: concentration in terms of time

D: diffusion coefficient

t: time

x: position



$$c(x,0) = 0 \qquad 0 \le x \le \alpha L$$
$$c(x,0) = c_0 \qquad \alpha L < x \le L$$
$$\frac{\partial c(0,t)}{\partial x} = \frac{\partial c(L,t)}{\partial x} = 0$$

Figure 30: Schematic of Fick's Law diffusion model (Karlsson and Isacsson, 2003b)

To solve the equation of Fick's Law with boundaries expressed in Figure 30, the result is the mathematical relation between the concentration of rejuvenator at position x and time t as follows:

$$c(x,t) = (1-\alpha).c_0 - \frac{2c_0}{\pi}.\sum_{n=1}^{\infty}\frac{\sin(\alpha n\pi)}{n}.\cos\left[\frac{n\pi x}{L}\right].e^{-\left[n\frac{\pi}{L}\right]^2 Dt} \qquad \textbf{(11)}$$

(Karlsson and Isacsson, 2003b)

There is a wide variety of materials used by Karlsson and Isacsson (2003). The bitumen in this research includes:

- Rejuvenator V115 from Nynas (R115) which is a heavy naphthetic petroleum distillate
- B180 from Mexico having penetration of 180 (A-B180)
- B180 from Saudi Arabia, penetration of 180 (B-B180)
- B85 from Venezuela, penetration 85 (C-B85)
- B60 from Venezuela, penetration 60 (C-B60)

The study was carried out under conditions of different testing temperatures and thickness of bitumen and rejuvenator layers. Results from the test indicated that the diffusion of rejuvenator was influenced by many factors, for instance, temperature, type of bitumen, rejuvenator, and the chemical composition.

Influence of type of bitumen on diffusion coefficient

Rejuvenator R115 is used together with three bitumens A-B180, B-B180 and C-B60. The thickness of bitumen and rejuvenators are equally 500 µm. The experiment is carried out at different temperatures. The results (Figure 31) indicate that the diffusion coefficients of

rejuvenator into bitumen A-B180 and B-B180 are almost the same and higher than B-C60. This phenomenon could be attributed to the fact that bitumen B-C60 has lower penetration than those of bitumens A-B180 and B-B180.

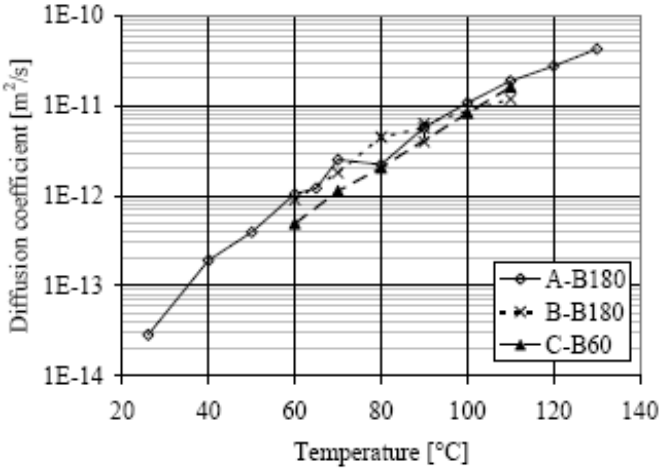


Figure 31: Influence of bitumen type on diffusion coefficient (Karlsson and Isacsson, 2003b)

Influence of temperature on diffusion coefficient

In this aspect, rejuvenator R115 is used together with A-B180. However, the test is repeated with different temperatures and four combinations of bitumen-rejuvenator layer thickness; 200/200 µm, 200/500 µm, 500/200 µm, and 500/500 µm. The test results (Figure 32) indicate a minor effect of layer thickness on the diffusion coefficient. However, below 90^{o}C, the diffusion coefficient in relation with different layer thickness deviates slightly. In general, the experimental results show the increasing tendency of diffusion coefficient if the test temperature increases.

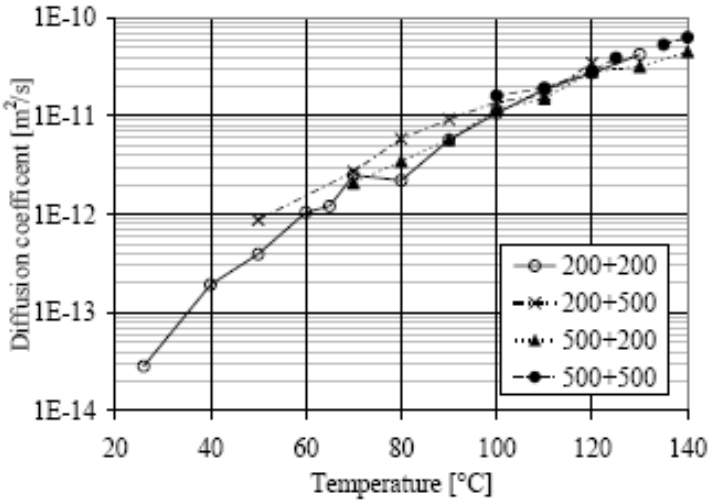


Figure 32: Influence of temperature on diffusion coefficient (Karlsson and Isacsson, 2003b)

Influences of chemical composition of rejuvenators on diffusion coefficient

To investigate the effect of composition on diffusion mechanism, a wide variety of markers are used together with bitumen A-B180. The proportion of marker is 3% by weight of the bitumen. Bitumen A-B180 mixed with different markers are in turn applied on top of pure A-B180. The test results (Figure 33) demonstrate that generally, the diffusion coefficient decreases if the molecular weight of marker increases. The same result has been reported by (Qiu and Bousmina, 2003).

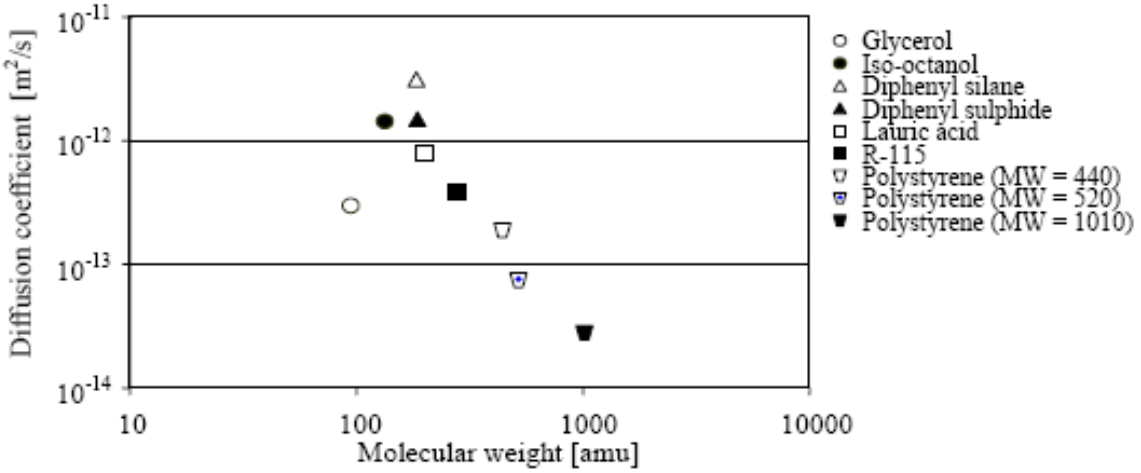


Figure 33: Influence of chemical composition of markers on diffusion coefficient (Karlsson and Isacsson, 2003b)

2.6 Segregation and consequences

2.6.1 Segregation

Segregation is defined traditionally as non-homogeneity of the asphalt mixture. Actually, segregation can be perceived as the concentration of coarse or fine materials in some areas of the paved mat in conventional asphalt mixture (Brock et al., 2003). In asphalt recycling aspect, there is not only the concentration of certain sizes of aggregate in one area but also the concentration of different binders in some areas. This happens in the case where the virgin bitumen or rejuvenator is not well distributed in the whole mixture or even when these two bitumens are well distributed, the diffusion process between these two binders cannot take place.

RAP material generally has different characteristics from that of pure virgin aggregate or bitumen. At ambient temperatures, aged bitumen normally with high viscosity, will act like

a solid and RAP has the same characteristics as those of black rock. However, when the temperature is high enough to turn aged bitumen into liquid state, RAP material will no longer act like black rock but be the same as the blend of aggregate and liquid bitumen.

During the recycled asphalt production, after RAP at ambient temperature is blended with superheated virgin aggregate, the energy transferred from virgin aggregate will heat up RAP. The increase of RAP temperature will gradually change the aged bitumen from solid to liquid state. Therefore, RAP material will change from a mixture of solid agglomerates into a mixture of solid particles with different sizes and aged liquid bitumen. The mixing process transforms from mixing among solid particles to mixing between solid particles and liquid bitumen. Hence, while blending virgin aggregate with RAP, there exist not only inter particulate forces as in virgin aggregate case but also the bridge force due to aged bitumen among aggregate particles.

The aim of heating RAP is also to use thermal energy transferred from superheated aggregate to soften the bond between aggregate particles as the higher the temperature, the lower the viscosity of aged bitumen. Once the viscosity of RAP binder reaches the critical point that the bond cannot hold two particles together, two particles will be separated and relocated. This mechanism will repeat during the mixing process in order to get a homogeneous blend between RAP and virgin aggregate. If the assumption is made that each RAP particle is black, with white colour for virgin aggregate, the ideal homogeneous mixture is illustrated in Figure 17.

However, this mechanism is affected by many factors. The first issue is that there are many sizes of RAP available, for instance, 50mm, 30mm, and 20mm. In addition, each size of RAP may not be made of one particle but probably comprise many smaller-sized particles. Hence, the time for the heat transferred from virgin aggregate to soften and break RAP into separate pieces for the relocation is quite different. According to heat transfer theory, the larger the size the particle is, the longer the time for heat transfer (Cutnell and Johnson, 2004).

Energy transferred from superheated aggregate will heat up the RAP and soften the bond between aggregate particles as the higher the temperature, the lower the viscosity of bitumen binder. This is aimed to destroy the bond among aggregate to relocate the position

of each particle. If the blending time among RAP and virgin aggregate is not enough to break RAP into separate pieces, certainly there will be some agglomerates of different particle sizes of RAP. The same phenomenon also happens even when the duration and temperature of mixing process are enough to make the whole RAP bitumen become liquid. Depending on the sizes and proportion of aggregate in the mixture, there might still exist agglomerates moving in the mixture, for instance, agglomerates of fillers and liquid bitumen.

If the bitumen bond between aggregate is strong enough, the system will be dominated by the free flowing of agglomerates of aggregate particles (Harnby et al., 2001). This mixture is demonstrated in Figure 18. The black agglomerates comprising different aggregate particles will be moving with virgin aggregate. If this situation exists, the virgin bitumen, or rejuvenator cannot completely interact and recover the properties of aged bitumen. This will lead to the fact that in the mixture, some particles are coated with aged bitumen which is stiff, the others with soft rejuvenator.

The study by McDaniel el al. (2000) maintained that the actual practice and total blending were almost the same. This conclusion could be applied for the case of 10% RAP as there was a consistent trend of the results. However, there was apparently not enough support for this conclusion with 40% of RAP in the recycled mixture (Huang et al., 2005). Even with 10% of RAP, the fact that total blending and actual practice were the same might not be firmly proved as in this case, the data showed there were 36 cases that test results from total blending, actual practice, and black rock were almost the same. The existence of small amount of RAP, particular 10% in this research, did not affect substantially the properties of the recycled mixture. If segregation occurs, there will be no considerable adversity to the performance of the recycled mixture.

There would be segregation during the mixing process, especially with higher percentages of RAP. For instance, with 40% RAP, there were 12 cases in which test results of total blending, actual practice and, black rock cases were different (McDaniel et al., 2000). The segregation was also identified in research by Noureldin and Wood (1987), where RAP was mixed with 3 rejuvenators, AC 2.5, AE 150, Mobilso 30. In 2 out of 3 cases, after stage-extractions and consistency tests, the inner layers had lower viscosities and higher penetrations than those values of the outer ones. In the whole mixture, some aggregates are

covered by soft rejuvenator, some still covered by stiff RAP bitumen. RAP binder and rejuvenator are not well mixed. This phenomenon is also reported in Huang et al (2005).

Huang et al. (2005) reported that, during mixing RAP and virgin binder, the RAP bitumen transferred from RAP aggregate to virgin aggregate was 6 to 6.8%. After this combination is mixed with rejuvenator, there would certainly be some aggregate covered by soft rejuvenator first, and the others covered by stiff aged binder in the mixture. The segregation consequently occurs due to the existence of bitumen with different consistency in the mixture. This situation will also reduce the capability of diffusion process as in order to diffuse efficiently; the rejuvenator must cover the RAP aggregates.

2.6.2 Consequences of segregation on the performance of asphalt mixture

Segregation can cause adverse effects on the quality of the mixture as well as the performance of the pavement during service life. Gardiner et al. (2000) stated that the existence of segregation in the mixture can cause substantially:

- Decreased fatigue life in areas that have high concentration of coarse aggregate.
- Increased moisture damage due to high air voids caused by segregation.
- Increased rutting and raveling, especially with high volumes of traffic.

Gardiner and Brown (2000) implemented a study to assess the adverse effects of segregation on the quality and performance of asphalt mixture. The data of segregation was gathered from the field, using sections between 80 and 160 meters long. Based on the data collected, the level of segregation compared to Job Mix Formula was classified as followed:

- Non-segregation: the percent passing any sieve differed less than 5%
- Low segregation: at least two sieves with a change more than 5%
- Medium segregation: at least two sieves with a change more than 10%
- High segregation: three sieves with a change more than 15%

The test samples then were prepared in the laboratory in accordance with the difference to Job Mix Formula (Table 19). Parameters used to evaluate the effects of segregation to the performance of mixture were permeability, resilient modulus, dynamic modulus, tensile strength at dry and wet, and low temperature condition. The influence of segregation to fatigue life was also evaluated. All the tests show the adverse effects of segregation to the performance of mixture (Table 20).

Property	Project 1-1				Project 6-1			
	None	Low	Medium	High	Fine	None	Medium	High
Cumulative Percent Passing, %								
37.500 mm	100	100	100	100	100	100	100	100
25.000 mm	100	100	100	100	90	90	82	75
19.000 mm	95	92	92	87	79	76	65	55
12.500 mm	77	71	62	42	64	59	46	33
9.500 mm	67	61	52	33	58	53	40	27
4.750 mm	50	46	37	23	41	37	27	18
2.360 mm	39	36	29	18	27	25	19	14
1.180 mm	32	30	24	16	19	17	15	12
0.600 mm	24	23	18	13	14	12	12	11
0.300 mm	15	15	12	9	11	10	9	9
0.150 mm	9	10	8	6	7	7	7	7
0.075 mm	6.1	7.5	5.1	3.8	5.5	5.2	5.2	5.2
Asphalt Content, %	4.25	3.78	3.20	2.40	3.68	3.30	2.28	1.70
Air Voids, %	9.5	10.7	12.8	19.6	7.6	9.2	9.7	10.8

Table 19: Gradations, bitumen contents, and target air voids of laboratory-simulated segregation mixtures (Gardiner and Brown, 2000)

Mixture Property	Percent of Non-Segregated Mix Property by Level of Segregation			
	Fine	Low	Medium	High
Permeability	Increased slightly	Increasing with level of coarse segregation		
Resilient Modulus	Little or slightly increasing stiffness	80 to 90%	70 to 80%	50 to 70%
Dynamic Modulus	Little or slightly increasing stiffness	80 to 90%	70 to 80%	50 to 70%
Dry Tensile Strength	110%	90 to 100%	50 to 80%	30 to 50%
Wet Tensile Strength	80 to 90%	75%	50%	30%
Low Temperature Tensile Stress	No conclusions due to test method difficulties			
Loss of Fatigue Life when Segregation in Upper Lifts, %	Not Estimated	38%	80%	99%
Rutting Potential	Not strongly influenced by gradation segregation until a high level of segregation is seen			

Table 20: Summary of the influence of segregation on mixture properties (Gardiner and Brown, 2000)

In the recycled mixture, beside those kinds of segregation normally occuring in conventional mixtures, there also chemical segregation as the rejuvenator cannot diffuse into RAP binder immediately. It might reduce the strength of the mixture or pavement after

being paved and compacted. Carpenter and Wolosick (1980) reported that the resilient modulus of recycled mixture reduced during the first two weeks and then started to increase to the equilibrium value due to the occurrence of diffusion process. There is also binder segregation due to the rejuvenator not being well distributed in the mixture due to improper mixing.

3 Laboratory RAP production

3.1 Introduction

One of the issues related to using RAP from the industry is the RAP variability. The variability includes not only the gradation of RAP but also the RAP binder content and origin. Each time RAP is acquired from the industry, the properties of RAP might be different. Even if the amount of RAP necessary for the whole research is obtained, the homogeneity of RAP is still not assured. The fact that RAP contains materials with different or unknown origin might seriously affect the result of the research.

The purpose of laboratory RAP production is to eliminate the problematic variability of RAP materials. Although the task is time consuming, laboratory RAP production helps to control RAP aggregate gradation as well as RAP binder content and origin. In addition, one of the objectives of this research is to study the effect of RAP sizes on mechanical properties of recycled asphalt mixture. The laboratory RAP production also helps to assure that every RAP piece is a lump, an agglomerate of RAP aggregate with different sizes bound together by RAP binder.

3.2 Materials

3.2.1 Bitumen

The bitumen used for laboratory RAP production is 40/60 Pen bitumen supplied by Shell. The properties of 40/60 Pen are shown in Table 21. The viscosity of 40/60 Pen bitumen is zero shear viscosity extrapolated from DSR data using Cross model at 60^{o}C (Section 4.3.1).

Penetration at 25^{o}C (dmm)	BS EN 1426 (2000)	50.6
Softening Point (^{o}C)	BS EN 1427 (2000)	56
Density (g/cm^{3})	BS EN ISO 3838 (1996)	1.03
Viscosity at 60^{o}C (Pa.s)	DSR-ZSV	440

Table 21: Properties of bitumen 40/60 Pen

3.2.2 Aggregate

The aggregate for laboratory RAP production primarily comprises three nominal sizes, 10 mm, 6 mm and dust. The aggregate is supplied by Dene limestone quarry. Gradation of each nominal size is in Table 22. The shaded areas present the aggregate sizes used in BS:

4987-1 (2005). After batching, the gradation of RAP aggregate conforms to the gradation requirement for 10 mm DBM for close graded surface course (BS:4987-1, 2005) (Figure 34). The physical properties of each nominal size of aggregate are shown in Table 23.

Sieve Size		Nominal size 10		Nominal size 6		Dust	
		Pass (%)	Retained (%)	Pass (%)	Retained (%)	Pass (%)	Retained (%)
31.5	mm						
20	mm						
14	mm	**100**	0.00	**100**	0.00	**100**	0.00
10	mm	**87.12**	12.88	**100**	0.00	**100**	0.01
8	mm	**46.25**	40.87	**99.47**	0.53	**100**	0.02
6.3	mm	**2.57**	43.68	**81.40**	18.07	**100**	0.03
4	mm	**1.79**	0.78	**16.91**	64.48	**98.53**	1.47
2.8	mm	**1.76**	0.03	**5.14**	11.78	**95.81**	2.72
2.36	mm			**5.14**	0.00		
2	mm	**1.65**	0.11	**4.26**	0.88	**85.22**	10.59
1	mm	**1.60**	0.05	**4.19**	0.07	**62.08**	23.14
0.5	mm	**1.55**	0.05	**4.19**	0.00	**43.97**	18.11
0.25	mm	**1.32**	0.23	**4.12**	0.07	**31.10**	12.87
0.125	mm	**1.01**	0.30	**3.98**	0.14	**22.31**	8.80
0.063	mm	**0.61**	0.40	**3.76**	0.21	**17.69**	4.61
Pan			0.61		3.76		17.69
Sum			100.00		100.00		100.00

Table 22: Gradation of Dene limestone aggregate

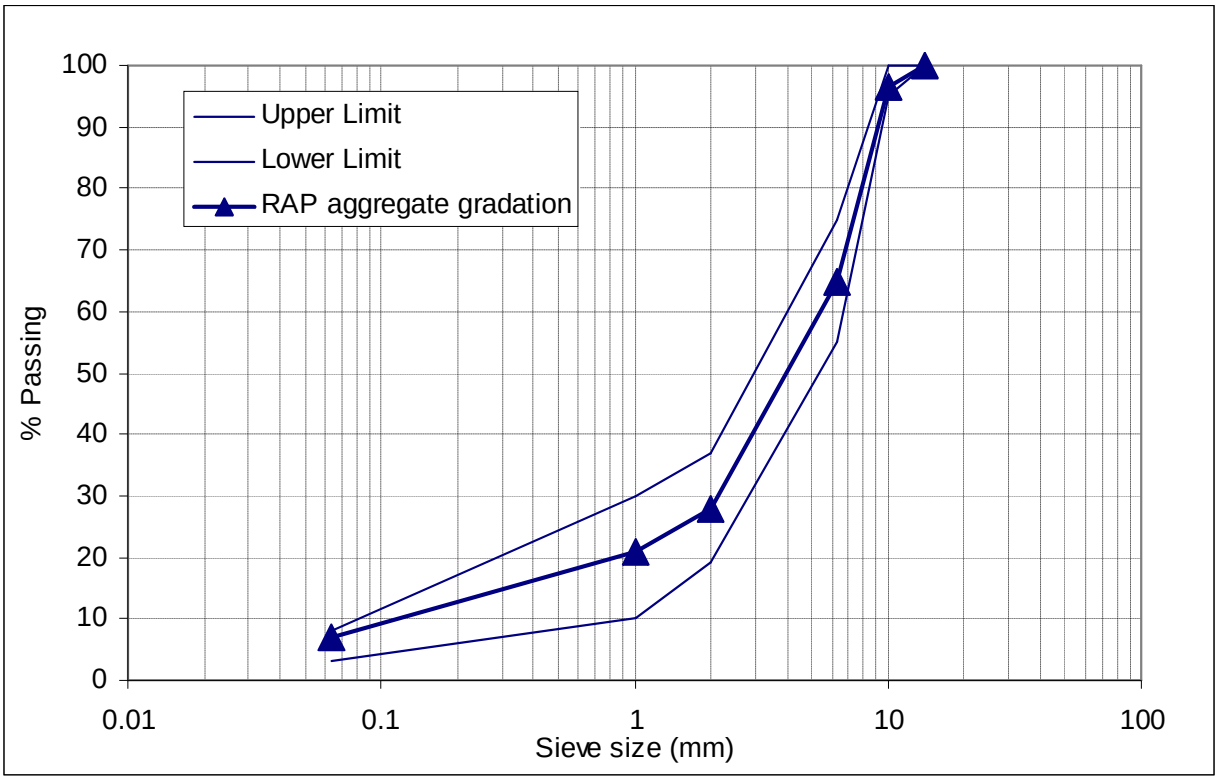


Figure 34: Design gradation of RAP aggregate

Size	6mm	Dust	10mm
Particle density on an oven dried basis g/cm^3	2.500	2.443	2.575
Particle density on a saturated surface-dried basis g/cm^3	2.547	2.478	2.612
Apparent particle density g/cm^3	2.622	2.533	2.673
Water absorption %	1.87	1.46	1.42

Table 23: Properties of Dene limestone aggregate

3.3 Procedure for RAP manufacture

The bitumen content of RAP material is 5.2% by weight of the total mixture. Maximum theoretical density of the mixture containing the designed aggregate gradation and 5.2% bitumen, determined by BS EN 12697-5:2002, is 2453 kg/m^3. The target air void content is 8%. Based on the target air void content and the maximum density of the mixture, the amount of bitumen and each aggregate fractions are calculated thus after compaction, each slab has the dimensions of 305 mm x 305 mm x 40 mm.

Procedure for manufacture of artificial aged slabs is as follows:

- Aggregate is heated overnight at 150^{o}C
- Bitumen is heated at to 150^{o}C for 3 hours
- Mixing for 2 minutes at 150^{o}C
- Compact the loose mixture in the mould of 305 mm x 305 mm until the thickness of 40mm is reached.
- Remove the compacted specimens
- Condition in force draft oven at 85^{o}C for 120 hours

3.4 Processing RAP

The artificial aged slabs are processed into two sizes, large RAP (denoted as LR) and small RAP (SR). For large size of RAP, after conditioned at 100^{o}C for 1 hour, artificially aged slabs will be broken manually. The aim of the conditioning duration is to soften the RAP and eliminate the degradation of RAP aggregate. During the breaking process, the size is visually adjusted therefore the maximum dimension is less than 40 mm. Small RAP

material is obtained by crushing large RAP material using a jaw crusher. The gap between two jaws of the crusher at static condition is set at 15 mm hence after being crushed, the maximum dimension of small RAP material is about 20 mm. The gradation of RAP materials are presented in Table 24. Figure 35 illustrates the appearance of both small and large RAP.

Sieve size		**Small RAP**		**Large RAP**	
		Pass (%)	**Retain (%)**	**Pass (%)**	**Retain (%)**
50	mm	**100**	0	**100**	0
37.5	mm	**100**	0	**26.2**	73.8
31.5	mm	**100**	0	**0**	26.2
20	mm	**92.74**	7.26		
14	mm	**47.82**	44.92		
10	mm	**32.13**	15.69		
6.3	mm	**13.6**	18.53		
4	mm	**3.74**	9.86		
3.35	mm	**2.23**	1.51		
2.36	mm	**1.38**	0.85		
1.18	mm	**0.38**	1		
Pan			0.38		
Sum			100		100

Table 24: Gradation of processed RAP materials

Figure 35: Appearance of RAP materials

3.5 Determine RAP properties

3.5.1 RAP aggregate

Although the degradation of RAP is deliberately eliminated by 1 hour conditioning at 100°C, the RAP aggregate gradation might still alter during the crushing process. After being extracted and recovered from small RAP material, RAP aggregate is subjected to particle size distribution test (BS-EN:933-1, 1997). The result shows the gradation of RAP aggregate after processing is almost the same as that of original (Figure 36).

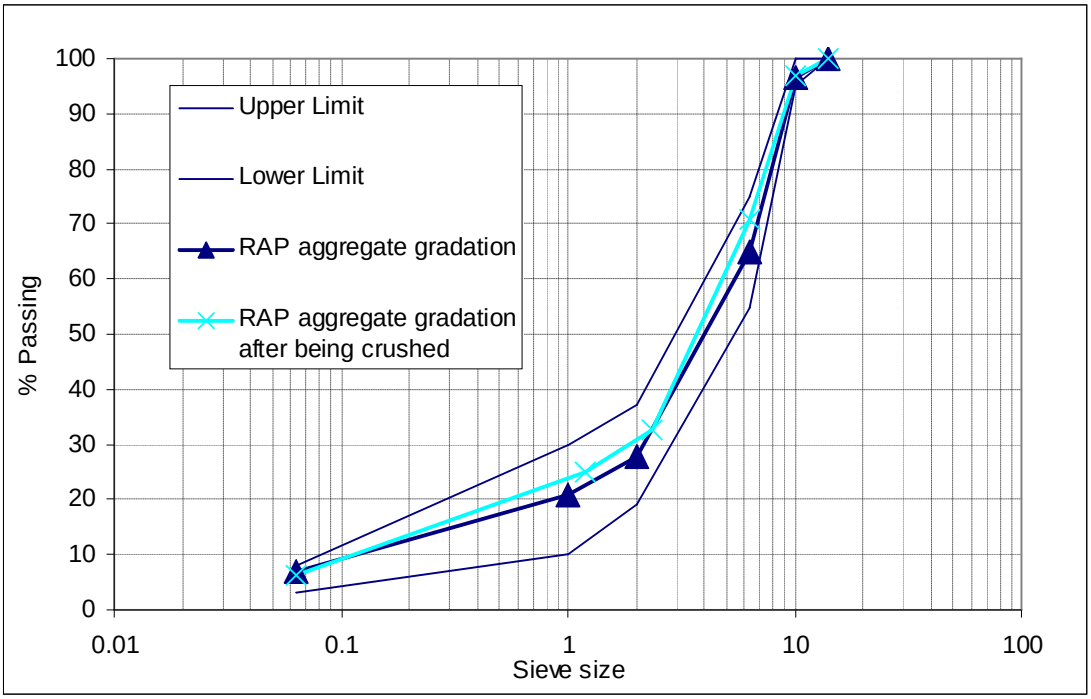


Figure 36: Gradation of RAP aggregate before and after processing

3.5.2 RAP binder

RAP binder, after being extracted and recovered from RAP material (BS-EN:12697-4, 2005), is subjected to penetration test at 25°C, softening point and density test. Rhelogical properties are also determined by dynamic shear rheometer (DSR) under strain-controlled mode. The strain is 0.8% to assure visco-elastic properties of RAP binder. The test temperatures range from 4 to 45°C when 8 mm plate is used with 2000µm thick specimen and 20 to 80°C for 25mm plate and 1000µm thick specimen. The properties of RAP binder are presented in Table 25. Viscosity of RAP binder is zero shear viscosity extrapolated from DSR data using Cross model at 60°C.

Penetration at 25^{o}C (dmm)	BS EN 1426 (2000)	31
Softening Point (^{o}C)	BS EN 1427 (2000)	58
Density (g/cm^{3})	BS EN ISO 3838 (1996)	1.03
Viscosity at 60^{o}C (Pa.s)	DSR-ZSV	1859

Table 25: Properties of RAP binder

4 Zero shear viscosity and the accuracy of viscosity mixing equations

4.1 Introduction

To estimate the viscosity of the blend between aged and virgin binder is a vital part in the recycled asphalt mixture design process. The estimation accuracy relies not only on the efficiency of viscosity mixing rules but also on the viscosity of aged and virgin binders. Inaccurate viscosity input might result in substantially erroneous prediction. The viscosity of bituminous binder has been normally determined at an arbitrary temperature of 60^{o}C. Absolute viscosity can be conventionally determined by capillary method. However, the limits of this approach are that it is time consuming and requires calibrations (Malkin and Isayev, 2006).

Viscosity can be also determined by dynamic shear rheometer (DSR) at low frequency, for instance, 0.05 or 0.1 rad/second. Chaffin et al. (1995) studied the efficiency of three mixing rules, Arrhenius, Grunberg and Nissan, and Epps, on 47 bituminous materials including straight run bitumen, bitumen fractions and commercial recycling agents. The dynamic viscosity η^* of all materials was measured at 60^{o}C, angular frequency of 0.1 rad/second under the geometry condition 25 mm plate and 500 μm gap. Chaffin et al (1995) claimed that the η^* at this specified frequency and temperature could be considered as a low frequency limiting complex viscosity η_o^*, independent of frequency or shear rate, and could be used instead of absolute viscosity. However, the difference between η_o^* and absolute viscosity depends on the type of bitumen. Especially with stiff bitumen, the difference might be considerable.

However, in practice, it is sometimes impossible to obtain the η_o^* of stiff bitumen due to the limit capability of the equipment (Chaffin et al., 1995). In addition, at high temperatures, for instance at 60^{o}C or higher, the viscosity values of soft bitumen are not stable under low shear rates. Figures 37 and 38 illustrate the complex viscosities of bitumen 160/220 Pen and 100/150 Pen at 60^{o}C versus different frequencies. The softer the bitumen, the more unstable

the complex viscosity values at low frequencies. If one value of low frequency is used to determine η_o^*, this value might not represent the viscosity of bitumen.

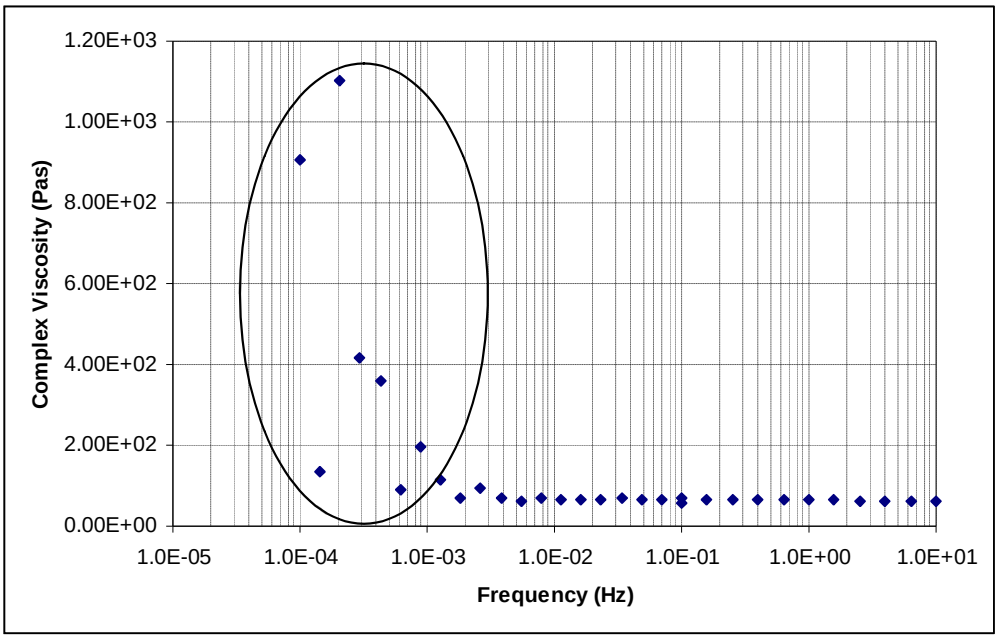


Figure 37: Complex viscosity of bitumen 160/220 Pen versus different frequency at 60°C

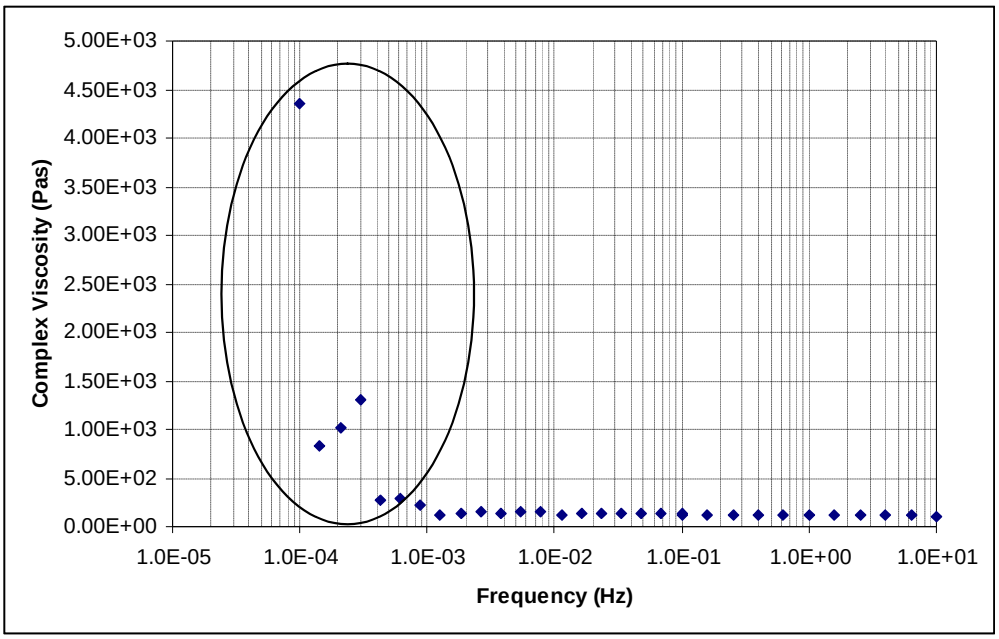


Figure 38: Complex viscosity bitumen 100/150 Pen versus different frequency at 60°C

The inaccurate viscosity determination might affect the efficiency of viscosity mixing equations. To eliminate the above limitations of DSR in determining bitumen viscosity, it is possible to increase the angular frequency. In addition, the temperature can also be reduced, rather than using the arbitrary temperature 60°C, and using the Cross model to obtain the

low frequency limiting complex viscosity (ZSV) by mathematical extrapolation. The first purpose of this experiment is to use zero shear viscosity to evaluate the efficiency of different viscosity mixing equations.

In addition, Chaffin et al. (1995) claimed that the interaction parameter G_{12} in Grunberg and Nissan equation has relation with the difference between viscosities of rejuvenator and aged binder. The bigger the viscosity difference, the higher the absolute value of G_{12}. In addition, Arrhenius is a special case of Grunberg and Nissan equation when G_{12} is equal to zero. This means the bigger the difference between viscosity of aged and virgin binder, the more the viscosity predicted by Arrhenius mixing rule deviates from the Grunberg and Nissan value. Based on experiment data, it is realized that the difference between viscosities of rejuvenator and aged binder is dependent on the temperature. Therefore, the purpose of this experiment is also to evaluate the effect of temperatures on efficiency of Arrhenius and the other equations. If the hypothesis of Chaffin et al. (1995) is correct, the adjustment in testing temperatures might improve the efficiency of Arrhenius equations.

4.2 Experiments

4.2.1 Materials

One aged bitumen and two rejuvenators are used in this study. The aged bitumen is extracted and recovered from artificial RAP by fractionating column method (BS-EN:12697-4, 2005). RAP was produced from 10 mm DBM (BS:4987-1, 2005) and binder 40/60 Pen with target air void content of 8%. The mixture is then conditioned at 85^{o}C for 120 hours for LTOA (Airey, 2003). Two rejuvenators are soft bitumen 160/220 and 100/150 Pen. The properties of bitumens are in the Table 26.

Bitumen	Penetration at 25^{o}C (dmm)	Specific Gravity
Aged binder	31	1.03 g/cm^3
100/150 Pen	119	1.02 g/cm^3
160/220 Pen	192	1.02 g/cm^3

Table 26: Properties of bitumens

There are two mixes in this study. Mix A represents blends of aged binder and 160/220 Pen and Mix B represents those of aged binder and 100/150 Pen. For both Mix A and Mix B,

the increment of 20% aged binder produced a total of 8 pairs of aged binder/rejuvenator in this project. Each blend is produced by pouring the determined proportions of liquid bitumen into a glass tin by using digital balance with the accuracy of 0.001gram. The weight of each blend is approximately 10 grams. All the blends are mixed manually by a small paddle for 30 seconds at 160^{o}C to assure the homogeneity.

4.2.2 Rheological testing

Rheological properties of each blend are determined using dynamic shear rheometer with 25 mm parallel plates and internal gap of 1000 μm. The complex viscosities of bitumen are measured over temperature range from 20 to 80^{o}C under strain-controlled mode. The strain is chosen at 0.8% to assure bitumen working in the visco-elastic regime under frequency range from 0.1 to 10 Hz.

4.3 Results and discussion

4.3.1 Zero shear viscosity (ZSV)

Zero shear viscosity or zero frequency complex viscosity is a theoretical concept. In practice, it is impossible to obtain those values by current laboratory methods such as rotational viscometry and rotational dynamic rheometry due to equipment limits. Hence, the Cross model for pseudo-plastic materials is used for extrapolation of the zero shear rate viscosity (Cross, 1965). This model describes the relationship between shear rate and apparent viscosity by the following equation:

$$\eta = \eta_{\infty} + \frac{\eta_o - \eta_{\infty}}{1 + \left(k \dot{\gamma} \right)^m} \qquad \textbf{(12)}$$

Where:

η : viscosity

$\dot{\gamma}$: shear rate

η_o : zero shear viscosity

η_{∞} : viscosity at infinite shear rate

k : material constant.

m : dimensionless material constant

As the rotational rheological device cannot cover sufficient range of shear rate, the assumption was made that $\eta >> \eta_\infty$ (Sybilski, 1996). Hence, the Cross model was simplified as followed:

$$\eta = \frac{\eta_o}{1+(k\omega)^m} \quad \textbf{(13)}$$

Cross model (Equation 13) was also used for extrapolation of zero shear viscosity from the dynamic oscillation data where η_o was zero shear viscosity, η_∞ was complex viscosity at infinite frequency and ω was oscillation angular frequency (Anderson et al., 2002).

Based on the rheological data, the theoretical zero shear viscosity is extrapolated by using Cross model with the help of Matlab software. The results of extrapolation work are presented in Table A-1 for blends of Mix A and Table A-2 for blends of Mix B with different proportion of aged binder at different test temperatures (Appendix A). Figure 39 is an example of the extrapolation work. The results show that the Cross model is fitted with the experimental data as almost all the R square values of the regression analysis are substantially high, except for high temperatures, for instance, higher than 60^{o}C. At these high temperatures, rejuvenators and those blends with low percentages of aged binder are soft and the complex viscosity values are almost independent of angular frequencies. Figure 40 illustrates the dynamic viscosities versus frequency of a blend of Mix A (20% RAP and 80% 160/220 Pen) at 70^{o}C. For these situations, a linear polynomial relation between complex viscosity and frequency (Equation 14) is used for zero frequency viscosity extrapolation instead of Cross model which requires the viscosity of material to be dependent on frequency, or shear rate (Cross, 1965).

$$\eta_0 = a\omega + b \quad \textbf{(14)}$$

Where:

a, b: material constant

ω: frequency

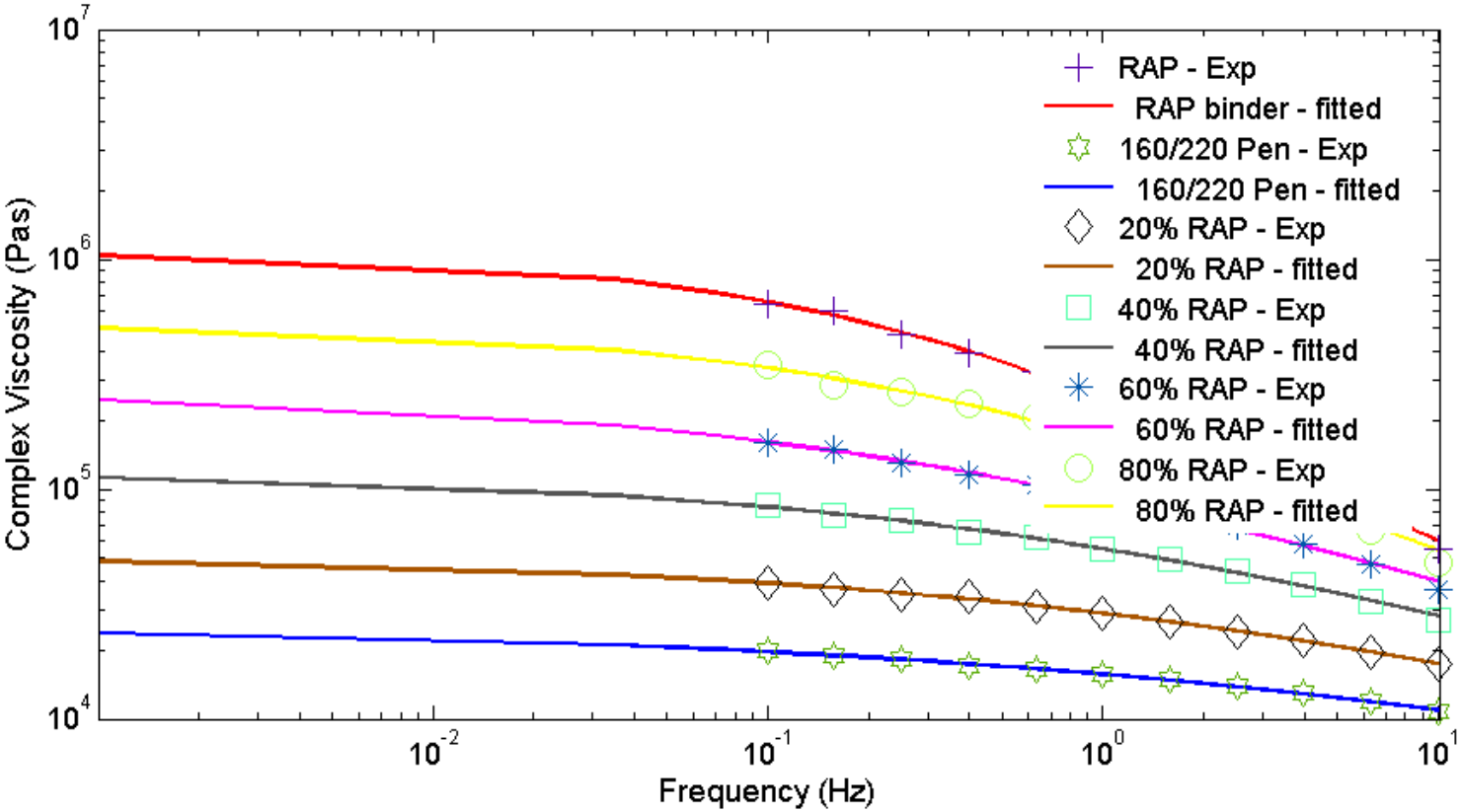


Figure 39: Extrapolated ZSV of Mix A blends at temperature of 25°C

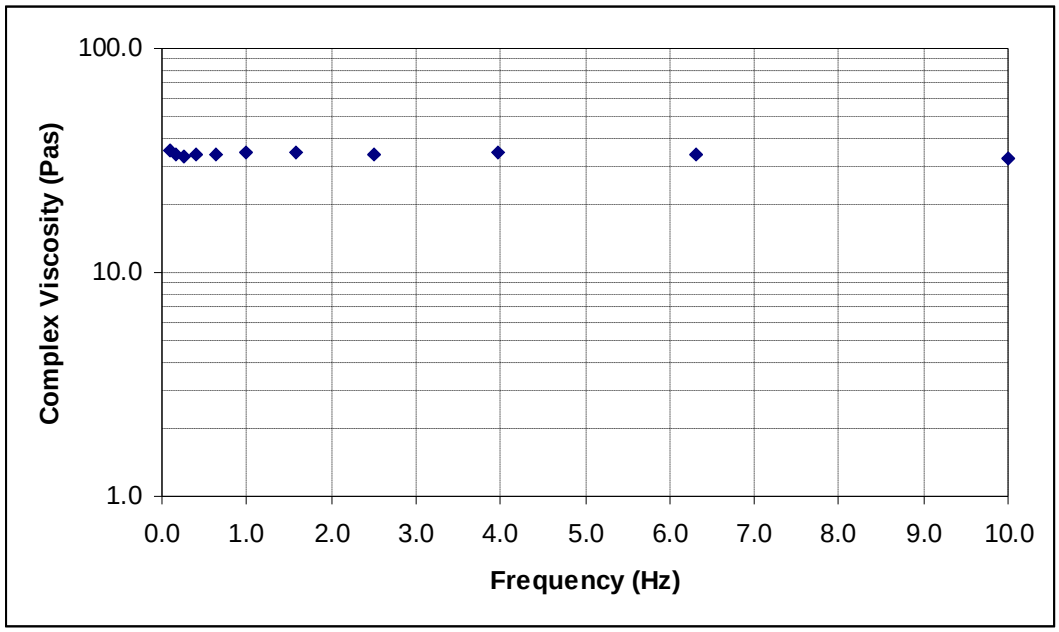


Figure 40: Complex viscosity versus frequencies of blend (20 % RAP and 80% 160/220 Pen) at 70°C

4.3.2 Efficiency of viscosity mixing equations

Four viscosity mixing equations are evaluated in this study, Grunberg and Nissan, Arrhenius (ASTM 4887), Epps, and DLV (Section 2.3.4). For the Grunberg and Nissan equation, parameter G_{12} is determined by fitting this equation into the experiment data at different testing temperatures using Matlab. For both Mixes A and B, the viscosity of each blend is calculated by each of four mixing equations with the same proportion of RAP binder, ZSVs of RAP binder and rejuvenator. The experiment data and predicted viscosity using four mixing equations for Mix A and Mix B are illustrated in Tables A-3 and A-4 (Appendix A). Each pair of predicted and experimental data is compared by using regression analysis with the help of Matlab software. Figure 41 illustrates the differences between experimental and predicted values using four different viscosity mixing equations. The difference between experimental and predicted data is evaluated by following indicators, R square value, Residuals (R), and Root Mean Square Error (RMSE) (Tables 27 and 28).

The Residual represents the difference from the predicted to the experimental values and is calculated by the following equation:

$$R_i = p_i - e_i \quad \textbf{(15)}$$

Where:

R_i : Residual of data point i

p_i : predicted value

e_i : experimental value

R is also presented by the percentage difference from the predicted and experimental value, the closer the R value to zero, the better the fit.

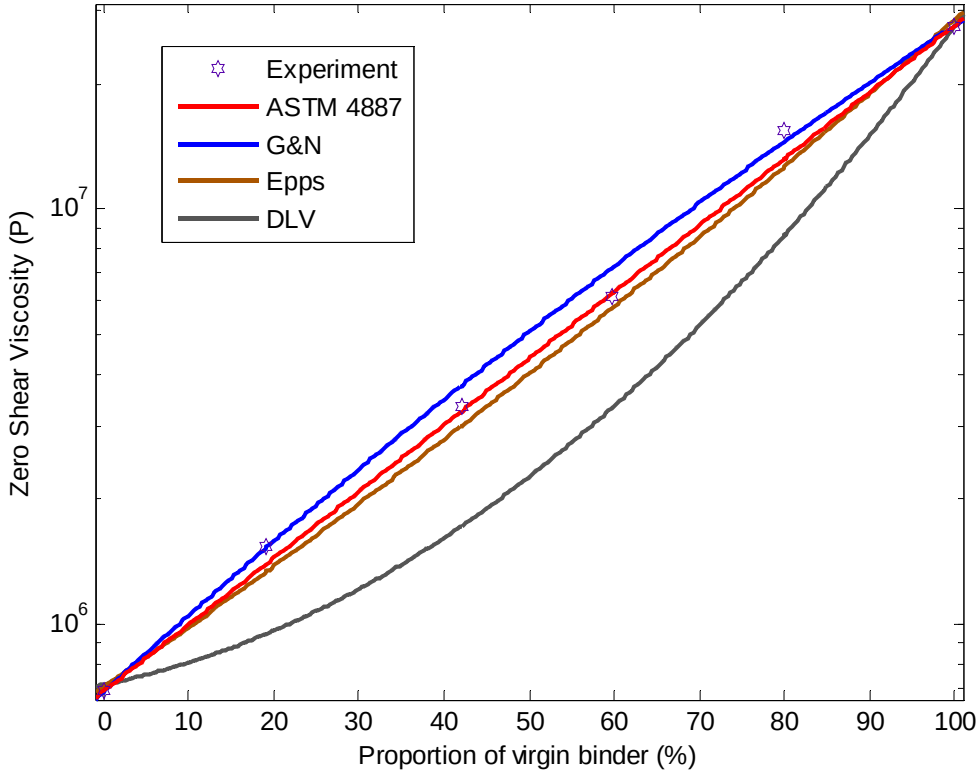


Figure 41: Experiment and predicted viscosity using different viscosity mixing equations of Mix A (Blends of different proportion of aged binder and 160/220 pen) at 20°C

The Root Mean Square Error (RMSE) is the standard deviation between predicted and experimental data sets. The closer the RMSE to 0, the better fit. RMSE is determined by the following equation:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(p_i - e_i)^2}{n}} \quad \textbf{(16)}$$

Where:

n : the number of data points evaluated

p_i : predicted value

e_i : experiment or actual value

The results from regression analysis for blends of Mix A and Mix B are presented in Tables 27 and 28. The R square values of regression analysis between four equations and experiment are almost the same. However in general, the RMSE generated by Grunberg and Nissan equation are smallest at almost every test temperatures. The RMSE values generated by DLV and Arrhenius equations (ASTM D4887) are in turn the first and second largest. At high temperatures, for instance, higher than 55^{o}C, these values from Epps and Grunberg and Nissan equation are almost identical.

In term of Residual values, the viscosity predicted using DLV method are the most deviant from actual values. Arrhenius equation, the most popular equation for estimating the viscosity of bitumen mixture (Chaffin et al., 1995), generates the second highest residuals. The results demonstrate that on the average, the predicted viscosities by Arrhenius equation (ASTM D4887) are within 30% of the experimental data. This supports the finding of Irvin (1977). DLV method could estimate the viscosity of the bitumen mixture within 50% of the actual value. This also substantiates the fact that DLV method does not perform well when soft bitumen is used as rejuvenator (Chaffin et al., 1995). Generally, Grunberg and Nissan equation again generates the lowest values of residual. Maximum Residual values generated by using Grunberg and Nissan and Epps equations are generally less than 20%. At temperatures higher than 45^{o}C, the residual generated by Grunberg and Nissan and Epps equation are almost similar, approximately 10%. All viscosity mixing equations show the tendency of improving accuracy when increasing the temperature (Tables 27 and 28).

Arrhenius equation (ASTM 4887) is a special case of Grunberg and Nissan when G_{12} is equal to zero. Table 29 presents the values of G_{12} of Mix A and Mix B blends at different temperatures. If the G_{12} is negative, Arrhenius equation overestimates the viscosity of the blend and vice versa. The higher the absolute value of G_{12}, the greater the difference the viscosity predicted by Arrhenius equation from the *G&N* value. Chaffin et al (1995)

claimed the variation is due to the difference between viscosity of aged binder and rejuvenator. However, the results in this experiment demonstrate that the difference between viscosity of aged binder and rejuvenator is not the only reason for the imprecise viscosity estimation.

Figure 42 presents the difference between viscosity of aged binder and rejuvenator versus G_{12} at different temperatures. The viscosity difference is expressed as the ratio of aged binder viscosity over that of rejuvenator. The results indicate there is no relation between viscosity difference and the G_{12} parameter. Therefore, the deviation of viscosity predicted by Arrhenius equation from actual values is not attributed to the viscosity difference. The inaccurate estimation using Arrhenius viscosity mixing equations is probably caused by interaction between aged and virgin binder.

As the bitumen has complicated chemical composition, the interaction occuring inside each blend of different bitumen binders is different from the others. The interaction is also different in mixtures comprised of the same two bitumen but different proportions (White et al., 1970). Therefore, the fact that one constant value of interaction parameter G_{12} is used universally would result in substantial errors in viscosity estimation.

Temperature	Grunbrerg and Nissan			ASTM 4887			Epps			DLV		
^{o}C	R-square	RMSE	Max Res (%)	R-square	RMSE	Max Res (%)	R-square	RMSE	Max Res (%)	R-square	RMSE	Max Res (%)
20	0.996	6.5E+05	17.4	0.991	9.4E+05	14.82	0.983	1.4E+06	20.8	0.9126	3.1E+06	48.3
25	1.000	8.5E+04	9.8	0.999	1.3E+05	10.77	0.993	3.4E+05	20.8	0.9365	1.0E+06	53.1
30	0.990	1.7E+05	36.7	0.979	2.3E+05	21.07	0.963	3.0E+05	27.8	0.8936	5.6E+05	48.9
35	1.000	1.5E+04	7.2	0.999	1.9E+04	12.76	0.997	3.8E+04	10.1	0.9621	1.5E+05	47.8
40	0.999	1.1E+04	10.4	0.999	1.0E+04	13.82	0.991	2.5E+04	16.9	0.9484	6.7E+04	46.5
45	1.000	2.3E+03	8.5	0.997	5.7E+03	22.20	0.999	4.2E+03	7.5	0.971	2.0E+04	39.9
50	0.998	1.9E+03	15.2	0.995	2.9E+03	30.39	0.997	2.2E+03	8.8	0.9702	8.0E+03	33.5
55	1.000	3.0E+02	6.1	0.993	1.3E+03	26.07	1.000	3.0E+02	5.8	0.9768	2.5E+03	33.5
60	1.000	7.9E+01	3.4	0.991	5.8E+02	23.93	1.000	1.1E+02	4.4	0.9782	1.0E+03	31.2
65	0.999	9.4E+01	8.8	0.992	2.5E+02	26.79	0.999	1.0E+02	7.3	0.9736	5.1E+02	27.9
70	0.998	7.0E+01	11.8	0.990	1.3E+02	29.49	0.997	6.7E+01	10.9	0.9719	2.4E+02	25.3
75	1.000	1.5E+01	5.5	0.981	9.5E+01	31.66	0.999	2.7E+01	12.9	0.9847	9.4E+01	20.6
80	0.999	1.4E+01	11.2	0.991	3.2E+01	26.19	0.998	1.4E+01	9.6	0.964	6.2E+01	24.5

Table 27: Mix A - Regression analysis between experiment and predicted values using different viscosity mixing equations at different temperatures

Temperature	Grunbrerg and Nissan			ASTM 4887			Epps			DLV		
^{o}C	R-square	RMSE	Max Res (%)	R-square	RMSE	Max Res (%)	R-square	RMSE	Max Res (%)	R-square	RMSE	Max Res (%)
20	0.977	1.6E+06	21.7	0.971	1.6E+06	17.7	0.967	1.7E+06	20.2	0.886	3.48E+06	37.5
25	0.995	2.8E+05	16.3	0.985	4.1E+05	22.7	0.980	4.9E+05	25.2	0.856	1.30E+06	40.9
30	0.987	1.9E+05	14.7	0.951	3.3E+05	22.8	0.943	3.6E+05	25.8	0.819	6.96E+05	44.1
35	0.999	2.1E+04	10.3	0.998	2.9E+04	11.7	0.994	5.4E+04	16.2	0.933	1.93E+05	39.9
40	0.998	1.2E+04	8.4	0.997	1.5E+04	8.0	0.989	2.5E+04	13.5	0.923	7.91E+04	42.2
45	0.996	7.5E+03	16.4	0.996	7.1E+03	19.7	0.993	8.8E+03	10.8	0.948	2.68E+04	36.8
50	0.999	1.3E+03	8.7	0.993	3.4E+03	23.9	0.999	1.4E+03	10.8	0.971	7.53E+03	35.3
55	0.996	9.8E+02	11.1	0.996	9.0E+02	12.0	0.993	1.3E+03	11.6	0.94	3.93E+03	32.4
60	1.000	1.0E+02	6.2	0.991	5.5E+02	18.3	0.999	1.5E+02	6.5	0.973	1.09E+03	28.8
65	0.997	1.8E+02	11.5	0.994	2.2E+02	20.2	0.996	1.7E+02	8.5	0.957	6.24E+02	30.2
70	0.997	7.0E+01	9.0	0.996	8.4E+01	15.1	0.996	7.8E+01	12.5	0.951	3.03E+02	36.1
75	0.999	2.0E+01	4.5	0.990	6.8E+01	18.4	0.999	2.4E+01	7.1	0.972	1.23E+02	23.6
80	0.997	1.9E+01	7.1	0.996	4.9E+01	10.6	0.994	2.4E+01	8.0	0.943	8.19E+01	27.1

Table 28: Mix B - Regression analysis between experiment and predicted values using different viscosity mixing equations at different temperatures

Temperature	Mix 1	Mix 2
20	0.2582	0.1719
25	0.1206	0.2160
30	0.3776	0.4509
35	-0.0916	0.0434
40	-0.0552	0.1172
45	-0.2128	-0.0507
50	-0.2242	-0.2477
55	-0.3121	-0.0141
60	-0.3276	-0.2512
65	-0.2724	-0.1357
70	-0.2624	-0.0995
75	-0.3950	-0.2253
80	-0.2260	-0.0574

Table 29: G12 parameter of Mix A and B at different temperatures

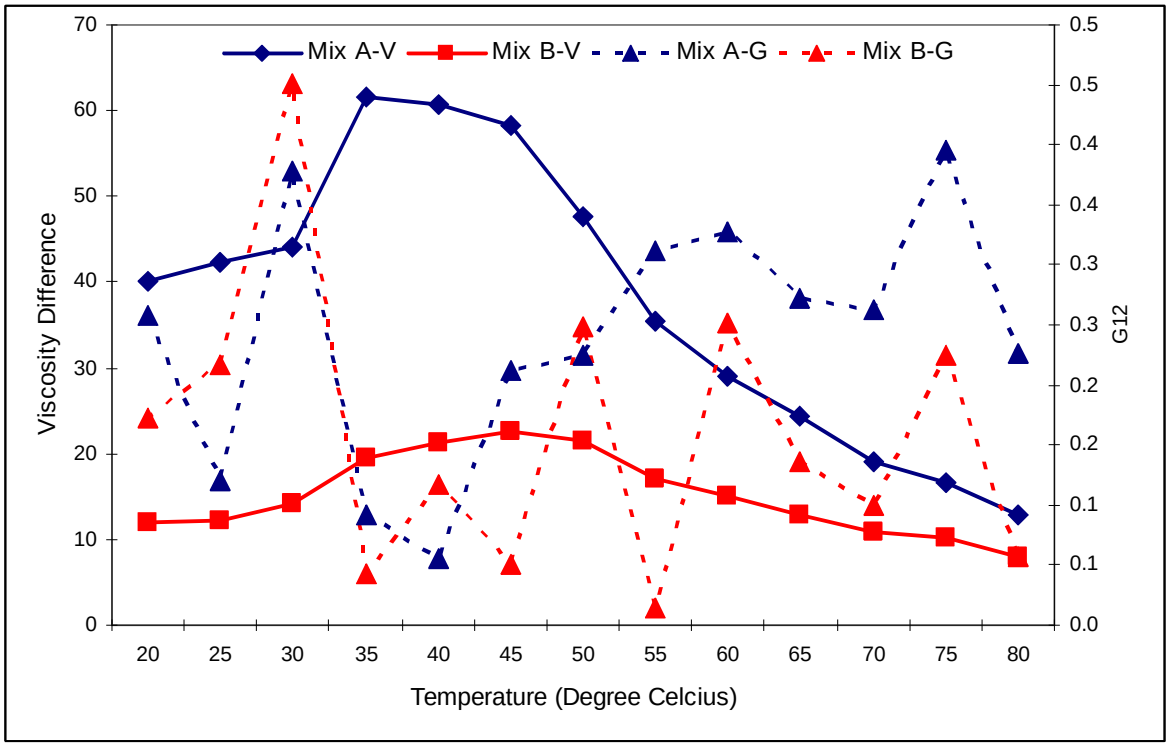


Figure 42: Viscosity difference and G12 versus temperatures

5 Effects of laboratory mixing methods on the homogeneity of hot recycled asphalt mixture

5.1 Introduction

This chapter contains the development of a new mixing protocol that simulates the mixing mechanism between RAP and virgin materials in asphalt mixing plants. The effects of different RAP/superheated virgin aggregate mixing durations and RAP sizes on homogeneity of hot recycled asphalt mixture are considered. The homogeneity of recycled mixtures is studied by using virgin binder with different colour from that of RAP binder. The red colour of virgin binder is obtained by mixing clear binder with iron oxide pigment. The proportion of pigment is 10% by weight of the binder making this binder red. The content of this chapter also includes the correlation between homogeneity and stiffness distribution of hot recycled asphalt mixtures.

5.2 Development of laboratory mixing protocol

It is essential that the laboratory mixing protocol should duplicate the mixing mechanism occurring in the actual asphalt mixing plants. The laboratory mixing process should include the following steps:

- Step 1: Virgin aggregate is superheated to predetermined temperature.
- Step 2: Superheated virgin aggregate is mixed with RAP material at ambient temperature in the mixer maintained at mixing temperature.
- Step 3: the combination of superheated virgin aggregate and RAP material is blended with virgin binder in the mixer maintained at mixing temperature.

Step 1 is to enable virgin aggregate enough thermal energy to heat up the RAP from ambient to mixing temperature. The purpose of Step 2 is to use the heat from superheated virgin aggregate to heat up and soften RAP materials, separating RAP lumps into single particles covered by RAP binder. The heat source for separating RAP lumps also comes from the mixer maintained at mixing temperature. During this process, RAP bitumen is also transferred onto the surfaces of virgin aggregate particles. Then, the combination of RAP and virgin aggregate is mixed with virgin binder in Step 3. The aim of this step is to assure that virgin binder can incorporate and rejuvenate the RAP binder. In addition, this step is also to ensure that the rejuvenated binder is well distributed all over the mixture and coats

every single aggregate particle. The mixing time for Step 3 is 2 minutes due to laboratory experience with the mixer. For the manufacture of conventional asphalt mixture, this duration is enough for virgin binder to coat all the aggregate particles.

The efficiency of the laboratory mixer is quite different from that of the industrial mixer for asphalt production. In the actual asphalt mixing plant, besides mechanical mixing effects, single virgin aggregate and RAP particles experience centrifugal force until this force is smaller than gravity and materials start to fall downward. Once the heat transferred from superheated virgin aggregate softens the RAP binder, the movement of each RAP particle due to gravity also enhances the separating progress of RAP lumps.

In the laboratory mixer, on the contrary, the bulk of materials is moving circularly under mechanical effect of mixing paddles. In fact, there is primarily horizontal and inconsiderable vertical movement. Once the heat transferred from superheated virgin aggregate weakens the bitumen bond, RAP particles are separated due to the mechanical effect of mixing paddles and external friction among surface of particles. The breaking progress is not enhanced by the vertical movement due to gravity of RAP materials.

In actual asphalt mixing plants, the continuous production process also assures the heat conductivity between superheated virgin aggregate and RAP material being more efficient than that in the laboratory. The laboratory production of recycled asphalt mixture requires the lid of the mixer to be opened several times during manufacture process for material intakes.

5.2.1 Estimation of superheated temperature of virgin aggregate

The amount of heat required to raise the RAP at ambient temperature to the mixing temperature is equal to the amount of heat dispersed from virgin aggregate so the temperature drops from superheated to mixing value. Based on the quantities of virgin aggregate, RAP, specific heat of RAP and virgin aggregate, the superheated temperature can be estimated.

The amount of heat (Cutnell and Johnson, 2004) required to raise the temperature of a mass is:

$$Q = mc\left(T_2 - T_1\right) \qquad \textbf{(17)}$$

Where:

m: the mass in quantity (kg)

c: specific heat (kJ/kg ^{o}C)

T_1, T_2: current and desired temperatures (^{o}C)

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

$$Q_1 = m_{RAP} c_{RAP} \left(T_m - T_a\right) \quad \textbf{(18)}$$

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

$$Q_2 = m_{agg} c_{agg} \left(T_s - T_m\right) \quad \textbf{(19)}$$

Where

m_{RAP}, m_{agg}: Quantities of RAP and virgin aggregate in the mixture (kg)

c_{RAP}, c_{agg}: specific heat of RAP and virgin aggregate (kJ/kg ^{o}C)

T_s, T_m, T_a: superheated temperature (^{o}C) for virgin aggregate, mixing temperature, ambient temperature of RAP. The mixing temperature will be determined in the next section.

5.2.2 Determine the superheated virgin aggregate/RAP mixing duration

Due to the efficiency difference, the short mixing time in the real industrial mixer, for instance, 60 second, might not be applicable in the laboratory mixer. To investigate the effect of mixing on the properties of hot recycled mixture, the superheated virgin aggregate/RAP mixing duration is adjusted based on the mixer used for the research. During the mixing duration, thermal energy transferred from superheated virgin aggregate and from the mixer will soften the bitumen bond and separate RAP lumps into single particles. The adjustment method is to start from short mixing time and gradually increase the mixing time until the change in RAP lumps size is insignificant. Consequently, the RAP/virgin aggregate mixing duration is decided to be 2, 4, 6 and 8 minutes for large RAP mixture and 1, 2, 4, 6, 8 minutes for small RAP mixture. Figure 43 illustrates that at 2 minutes mixing time, the RAP still remains approximately the original size. Figure 44 is for 8 minutes mixing time when the change in RAP size under mechanical mixing is negligible.

Figure 43: RAP size after 2 minutes RAP/superheated virgin aggregate mixing time

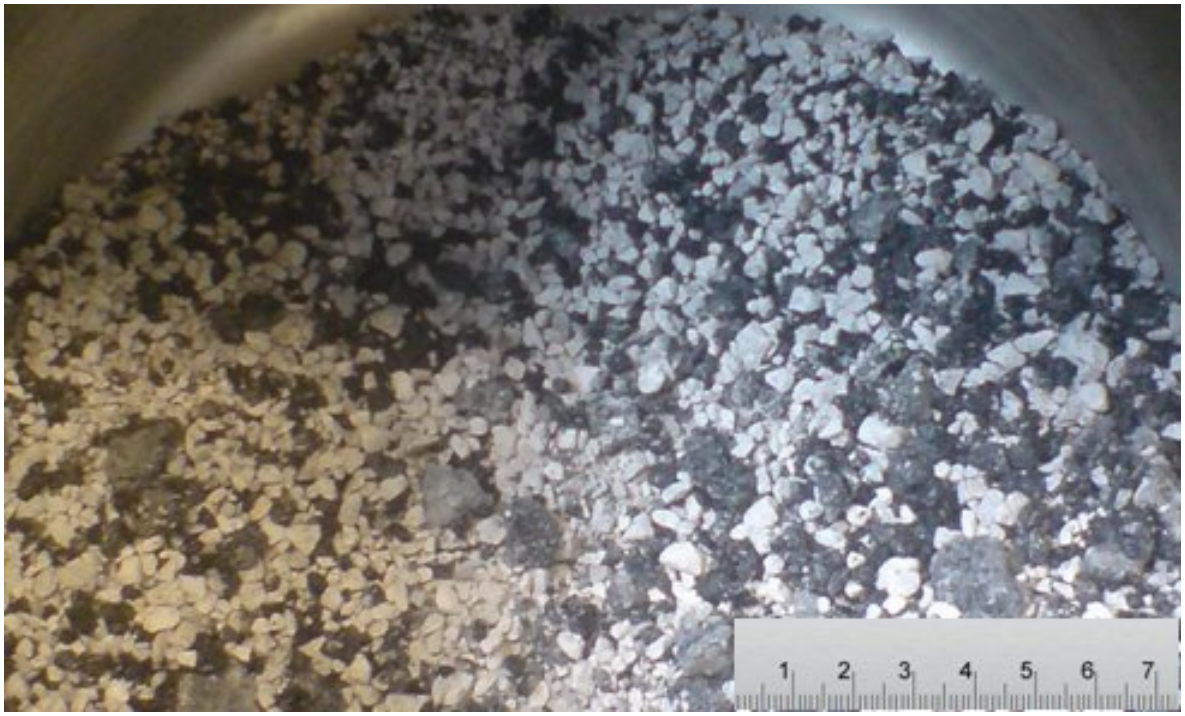


Figure 44: RAP size after 8 minutes RAP/superheated virgin aggregate mixing time

5.2.3 Determine the mixing temperature

The mixing temperature in Step 3 is determined based on the virgin binder used as rejuvenator. The optimum mixing temperature is the temperature at which the viscosity of virgin binder has the viscosity value of 0.2 Pa.s (Read and Whiteoak, 2003). The viscosity of virgin binder is determined by Brookfield viscosity test at 120, 150, and 180^{o}C. The temperature at 0.2 Pa.s viscosity is interpolated by linear relationship between double log viscosity and temperature (Heukelom, 1973). In this experiment, mixing temperature is 135^{o}C

5.3 Method for segregation evaluation

The primary characteristic attributed to the difference between conventional asphalt and recycled asphalt mixture is reclaimed material (RAP), a combination of aged binder and aggregate. Hence, the segregation that occurs in recycled asphalt mixture includes not only the different concentration of aggregate sizes and bitumen but also the distribution of RAP material, new material and additive if applicable. Therefore, most measuring and segregation detection techniques for conventional asphalt mixture are not applicable or not efficient for recycled asphalt mixture. Unfortunately, the segregation level might considerably affect the quality of recycled asphalt mixture and is determined mainly on how well new and RAP materials are mixed (Tia et al., 1980).

The method using infrared scanner can only classify between the bitumen-rich and aggregate-rich areas due to the difference in thermal properties (Gardiner and Brown, 2000). Similarly, the segregation detection method based on density, for instance, X-ray scanner, can only identify the location of air void, aggregate and bitumen due to the significant difference in density of these components. However, these kinds of equipment cannot identify the position of RAP and new binder as the density of these binders are approximately the same. Figure 45 illustrates the images taken by X-Ray photo machine and normal digital camera of RAP binder and Shell clear binder (Mexphalte C 160/220 pen) dyed by red iron oxide pigment. The proportion of the pigment is 10% by weight of the clear binder. Although the density of iron oxide is quite different from those of clear and RAP binder, 5.25 g/cm^3 to 1.03 g/cm^3, the X-ray scanner image cannot show any difference between RAP binder and clear binder dyed by iron oxide pigment. Meanwhile, RAP binder

is visually recognized as pure black and Mexphalte C dyed by 10% iron oxide has colour of red (Figure 43).

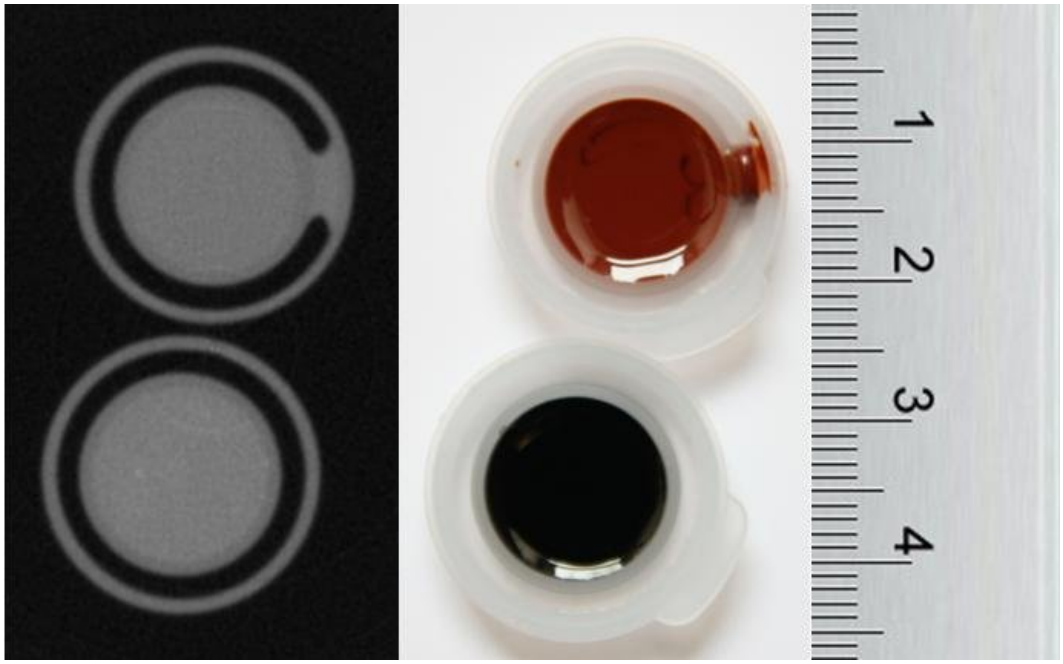


Figure 45: Images taken by X-Ray scanner and normal digital camera of Shell Mexphalte C dyed by 10 % iron oxide and RAP binder

The dye chemistry method (Lee et al., 1983) can identify the location of recycling agent due to the detection of chemical tracer. However, in undetected areas this method cannot classify virgin aggregate and RAP lumps. The result of this method is only correct in cases where the detected areas contain RAP binder and recycled agent, and the undetected areas contain only aggregate. Unfortunately, the undetected areas contain not only aggregate but also RAP material as RAP lumps.

To assess the effect of mixing process on homogeneity of recycled mixture, the RAP should be clearly identified from virgin materials. In this research, RAP material is artificially made in the laboratory. The colour of RAP binder will be purely black. On the contrary, virgin binder, the blend of synthetic clear binder (Shell Mexphalt C 160/200 Pen) and 10% of iron oxide by weight of the binder, will have the colour of red. The preparation of testing specimens conforms to the procedures in Section 5.4 .

The hypothesis of using virgin binder with different colour is if RAP material is not well mixed with virgin binder, the areas of black (RAP materials) and red (virgin material) are clearly visualized. In addition, the phenomenon that RAP materials are not fully separated

into single aggregate particles covered by RAP binder but exist as RAP lumps in the recycled mixture is also easily identified. After manufacture, surfaces of slices cut from specimens are recorded by digital camera. The analysis of these surfaces based on vertical order help to understand the distribution of RAP and virgin materials in the mixture in a 3D manner.

Samples for visual segregation assessment are also subject to mechanical properties evaluation. The purpose is to link the homogeneity level and the mechanical properties of recycled asphalt mixture. Stiffness of each sample is measured by Indirect Tensile Stiffness Modulus (ITSM) test at 20^{o}C (BS-EN:12697-26, 2004). The stiffness data is then statistically analyzed in conjunction with RAP (or virgin material) distribution pattern to characterize the correlation between mixture homogeneity and mechanical properties.

5.4 Specimens preparation

5.4.1 Materials

The proportion of RAP is 40% in the recycled mixture. Aggregate gradation of recycled mixture is designed the same as that of RAP (BS:4987-1, 2005). The bitumen content of RAP and recycled mixture are the same, 5.2% by weight of total mixture. Virgin binder is prepared by preheating synthesis clear binder (Shell Mexphalt C 160/220 Pen) to 135^{o}C and blending with iron oxide powder. The amount of pigment is 10% by weight of virgin binder to make the color of virgin binder red.

5.4.2 Mixing procedure

The mixing process is implemented in the Mixer A (Section 6.2.2). The mixing procedure is determined as follows:

- Step 1: Virgin aggregate is superheated to 215^{o}C for 8 hours. Virgin binder is preheated at 135^{o}C for 2 hours
- Step 2: RAP, both large and small sizes, denoted as LR and SR, are blended with superheated virgin aggregate at ambient temperature in the mixer maintained at 135^{o}C for different durations. The mixing durations for large RAP (LR) are 2, 4, 6, 8 and 1, 2, 4, 6, 8 minutes for small RAP (SR).

- Step 3: the blend of RAP and virgin aggregate is mixed with virgin binder for 2 minutes. Before being poured into the mixer, virgin binder is well stirred manually to prevent the settlement of iron oxide at the bottom of the container.

5.4.3 Compacting procedure

The loose mixture is compacted by gyratory compactor at 130^{o}C until the targeted density is obtained (BS-EN:12697-31, 2004). The targeted air void content of each specimen is 4%. The amount of materials is estimated so the final cylindrical specimen has the diameter of 150 mm and 100 mm height.

5.4.4 Machining specimens for segregation assessment

After being de-moulded the next day, a cylinder of 100 mm diameter and 100 mm height is cored from each compacted specimen. Two samples with approximately 40 mm thick, samples 1 and 2, are cut from this core for stiffness evaluation (BS-EN:12697-26, 2004). The surfaces of these samples are photographed by digital camera for visual segregation assessment. After stiffness measurement, these samples are sliced up into slices approximately 10 to 15mm thick. Surface image of each slice is also recorded by digital camera for further visual analysis. This is aimed to investigate the relationship between the heterogeneity and stiffness distribution of recycled mixtures with different mixing durations.

5.5 Results and analysis

5.5.1 Visual assessment for segregation

Figures 46 to 49 illustrate the surface characteristic of specimens manufactured with large RAP and different mixing times. Both surfaces of specimens for stiffness evaluation and surface of slices cut from these specimens after stiffness evaluation are included. Figures 50 to 54 show the surfaces of slices from specimens prepared from small RAP with different mixing times. The slices are in order from the bottom to top. The surfaces analysis of slices in vertical order will give a clear picture of how RAP lumps are distributed in the cylindrical specimen.

Due to the colour difference between that of virgin (red), RAP binder (black), and aggregate, the locations of these components are easy to visualize. The advantage of using virgin binder with different colour from that of RAP binder is to help identify the location

of RAP lumps which is impossible with the other methods. The area containing just black binder and aggregate will be definitely RAP materials. This helps to better understand whether virgin binder can incorporate and rejuvenate the properties of RAP binder or RAP might work as inert lumps in the recycled mixture.

RAP materials exist as lumps, which is the agglomerate of single aggregate particles, including filler stuck together by bitumen. Once RAP material is mixed with superheated virgin aggregate, the thermal energy transferred from hot virgin aggregate will increase the temperature of RAP materials. Due to the inherent properties of bitumen, the bonding strength among RAP aggregate particles will be weakened. Under the mechanical effect of the mixing paddles, RAP lumps are gradually separated into single pieces. In fact, the factors that manipulate the efficiency of RAP separating process are, for instance, mixing temperature and mechanical effect. In addition, due to the fact that the energy transfer process occurs gradually, depending on size of material and contact surface (Cutnell and Johnson, 2004), the efficiency of mixing process is also attributed to mixing duration.

The surface images show that RAP/superheated virgin aggregate mixing duration seriously affects the homogeneity level of recycled mixtures, especially recycled mixture with large RAP. For recycled mixture with large RAP and short mixing time, for instance 2 minutes, the size of RAP areas on the surface of slices are large (Figure 46). This is because the mixing duration (energy) is not enough to degrade RAP lumps into separate particles. RAP lumps are almost inert and scattered in specimen at approximately their original size. In addition, RAP lumps are not well distributed in the specimen. In some slices, for instance, (Figures 46 b and c), the occurrence of RAP is intensive. This means the density of RAP are extremely high. However, in the other slices, the presence of RAP is negligible (Figures 46 a and h). Actually, these areas contain primarily virgin materials.

The homogeneity of recycled mixture is clearly improved once the RAP/superheated virgin aggregate mixing duration is extended. With large RAP recycled mixtures, Figures 46 to 49 show that when the mixing duration increases, the size of RAP areas in the surface of each slice gradually becomes smaller. This phenomenon is as expected as the longer the mixing time, the more thermal energy is transferred from superheated virgin aggregate. The effect of mechanical mixing process plus the weakening of bitumen bond between RAP aggregate particles slowly disintegrates the RAP lumps into smaller sizes. Therefore, the mixing

efficiency is enhanced as more active RAP particles are involved in the mixing process and well distributed around the mixture.

During the mixing process, the separation of RAP lumps also offers the chance for RAP binder to be rejuvenated by virgin binder. Visually, it is assumed that if the RAP binder is rejuvenated by virgin binder or these two binders are integrated, the colour of virgin binder will somehow be changed. The red colour of virgin binder will be darker due to the black effect of RAP binder.

The surface images show the same tendency for both large and small RAP recycled mixtures, the longer the RAP/superheated virgin aggregate mixing duration, the darker the red color of the virgin binder. This indicates more integration between RAP and virgin binder. In addition, the areas of pure black and red binder are also reduced. This is as expected as the longer the mixing time, the more single pieces of RAP are separated from RAP lumps. Hence, the total exposure surface of RAP particles for rejuvenating process increases and more RAP binder is rejuvenated by virgin binder.

The rejuvenating process is enhanced not only by the total exposed surface of RAP particles but also the temperature of RAP binder itself. This is because the diffusion of virgin into RAP binder is significantly influenced by the temperature, the higher the temperatures, the more efficient the diffusion process (Karlsson and Isacsson, 2003b). During the RAP/superheated virgin aggregate mixing duration, the thermal energy transferred from superheated virgin aggregate and the mixer increases the temperature of RAP binder and progresses the rejuvenation between RAP and virgin binder.

The surface images also demonstrate that RAP/superheated virgin aggregate mixing duration significantly affects the integration between RAP and virgin binder. RAP binder cannot be diffused efficiently by virgin binder unless RAP binder is heated up enough or activated using thermal energy from virgin aggregate and mixer during the mixing duration. Figure 46 shows the surface images of recycled mixture made of large RAP, 2 minutes mixing duration and Figure 50 for mixture composed of small RAP, 60 seconds mixing duration. The colour of virgin binder almost remains unchanged as original red. In fact, the mixing time or the thermal energy from superheated virgin aggregate is not enough to

activate the RAP binder for diffusion. RAP binder is inert and there is not considerable integration between RAP and virgin binder.

The surface images show that the size of RAP seriously affects the homogeneity level of recycled mixture. With the same RAP/superheated virgin aggregate mixing duration, for instance 2 minutes, the areas of inert RAP lumps of samples composed of large RAP are considerably larger and more intensive than those of small RAP (Figures 46 and 51). It is reasonable as the larger the RAP size, the more thermal energy and mixing effort required for separating RAP lumps. It is expect that when the mixing time is extended, all the RAP lumps can be disintegrated as single pieces covered by RAP binder and well distributed over recycled mixture. However, even when small RAP is used with 8 minutes RAP/superheated virgin aggregate mixing duration, there is still a considerable portion of RAP works as lumps (Figures 55 and 56). This validates the fact that “complete blending” between RAP and virgin binder assumed in the design process never occurs during mixing. Hence, the mechanical properties of recycled mixture might be not as consistent as predicted. This circumstance might be worse under really short mixing time, about maximum 90 seconds total, in the industrial mixer.

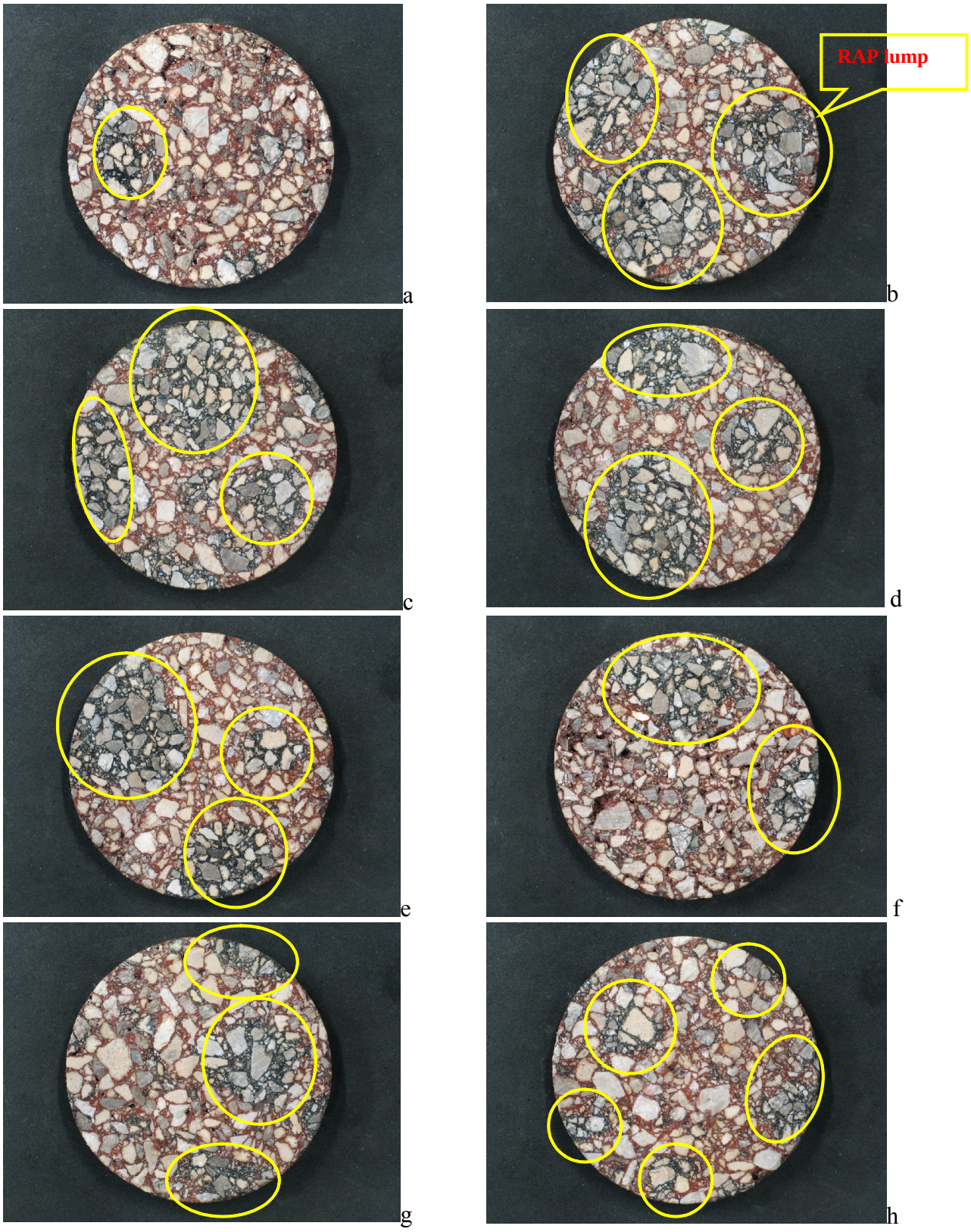


Figure 46: LR mixture – 2 minutes mixing time

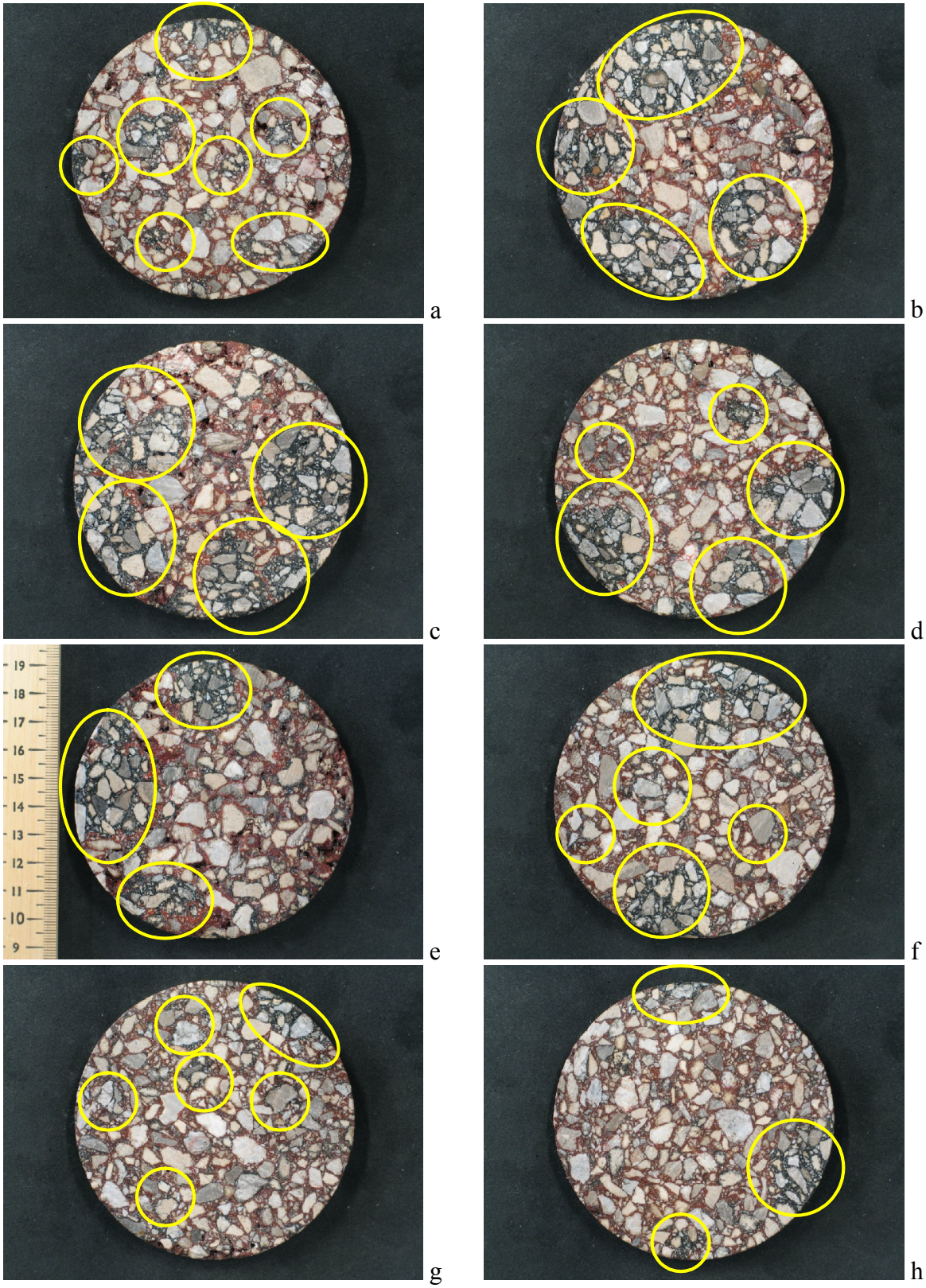


Figure 47: LR mixture – 4 minutes mixing time

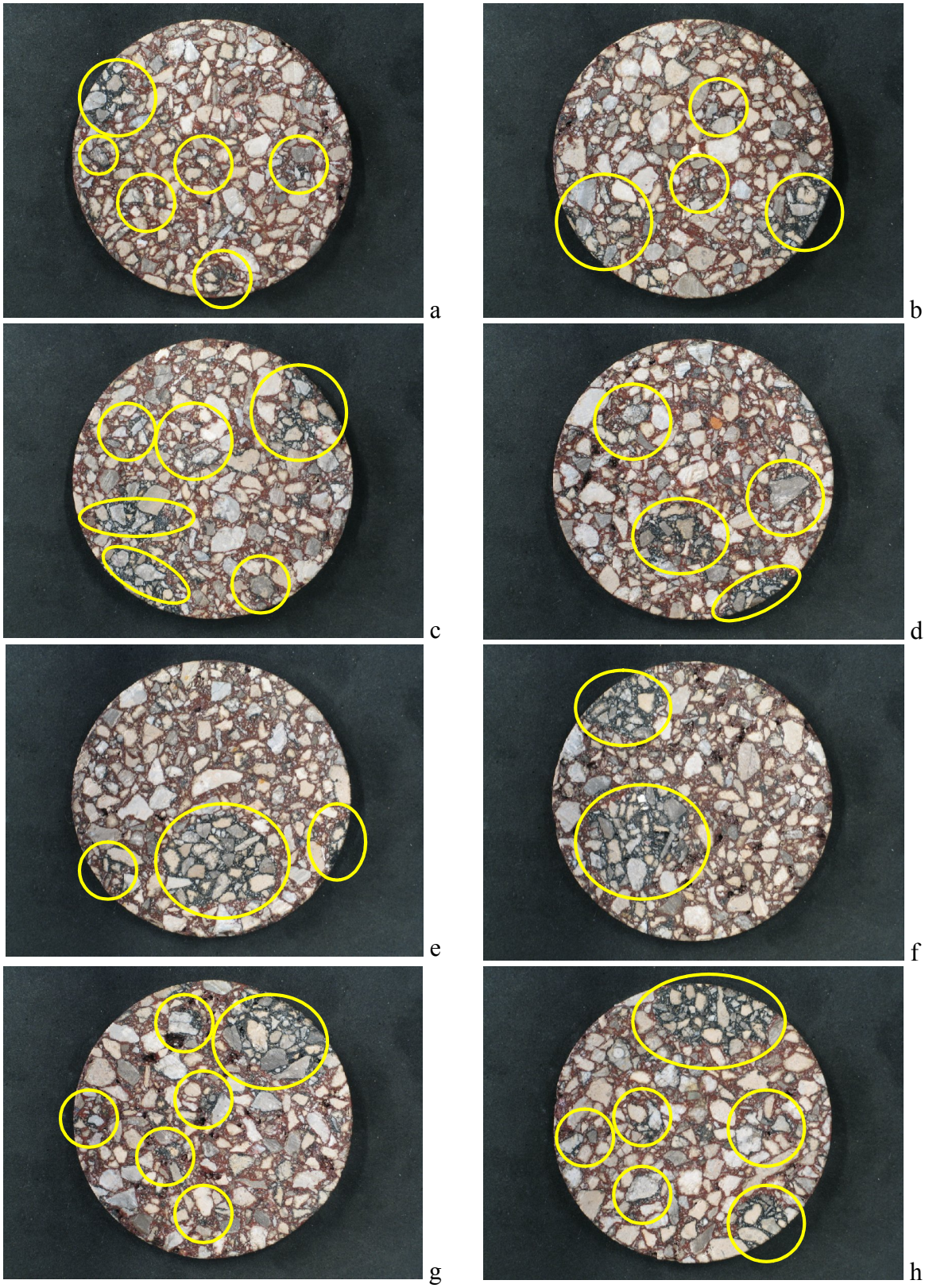


Figure 48: LR mixture – 6 minutes mixing time

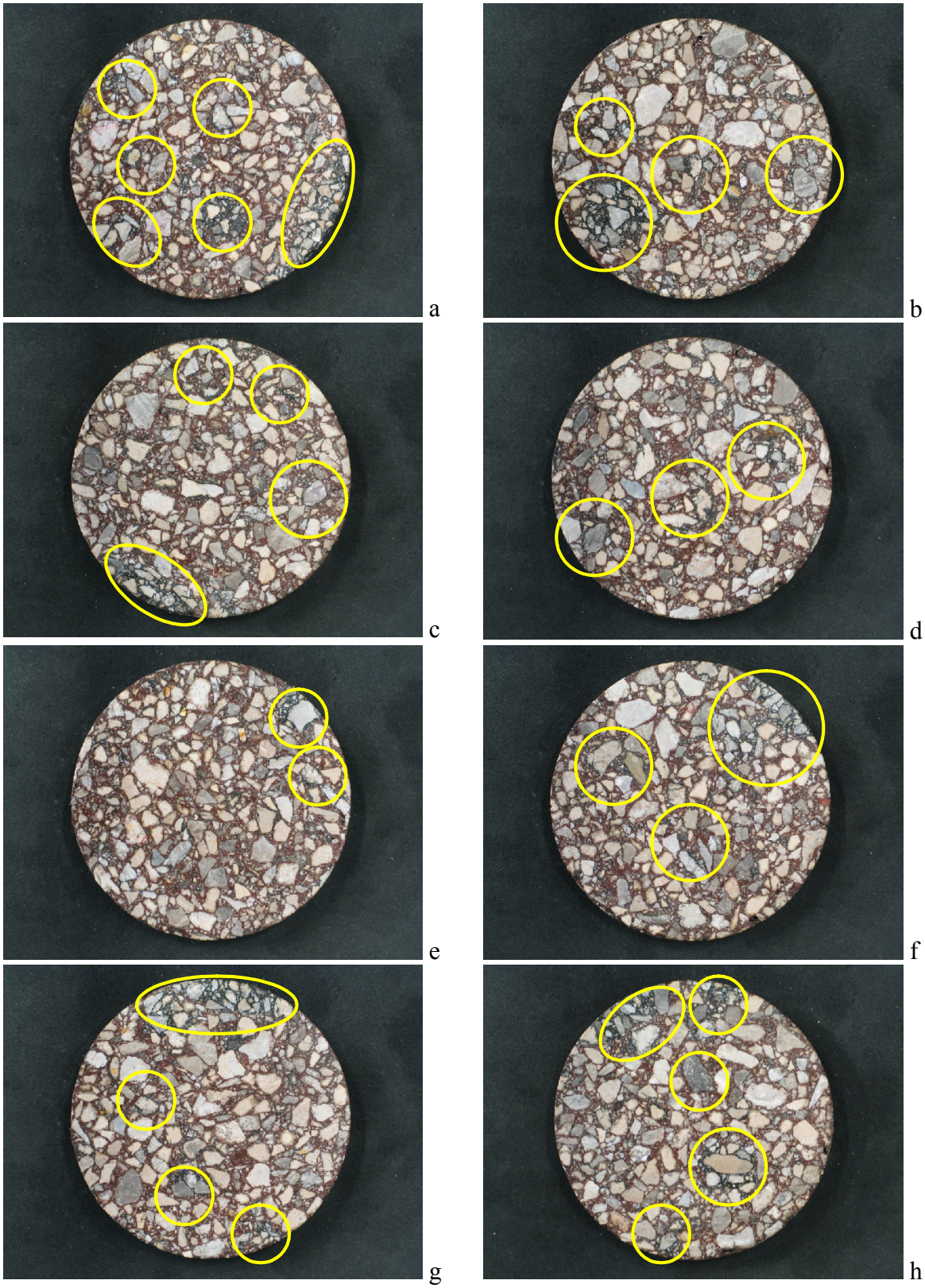


Figure 49: LR mixture – 8 minutes mixing time

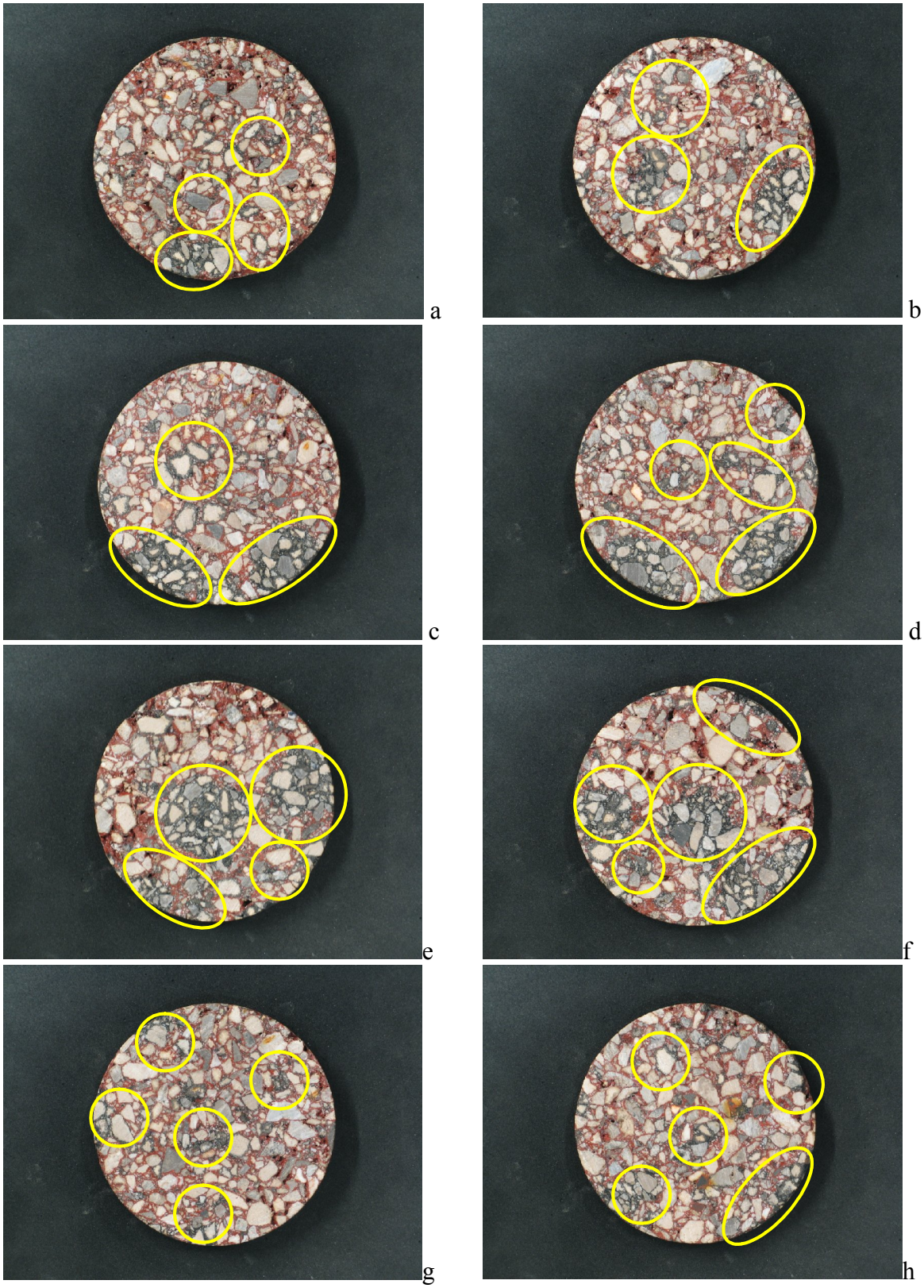


Figure 50: SR mixture – 1 minute mixing time

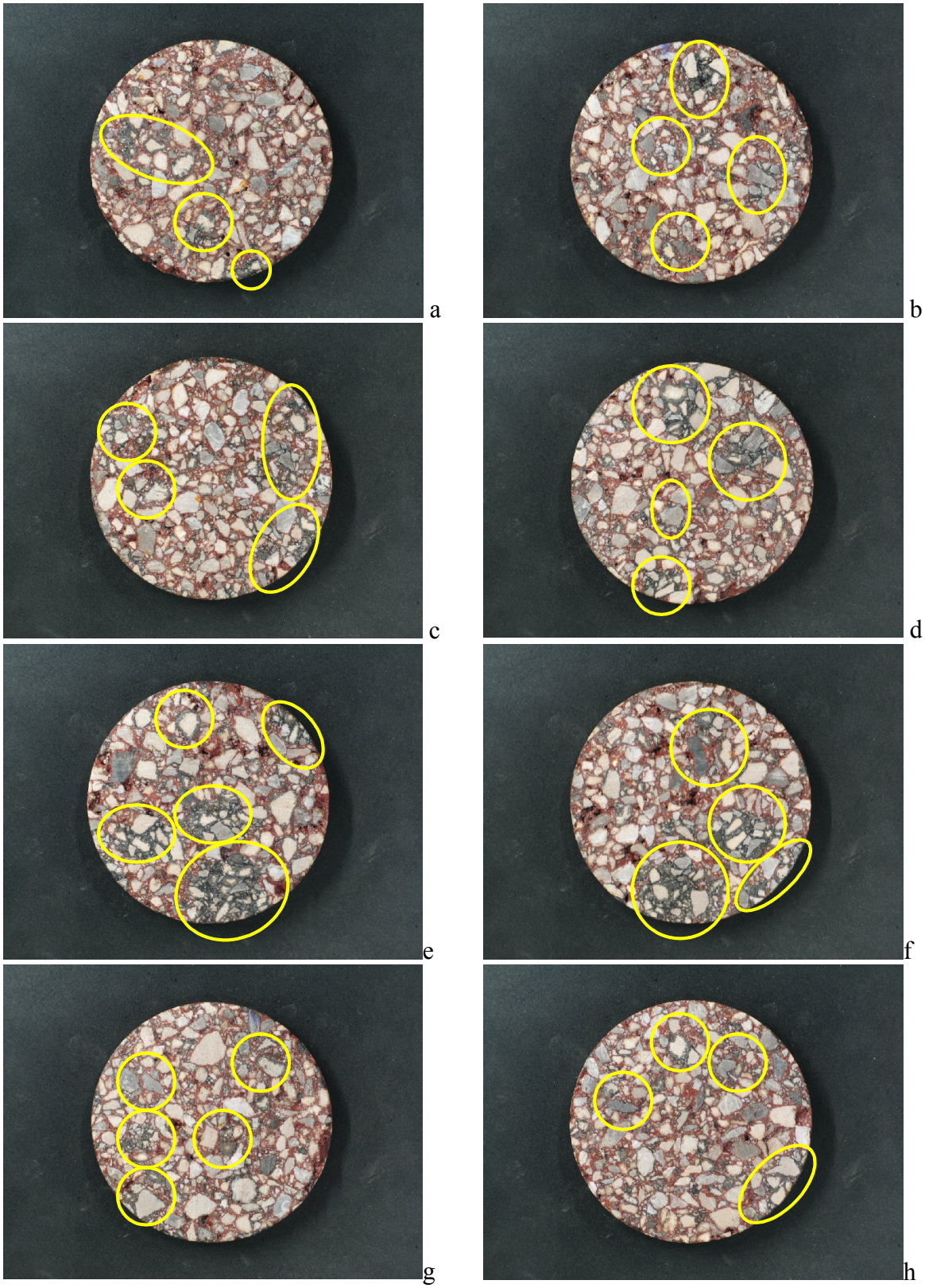


Figure 51: SR mixture – 2 minutes mixing time

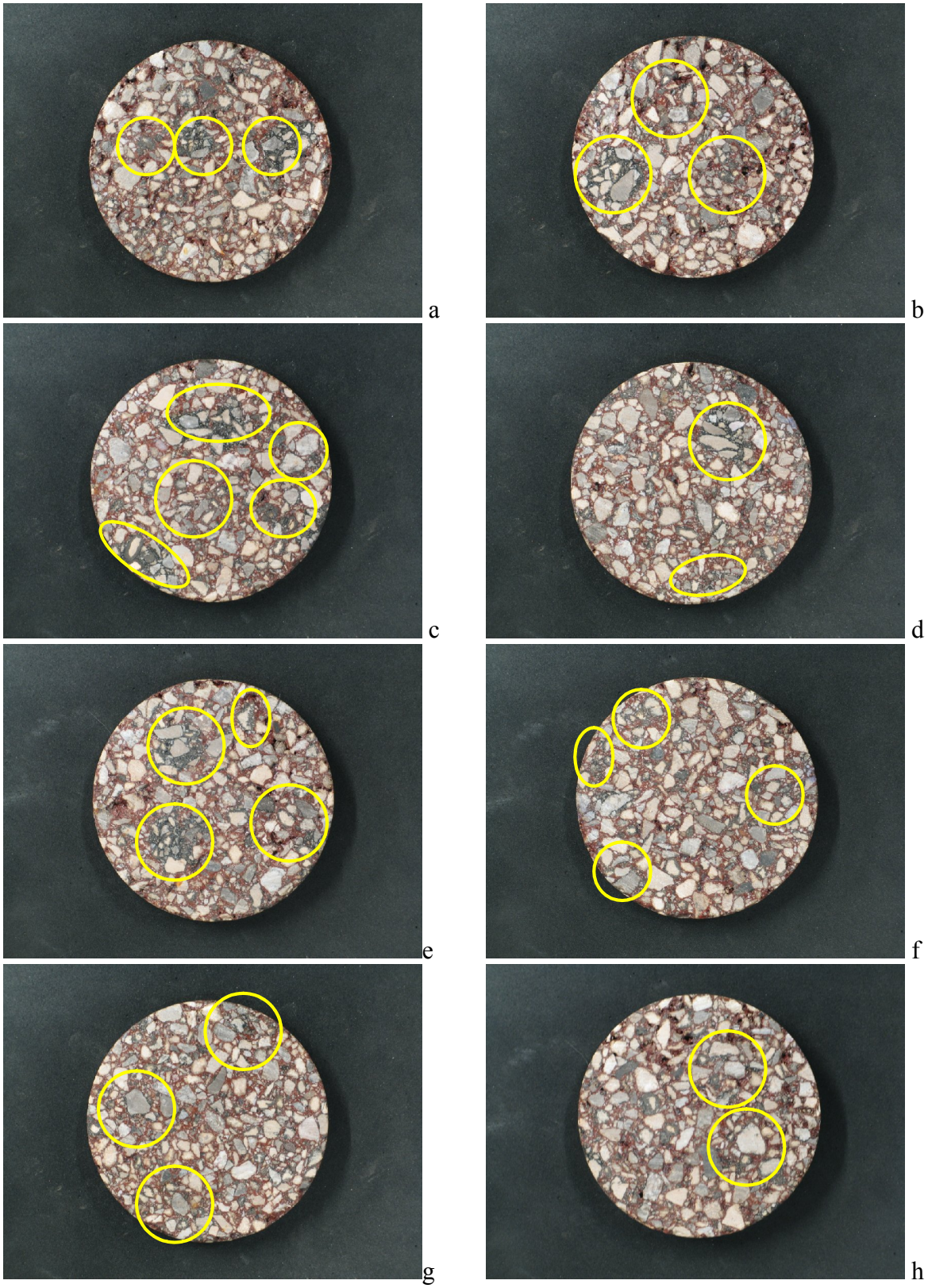


Figure 52: SR mixture – 4 minutes mixing time

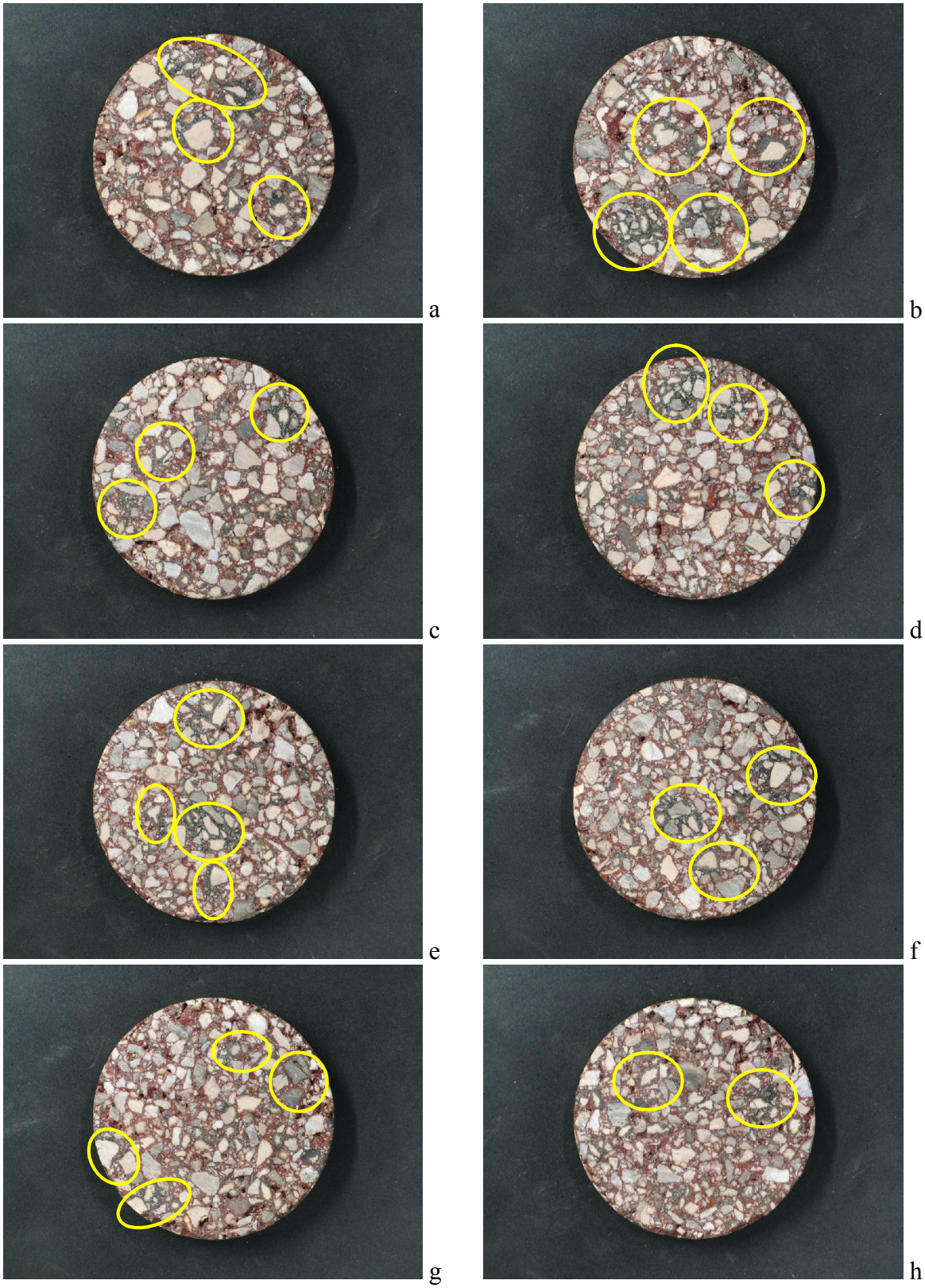


Figure 53: SR mixture – 6 minutes mixing time

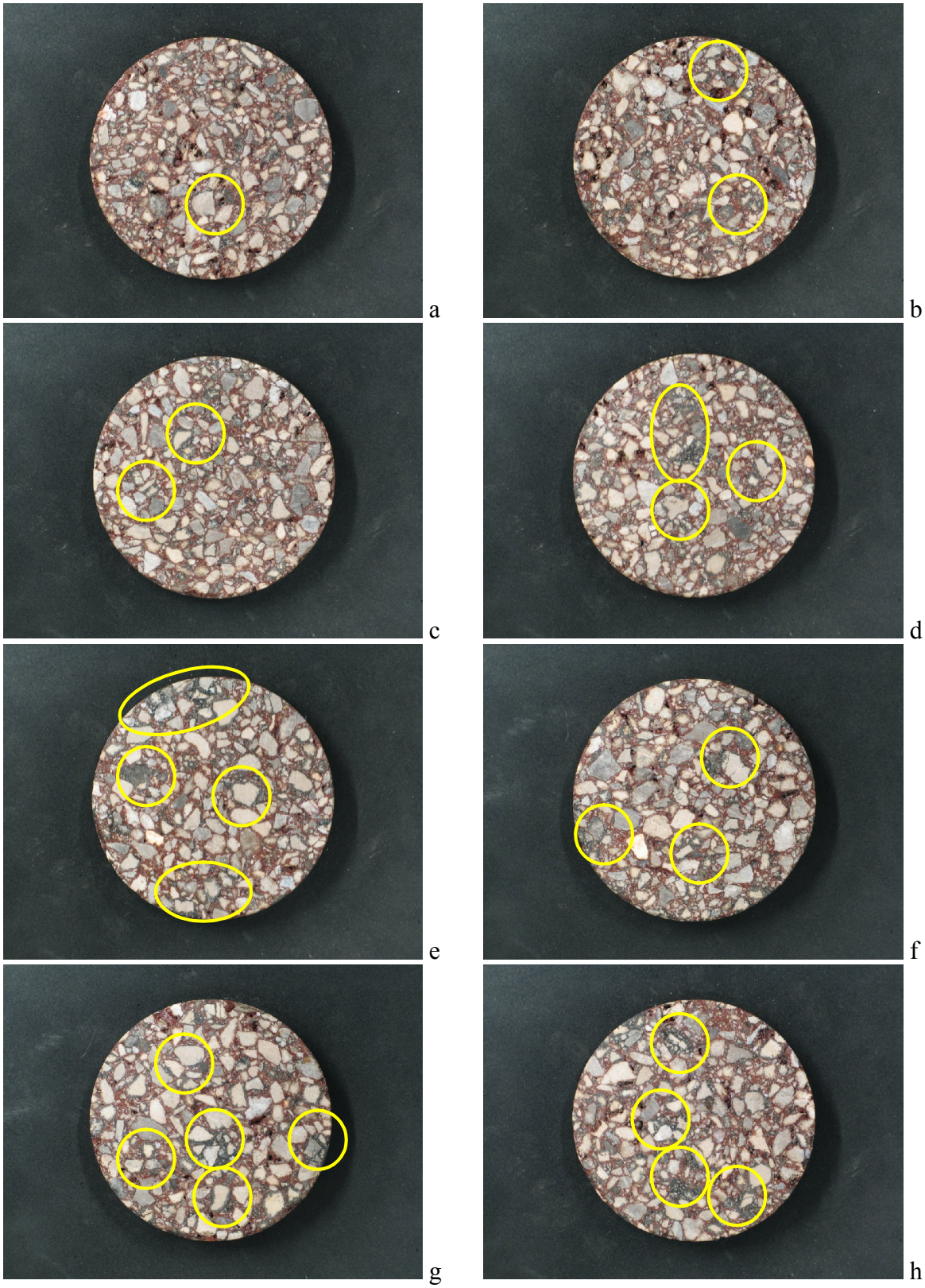


Figure 54: SR mixture – 8 minutes mixing time

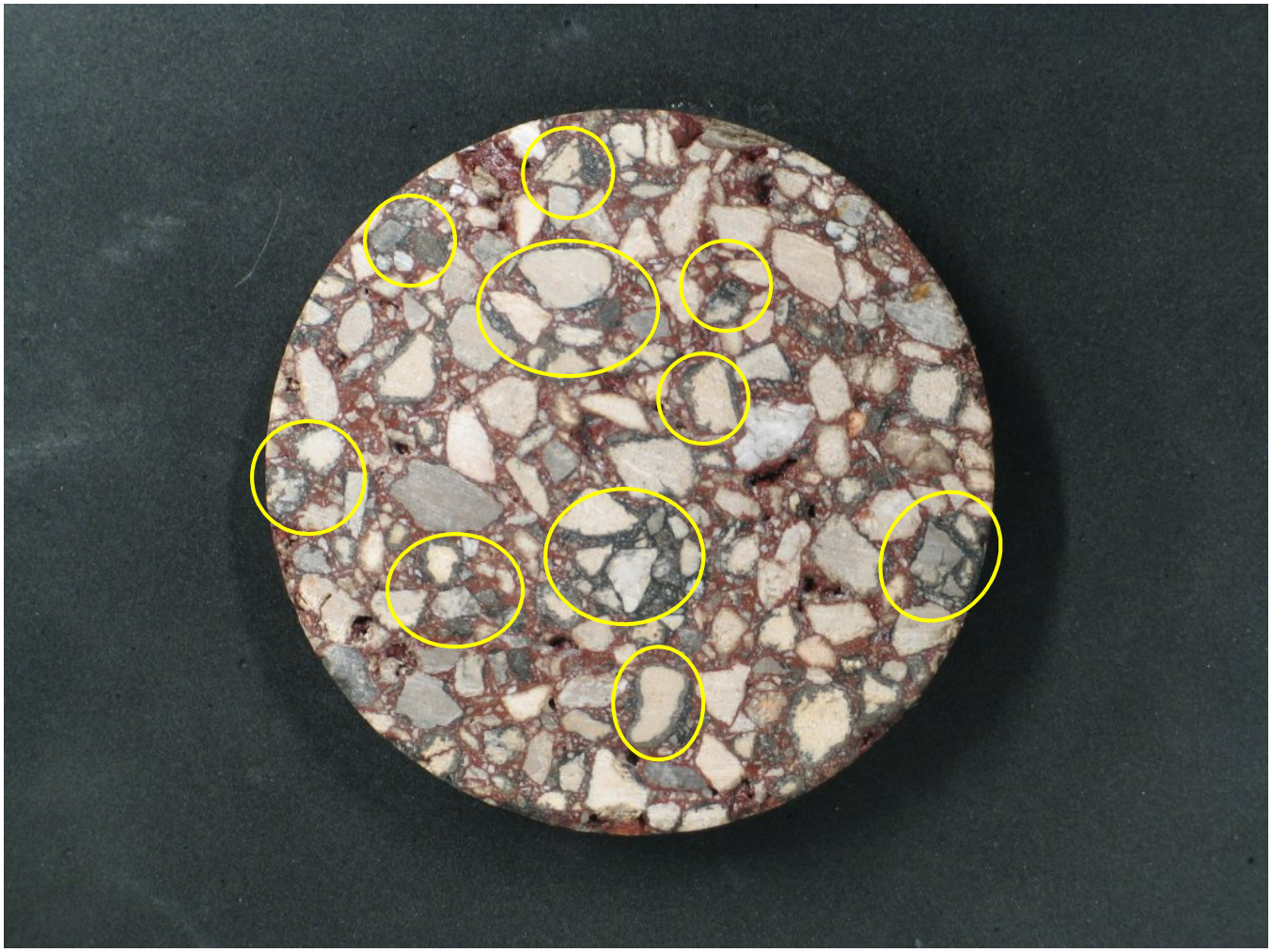


Figure 55: Large version of Figure 54 g

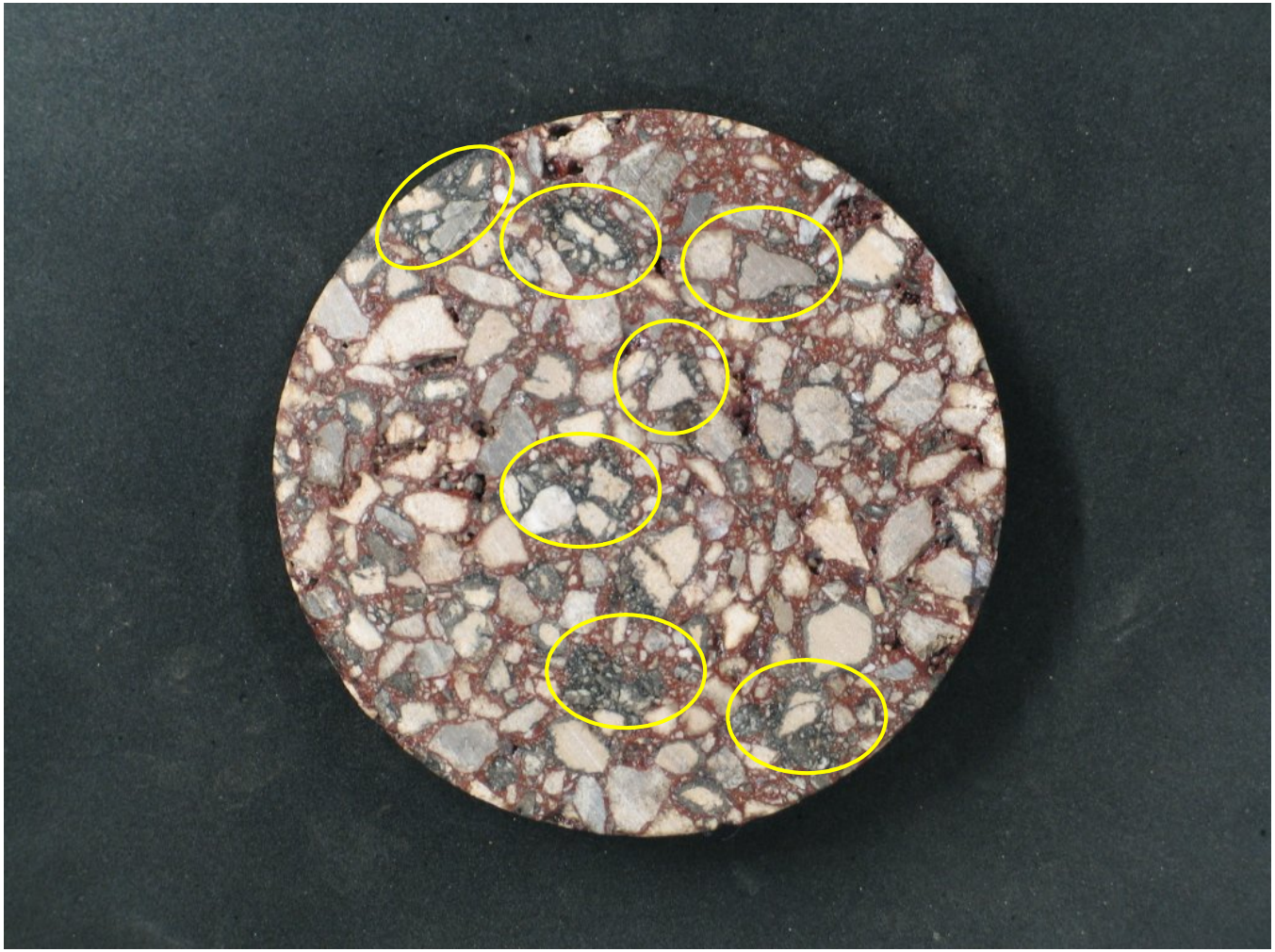


Figure 56: Large version of Figure 54 h

5.5.2 Mechanical assessment

Together with visual assessment for segregation, specimens composed of large RAP with different mixing durations were also subjected to mechanical properties evaluation. The aim is to link together the homogeneity level and mechanical performance of recycled asphalt mixture. The stiffness of each specimen is measured by indirect tensile stiffness modulus test (ITSM) (BS-EN:12697-26, 2004). The test is carried out at temperatures of 20^{o}C, 124 milisecond risetime and 5 μm horizontal diametral displacement to ensure that the specimen responds as an elastic material.

Conventionally, stiffness of each specimen is the mean value of stiffness measured at two perpendicular directions unless the difference between these two values is greater than 10% of the mean. However, the surfaces of specimens for stiffness evaluation demonstrate there is considerable segregation in recycled mixture. In addition, it is also realized that stiffness variation with different measured directions of most specimens are not satisfied by the standard. This issue might be attributed to the heterogeneity of recycled mixture. Therefore, the stiffness values of each specimen are measured by four directions along the circumference (Figure 57) with the hypothesis that the specimens with higher level of heterogeneity might have greater variations among stiffness at different directions.

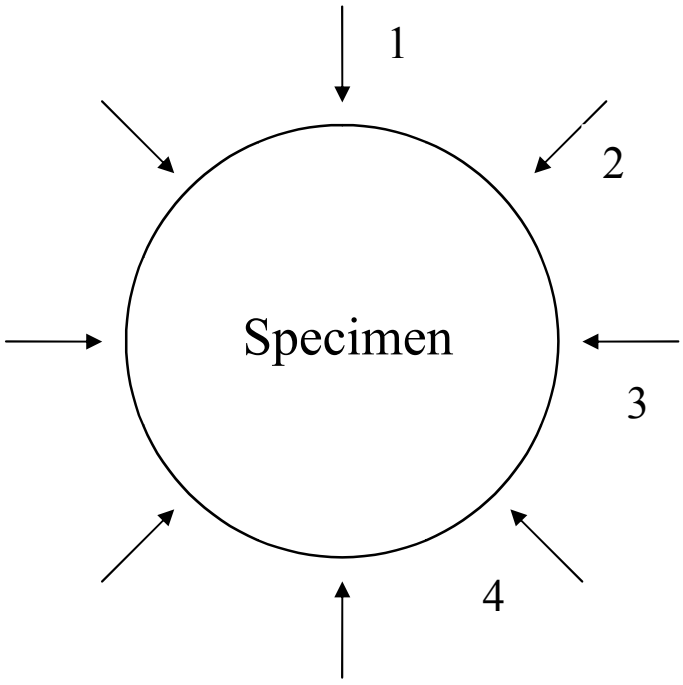


Figure 57: Stiffness measurement scheme

Mixing Time (mins)	Samples	Air void Content %	Stiffness in Different Directions (Mpa)				Mean Stiffness (MPa)	COV (%)
			1	2	3	4		
2	1	4.6	1813	2232	1778	2078	1975	11
	2	8	1306	1197	1374	1844	1430	20
4	1	5.5	1452	2816	2004	2183	2114	27
	2	6.5	2324	1959	1774	1491	1887	18
6	1	6.9	1690	1591	1408	1472	1540	8
	2	5.8	2147	2106	2002	1850	2026	7
8	1	6	1977	2098	1999	1873	1987	5
	2	5.5	1924	1950	1881	2175	1983	7

Table 30: Stiffness versus different RAP/superheated virgin aggregate mixing duration

Table 30 presents the results of stiffness values versus different mixing times. The data demonstrates that mixing time significantly influences the stiffness variation. For short mixing time, the differences among stiffness values obtained from the same specimen are considerable. For sample 2 (2 minutes mixing time), the maximum stiffness value is 1844 MPa while the minimum is 1197 MPa. The coefficient of stiffness variation is 20%. Similarly, for sample 1 (4 minutes mixing duration), maximum and minimum stiffness values are in turn 2816 MPa, 1452 MPa, and the coefficient of variation is 27%. In addition, the variations in stiffness values do occur not only in the same specimen but also in different specimens with similar mixing time. For example, for 2 minutes mixing time, mean stiffness of sample 1 is 1975 MPa compared to 1430 MPa of sample 2. Likewise, the mean stiffness of sample 1 (6 minutes mixing time), is 1540 MPa, significantly different from that of sample 2, 2026 MPa.

The reason for the stiffness variation might be due to the difference of air void content of specimens. Stiffness decreases once the air void content increases (Tayebali et al., 1994). Figure 58 also shows the tendency that stiffness generally decreases once the air void content increases. However, the stiffness value difference is not only attributed to the variation of air void content. For instance, sample 2 (2 minutes mixing time) has stiffness value of 1844 MPa (measuring direction 4) which is considerably higher than regressed

stiffness of 8% air void content. Similarly, sample 1 (4 minutes mixing time) has stiffness of 2816 MPa (measuring direction 2) which is considerably higher than expected with 5.5% air void content. On the contrary, although the stiffness of sample 1 (2 minutes mixing time) is expected to be high with 4.6% air void content, it is quite low with 1813 MPa (measuring direction 1) and 1778 MPa (measuring direction 3).

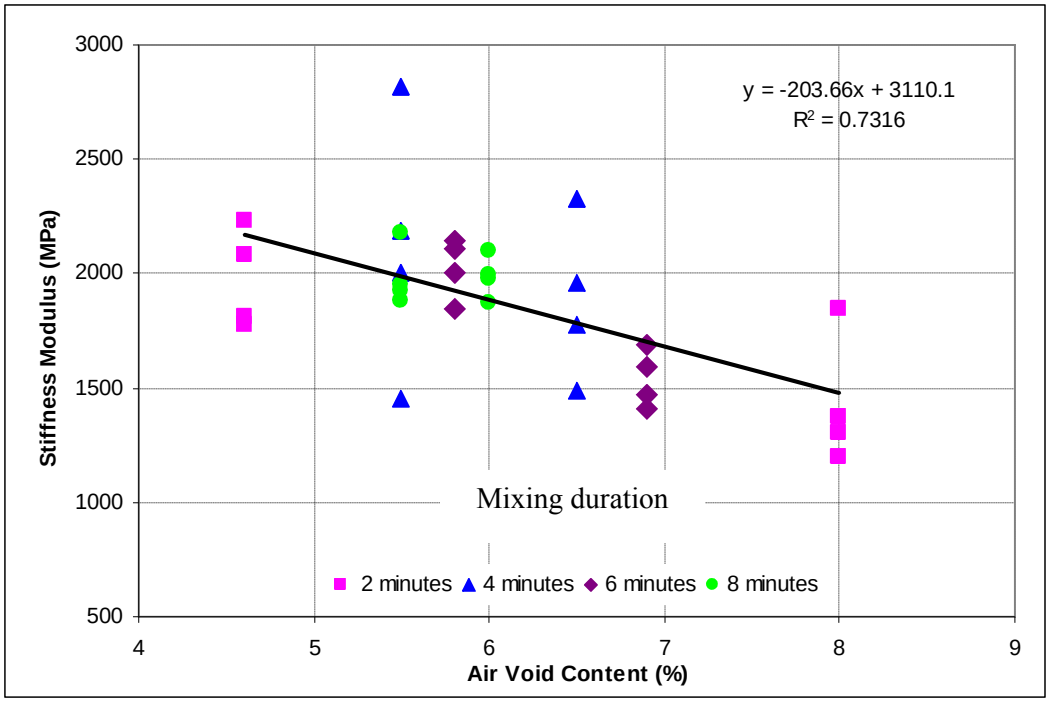


Figure 58: Stiffness modulus versus air void content

The variation in stiffness values is attributable to the heterogeneity of recycled mixture. For short mixing duration, RAP lumps are not fully disintegrated into single particles coating by RAP binder. Therefore, the virgin binder that should be in contact and rejuvenate the RAP binder could not be in the right place and fulfill its function. This results in some areas with high concentration of RAP while the others contain primarily virgin materials.

This situation is exaggerated by the manufacturing process. There is a lack of vertical movement of material in the mixing bowl due to the properties of the mixer. During mixing process, RAP and virgin materials are not mixed together vertically. RAP lumps tend to move up to the surface due to bigger sizes (Figure 59). This results in the situation that when the loose mixture is transferred to the mould for compaction, RAP lumps tend to move first and settle down at the bottom of the mould. Figures 46 and 47 show that although came from the same compacted specimen, specimen 1 (at the bottom) tends to

have considerably higher proportion of RAP than specimen 2 (on top). In addition, the stiffness of specimen 1 is also considerably higher than that of specimen 2 (Table 30).

Figure 59: Small particles tend to move downward to the bottom during mixing process

It has been maintained that the uneven distribution of RAP materials results in the variation of stiffness values. An effort has been made to investigate and quantify this relationship by correlating:

- the stiffness: determining the stiffness of specimen at four measuring directions and
- RAP (or virgin materials) distribution pattern: by visual surface assessment of the stiffness-measured specimen and slices machined from this specimen.

However, there is no clear correlation between the distribution of RAP (or virgin materials) and stiffness values. This is because the material distribution patterns are not consistent along the vertical direction of the specimen. Figures 46 a and d illustrate the surfaces at both ends of specimen 1 (made from large RAP and 2 minutes mixing time) and b and c are for the surfaces of the slices machined from this specimen. Unfortunately, the characteristics of these surfaces are all different. For different mixing durations and RAP

materials, large and small, the phenomenon is the same. If the relation between stiffness values and materials distribution patterns are evaluated based only on the surfaces at both ends of specimen (Lee et al., 1983), the result will be certainly different.

The stiffness data demonstrates the tendency that the homogeneity of recycled mixture is substantially enhanced once the RAP/superheated virgin aggregate duration is extended. Not only the coefficient of stiffness variation in each specimen decreases (Table 30) but also does the general coefficient of variation. Table 31 shows that the general coefficient of variation significantly decreases from 22% to 5% once the mixing duration increases from 2 to 8 minutes.

Mixing time (minutes)	Mean Stiffness (MPa)	Standard Deviation	Coefficient of Variation (%)
2	1702	374	22
4	2000	449	22
6	1783	286	16
8	1984	105	5

Table 31: Mean stiffness versus RAP/superheated virgin aggregate mixing duration

5.6 Summary

The newly developed mixing method has duplicated the mixing mechanism that really occurs in the industrial asphalt mixing plant. The mixing mechanism includes the following steps:

- Virgin aggregate are superheated
- RAP material at ambient temperature is blended with superheated virgin aggregate. The heat transferred from superheated virgin aggregate helps to soften RAP agglomerate, weakening the bitumen binding among RAP aggregate particles. Under mechanical mixing effort, these RAP lumps will be disintegrated and blended with virgin aggregate.
- The RAP/superheated virgin aggregate blend will be mixed with virgin bitumen or rejuvenator, the more the RAP material is disintegrated, the more likely and effective the rejuvenating process.

Different mixing efforts (different RAP/superheated virgin aggregate mixing durations) have depicted a clear picture of mixing mechanism between RAP and virgin materials. The longer the mixing time, the more RAP and virgin materials are incorporated and hence the homogeneity level of recycled mixture is enhanced. The visual assessment also demonstrates that even when small RAP size is used and at considerable mixing duration, RAP material, especially RAP binder, is not fully blended or rejuvenated by virgin binder. This phenomenon is different from the assumption in the recycled mixture design process where RAP and virgin binder are fully blended.

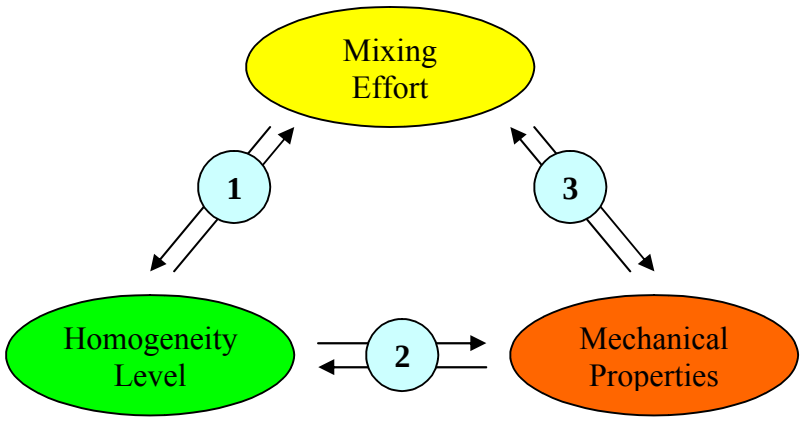


Figure 60: Relation between mixing effort, homogeneity and mechanical properties of recycled asphalt

The relation among mixing effort, homogeneity level, and mechanical properties of hot recycled mixture is illustrated in Figure 60. Each factor will mutually influence the others. Due to the fact that the RAP and virgin materials distribution do not follow any consistent pattern, the relation between mixing effort and homogeneity level (1) could not be quantified and neither could that between homogeneity level and mechanical properties (2). The more mixing effort, the more homogeneity and less variation in mechanical properties. There is no clear numerical parameter or values to characterize these relations. However, the relation between mixing effort and mechanical properties (3) can be quantified. In this preliminary experiment, there is a relation between mixing duration and stiffness values. Hence, stiffness measurement proves to be potential tool to investigate the effect of mixing effort on mechanical properties of hot recycled mixtures.

The preliminary investigation of the effect of mixing process on mechanical properties of hot recycled asphalt mixture shows the likely tendency that the more mixing, the less variation in stiffness values. This might be due to the heterogeneity of recycled mixture. Not enough mixing effort results in some places containing primarily RAP and the others are dominated by virgin materials. The difference among RAP and virgin materials properties, especially RAP and virgin binder, contributes to the considerable variation in stiffness values. However, this preliminary statement needs to be further investigated and verified as the number of testing samples is limited to 2 for each RAP/superheated virgin aggregate mixing duration. In addition, due to visual assessment, the virgin binder is dyed by iron oxide (10% by weight of virgin binder) which might affect the mixing characteristic of virgin binder and the stiffness distribution.

6 Effects of mixing procedures and RAP materials on stiffness distribution of hot recycled asphalt mixtures

6.1 Introduction

As the clear binder is dyed red by 10% by weight of iron oxide, the proportion of the pigment certainly alters the flow characteristic of binder. This might affect the mixing process and rejuvenation between virgin and aged binder. Therefore, this chapter also investigates the effect of different mixing methods and RAP sizes on stiffness of recycled asphalt mixtures. However, normal straight run bitumen 160/220 Pen is used as virgin binder. Recycled asphalt mixtures are manufactured by different methods, black rock (BR), complete blending (CB), the SHRP procedure, and the field simulation method (FS) developed in Section 5.2. In FS method, RAP/superheated virgin aggregate mixing duration varies from 2 to 8 minutes. Both large and small RAP materials are used in this experiment. The stiffness distributions of recycled asphalt mixtures manufactured by different methods are statistically compared to each other and those of BR and CB mixtures to investigate the effect of mixing procedures and RAP materials.

6.2 Experiment design

6.2.1 Effects of mixing protocols and RAP sizes on stiffness of hot recycled asphalt mixture

To investigate the effect of mixing protocols on stiffness distribution, recycled specimens are manufactured by different methods. The mixing methods include the newly developed method that duplicates the mixing mechanism in the industrial mixer (denoted as FS: field simulation) with different RAP/superheated virgin aggregate mixing durations; and the conventional method (from SHRP). The procedures are explained in Section 6.3.1. Specimens are manufactured using the Mixer A (Section 6.2.2). In field simulation method (FS), the RAP/superheated virgin aggregate mixing durations range from 2 to 8 minutes. Both sizes of RAP, large and small are used (denoted as LR and SR). The stiffness of recycled specimens are measured by indirect tensile stiffness test (ITSM) (BS-EN:12697-26, 2004). The summary of experiments to investigate the effect of mixing protocols on stiffness is shown in Table 32.

The experiment also includes the stiffness measurement of control mixtures that present the "Black Rock" (BR) case where RAP binder is inert; and "Complete Blending" (CB) assumed in the design process in which RAP binder is fully interacted with virgin binder or rejuvenator. The aim is to compare the mechanical properties of control mixtures with recycled mixtures manufactured by different protocols. The difference in mechanical properties compared to those of control mixtures will demonstrate the effects of mixing procedures and properties of RAP materials on the quality of hot recycled asphalt mixtures.

LR	FS	RAP/Virgin aggregate mixing duration (minutes)			
		2	4	6	8
		×	×	×	×
	SHRP	×			
SR	FS	RAP/Virgin aggregate mixing duration (minutes)			
		2	4	6	8
		×	×	×	×
	SHRP	×			

Table 32: Test plan to study the effects of mixing method on stiffness

6.2.2 Effect of mixing equipment on stiffness distribution of hot recycled asphalt mixtures

Two mixers with different mechanical mixing effects, mixers A and B, are employed. The characteristics of each mixer are as follows:

Mixer A

The schematic of mixer A is illustrated in Figure 61. There are two mixing paddles moving with different orbits that help to drive and blend materials in the mixing bowl. The heat supply of this mixer is maintained by heating the oil that moves between the external and internal walls of mixing bowl. There is a thermocouple attached to the oil to control the heat supply hence the mixer can be maintained at the required temperature.

Mixer B

The schematic of mixer B is presented in Figure 62. There are four mixing paddles used to guide and blend materials in the mixing bowl. However, due to the rotating axis of mixer B being not vertical (90^o) but 60^o compared to the ground plane, the movement of material

inside the mixing bowl consists of not only horizontal but also vertical direction. Mixer B also allows reverse rotation. Also different from mixer A, the heat supplied for the mixer B is controlled by the thermocouple that measures the air inside the mixer.

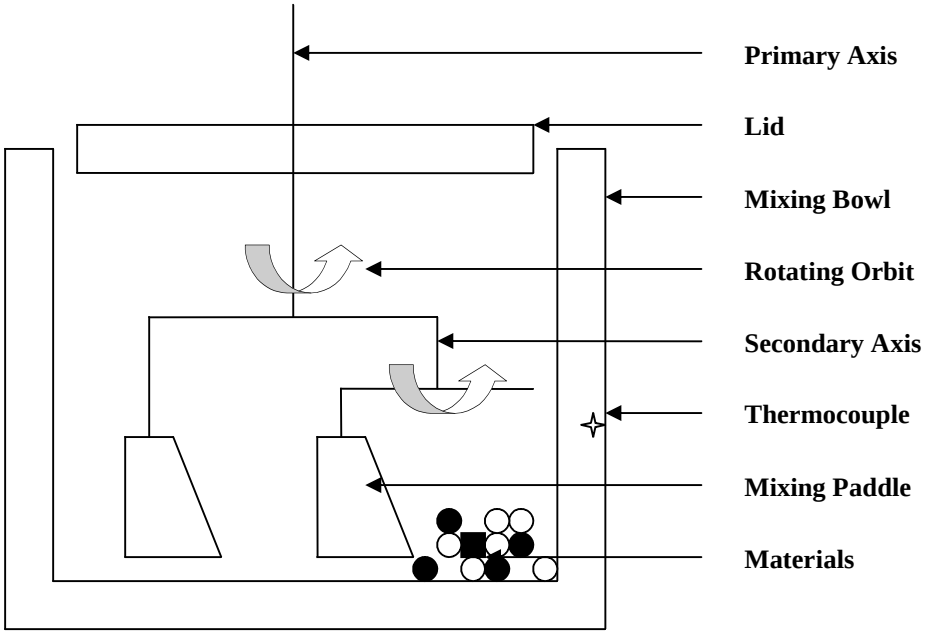


Figure 61: Schematic of Mixer A

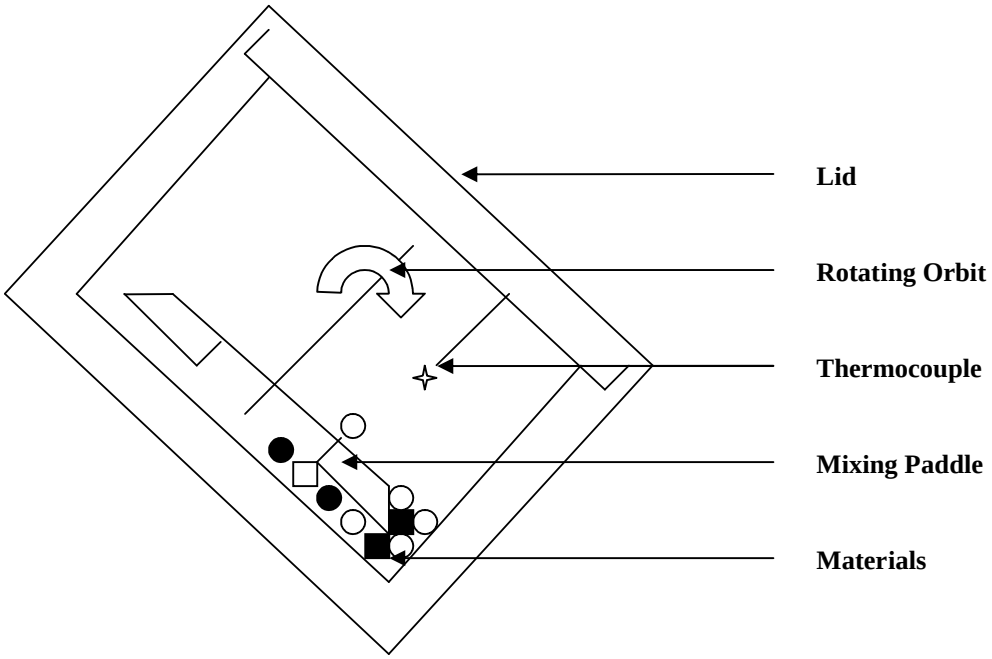


Figure 62: Schematic of Mixer B

The summary of experiments to study the effect of mixers on stiffness distribution of hot recycled mixtures is presented in Table 33.

Mixer Type	RAP Sizes	Mixing time (minutes)	
		2	6
A	LR	×	×
	SR	×	×
B	LR	×	×
	SR	×	×

Table 33: Test plan to study the effects of mixer on stiffness of recycled asphalt

6.2.3 Effect of mixing protocols on RAP binder properties

Different mixing protocols will generate conditions that RAP materials are exposed at high temperature for a certain period of time. This might alter the properties of RAP binder. Depending on the exposure condition (Section 6.3.1), RAP binders are extracted and recovered from RAP materials. The rheology properties of these conditioned RAP materials are studied by Dynamic Shear Rheometer (DSR) and compared to that of original RAP binder to quantify the effect of mixing procedure on properties of RAP. The summary of experiments to investigate the effect of mixing protocol on properties of RAP binder is shown in Table 34.

LR	FS	RAP/Virgin aggregate mixing duration (minutes)	
		2	8
		×	×
	SHRP	×	
SR	FS	RAP/Virgin aggregate mixing duration (minutes)	
		2	8
		×	×
	SHRP	×	

Table 34: Test plan to study the effects of mixing methods on binder properties

6.3 Materials and specimens manufacture

6.3.1 Material preparation and mixing procedure

Hot recycled mixtures

In this experiment, Shell bitumen 160/220 Pen is used as rejuvenator. The properties of 160/220 Pen bitumen are showed in Table 35. Although the origin of bitumen is not allowed to be revealed due to Shell Global policy, all the bitumen binders used for the whole research come from the same crude oil source. This is to eliminate the effect of different crude oil sources on mechanical properties of recycled asphalt mixture. The proportion of RAP in the recycled asphalt mixture is estimated using Grunberg and Nissan viscosity mixing rule at 60^{o}C. The amount of RAP in recycled mixture is 40% thus the viscosity of recycled blend is approximately similar to that of 70/100 Pen bitumen (Table 35). Figure 63 illustrates the master curves of 70/100 Pen and recycled blend with aged/virgin binder ratio of 4/6. The result shows that if aged and virgin binder is completely mixed, the properties of recycled binder are almost similar to those of the 70/100 Pen bitumen.

	160/220 Pen	70/100 Pen
Penetration at 25^{o}C (dmm)	192	83
Softening Point (^{o}C)	37.4	47.2
Density (g/cm^{3})	1.021	1.028
Viscosity at 60^{o}C (Pas)	64	192

Table 35: Properties of bitumen 160/220 Pen and 70/100 Pen

The materials for recycled mixtures conform to the requirements for surface course 10 mm DBM (BS:4987-1, 2005). Both sizes of RAP, large and small, are used and denoted as LR and SR. As bitumen content of RAP material is 5.2% and the aggregate gradation of RAP is the same as that of virgin aggregate (Figure 34), amount of rejuvenator required is also 5.2% of the total weight of virgin materials.

Field Simulation method (FS)

- RAP materials, both large (LR) and small size (SR), are conditioned at room temperature. The room temperature is maintained by thermal control system at 25^{o}C.

- Virgin aggregate is superheated at 215°C for 8 hours.
- Rejuvenator is preheated at 135°C for 2 hours.
- The mixer temperature is maintained at 135°C.
- RAP material is mixed with superheated virgin aggregate for 2, 4, 6, 8 minutes.
- The combination of RAP and virgin aggregate is then blended with virgin binder for 2 minutes.

SHRP method

- RAP materials, both large (LR) and small size (SR), are conditioned at 110°C for 2 hours.
- Virgin aggregate is conditioned at 150°C for 8 hours.
- The mixer temperature is maintained at 135°C.
- Preheated RAP material is mixed with preheated virgin aggregate for 30 seconds in the mixer maintained at 135°C.
- The combination of RAP and virgin aggregate is then blended with virgin binder for 2 minutes.

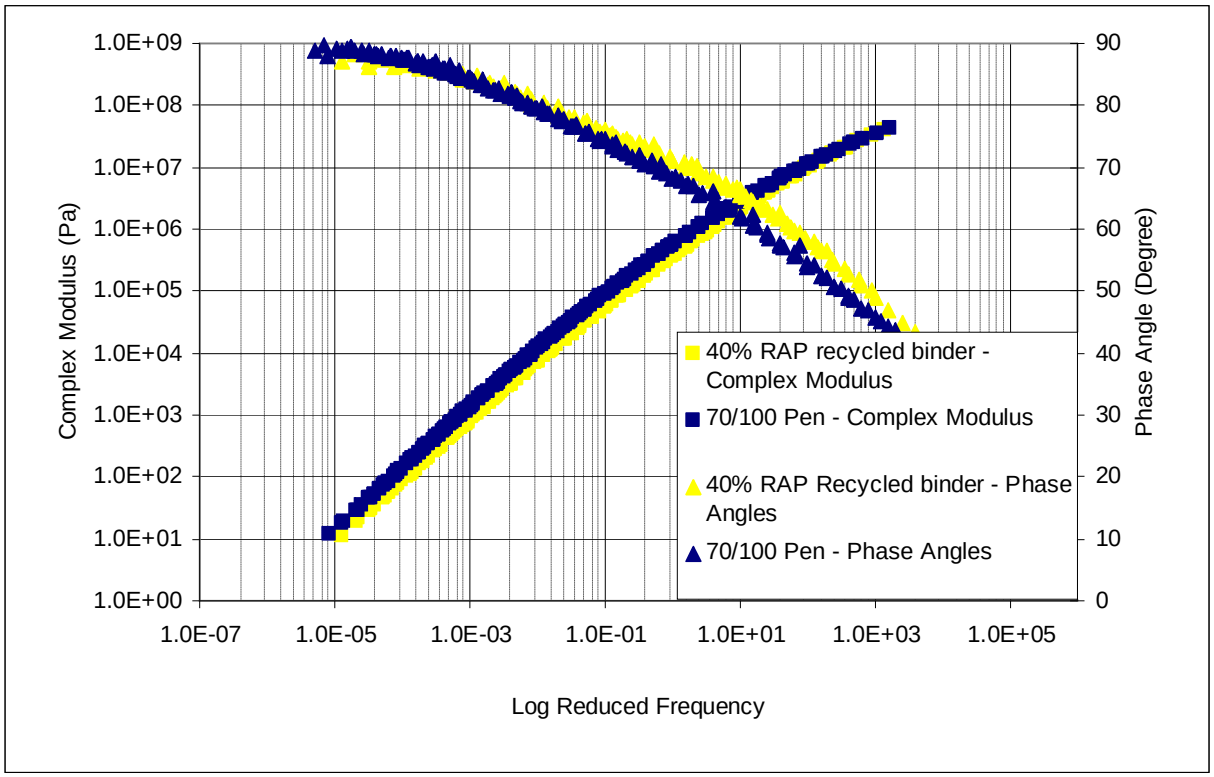


Figure 63: Master-curves of 70/100 Pen and recycled blend with 40% RAP and 60% 160/200 Pen bitumen

Control mixtures

"Black Rock" mixture (BR)

In Black rock case, there is an assumption that there is no interaction between RAP and virgin binder. RAP binder is normally extracted and recovered from RAP material. After batching, the combination of recovered RAP and virgin aggregate are then mixed with pure virgin binder or rejuvenator (McDaniel et al., 2000). However, after binder recovery process (BS-EN:12697-4, 2005), RAP binder still exists in recovered RAP aggregate, even if RAP material is solvated in methylene chloride solution and soaked overnight. If recovered RAP aggregate is used, the result is probably altered as rejuvenator might interact with remaining RAP binder. Due to the fact that original RAP and virgin aggregate are the same, the Black Rock mixture is manufactured from total virgin aggregate instead and virgin binder 160/220 Pen. The bitumen content is 5.2% by weight of total mixture. The preparation and mixing procedure for Black Rock mixture are as follows:

- Batched aggregate is preheated at 135^{o}C for 8 hours.
- Virgin binder (160/220 Pen) is preheated at 135^{o}C for 2 hours.
- Mixer is maintained at 135^{o}C.
- Preheated aggregate and binder is mixed in the mixer for 2 minutes.

"Complete Blending" Mixture (CB)

In Complete Blending case, RAP binder is assumed to be fully blended with rejuvenator. Therefore, RAP binder, after being extracted and recovered, is fully rejuvenated by virgin binder before blending with batched aggregate. The same phenomenon occurs as for recovery process, RAP binder is not fully extracted and recovered from RAP materials. If RAP aggregate is used, the remaining RAP binder on recovered aggregate will deviate the assumption of Complete Blending case. Hence, instead of batching recovered and virgin aggregate, Complete Blending mixture in this case is made of pure virgin aggregate. The bitumen content is 5.2% by weight of total mixture and the preparation of rejuvenated binder for complete blending case is as follows:

- RAP binder is extracted and recovered from RAP materials
- RAP binder is blended with virgin binder (160/220 Pen) at 160^{o}C by mechanical mixer to produce homogeneous blend. The proportion of RAP/virgin binder is 4/6, the same as the proportion of RAP material in hot recycled mixture.

The preparation and mixing procedure for Complete Blending (CB) mixture are as follows:

- Batched aggregate is conditioned at 150^{o}C for 8 hours
- Rejuvenated binder is conditioned at 150^{o}C for 2 hours
- Mixer is maintained at 150^{o}C
- Aggregate and rejuvenated binder are mixed in the mixer for 2 minutes

The target of rejuvenated binder with 40% RAP binder is bitumen 70/100 Pen (Section 6.3.1). Hence, there is also a mixture made of virgin aggregate and bitumen 70/100 Pen, denoted as CB-V. The bitumen content of this mixture is 5.2% by weight of total mixture. This is to appraise the quality of recycled mixture compared to that made from virgin materials. The material preparation and mixing procedure are the same as those for CB mixture.

6.3.2 Compaction

The loose mixtures are compacted straight away after mixing by roller compacter (BS-EN:12697-33, 2003). The internal dimensions of the mould are 305 mm x 305 mm. The target height of compacted slab is 60 mm. For both recycled and control mixtures, the amount of materials is determined based on maximum density, the bulk specific gravity at target air void content 4%, and the volume of the slab after compaction.

6.3.3 Machining and storage of specimens

Compacted slabs are demoulded the next day and 5 specimens are cored from each slab. The scheme of coring process is illustrated in Figure 64. To eliminate the surface defects due to compaction, each specimen is cut at both ends to achieve the thickness of 40 mm. The bulk specific density of each specimen is determined (BS-EN:12697-6, 2003) to estimate the air void content (BS-EN:12697-8, 2003). All the specimens are then conditioned at 20^{o}C for 15 days before ITSM test. After stiffness determination, the specimens are stored at 5^{o}C for further testing.

6.4 Assessment method

The assessment method is primarily based on the comparison among stiffness data of recycled mixtures manufactured by different mixing efforts. Due to RAP and virgin binder properties being different, the hypothesis is that if RAP lumps are fully separated and well blended with virgin material, stiffness values of different measuring directions will be approximately the same. On the contrary, the heterogeneity of recycled mixture will result

in the considerable variance in stiffness values where mixing duration is not long enough. In addition, as testing specimens are cored from roller-compacted slabs, the quality of mixing is also revealed by the stiffness values between different samples.

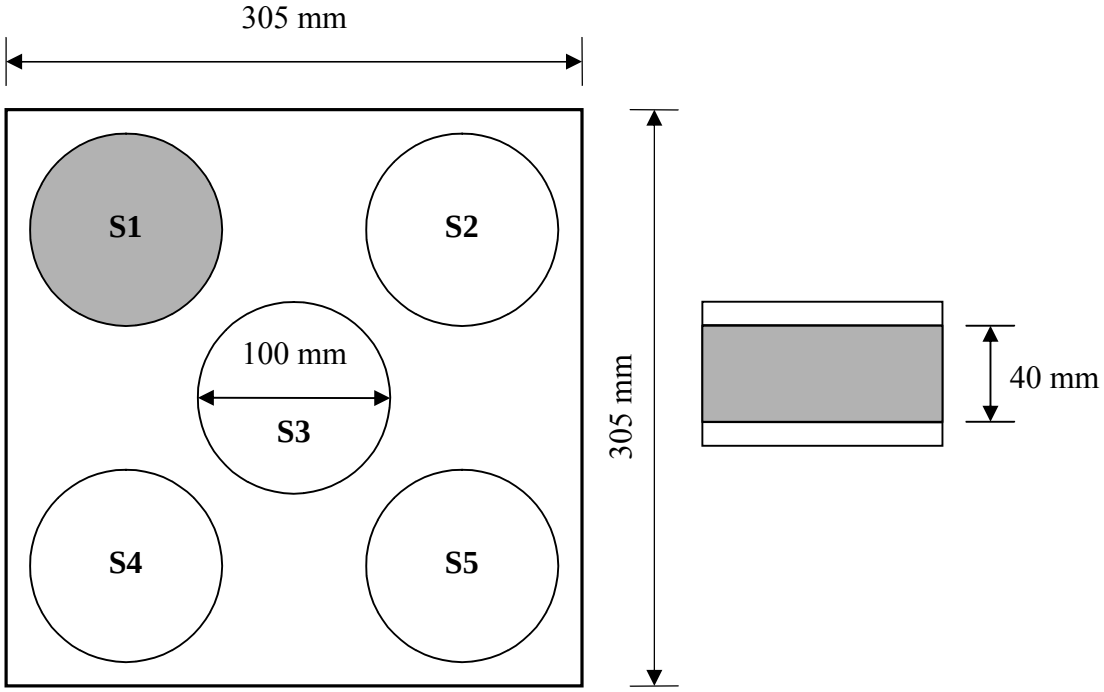


Figure 64: Coring and cutting scheme for compacted slabs

The total number of specimens tested for each case, for instance 2 minutes RAP/superheated virgin aggregate mixing duration, is ten. Stiffness is determined at 20^{o}C, 5μm strain, 124 millisecond rise-time to ensure specimens are in the linear elastic regime (BS-EN:12697-26, 2004). As the stiffness values of each sample are measured in four directions at 45^{o}C angular increments, 40 stiffness values are generated for each case. To eliminate the effects of diffusion on mechanical properties, stiffness measurement is implemented 15 days after the day of compaction.

The stiffness distribution is then analyzed by statistical tools, for instance, hypothesis test, descriptive statistics, Anderson Darling statistic test. Stiffness distributions relevant to different mixing efforts are compared to each other and also to those of "Black Rock" and "Complete Blending" case to study the effect of mixing on mechanical properties of hot recycled mixtures. Air void characteristic of testing specimens is also considered due to its effect on stiffness values.

6.5 Results and analysis

6.5.1 Air void contents

Five cylindrical specimens are cored from roller-compacted slab. It is difficult to control the air void content of each specimen. Although the target air void content is set at 4% volume, there is some scatter in air void content data. Specimens at the centre of slab tend to have lower air void content. The air void data is presented in Table 36. The standard deviation (SD) or coefficient of variation (COV) indicates the scatter of air void content around the mean of each set of specimens.

		Mean (%)	SD	COV
LR	FS-2	5.088	1.270	0.250
	FS-4	5.626	0.692	0.123
	FS-6	4.493	0.769	0.171
	FS-8	5.263	0.903	0.172
	SHRP	4.835	0.512	0.106
SR	FS-2	5.218	0.460	0.088
	FS-4	5.634	0.640	0.114
	FS-6	6.086	1.645	0.270
	FS-8	5.353	1.143	0.214
	SHRP	3.481	0.377	0.108
CB		4.696	0.472	0.101
CB-V		4.313	0.917	0.213
BR		5.185	0.533	0.103

Table 36: Air void content of recycled mixture manufactured by different mixing method

The effect of air void content on stiffness of asphalt mixture has been investigated by several researchers (Tayebali et al., 1994) (Read, 1996). Therefore, in order to compare stiffness values of different asphalt mixtures, the air void contents of these materials must be approximately the same. To compare whether the mean air void content of each data set are identical, the *t*-test is used. The hypothesis of the test is if there is no significant difference between the means of two data sets, the standard error of the difference in means *t* must be smaller than the critical value $t_{critical}$ for the relevant confidence level. The confidence level is 95% hence $t_{critical}$ must be in the range [-2.101; 2.101].

The summary of the statistical *t*-test is presented in Table 37. Pairs of air void content sets that do not conform to the hypothesis of *t*-test are highlighted. The results show that almost all mean air void contents are approximately similar to the others except control mixture

made of bitumen 70/100 Pen (CB-V) and recycled mixture made from small RAP by SHRP mixing method (SR-SHRP). In general, the air void contents of these two sets of asphalt mixtures are considerably lower than those of the others.

	FS-8													
	FS-6	2.052												
LR	FS-4	-1.009	-3.462											
	FS-2	0.356	-1.266	1.176										
	SHRP	1.304	-1.169	2.906	0.584									
	FS-8	-0.195	-1.972	0.646	-0.49	-1.307								
	FS-6	-1.381	-2.701	-0.812	-1.514	-2.285	-1.15							
SR	FS-4	-1.059	-3.603	-0.027	-1.214	-3.082	-0.68	0.806						
	FS-2	-0.14	-2.577	1.551	-0.305	-1.76	0.345	1.598	1.666					
	SHRP	5.756	3.735	8.606	3.833	6.729	4.916	4.853	9.154	9.22				
Control	BR	0.234	-2.339	1.594	-0.224	-1.499	0.419	1.638	1.701	0.15	-8.25			
Mixes	CB	1.758	-0.711	3.508	0.913	0.629	1.677	2.554	3.723	2.5	-6.35	2.17		
	CB-V	2.333	0.476	3.613	1.563	1.571	2.242	2.963	3.732	2.79	-2.65	2.559	1.174	
		LR					SR					Control Mixes		
		FS-8	FS-6	FS-4	FS-2	SHRP	FS-8	FS-6	FS-4	FS-2	SHRP	BR	CB	CB-V

Table 37: Air void comparison by *t*-test

6.5.2 Effects of mixing time on stiffness

The summary of stiffness data is presented in Table 38. The mean stiffness comparison among different sets of asphalt materials by *t*-test is shown in Table 39. The hypothesis is if two means of stiffness are similar with confidence level of 95%, the calculated *t* value must be in the range [-1.991; 1.991]. Each pair of stiffness sets that conforms to the hypothesis is highlighted. The results show clearly that the mean stiffnesses of different sets of specimen are quite different each other. For BR case, the difference is understandable as the viscosity of bitumen 160/220 Pen is extremely low compared to that of the other bitumen. However, except the BR case, the materials for the manufacture of the other recycled asphalt mixtures are exactly the same. In fact, in these cases, if the RAP binders are fully extracted and mixed with virgin bitumen (bitumen 160/220 Pen), these result blends will have similar characteristics.

It has been argued that the stiffness difference among sets of recycled asphalt mixtures is attributed to difference in air void characteristics. For instance, as a result of air void analysis (Tables 36 and 37), the mean air void content of CB-V and SR-SHRP asphalt are considerably lower than those of the other asphalt mixtures. However, the air void comparison also demonstrates that apart from CB-V and SR-SHRP, the air void contents of the other asphalt mixtures are statistically similar. Hence, if the stiffness values of these asphalt mixtures are different, the reason must be due to different mixing characteristics.

		Mean	**SD**	**COV**
LR	FS-2	1262	483	0.383
	FS-4	1412	314	0.222
	FS-6	1610	197	0.122
	FS-8	1720	66	0.038
	SHRP	1614	102	0.063
SR	FS-2	1732	240	0.139
	FS-4	1733	77	0.044
	FS-6	1808	96	0.053
	FS-8	1866	139	0.075
	SHRP	1774	47	0.026
CB		2294	144	0.063
CB-V		2409	210	0.087
BR		752	117	0.156

Table 38: Summary of stiffness values (MPa) of recycled mixtures manufactured by different mixing methods

	FS-8													
	FS-6	3.367												
LR	FS-4	6.685	3.379											
	FS-2	6.212	4.457	1.852										
	SHRP	5.532	-0.12	-3.874	-4.765									
	FS-8	-5.964	-6.704	-8.355	-7.756	-9.207								
	FS-6	-4.743	-5.709	-7.62	-7.274	-8.723	2.158							
SR	FS-4	-0.739	-3.661	-6.27	-6.345	-5.847	5.309	3.888						
	FS-2	-0.316	-2.705	-5.394	-5.902	-3.244	3.441	2.149	0.03					
	SHRP	-4.162	-5.109	-7.205	-6.934	-8.966	3.971	2.035	-2.909	-1.277				
Control	BR	45.569	23.683	12.465	6.29	35.049	38.709	44.02	44.276	26.329	51.194			
Mixes	CB	-22.973	-17.747	-16.158	-13.232	-24.389	-13.548	-17.785	-21.836	-14.264	-21.812	-52.615		
	CB-V	19.823	17.569	-16.705	-14.047	-21.553	-13.66	-16.483	-19.181	-14.654	-18.72	-43.641	-2.866	
		LR					SR					Control Mixes		
		FS-8	FS-6	FS-4	FS-2	SHRP	FS-8	FS-6	FS-4	FS-2	SHRP	BR	CB	CB-V

Table 39: Stiffness comparison by *t*-test

The most significant feature that separates recycled asphalt from virgin asphalt is the recycled asphalt mixtures contain RAP materials, agglomerate lumps of RAP binder and aggregate. In order to manufacture homogeneous recycled asphalt, RAP lumps should be fully separated into single pieces and uniformly distributed in the whole mixture. Therefore, virgin binder can rejuvenate and alter the properties of RAP binder. If this cannot occur, then there will be some areas with high concentration of RAP and vice versa, other areas are dominated by virgin material. Due to the fact that properties of RAP binder are entirely different from those of virgin binder, there will be a substantial variation in stiffness values.

Figures 65 to 68 illustrate the relation among stiffness values, the location of specimens cored from roller-compacted slabs, and the stiffness measured at different directions for recycled asphalt mixtures manufactured from large RAP (LR) with different mixing durations. The results show that mixing time between RAP and superheated virgin aggregate significantly affects the homogeneity of recycled asphalt mixtures. With short mixing duration, for instance 2 minutes, the degree of stiffness fluctuation is really high (Figure 65). The stiffness values are not only different from specimen to specimen but also different between measured directions in the same specimen. Tables 40 to 43 show the stiffness values measured at different directions for specimens made of large RAP with different mixing durations.

The data demonstrates that the homogeneity level of hot recycled asphalt mixture is considerably improved once the RAP/superheating virgin aggregate mixing duration is extended. Stiffness difference between specimens are considerably reduced and this phenomenon is substantiated by the fact that the general coefficient of variation significantly decreases from 38.3 to 3.8% (Table 38) once the mixing duration increases from 2 to 8 minutes. In addition, the stiffness coefficient of variation in each specimen is also reduced to less than 10% once the mixing duration is increased to 8 minutes (Table 43). The longer the mixing time, the closer the homogeneity of recycled mixture approaches that of complete blending (CB) mixture (Table 44).

The mixing duration between RAP and superheated virgin aggregate is an important factor that determines the quality of hot recycled mixture. During the mixing process, the heat transferred from superheated aggregate will soften the RAP lumps. Under mechanical effects of mixing paddles, RAP lumps are separated into single pieces covered by RAP

binder from circumference to the centre and distributed all over the mixture. If the mixing time is not long enough, RAP lumps cannot be separated and hence, not well distributed in the mixture. Consequently, this will result in the considerable variation in stiffness values.

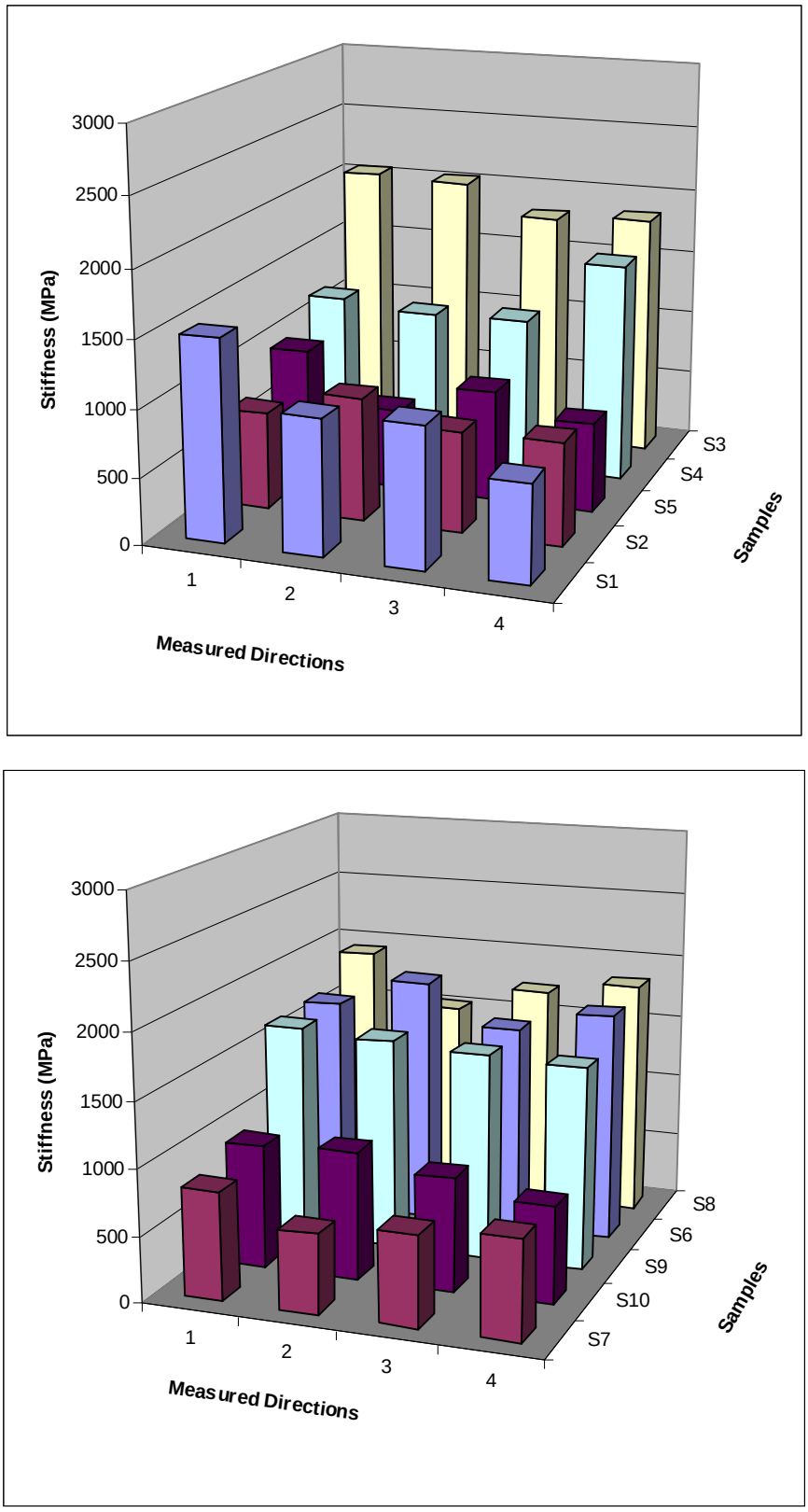
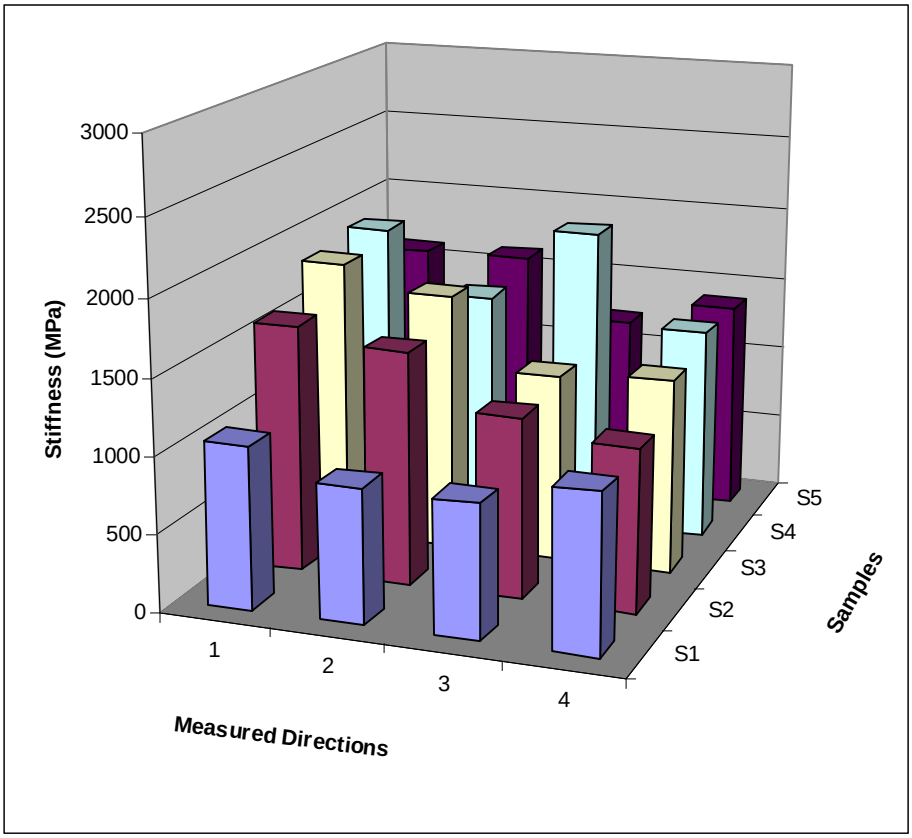


Figure 65: Stiffness versus core location and measuring direction of LR FS-2 mixture



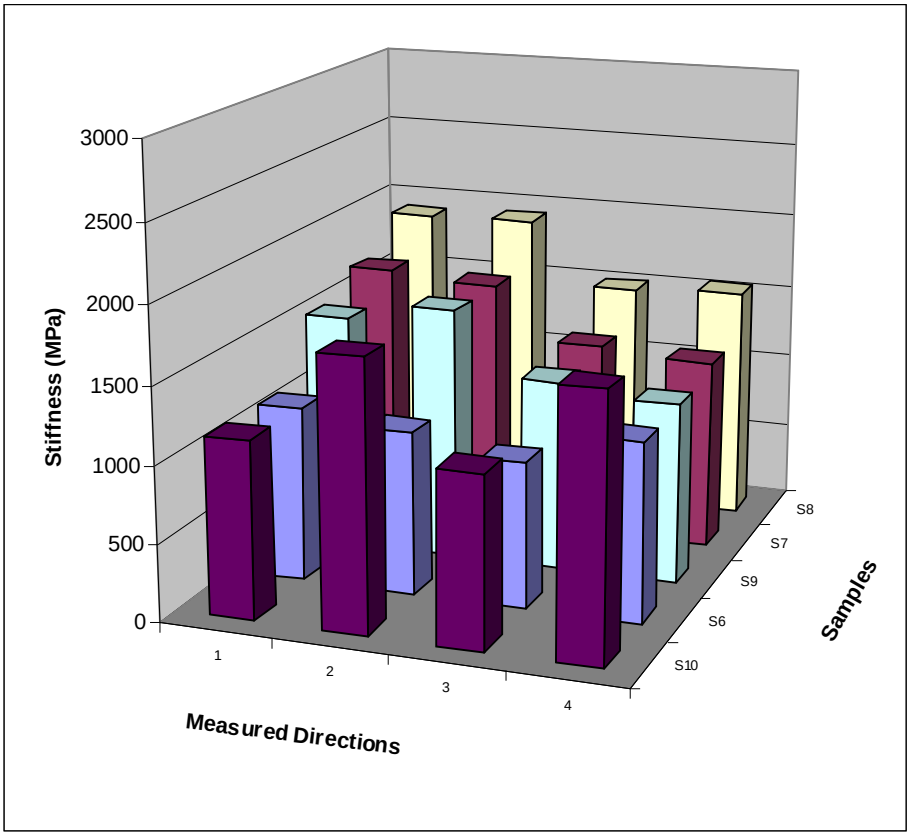
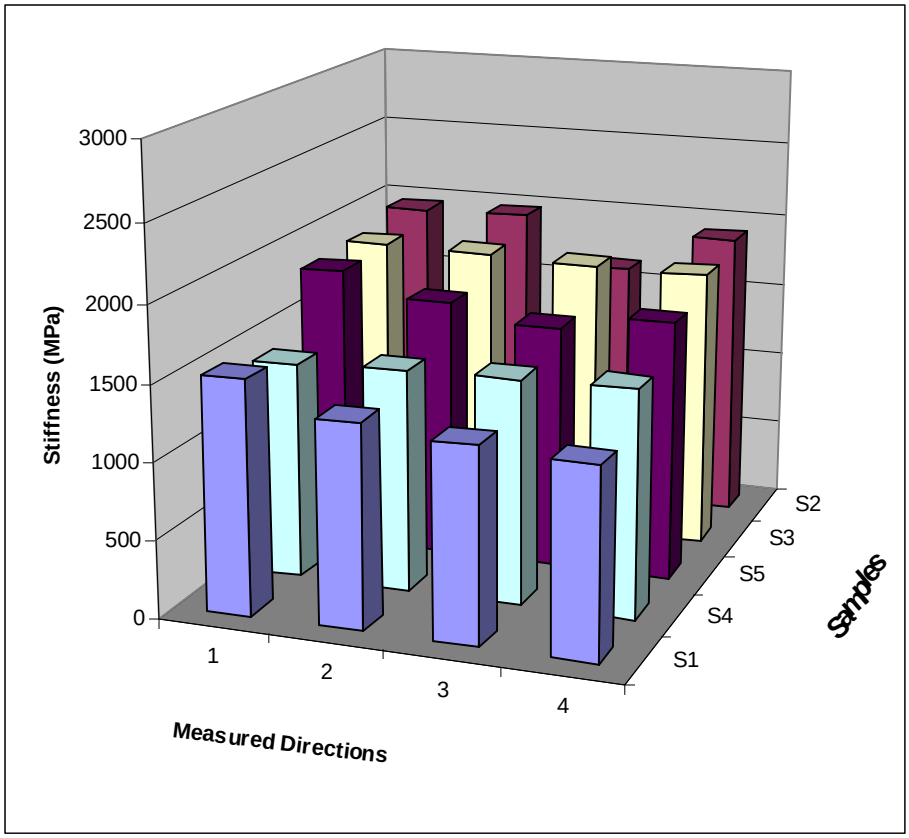


Figure 66: Stiffness versus core location and measuring direction of LR FS-4 mixture



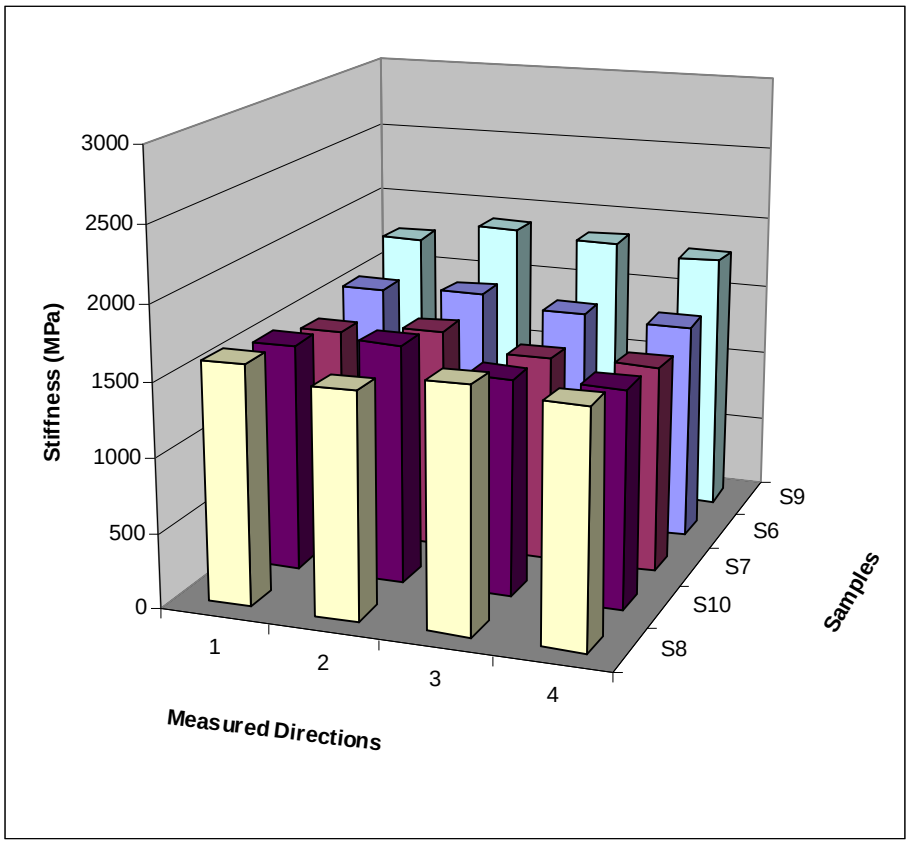
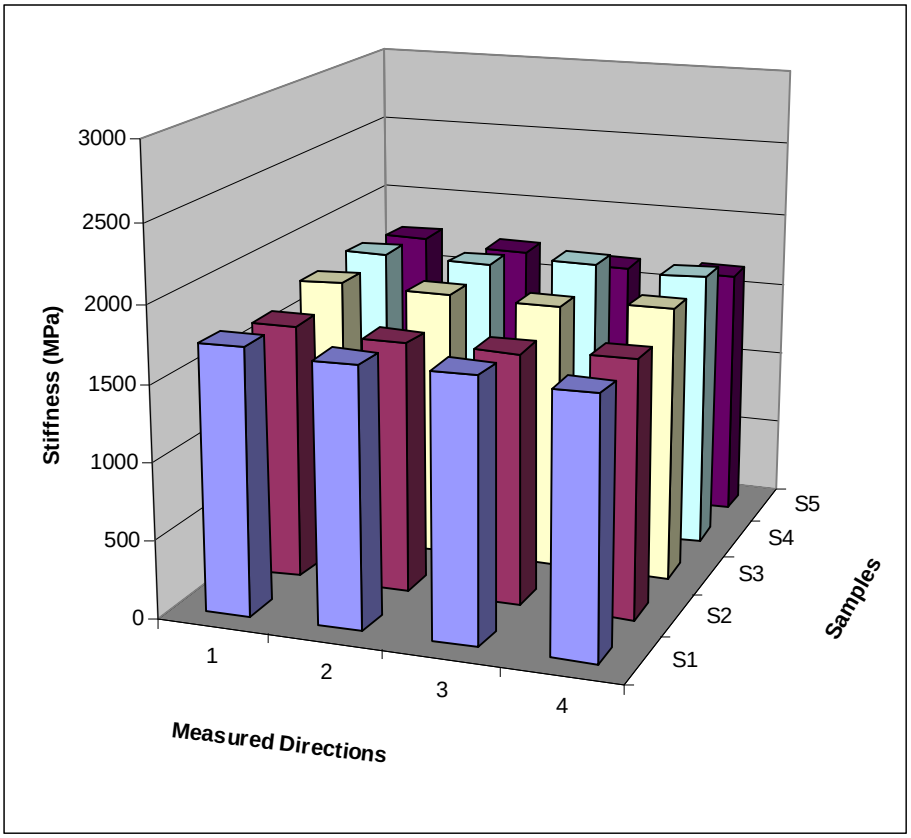


Figure 67: Stiffness versus core location and measuring direction of LR FS-6 mixture



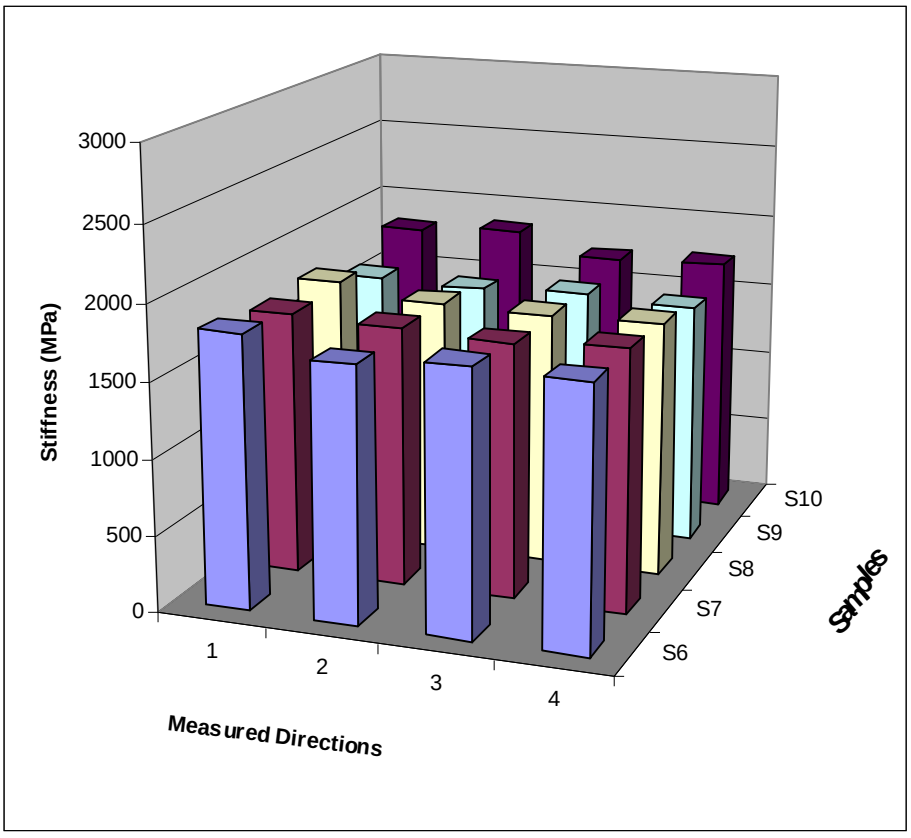


Figure 68: Stiffness versus core location and measuring direction of LR FS-8 mixture

Samples	Air Void Content (%)	Stiffness in Different Directions (MPa)				Mean Stiffness (MPa)	Standard Deviation	COV (%)
		1	2	3	4			
S1	5.8	1499	1007	1047	731	1071	318	29.7
S2	4.1	722	920	753	768	791	88	11.1
S3	5.7	2049	2023	1792	1840	1926	129	6.7
S4	5.7	1205	1144	1168	1660	1294	245	18.9
S5	4.0	978	597	827	666	767	171	22.3
S6	4.2	1676	1908	1598	1768	1738	133	7.7
S7	7.9	823	603	691	756	718	94	13.1
S8	5.4	1928	1529	1723	1829	1752	171	9.8
S9	4.4	1665	1621	1583	1555	1606	48	3.0
S10	3.7	944	973	862	740	880	104	11.8

Table 40: Stiffness values of LR FS-2 specimens

Samples	Air Void Content (%)	Stiffness in Different Directions (MPa)				Mean Stiffness (MPa)	Standard Deviation	COV (%)
		1	2	3	4			
S1	5.3	1063	881	872	1035	963	100	10.4
S2	7.3	1623	1530	1183	1068	1351	267	19.8
S3	5.5	1854	1703	1239	1285	1520	305	20.1
S4	4.9	1925	1517	2012	1405	1715	299	17.4
S5	6.1	1613	1620	1218	1387	1460	194	13.3
S6	5.4	1140	1062	952	1168	1081	97	9.0
S7	5.1	1692	1648	1298	1256	1474	228	15.5
S8	5.3	1914	1933	1503	1540	1723	233	13.5
S9	6.0	1543	1663	1250	1186	1411	229	16.2
S10	5.4	1150	1745	1114	1699	1427	341	23.9

Table 41: Stiffness values of LR FS-4 specimens

Samples	Air Void Content (%)	Stiffness in Different Directions (MPa)				Mean Stiffness (MPa)	Standard Deviation	COV (%)
		1	2	3	4			
S1	4.6	1524	1328	1270	1232	1339	130	9.7
S2	3.6	1957	1974	1647	1911	1872	152	8.1
S3	4.1	1868	1863	1835	1839	1851	17	0.9
S4	6.1	1415	1447	1462	1480	1451	28	1.9
S5	4.0	1850	1701	1604	1700	1714	102	6.0
S6	4.6	1559	1584	1509	1486	1535	45	2.9
S7	4.3	1431	1505	1390	1406	1433	51	3.6
S8	4.2	1610	1512	1623	1568	1578	50	3.2
S9	3.9	1760	1888	1847	1779	1819	60	3.3
S10	5.5	1528	1606	1452	1461	1512	71	4.7

Table 42: Stiffness values of LR FS-6 specimens

Samples	Air Void Content (%)	Stiffness in Different Directions (MPa)				Mean Stiffness (MPa)	Standard Deviation	COV (%)
		1	2	3	4			
S1	3.6	1727	1687	1697	1660	1693	28	1.7
S2	5.3	1666	1623	1629	1669	1647	24	1.5
S3	5.6	1768	1759	1744	1794	1766	21	1.2
S4	4.8	1795	1786	1853	1825	1815	30	1.7
S5	6.4	1751	1712	1657	1662	1696	45	2.7
S6	6.4	1806	1678	1744	1724	1738	53	3.0
S7	4.6	1747	1718	1690	1728	1721	24	1.4
S8	5.3	1780	1699	1685	1696	1715	44	2.6
S9	6.1	1637	1620	1651	1612	1630	17	1.0
S10	4.5	1823	1865	1721	1745	1789	67	3.7

Table 43: Stiffness values of LR FS-8 specimens

Samples	Air Void Content (%)	Stiffness in Different Directions (MPa)				Mean Stiffness (MPa)	Standard Deviation	COV (%)
		1	2	3	4			
S1	4.3	2406	2415	2373	2386	2395	19	0.8
S2	5.1	2221	2255	2103	2186	2191	65	3.0
S3	5.5	2095	2103	2077	2084	2090	12	0.6
S4	4.7	2324	2233	2283	2317	2289	42	1.8
S5	4.7	2286	2202	2204	2282	2244	47	2.1
S6	5.0	2265	2358	2259	2269	2288	47	2.1
S7	4.6	2483	2470	2268	2488	2427	106	4.4
S8	4.9	2130	2119	2099	2076	2106	24	1.1
S9	4.2	2406	2356	2346	2259	2342	61	2.6
S10	4	2531	2562	2536	2496	2531	27	1.1

Table 44: Stiffness values of CB specimens

Longer mixing duration not only advances the distribution of RAP materials all over the recycled mixture but also enhances the rejuvenation process between virgin and RAP binder. If the rejuvenation can only occur once new virgin binder is in contact with RAP binder, the more exposed area of RAP materials to virgin binder, the better this process. When the mixing time is increased, the fact that more pieces are separated from RAP lumps will enlarge the total RAP exposed area for rejuvenation. As more RAP binder is incorporated with virgin binder, the stiffness values of recycled mixture generally increase.

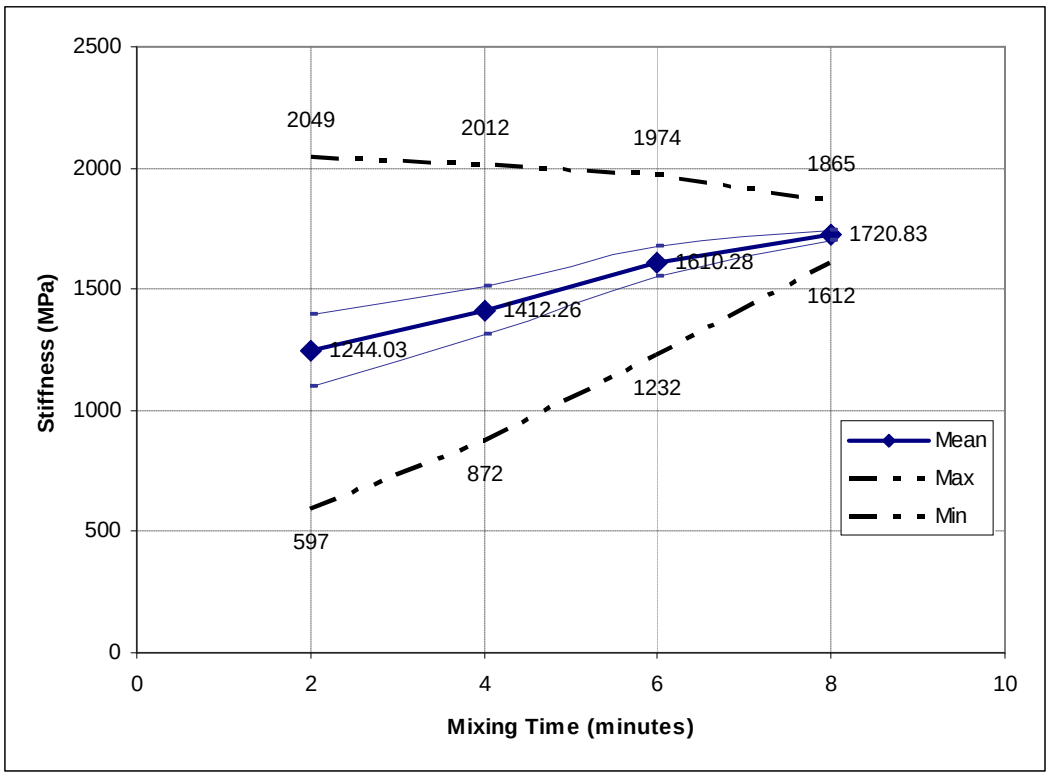


Figure 69: Stiffness versus mixing time of LR FS mixtures

Figure 69 shows the relation between RAP/superheated virgin aggregate mixing durations and stiffness of recycled mixtures made with large RAP (LR). The three continuous centre lines present the mean stiffness and the boundaries of the mean with 95% confident level. The top and the bottom dashed lines are for the maximum and minimum stiffness values versus mixing durations. The data show that the mean stiffness increases considerably, from 1200 MPa to 1700 MPa once the mixing durations are extended from 2 to 8 minutes. The data also shows that even at very short mixing duration, for instance 2 minutes, the means stiffness is far different from that of black rock (BR) case, 751 MPa.

The increase in stiffness value might be attributed to the incorporation or rejuvenation between virgin and RAP binder. However, this is not the only reason as the increase of stiffness values might be also due to the distribution of RAP materials. As the stiffness of RAP is considerably higher than that of virgin binder, the specimens with higher concentration of RAP will have higher stiffness. This situation is exaggerated in the case where the mixing time is not sufficient to separate RAP lumps and these lumps are randomly distributed over the mixture.

It is sometimes impossible to identify the causes, distribution or rejuvenation, credited to the increase of stiffness values as the distribution of RAP over the mixture and incorporation between RAP and virgin binder occurs simultaneously. However, it is possible to recognize between distribution and rejuvenation, which could be dominantly the reason for the increase of stiffness. If the increase in stiffness is attributed to the distribution of RAP lumps, stiffness values are considerably different from specimen to specimen. In addition, the stiffness values measured at different directions of each specimen are also different. Most importantly if RAP material is merely distributed, the properties of the mixture will be dominated by the characteristic of virgin material. On the contrary, the properties of the mixture will be dominated by the properties of RAP binder where RAP material predominates. When the mixing time is increased, as RAP lumps start to separate and more RAP binder is rejuvenated by virgin binder, the properties of both RAP and virgin binder have changed. Virgin binder stiffened by RAP bitumen will increase the minimum value of stiffness. In addition, the incorporation between RAP and virgin binder also reduces the variation among stiffness values.

Anderson-Darling test for standard distribution

To better understand the reason for the increase of stiffness values, stiffness data is further investigated using the Anderson-Darling test (Anderson and Darling, 1952). This statistical test is used to validate whether the stiffness values of recycled asphalt mixture match the standard distribution with chosen confidence interval. The confidence level for the test is 95%. The theory of the test is to plot the empirical continuous distribution function (CDF) of the data and compare it to that of the standard distribution. Anderson-Darling parameter (AD) presents the difference between empirical data and theoretical normal distribution and is expressed as following:

$$AD^2 = -N - S \quad \textbf{(20)}$$

$$S = \sum_{i}^{N} \frac{(2i-1)}{N} \left[\log F(Y_i) + \log(1 - F(Y_{N+1-i})) \right] \quad \textbf{(21)}$$

Where:

N: number of samples

F: assumed normal distribution function with estimated μ and δ

Y_i: the sorted, standardized sample value

The hypothesis of the Anderson-Darling test is if the data set conforms to the standard distribution, Anderson-Darling parameter has to be smaller than 0.787 and P value must be higher than (*1-Confidence level*). The smaller the AD value is, the better the data fits into normal distribution (Stephens, 1974).

Stiffness distribution of Control Asphalt Mixtures

The stiffness distributions of three control asphalt mixtures, BR, CB, and CB-V, are illustrated in Figure 70. The results from the Anderson-Darling test demonstrate that stiffness values of three control asphalt mixtures conform to the normal distribution (Figure 71). Coefficient of variation (COV) values are less than 15%. With 95% confidence interval, the AD parameter ranges from 0.3 to 0.5. The mean stiffness values of CB and CB-V are approximately the same, less than 10% difference. The result is as expected as the rheological properties of recycled binder (CB) with 40% RAP binder is almost identical to that of bitumen 70/100 Pen.

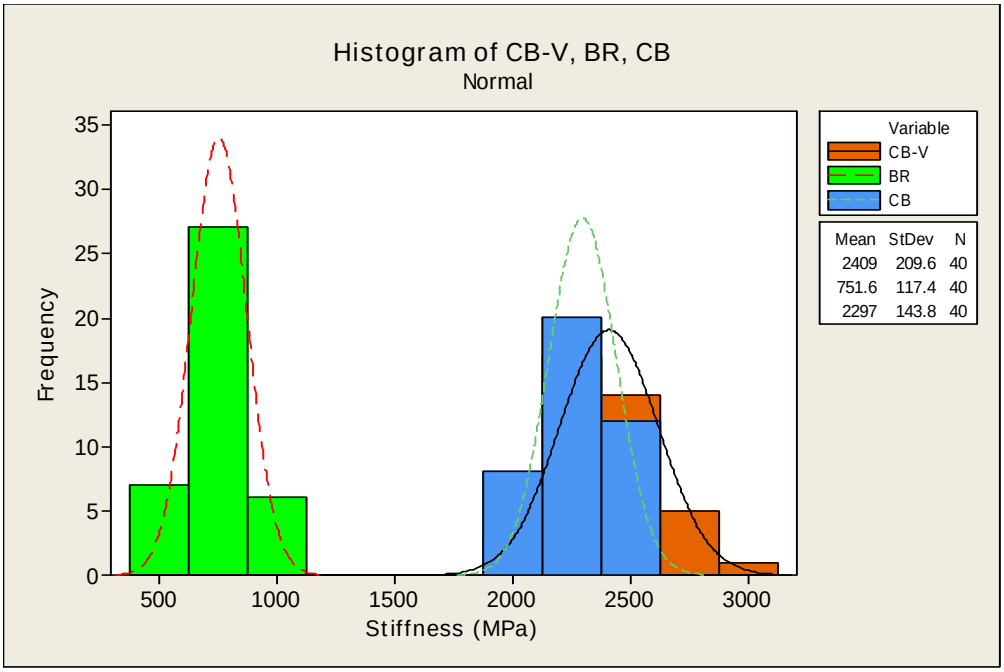


Figure 70: Stiffness distribution of control mixtures

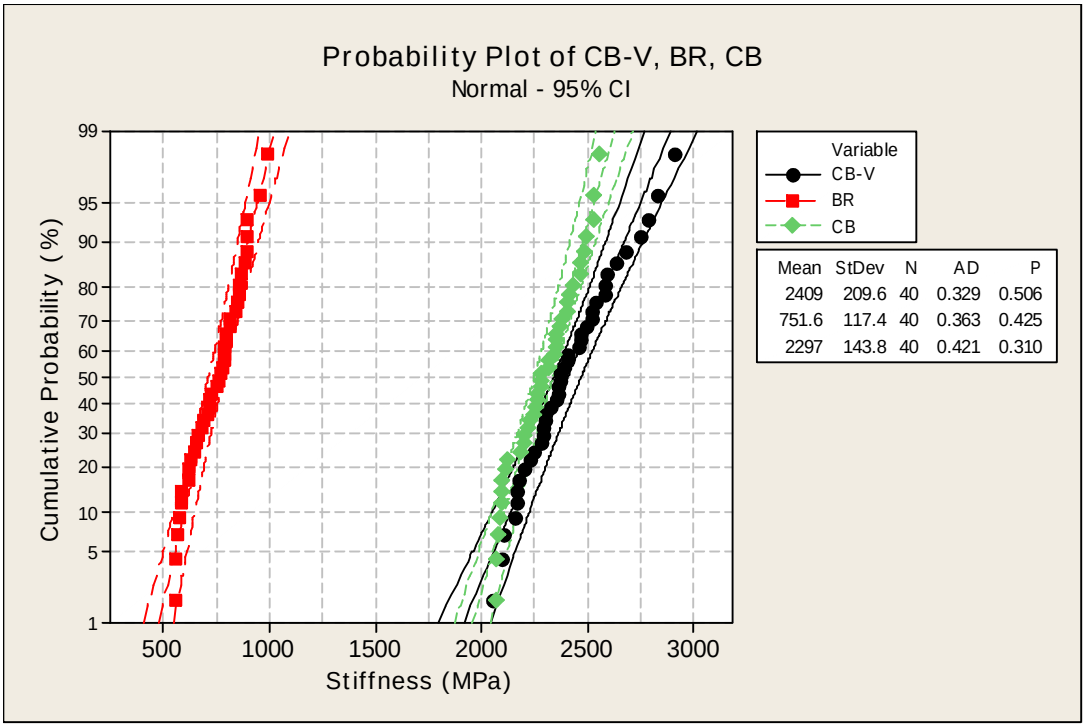


Figure 71: Probability plot of stiffness values – control mixtures

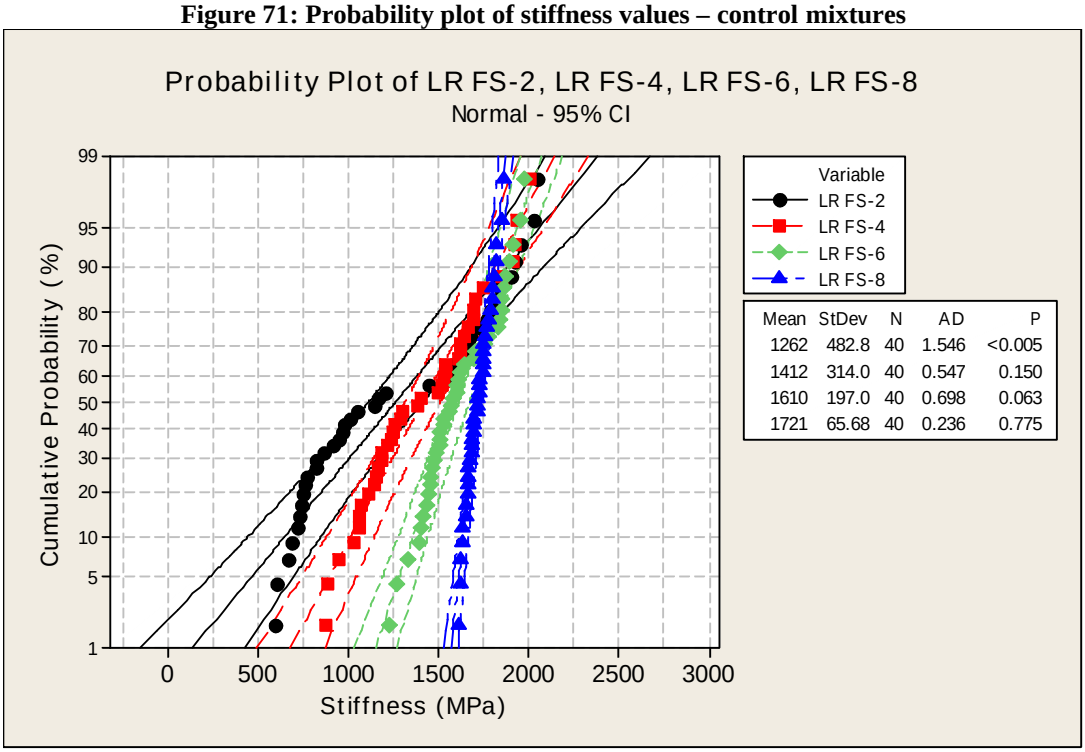


Figure 72: Probability plot of stiffness values – LR FS mixtures

Figure 72 presents the stiffness cumulative probability of recycled asphalt mixtures composed of large RAP manufactured with different RAP/superheated virgin aggregate mixing durations. Results from the Anderson-Darling test show that only at 8 minutes mixing time, the AD value is the same level as that of the control asphalt. At lower mixing

times, AD values are high, especially with 2 minutes mixing time, the stiffness distribution does not conform to the standard distribution.

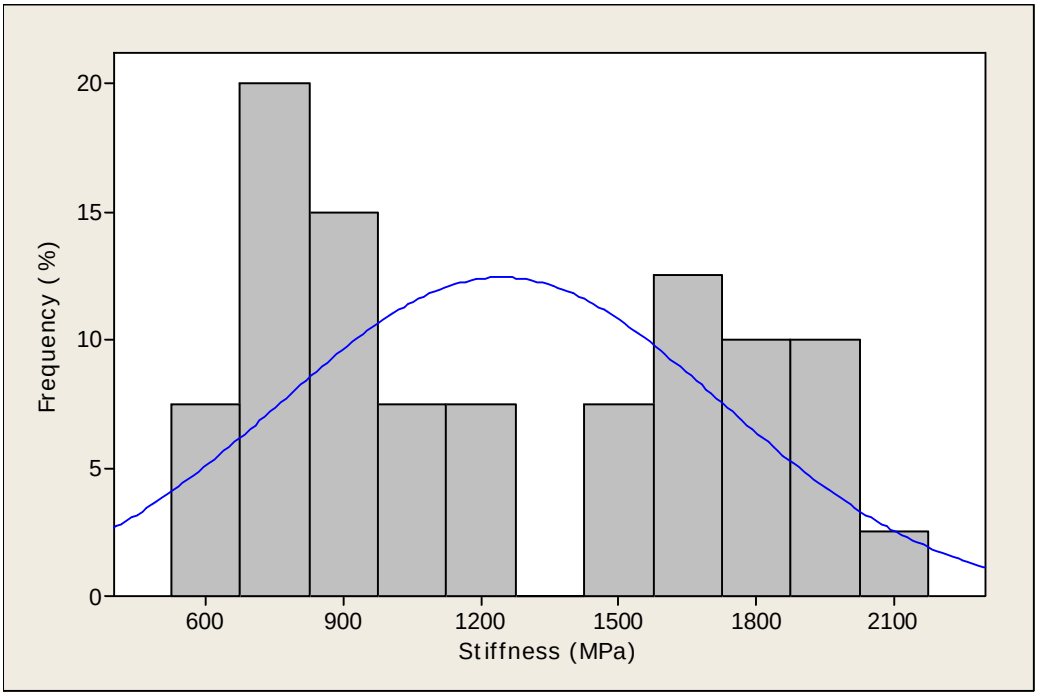


Figure 73: Stiffness histogram of LR FS-2 mixture

The stiffness histogram of recycled mixture composed of large RAP and 2 minute mixing duration (LR FS-2) is shown in Figure 73. It is quite clear that rather than conforming to the normal distribution, stiffness modulus values gather primarily into two main groups, G1 whose stiffness values range from 500 to 1200, and G2 from 1400 to 2200 MPa. If the stiffness values of 2 minute mixing time are analyzed by these two groups, G1 and G2, the distribution of stiffness values in each separated group conforms to the standard distribution (Figure 74). The AD parameter for each group is almost the same level as that of control mixtures (Figure 75).

If the comparison is based on only the mean stiffness, the properties of LR FS-2 are far different from that of the BR case. In fact, this expresses a considerable interaction between RAP and virgin binder hence, the mean stiffness of LR FS-2 is about 1262 MPa compared to 751 MPa of the BR case. However, the stiffness distribution shows that group 1 of LR FS-2 has 22 values varying from 500 MPa to 1200 MPa. In addition, the mean stiffness of this group is 860 MPa, insignificantly different from that of the BR case. Figure 76 shows the inter-quartile stiffness ranges of LR FS-2 group 1 and the BR case. This group possesses the same characteristics as that of the BR mixture. The stiffness distribution

indicates that there is insubstantial interaction between RAP and virgin binder and the properties of LR FS-2 is almost dominated by virgin binder, or RAP acts as “Black Rock”. If the mixing duration is insufficient, RAP lumps are not heated up. Therefore, the bondage between RAP aggregate pieces are neither weakened nor deactivated. Mechanical mixing therefore only distributes RAP at approximately original size all over the mixture.

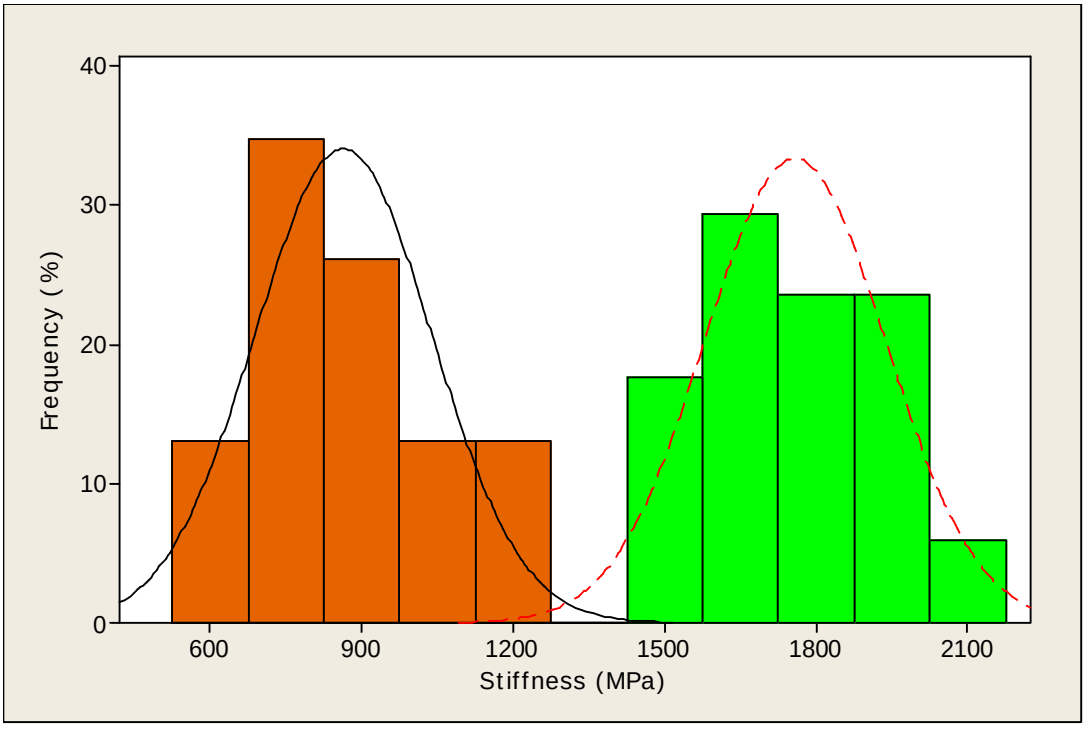


Figure 74: Stiffness histogram of LR FS-2 mixture – Stiffness grouping analysis

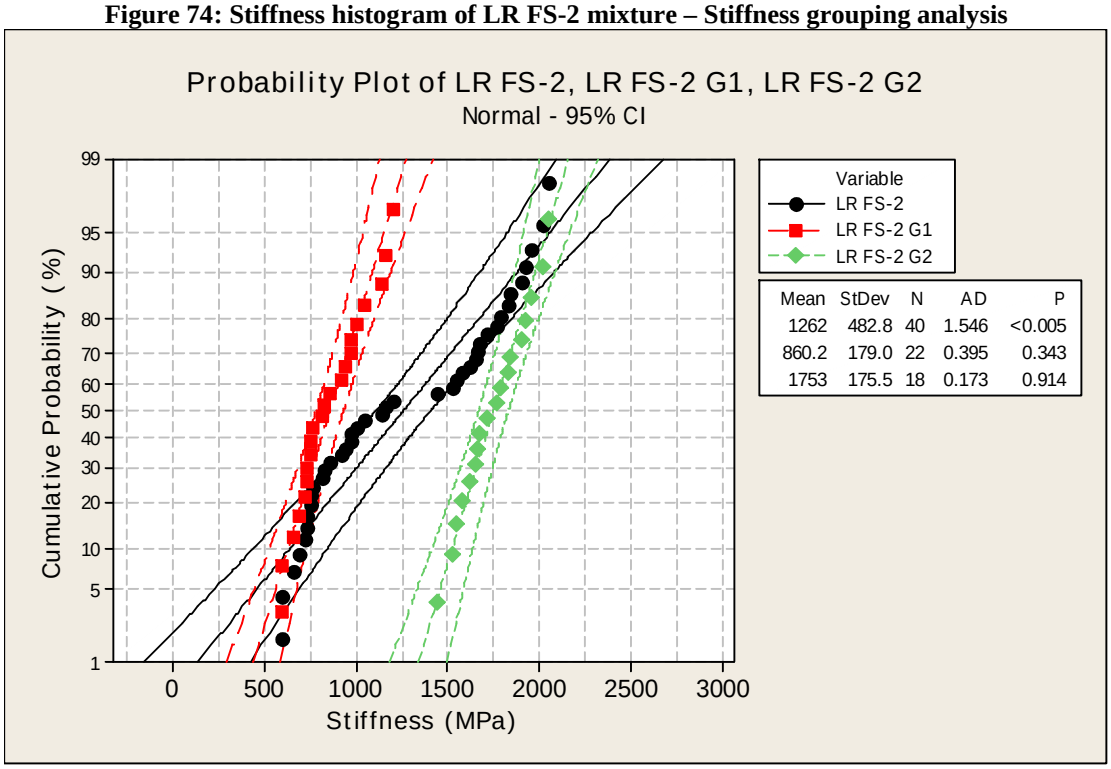


Figure 75: Stiffness probability plot of LR FS-2 – Stiffness grouping analysis

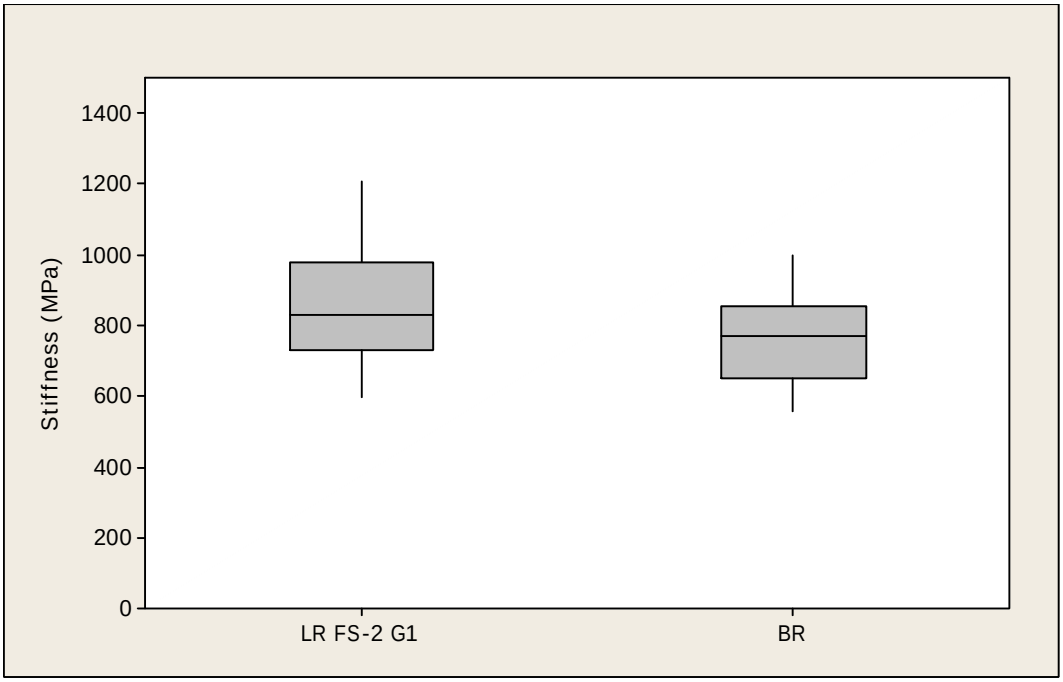


Figure 76: Inter-quartile stiffness ranges of LR FS-2 group 1 and BR mixture

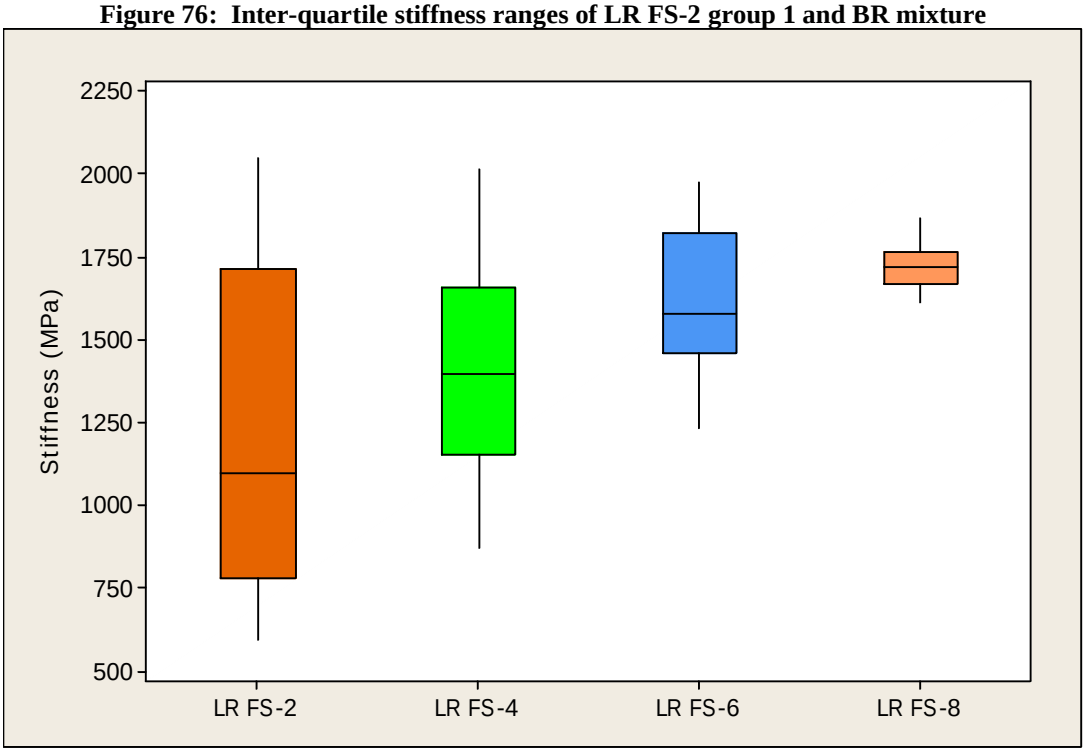


Figure 77: Inter-quartile stiffness ranges of LR FS mixtures

When the mixing time is increased, the RAP binder is heated up and becomes softer. RAP lumps will start to disintegrate first from outside to centre once the bituminous bond between RAP aggregate particles is prevailed by mechanical mixing effort. Under mechanical effects, separated pieces will be moved around and mixed up with virgin aggregate and binder. RAP material no longer acts as “Black Rock” but starts to integrate with virgin binder. The more RAP pieces are disintegrated, the more interaction between

RAP and virgin binder. Due to the incorporation between RAP binder and rejuvenator, the stiffness values generally increase. Figure 77 illustrates the inter-quartiles stiffness range for recycled mixtures composed of large RAP (LR) by field simulation method (FS) with different mixing durations. The bottom line presents the end of the first quartile data and the centre line is for the median. The data shows the minimum stiffness value increases from 597 to 1612 MPa when the mixing time increases from 2 to 8 minutes. In addition, the data also indicates the first quartile of stiffness data and the stiffness median increases considerably once the RAP/superheated virgin aggregate mixing duration is extended.

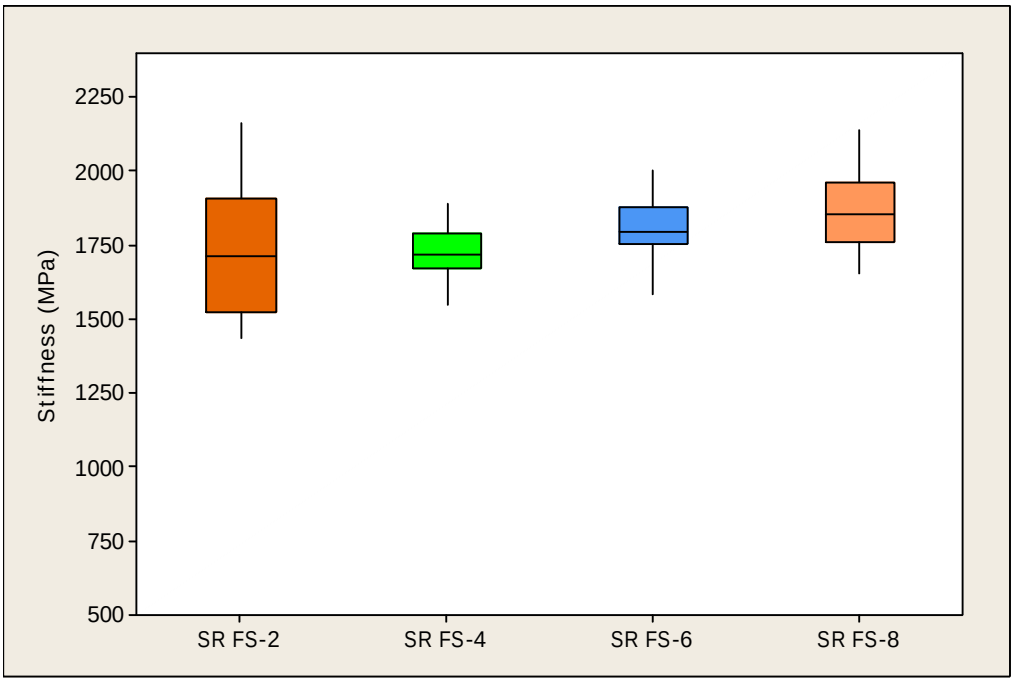


Figure 78: Inter-quartile stiffness ranges of SR FS mixtures

While the mixing duration considerably affects the stiffness values of recycled mixture composed of large RAP, it only slightly influences the stiffness values of small RAP recycled mixtures. Figure 78 shows that when the mixing duration increases from 2 to 8 minutes, the mean stiffness values of SR recycled mixtures change unnoticeably. This is because under the mechanical mixing efforts, the original size of large RAP is significantly reduced. Therefore, the stiffness of LR recycled mixture increases due to more virgin binder interacting with RAP binder. However, the original size of small RAP only changes slightly due to small RAP being already crushed into smaller size before use. The mechanical mixing effort could not disintegrate those RAP lumps composed of fine aggregates and fillers or the coarse aggregate covered by filler mastic. However, the increase in mixing time considerably increases the homogeneity of recycled mixture

composed of small RAP materials. Figure 78 shows that the inter-quartile stiffness range of SR FS mixtures is considerably narrowed once mixing time is extended.

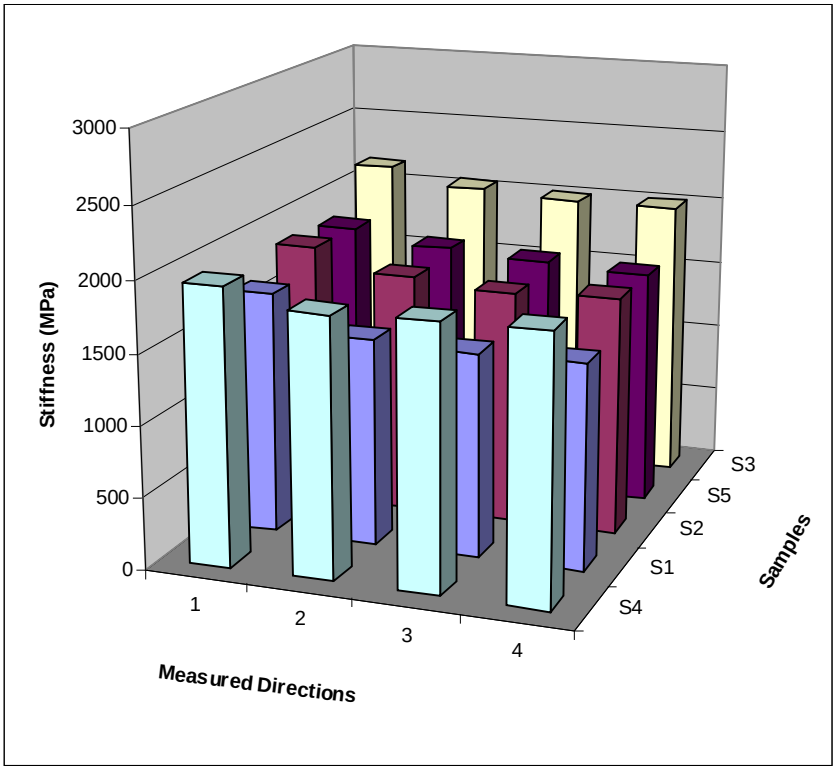
6.5.3 Effects of RAP sizes on stiffness

The size of RAP lumps substantially affects the homogeneity of the recycled mixtures. For the same RAP/superheated virgin aggregate mixing duration, the recycled mixtures composed of small RAP material have higher levels of homogeneity than the mixtures composed of large RAP. Figures 79 and 80 illustrate the relation among stiffness values, the location of specimens cored from roller-compacted slabs, and the stiffness measured at different directions of recycled asphalt mixtures composed of small RAP (SR) with 2 and 4 minutes mixing duration. For the case of 2 minutes mixing time, the stiffness coefficient of variation for SR mixture is 13.9 compared to 38.3% of LR mixture (Table 38). In addition, the stiffness in Table 45 also shows that stiffness variation in each specimen of SR FS-2 mixture is also lower, maximum 10% compared to 30% of LR FS-2 mixture. For 4 minutes mixing duration, the phenomenon is the same. Stiffness coefficient of variation for SR mixture is 4.4% compared to 22.2% of LR mixture and the stiffness variation in each specimen is a maximum of 6% compared to 24% of LR mixture (Tables 38 and 46).

Size of RAP affects not only the homogeneity level but also the interaction between RAP and virgin binder. At 2 minutes mixing duration, the properties of recycled mixture composed of large RAP are primarily dominated by virgin binder. In fact, RAP acts as "Black Rock". On the contrary, there is a considerable interaction between RAP and virgin binder in recycled mixture composed of small RAP materials. The interaction is indicated by the mean and the minimum stiffness values of SR mixtures being far different from those of LR mixtures (Figure 81) for the same mixing duration. For instance, at 2 minutes mixing duration, the minimum stiffness of SR mixture is 1497 MPa compared to 597 MPa of LR mixture, and the mean stiffness is 1806 MPa compared to 1262 MPa.

The phenomenon is as expected as the interaction between RAP and virgin binder is controlled by the total surface area of RAP materials. This total surface area is also the exposed area of RAP material to virgin binder for rejuvenation. The larger the total exposed area, the higher the probability that the virgin binder can coat and penetrate into RAP binder. In addition, the total surface area is inversely related to the size of RAP materials. As small RAP materials have larger total surface area, the recycled mixtures composed of

small RAP tend to have higher stiffness values due to more interaction between RAP and virgin binder.



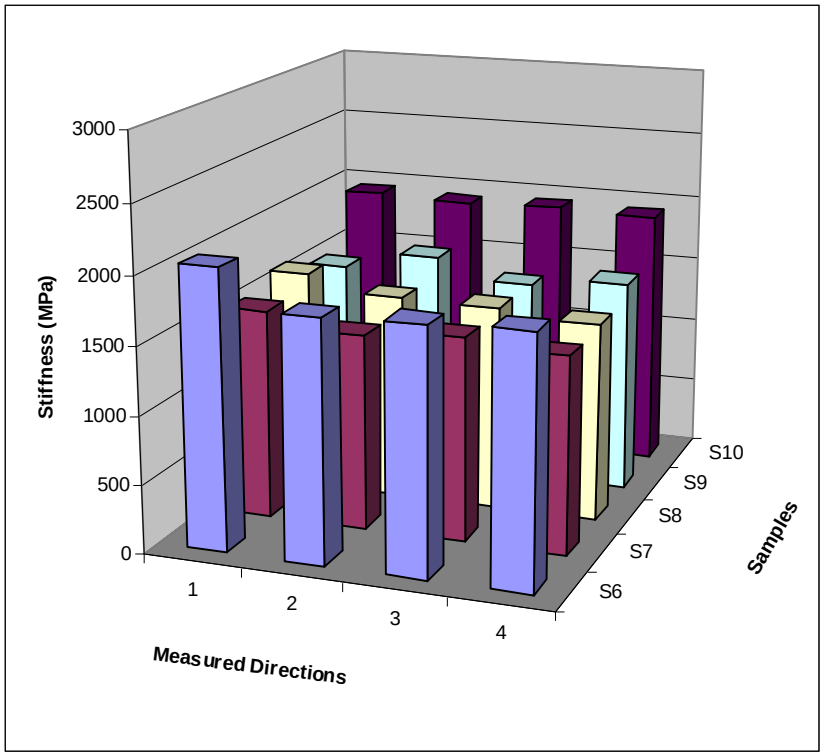
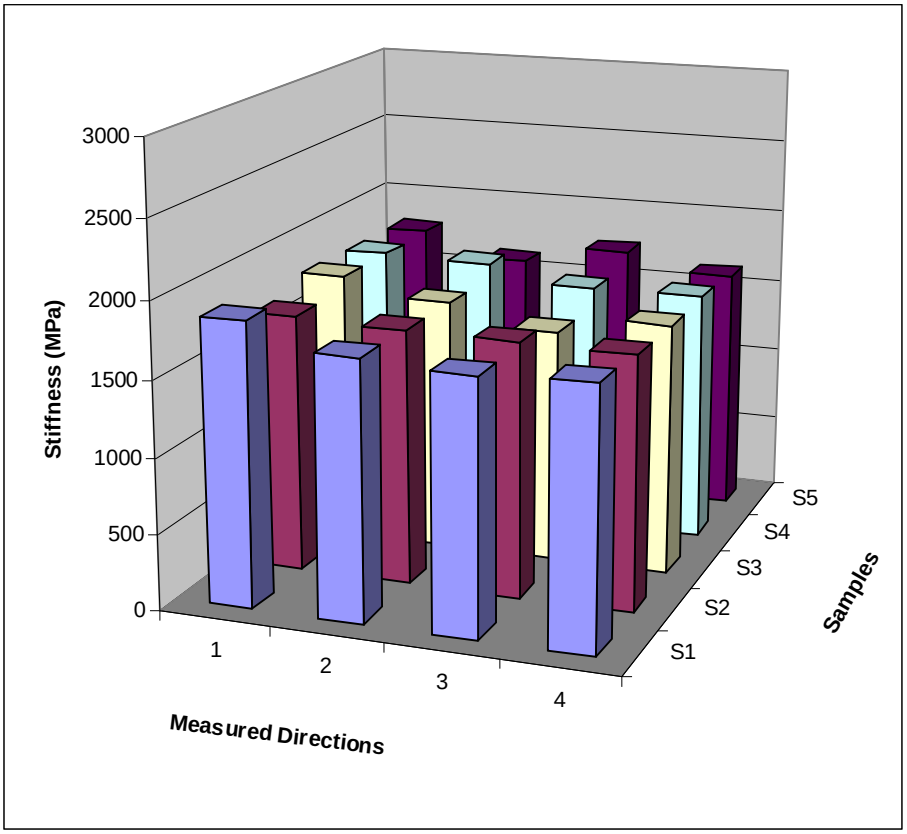


Figure 79: Stiffness versus core location and measuring direction of SR FS-2 mixture



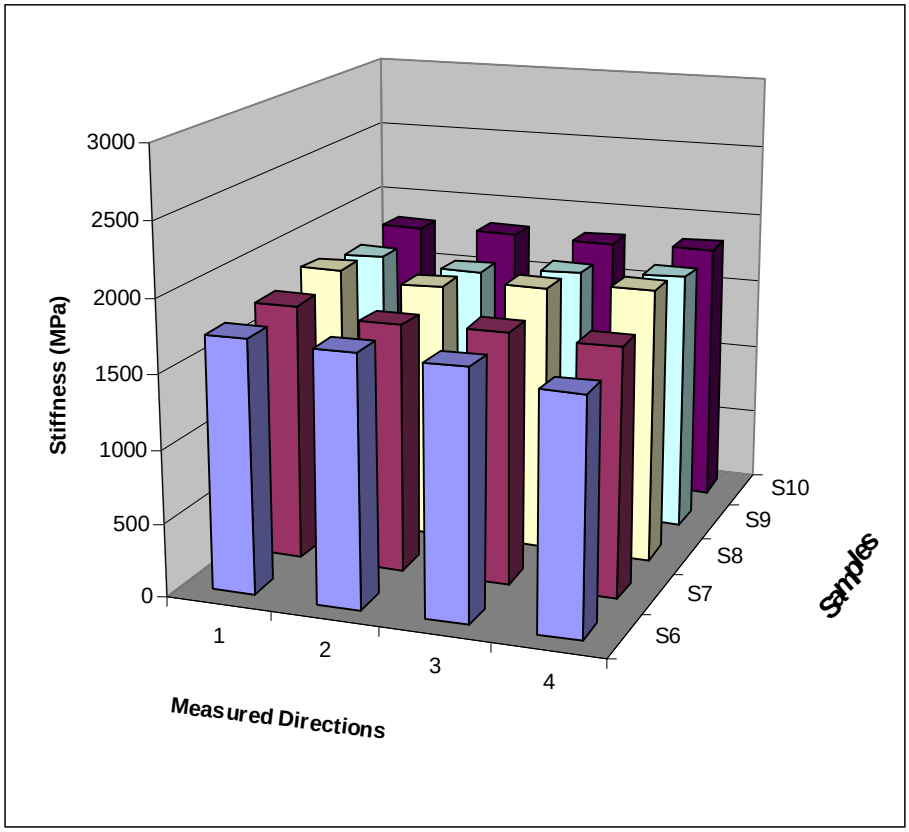


Figure 80: Stiffness versus core location and measuring direction of SR FS-4 mixture

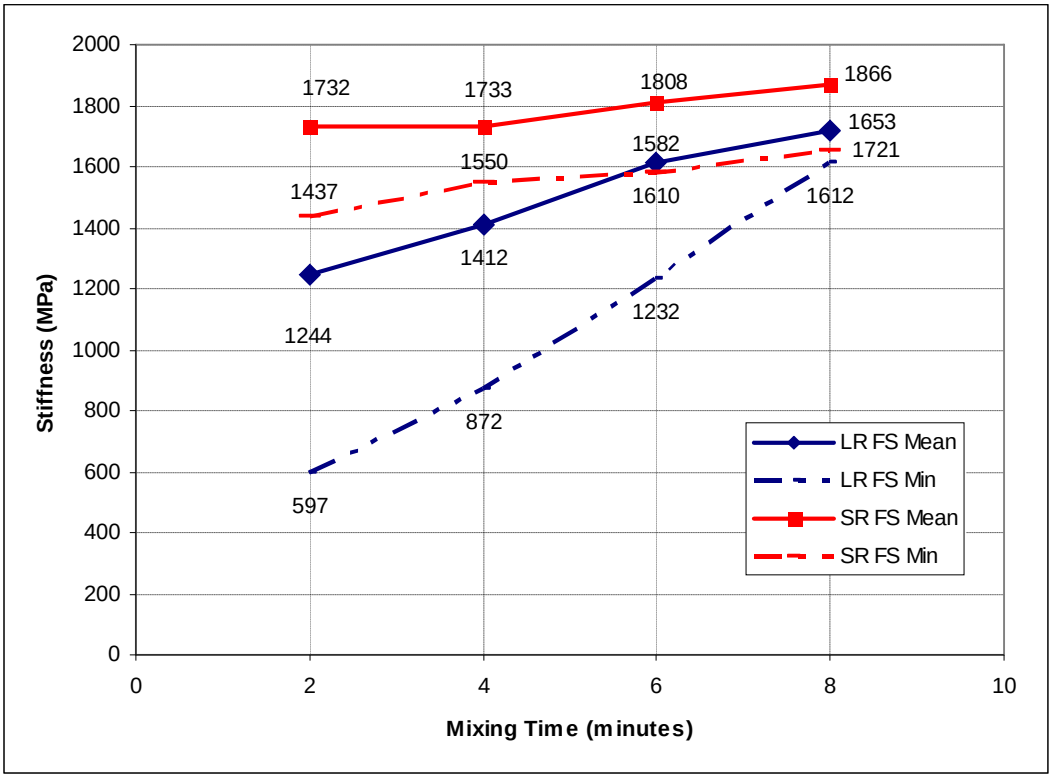


Figure 81: Stiffness range of LR and SR recycled mixtures manufactured by FS methods

Samples	Air Void Content (%)	Stiffness in Different Directions (MPa)				Mean Stiffness (MPa)	Standard Deviation	COV (%)
		1	2	3	4			
S1	5.6	1709	1459	1437	1451	1514	130	8.6
S2	5.4	1871	1714	1660	1697	1736	93	5.4
S3	4.6	2161	2048	2005	2008	2056	73	3.6
S4	5.2	1953	1825	1854	1867	1875	55	2.9
S5	5.5	1843	1754	1714	1682	1748	70	4.0
S6	6.1	2052	1772	1793	1821	1860	130	7.0
S7	5.1	1550	1447	1498	1446	1485	50	3.4
S8	4.7	1646	1528	1518	1472	1541	74	4.8
S9	4.9	1525	1658	1504	1583	1568	69	4.4
S10	5.0	1946	1922	1942	1927	1934	12	0.6

Table 45: Stiffness values of SR FS-2 specimens

Samples	Air Void Content (%)	Stiffness in Different Directions (MPa)				Mean Stiffness (MPa)	Standard Deviation	COV (%)
		1	2	3	4			
S1	6.2	1860	1702	1664	1698	1731	88	5.1
S2	5.7	1703	1681	1677	1667	1682	15	0.9
S3	5.4	1790	1674	1550	1661	1669	98	5.9
S4	5.2	1782	1766	1659	1673	1720	63	3.7
S5	6.1	1782	1619	1745	1632	1695	81	4.8
S6	6.0	1734	1712	1697	1601	1686	59	3.5
S7	6.6	1766	1706	1721	1698	1723	30	1.7
S8	4.3	1835	1779	1834	1889	1834	45	2.5
S9	5.5	1764	1714	1769	1803	1763	37	2.1
S10	5.3	1816	1831	1818	1831	1824	8	0.4

Table 46: Stiffness values of LR FS-4 specimens

6.5.4 Effects of mixing methods on stiffness

Mixing methods significantly affect stiffness distribution of hot recycled mixture. Figure 82 shows that stiffness of recycled mixtures manufactured by SHRP method is quite different from that of mixtures produced by field simulation (FS) method, especially for the recycled mixtures composed of large RAP. While stiffness of LR FS-2 mixture is relatively close to that of the BR mixture, the stiffness of LR SHRP and LR FS-8 are comparatively close to that of the CB mixture. In addition, in the SHRP method, the sizes of RAP contribute almost no effects on stiffness of recycled mixture. Figure 83 shows that the stiffness values of recycled mixture composed of large and small RAP by SHRP methods are approximately the same. On the contrary, RAP sizes significantly affect stiffness values of recycled mixtures manufactured by field simulation method (FS). This is due to the mixing mechanisms as these approaches determine how RAP and virgin materials interact with each other.

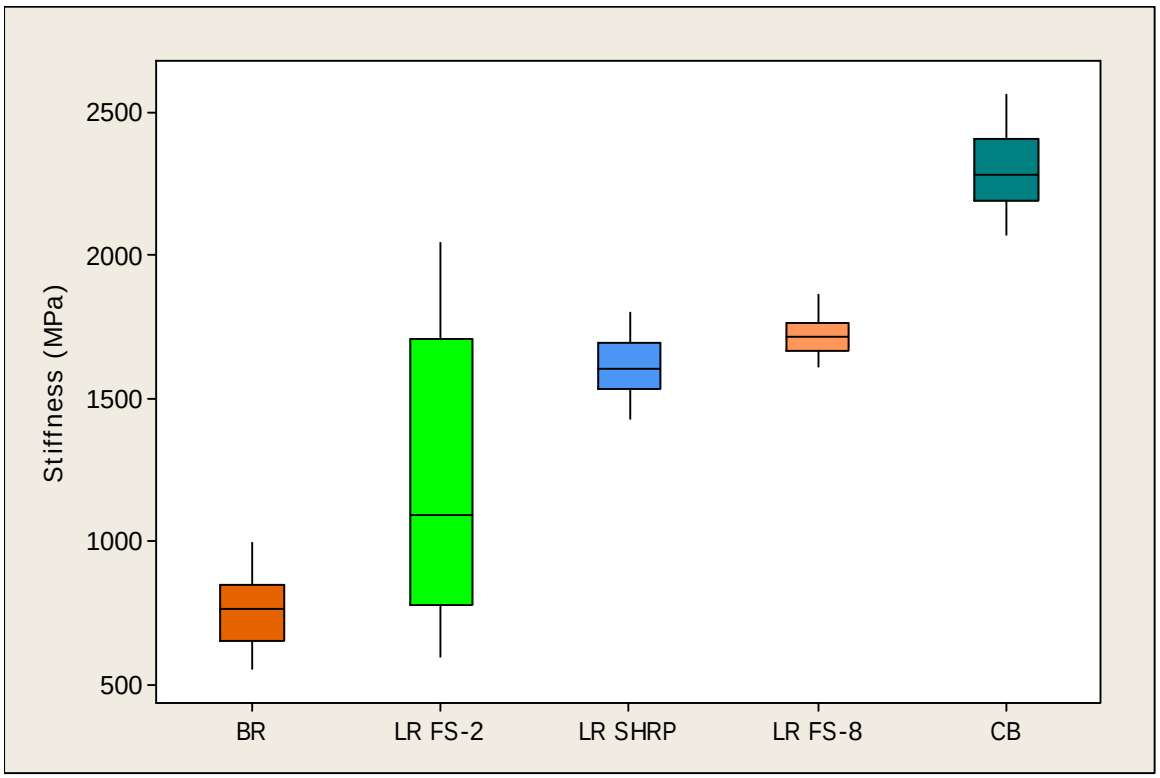


Figure 82: Inter-quartile stiffness ranges of control and LR mixtures manufactured by different methods

In the SHRP method, RAP lumps are conditioned in a force draft oven at 110^{o}C. The conditioning temperature is considerably higher than the softening point, 58^{o}C, of RAP

binder. Although the heat transfer process is significantly influenced by the size of material (Cutnell and Johnson, 2004), under the conditioning duration of 2 hours, both small and large sizes of RAP material are entirely heated. The heat that RAP materials absorb during the conditioning duration will soften the RAP binder and weaken the bituminous bond between RAP aggregate particles. Under the mechanical mixing effort, these RAP lumps are disintegrated into smaller pieces and will be blended and rejuvenated by virgin binder. This is why when using the SHRP method, mixtures composed of large and small RAP have approximately the same stiffness value (Figure 83).

The mixing mechanism of the field simulation (FS) method, on the contrary, is quite different from that of SHRP. In this approach, RAP materials at ambient temperature are mixed with superheated virgin aggregate. RAP lumps exist as unbreakable agglomerates under normal mechanical mixing at ambient temperature. However, under the heat transferred from superheated virgin aggregate, RAP binder will be softened and the bonds among RAP aggregate particles will be deactivated. The superheated temperature of virgin aggregate is 215^{o}C. Although this temperature is extremely higher than the softening point of RAP binder, a certain duration or critical duration is required so that the heat can be transferred from superheated virgin aggregate to completely heat up RAP materials.

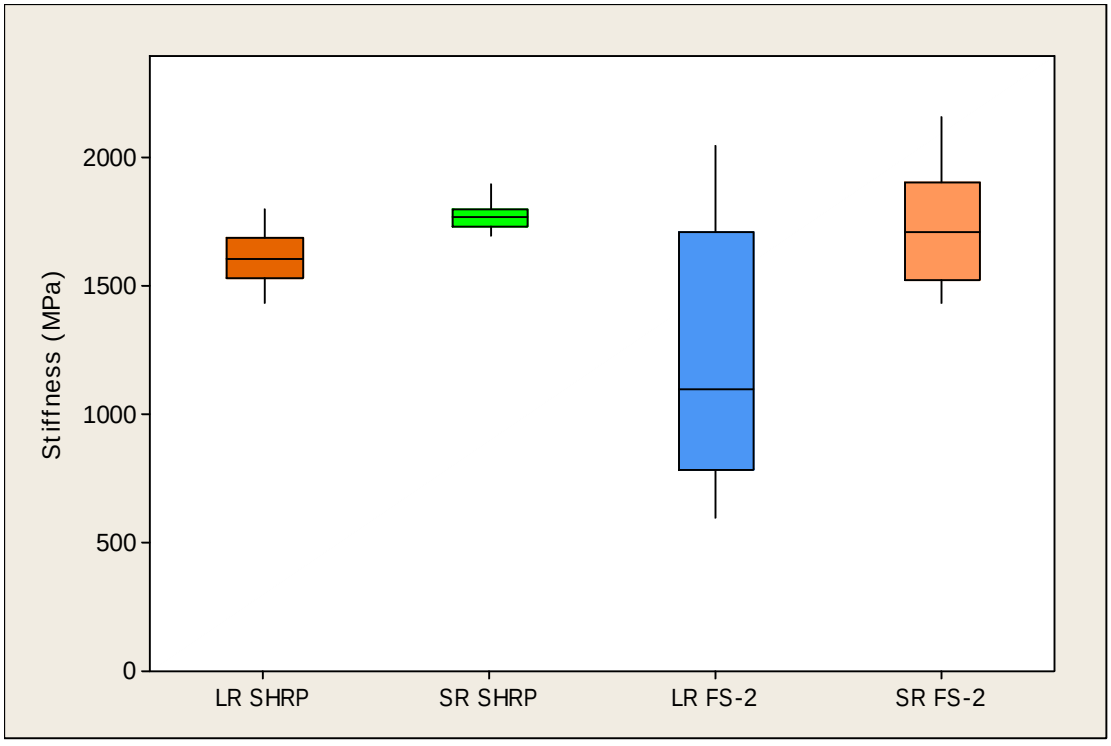


Figure 83: Inter-quartile stiffness ranges of SHRP mixtures and FS-2 mixtures

As the mechanical mixing efforts remains constant during the mixing process, mixing duration in FS method, or the amount of heat transferred from virgin aggregate, is a critical factor that determines the quality of hot recycled mixture. Due to the heat transferred from virgin aggregate, the bitumen bond between RAP aggregates will be gradually weakened until being overcome by mechanical mixing power. At this critical point, RAP lumps start to disintegrate. Due to the fact that heat transfer process is significantly influenced by the sizes of material (Cutnell and Johnson, 2004), the bigger the size of RAP lumps, the longer the critical mixing duration is required.

In the case that the mixing duration is not sufficient, RAP materials will be distributed all over the mixture at approximately original size. The incorporation between RAP and virgin binder in this case will depend primarily on RAP size. Due to the total surface area, the smaller the size of RAP, the more interaction between RAP and virgin binder occurs. If the large size of RAP is used, an inconsiderable proportion of RAP will interact with virgin binder and RAP materials will act as black rock. The longer the mixing time, the more RAP aggregate pieces are separated, and the more RAP binder will interact with virgin binder. Hence, when the mixing time is extended to 8 minutes, the stiffness of LR FS-8 approaches that of CB mixture. If the mixing duration is the same, recycled mixtures composed of small RAP will have better incorporations between RAP and virgin binder than large RAP mixtures.

The experimental data also indicates that SHRP method tends to overestimate the mechanical properties of hot recycled mixtures. The RAP extensive preheating duration in the SHRP method coincidently advances the incorporation between RAP and virgin materials, especially when large sizes of RAP materials are used. In addition, such a long preheating duration is by no means practical in the real industry due to the length constraint of the mixer and economical issues (Lee et al., 1983). Hence, field simulation (FS) method would better exemplify what occurs in the real industrial mixers.

The data in Table 38 show that stiffness of SHRP mixture is approximately similar to that of FS-4 or FS-6 mixtures. This is because in FS method, there is a critical period of time which is required to transfer the heat from superheated virgin aggregate to soften RAP materials. If the RAP/superheated virgin aggregate mixing duration is shorter than the required duration, the interaction between RAP and virgin binder of FS mixture will be less

than that of the SHRP mixture. Therefore, stiffness of FS mixture is certainly lower than that of SHRP mixture.

It is interesting that both methods, SHRP and FS, could not produce the recycled mixtures that possess the stiffness values approximately the same as that of the complete blending case. Figure 84 and Table 38 show that the mean stiffness of SHRP mixture, even when small RAP is used, is far different from that of complete blending mixture, 1773 MPa compared to 2294 MPa. By FS method, even at 8 minutes mixing time which is never practical in the industry, the mean stiffness is 1865 MPa. This finding is quite different to the result of McDaniel et al. (2000) where the properties of actual blending mixture (similar to SHRP method in this research) is the same as that of complete blending.

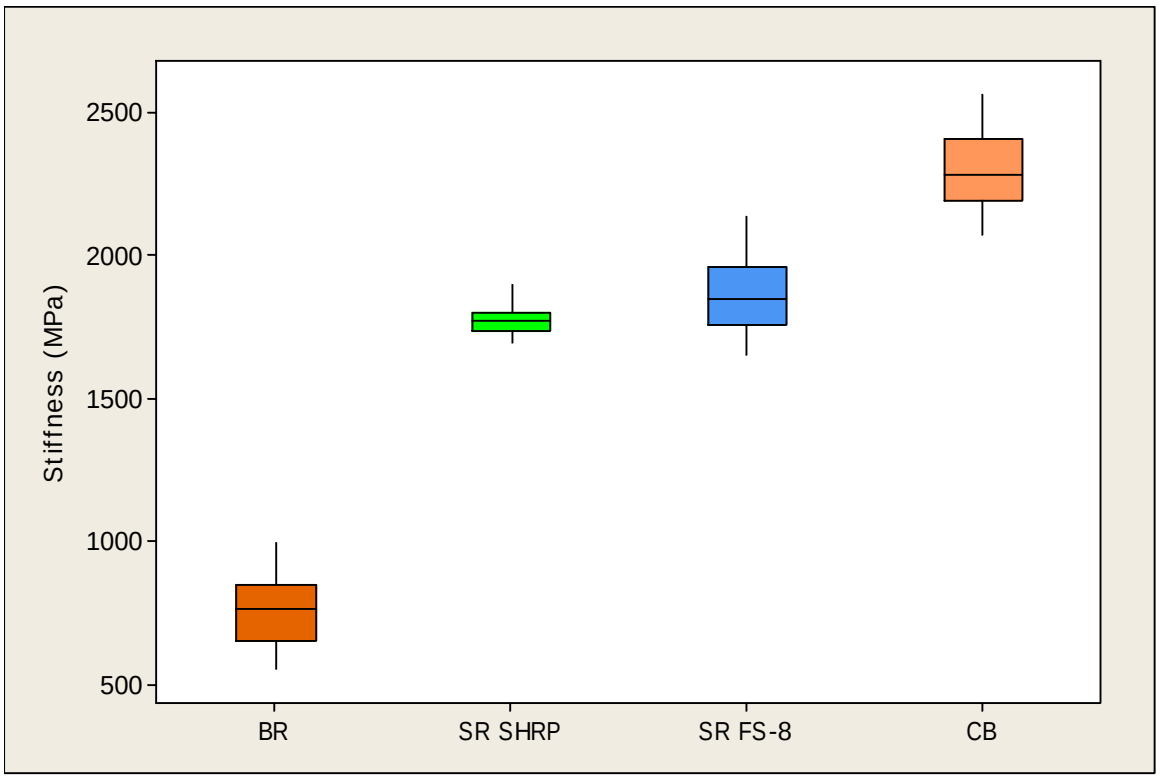


Figure 84: Inter -quartile stiffness ranges of control and SR mixtures manufactured by different methods

Theoretically, the complete blending situation will exist once all the RAP binder is activated and rejuvenated by virgin binder. If RAP lumps are entirely disintegrated into single pieces of aggregates, including also fine aggregate particles and filler, coated by RAP binder; and under mechanical mixing, virgin binder could cover every single piece of RAP binder-coated aggregate, the complete blending might occur. In this case, the stiffness

of recycled mixture will be approximately the same as that of complete blending mixture. However, this situation is hardly happens in reality. This is because mechanical mixing can disintegrate coarse aggregate from the RAP lumps. However, this process does not separate fine aggregates from RAP lumps, or especially, filler from filler mastic. Figures 55 and 56 show that after 8 minutes mixing time by the FS method, although the original size of RAP is reduced, RAP materials still exist as agglomerates. Consequently, there will be a proportion of RAP binder that is not activated and rejuvenated by virgin binder.

6.5.5 Effect of mixing equipment on stiffness

The heat supply in mixer A is controlled by the thermocouple attached on the mixing bowl. On the contrary, the temperature in mixer B is controlled by the temperature of the air inside the mixing apartment. Due to the difference in mixing operation, the temperatures of the loose recycled mixtures after mixing are also different. During the manufacture process, although the temperatures are set the same, the loose recycled mixtures manufactured by Mixer B always have considerably higher temperature than those produced by Mixer A. Therefore, a small experiment was carried out with the aim to eliminate the effects of differences in mixing temperature on the mechanical properties of recycled mixture. In this experiment, temperature is recorded by external thermocouple attached directly to the loose mixture during the mixing process. The results indicate that the setting temperature of Mixer B should be about 20^{o}C lower than that of Mixer A in order to produce the loose mixture with the same temperature.

	LR FS-2		LR FS-6		SR FS-2		SR FS-6	
	Mean	**COV (%)**	**Mean**	**COV (%)**	**Mean**	**COV (%)**	**Mean**	**COV (%)**
Mixer A	5.09	25.0	4.49	17.1	5.21	8.6	6.08	27.1
Mixer B	5.15	20.8	3.47	19.9	4.75	11.4	3.46	14.2

Table 47: Air void summary of recycled specimens manufactured by different method and equipments

Table 47 presents the summary of air void content and coefficient of variation of recycled mixtures manufactured by both Mixers A and B. The result shows that the air void contents are approximately similar except LR FS-6 and SR FS-6 mixtures produced by Mixer B which have slightly lower volumes of air void content.

The summary of stiffness values are shown in Table 48. The results show that for 2 minutes mixing time, the mean stiffness values of large RAP mixtures manufactured by both Mixer

A and B are slightly different. In addition, the stiffness values distribution has almost the same pattern as that of mixture manufactured by Mixer A. Table 49 and Figure 85 illustrate the relation among stiffness values, the location of specimens cored from roller-compacted slabs, and the stiffness values measured in different directions of LR FS-2 mixtures produced by Mixer B. Besides the general variation coefficient of stiffness being 29.2%, the stiffness values measured in different directions for the same specimens also vary substantially. In addition, this mixture has 20 stiffness values lower than 1200 MPa. The mean stiffness of this group, 1026 MPa, is quite close to 751 MPa of Black Rock (BR) mixture, indicates that there is inconsiderable interaction between RAP and virgin binder.

	Method	Mean	SD	COV (%)	Max	Min	Median
Mixer A (MA)	**LR FS-2**	1262	483	38.3	2049	597	1156
	LR FS-6	1610	197	12.2	1974	1232	1576
	SR FS-2	1732	204	11.8	2161	1437	1714
	SR FS-6	1808	96	5.3	2002	1582	1794
Mixer B (MB)	**LR FS-2**	1342	392	29.2	2048	752	1219
	LR FS-6	1690	77	4.6	1839	1533	1679
	SR FS-2	1771	74	4.2	1896	1631	1779
	SR FS-6	1825	63	3.5	1947	1702	1827

Table 48: Stiffness (MPa) of recycled specimens manufactured by different methods and equipment

When the mixing time is extended from 2 to 6 minutes, the interaction between RAP and virgin binder of large RAP mixture manufactured by Mixer B is far better than that of Mixer A. Although there is insignificant difference in the mean stiffness, 1610 MPa by mixer A and 1690 MPa by mixer B, the minimum stiffness value of Mixer B mixture is 1533 MPa compared to 1232 MPa of mixture manufactured by Mixer A. The minimum stiffness value of Mixer B mixture is almost the same as the median stiffness of Mixer A mixture, 1576 MPa (Table 48). In addition, the homogeneity of Mixer B mixture is also much better. Not only the general stiffness coefficient of variation but also the stiffness variations in each specimen (Table 50 and Figure 86) are lower than those of Mixer A mixture. This is because Mixer B is more efficient in than Mixer A. The tilt axis of Mixer B allows the material in the mixing apartment to move not only horizontally but also

vertically. In addition, Mixer B has a function that can reverse the mixing direction also enhances the homogeneity of the recycled mixture.

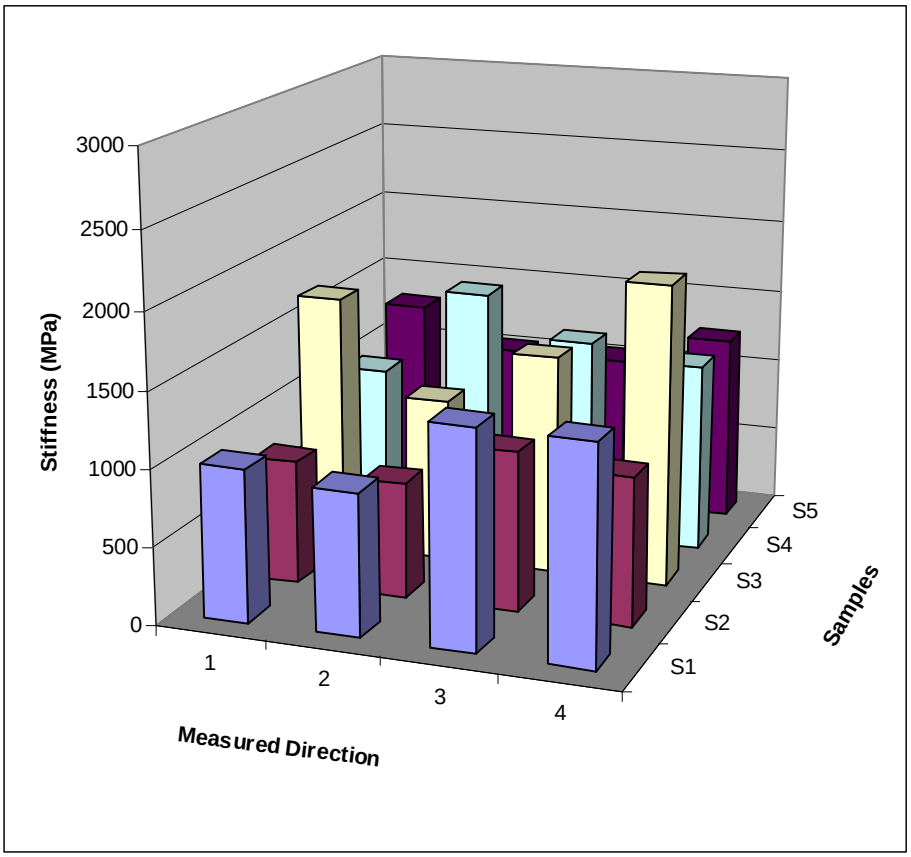
The data indicates that when the mixing time is not sufficient to deactivate all the bitumen bonds in RAP lumps, the effect of mechanical mixing can only distribute the RAP material all over the mixture. However, when the mixing duration is adequate (reaches critical point), mechanical mixing will separate RAP lumps and enhance the interaction between RAP and virgin binder. The more efficient the mechanical mixing, the higher the homogeneity level of recycled asphalt mixtures which are manufactured. The length of critical duration depends primarily on RAP size. The bigger the size of RAP, the longer the critical duration.

Samples	Air Void Content (%)	Stiffness in Different Directions (MPa)				Mean Stiffness (MPa)	Standard Deviation	COV (%)
		1	2	3	4			
S1	6	996	934	1422	1415	1192	263	22.1
S2	6.3	813	752	1044	969	895	135	15.1
S3	4.7	1703	1082	1448	1994	1557	387	24.9
S4	6.3	1018	1622	1349	1261	1313	249	19.0
S5	5.5	1294	1034	1042	1245	1154	135	11.7
S6	5.5	1179	1070	1115	1043	1102	59	5.4
S7	5.2	1093	1078	1194	1022	1097	72	6.6
S8	5.2	1002	1044	1967	1996	1502	554	36.9
S9	3.0	2028	1934	1473	1271	1677	363	21.6
S10	3.8	2048	1931	2005	1752	1934	131	6.8

Table 49: Stiffness values of LR FS-2 specimens – Mixer B

Samples	Air Void Content (%)	Stiffness in Different Directions (MPa)				Mean Stiffness (MPa)	Standard Deviation	COV (%)
		1	2	3	4			
S1	3.8	1832	1738	1739	1576	1721	107	6.2
S2	4.9	1566	1563	1533	1570	1558	17	1.1
S3	3.7	1727	1669	1655	1654	1676	35	2.1
S4	3.7	1744	1639	1662	1603	1662	60	3.6
S5	3.4	1733	1679	1648	1660	1680	36	2.1
S6	3.6	1714	1636	1634	1787	1693	73	4.3
S7	3.4	1772	1748	1634	1651	1701	69	4.1
S8	2.8	1647	1760	1678	1687	1693	48	2.8
S9	2.3	1839	1787	1754	1815	1799	37	2.1
S10	3.1	1762	1742	1730	1630	1716	59	3.4

Table 50: Stiffness values of LR FS-6 specimens – Mixer B



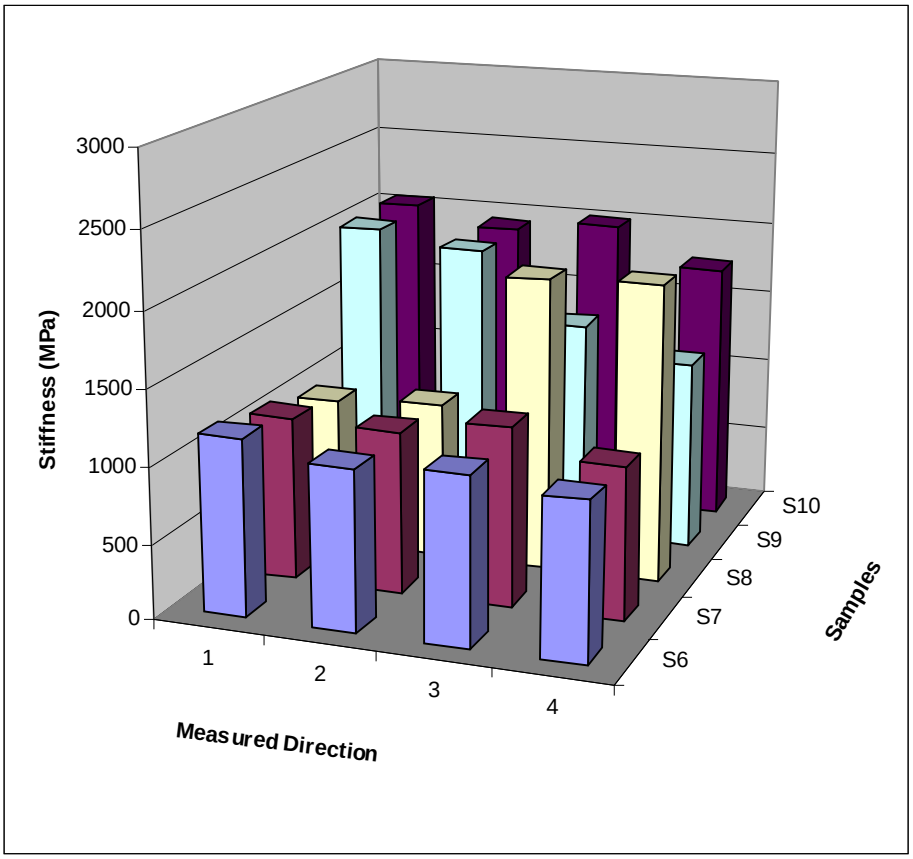
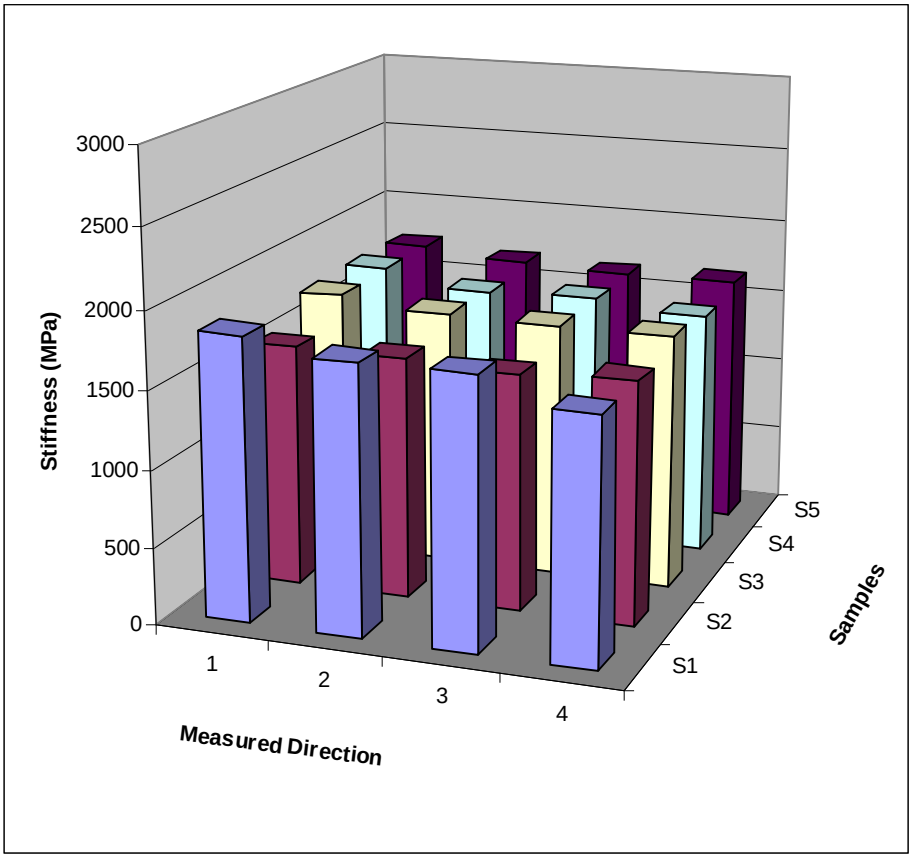


Figure 85: Stiffness versus core location and measuring direction of LR FS-2 mixture – Mixer B



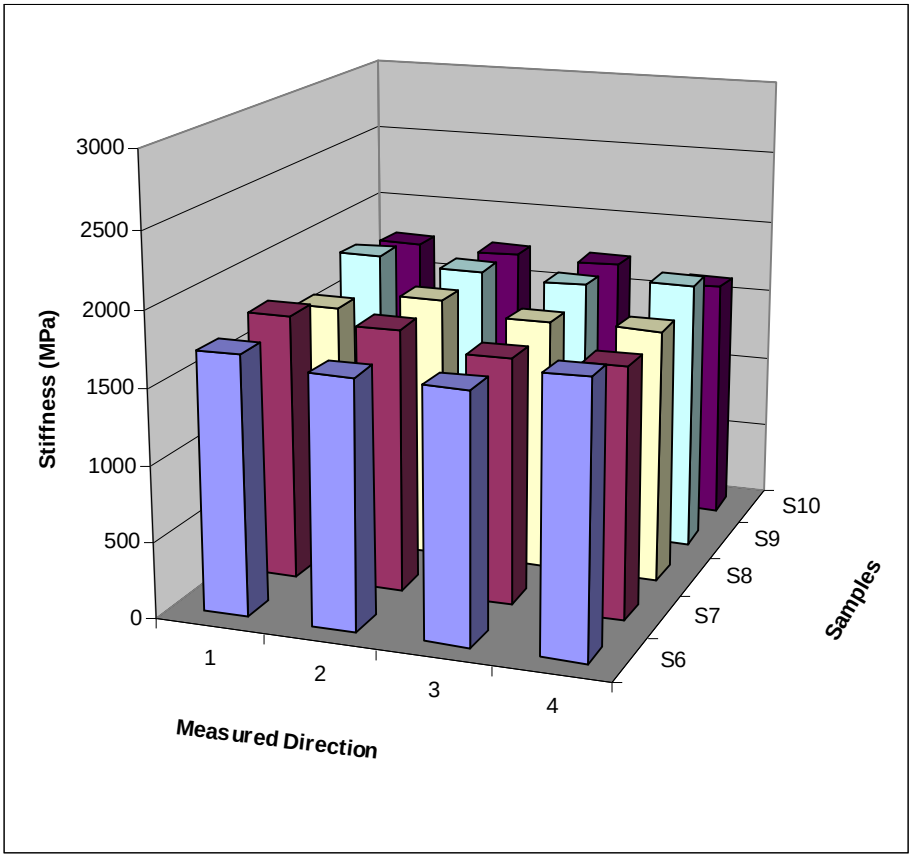


Figure 86: Stiffness versus core location and measuring direction of LR FS-6 mixture – Mixer B

6.5.6 Effects of mixing methods on RAP binder properties

The increase of stiffness may also be attributed to the aging of RAP binder. This is because during the mixing process, RAP binder might be aged more due to the exposure to high temperature from superheated aggregate as well as the mixer for a long period of time. An experiment has been carried out to investigate if there is any alteration to RAP binder properties during the mixing process. In this experiment, RAP lumps including both small (SR) and large sizes (LR), are mixed with superheated virgin aggregate for different mixing durations. The procedures are the same as those in the manufacture process of field simulation method (FS). For the SHRP method, RAP lumps are conditioned in the force draft oven at 110^{o}C for 2 hours.

After being extracted and recovered, rheological properties of processed RAP binders are studied by Dynamic Shear Rheometer (DSR). The thickness of testing specimen is 1000 μm for 25 mm plate and 2000 μm for 8 mm plate. Testing temperatures range from 5 to 45^{o}C for 8 mm plate and from 20 to 80^{o}C for 25 mm plate. Rheological testing is carried out under 0.8% strain to ensure bitumen responds in linear visco-elastic region. The test frequencies range from 0.1 to 10 Hz. Master-curves of these processed RAP binders are constructed from rheological data and compared to that of original RAP binder. Figures 87 and 88 show the complex modulus and phase angle versus log reduced frequency of original RAP and processed RAP binders. The data indicates there is no significant alteration to RAP binder after RAP lumps are mixed with superheated virgin aggregate by FS method. For the SHRP method, the RAP binder extracted from small RAP lumps shows noticeably more ageing compared to original RAP binder.

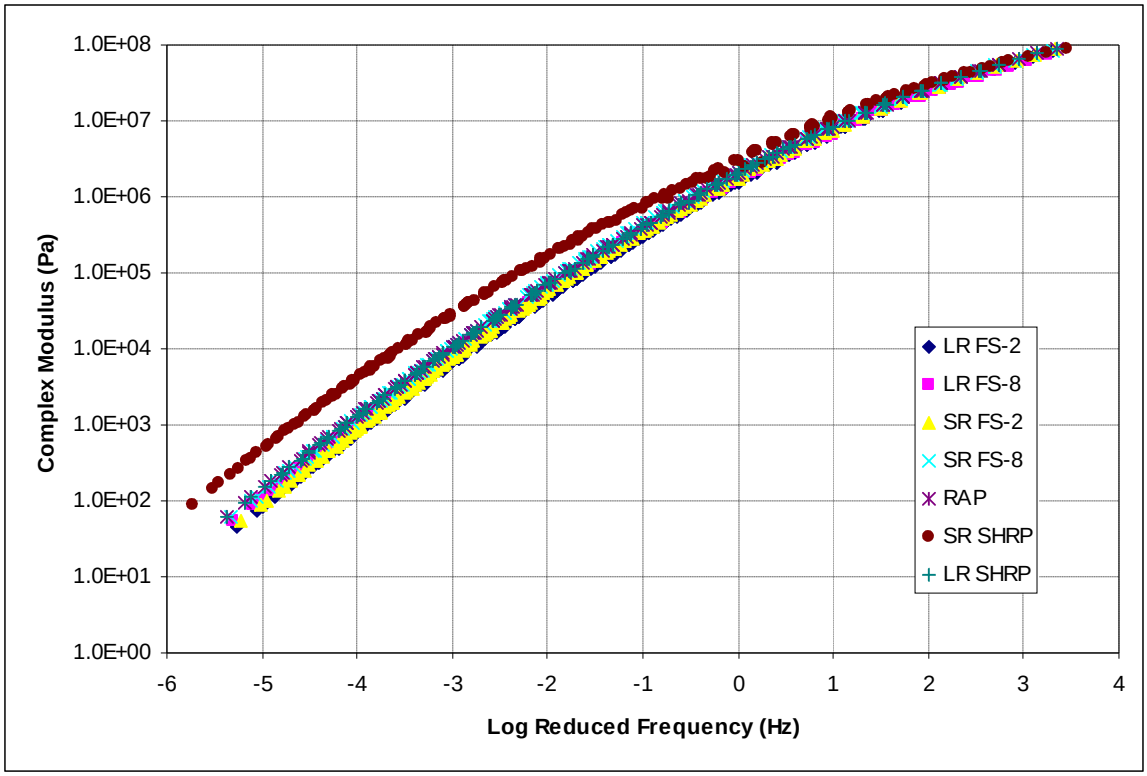


Figure 87: Complex modulus versus log reduced frequency of RAP binder before and after processed by different mixing methods

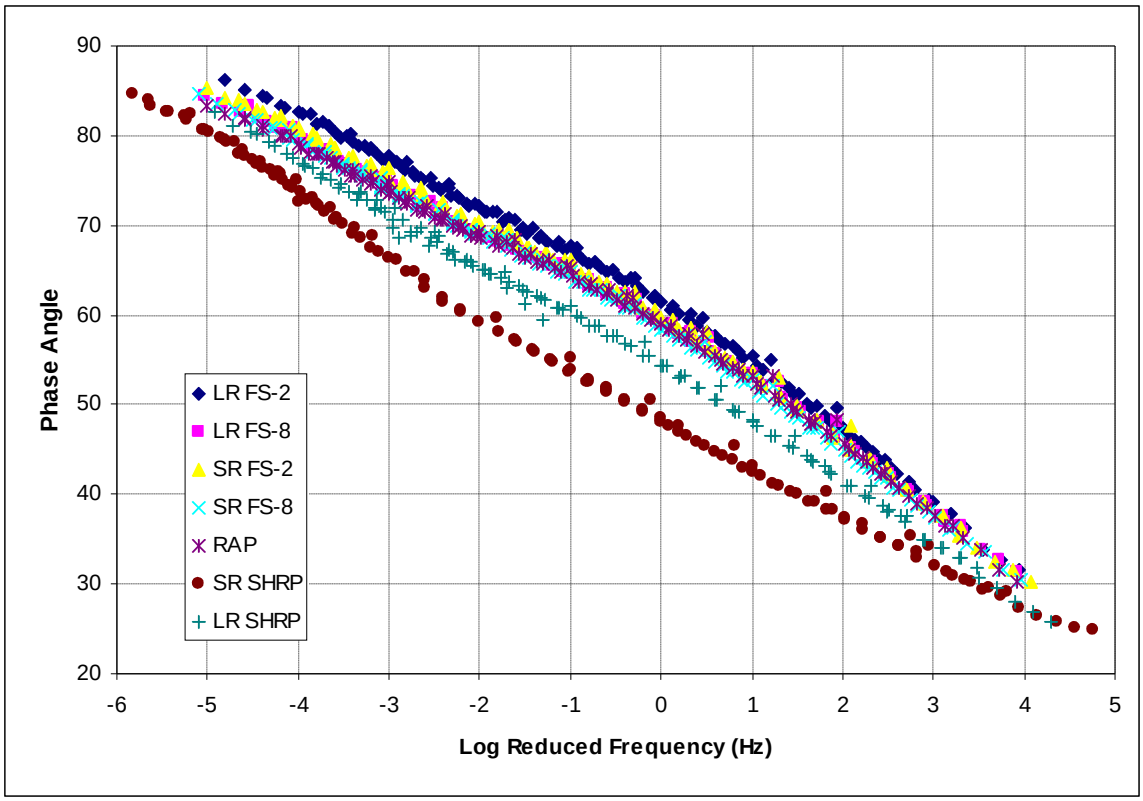


Figure 88: Phase angle versus log reduced frequency of RAP binder before and after processed by different mixing methods

6.6 Summary

Stiffness values of cylindrical specimens measured in different orientations indirectly express the heterogeneity of recycled mixture. The variation in stiffness values at different measured directions will be substantial for a heterogeneous mixture and minor in the case where the recycled mixture is homogeneous.

The mixing methods considerably affect the reaction between RAP and virgin binders as the mixing mechanisms determine how RAP and virgin binder are blended together. In the SHRP method, the mixing condition favourably enhances the interaction between RAP and virgin binders. The long preheating condition at a temperature considerably higher than the softening point of the RAP binder coincidently deactivates the bitumen bond between RAP aggregate particles. Under mechanical mixing, the RAP lumps are separated thereby increasing the contact areas between RAP and virgin binders.

On the contrary in the FS method, RAP is mixed with superheated virgin aggregate. The thermal energy transferred from virgin aggregate will help to increase the RAP temperature and weaken the bitumen bond between RAP aggregates. As the thermal transfer process is time dependent, the point that the bitumen bond is overcome by mechanical mixing effort is defined as a critical point. At this critical point, RAP lumps under mechanical mixing will start to disintegrate into separate pieces of aggregate coated by RAP binder. If the RAP/superheated virgin aggregate duration does not exceed the critical duration, the mechanical mixing effort only distributes the RAP all over the mixture at its approximately original size. In this case, the incorporation between RAP and virgin binder depends primarily on the original size of RAP. The smaller the original size of RAP materials, the better the interaction between RAP and virgin binder.

The increase in mixing duration significantly improves the homogeneity level of recycled mixture. Not only the stiffness variation among different specimens but also the variation of stiffness values measured in different directions for the same specimen significantly reduces. The homogeneity level is also substantially affected by the sizes of RAP material. For the same mixing effort, the recycled mixtures composed of small RAP are generally more homogeneous than those made from large RAP. The more homogeneous the recycled mixture, the more interaction between RAP and virgin binder. Therefore, the stiffness of

recycled mixture generally increases once the RAP/superheated virgin aggregate mixing duration is extended.

Although the increase of mixing duration has positive effects on the homogeneity, the complete blending between RAP and virgin binder assumed in the design process would never exist in the production of recycled asphalt mixtures. Qualitatively, even at favourable conditions of considerably long mixing times compared to those in the real asphalt mixing plant, there still exist a considerable proportion of RAP as lumps. Quantitatively, as RAP binder is not completely blended with virgin binder, the stiffness values of recycled asphalt mixtures are lower than those of Complete Blending mixture.

7 Effects of mixing methods on fatigue life of hot recycled asphalt mixtures

7.1 Introduction

This chapter investigates the effect of different mixing methods and RAP sizes on fatigue life of recycled mixtures. The materials used in this chapter are the same as those in Chapter 6. Fatigue life of recycled mixtures manufactured by different mixing methods are determined by indirect tensile fatigue test (BS-EN:12697-24, 2004). The fatigue lives of recycled mixtures are compared based on the parameters of the fatigue equations and the number of loading cycles to fatigue failure at 100 microsrain.

7.2 Materials preparation and testing plan

The materials for this experiment are those specimens used for ITSM (Section 6.3.1). After stiffness measurement, these specimens are subjected to indirect tensile fatigue test (ITFT) to determine the number of loading cycles to failure. The indirect tensile fatigue test is carried out under stress-controlled mode by Nottingham Asphalt Tester (NAT) at 20^{o}C. The rise time is 124 milisecond with the cyclic load pulse of 0.67 Hz. The failure criteria is the point where total vertical deformation of specimen reaches 9 mm (BS-EN:12697-24, 2004). The schematic of the indirect tensile fatigue test is illustrated in Figure 89.

The number of specimens tested for each set of material, for instance, LR FS-2, is 10. The target stress levels are selected to obtain a wide range of fatigue lives. The maximum is at least ten times greater than the minimum fatigue life (DD-ABF, 1996). Normally, for this experiment, the target stress levels vary from 100 to 400 kPa. However for Black Rock case with lower stiffness modulus, the range of stress level is from 50 to 200 kPa.

Before fatigue testing, stiffness under the same stress level that specimen will experience in the fatigue test is determined by indirect tensile stiffness test (DD-213, 1993). Conventionally, the stiffness is the average of two stiffness values at two perpendicular directions of specimen. However, due to the stiffness modulus values of recycled specimen varying considerably with different measuring directions, stiffness under certain stress level is measured at the direction that specimen has the lowest stiffness modulus. This is also the

direction for the fatigue test due to the assumption that failure will occur initially at the weakest direction.

Figure 89: Schematic of ITFT test

The initial maximum tensile strains at the centre of specimen are plotted against the relevant numbers of loading cycles to failure on logarithmic scales. The initial maximum tensile strain at the centre of specimen is calculated as follows (DD-ABF, 1996):

$$\varepsilon_{x,\max} = \frac{\sigma_{x,\max} \times (1+3\nu)}{S_m} \times 1000 \qquad \textbf{(22)}$$

Where: $\sigma_{x,\max}$ is the maximum tensile stress at the centre of specimen (kPa)

ν is Poisson's ratio (assumed to be 0.35)

S_m is the indirect tensile stiffness modulus at $\sigma_{x,\max}$ (MPa)

Based on the testing data of 10 specimens for each set of material, linear regression analysis using Least Squares method is applied to obtain the best-fitted equation for fatigue life. The

empirical relationship that is used for regression analysis is expressed as follows (Pell, 1973):

$$N_f = K_1(\varepsilon_i)^{K_2} \quad \textbf{(23)}$$

Where: N_f Number of load applications to failure at particular level of initial strain

ε_i Initial tensile strain

K_1, K_2 Material Coefficients

The fatigue lives of recycled asphalt mixtures are then compared to each other and to those of control mixtures to study the effects of different mixing protocols and RAP materials on fatigue life of hot recycled asphalt mixtures.

7.3 Results and analysis

The parameters of fatigue equations of control mixtures and recycled mixtures manufactured by different methods are summarized in Table 51. The R square values indicate that the empirical relationship (Equation 23) between number of loading cycles to failure and initial maximum strain at the centre of specimen fits the experimental data. As fatigue failure normally occurs between 30-200 microstrain range (Read, 1996), the numbers of loading cycles to failure at 100 microstrain of different mixtures are also extrapolated for comparison purposes (Table 52).

7.3.1 Control mixtures

Figure 90 illustrates the regressed fatigue lines of three control mixtures, BR, CB and CB-V. The results show that regressed fatigue lines of CB and CB-V mixtures are almost statistically the same. This is because the rheological properties of recycled bitumen for CB mixture is almost the same as that of 70/100 Pen binder (Section 6.3.1). However, due to the fact that 160/220 Pen is considerably softer than fully blended recycled binder and 70/100 Pen bitumen, CB and CB-V have longer fatigue life than that of BR mixture (Table 52). The results confirm the finding of Cooper and Pell (1974) that under stress-controlled mode, the mixture with the stiffer bitumen will provide longer fatigue life. In addition, the fatigue life of BR mixture is more stress dependent than that of CB and CB-V mixtures. The K2 values of CB and CB-V are approximately similar and extremely lower than that of the BR mixture.

7.3.2 Recycled mixtures

Figures 91 and 92 present the regressed fatigue lines of LR and SR recycled mixtures manufactured by different mixing protocols. The results show that for both LR and SR mixtures, the fatigue lines are slightly improved once the mixing time is extended. Although there are not considerable differences between these fatigue lines, the boundaries with 95% confidence of these regressed lines are extremely different, especially with LR mixture. Figure 93 shows that the boundary with 95% confidence of fatigue line of LR recycled mixture is significantly narrower once the mixing time increases from 2 to 8 minutes. This is due to the homogeneous level of recycled asphalt mixture. Actually, the variation in stiffness values is considerably reduced when the mixing duration is increased (Section 6.5.2). The results indicate that to increase mixing effort also means to improve the reliability of fatigue line of recycled asphalt mixture.

As more RAP and virgin binder can be interacted, the stiffness of recycled mixture generally increases once the mixing time is extended. This results in the substantial increase of fatigue life. Figure 94 illustrates the correlation between stiffness and fatigue life at 100 microstrain versus mixing times of recycled mixtures composed of large RAP material. The data clearly shows that when the mixing time increases, while the stiffness increases linearly, the fatigue life increases exponentially. Even for recycled mixture composed of small RAP material, while the stiffness increases slightly, there is a noticeable increase in fatigue life, approximately five times once the mixing time is extended from 2 to 8 minutes (Figure 95). The phenomena will be more pronounced if the fatigue lives of the recycled asphalt mixtures are extrapolated at 30 microstrain. However, the confidence with such a large extrapolation will be certainly low. The data indicates that a small increase in stiffness value can be associated with a tremendous extension of the fatigue life of recycled asphalt mixture.

In addition, the data also demonstrates that the fatigue line of recycled mixture is gradually less dependent on the initial maximum tensile strain or stress level. For recycled mixture composed of large RAP material, the mean K2 values reduced from -2.081 to -3.899 when the mixing time increases from 2 to 8 minutes (Table 51). In fact, the dependence of fatigue life on stress level gradually transforms from that of black rock to complete blending when the mixing time increases.

The size of RAP also significantly affects the number of loading cycles to fatigue failure of hot recycled mixtures. This is because to produce a hot recycled asphalt mixture with a certain level of homogeneity, the bigger the size of RAP material, the more mixing effort is required. In addition, the homogeneity and stiffness of recycled mixture are mutually correlated. In fact, with the same mixing efforts, recycled mixtures composed of large RAP generally have lower stiffness than that of small RAP mixtures (Section 6.5.3). The results from fatigue testing also demonstrate that with the same mixing effort, recycled mixtures composed of large RAP have much lower fatigue life than that of small RAP mixtures (Figure 96).

Mixing methods also have considerable effects on fatigue life of recycled mixture as the mixing mechanisms determine how RAP and virgin materials are blended with each other. The data from fatigue test is in an agreement with stiffness data. The fatigue lives of SHRP mixtures are approximately the same as those of mixtures manufactured by FS method with 4 to 6 minutes mixing time (Table 52). In addition, the fatigue lives of recycled asphalt mixtures are substantially lower than those of the complete blending (CB) case. Even when small RAP material is used with 8 minute mixing time, the fatigue life of SR FS-8 mixture is just about half of the CB mixture. This supports the statement in Section 5.5.1 that the complete blending between RAP and virgin binder assumed in the design would never occur in the industry.

	R	K1			K2		
	Square	Min	Mean	Max	Min	Mean	Max
LR FS-2	0.73	8.28E+05	2.92E+08	1.03E+11	-3.097	-2.081	-1.066
LR FS-4	0.85	1.94E+07	2.35E+09	2.79E+11	-3.275	-2.441	-1.067
LR FS-6	0.95	4.69E+09	1.29E+11	3.47E+12	-3.698	-3.117	-2.536
LR FS-8	0.99	1.20E+12	1.07E+13	6.31E+13	-4.278	-3.899	-3.519
LR SHRP	0.91	2.65E+08	1.71E+10	1.10E+12	-3.468	-2.753	-2.039
SR FS-2	0.96	7.00E+09	1.23E+11	2.18E+12	-3.634	-3.132	-2.631
SR FS-4	0.94	2.79E+09	1.21E+11	5.26E+12	-3.757	-3.101	-2.446
SR FS-6	0.98	6.65E+10	5.85E+11	5.15E+12	-3.694	-3.314	-2.934
SR FS-8	0.98	6.78E+11	6.18E+12	5.65E+13	-4.088	-3.699	-3.311
SR SHRP	0.95	5.81E+10	2.49E+12	1.07E+14	-4.268	-3.619	-2.971
CB-V	0.94	2.58E+11	2.45E+13	2.34E+15	-4.705	-3.907	-3.108
CB	0.97	8.71E+11	2.04E+13	4.75E+14	-4.462	-3.896	-3.331
BR	0.96	3.73E+06	1.94E+07	1.01E+08	-1.892	-1.610	-1.328

Table 51: Parameters of fatigue equation at 95% confidence of control and recycled asphalt mixtures manufactured by different mixing methods

	Fatigue life at 100 microstrain
LR FS-2	20038
LR FS-4	30807
LR FS-6	74896
LR FS-8	170696
LR SHRP	53345
SR FS-2	67056
SR FS-4	75659
SR FS-6	137838
SR FS-8	247131
SR SHRP	143872
CB-V	377413
CB	327959
BR	11713

Table 52: Extrapolated fatigue life at 100 microstrain of recycled asphalt mixtures manufactured by different mixing methods

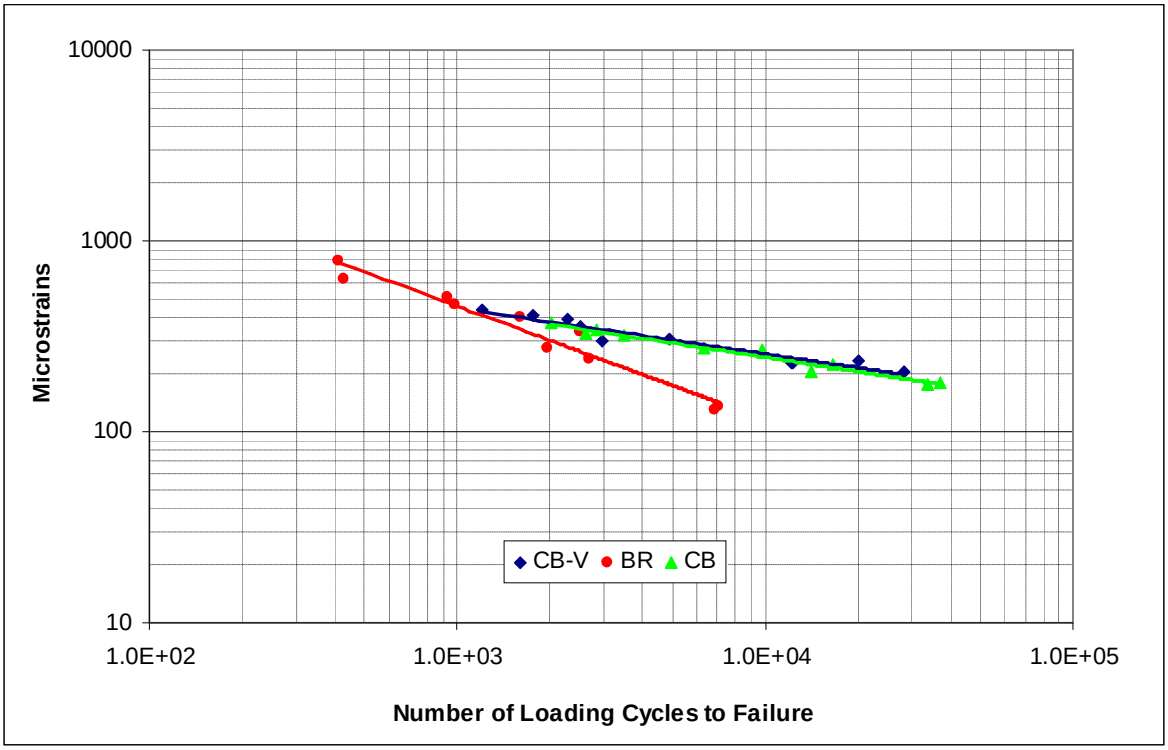


Figure 90: Fatigue lines of control mixtures

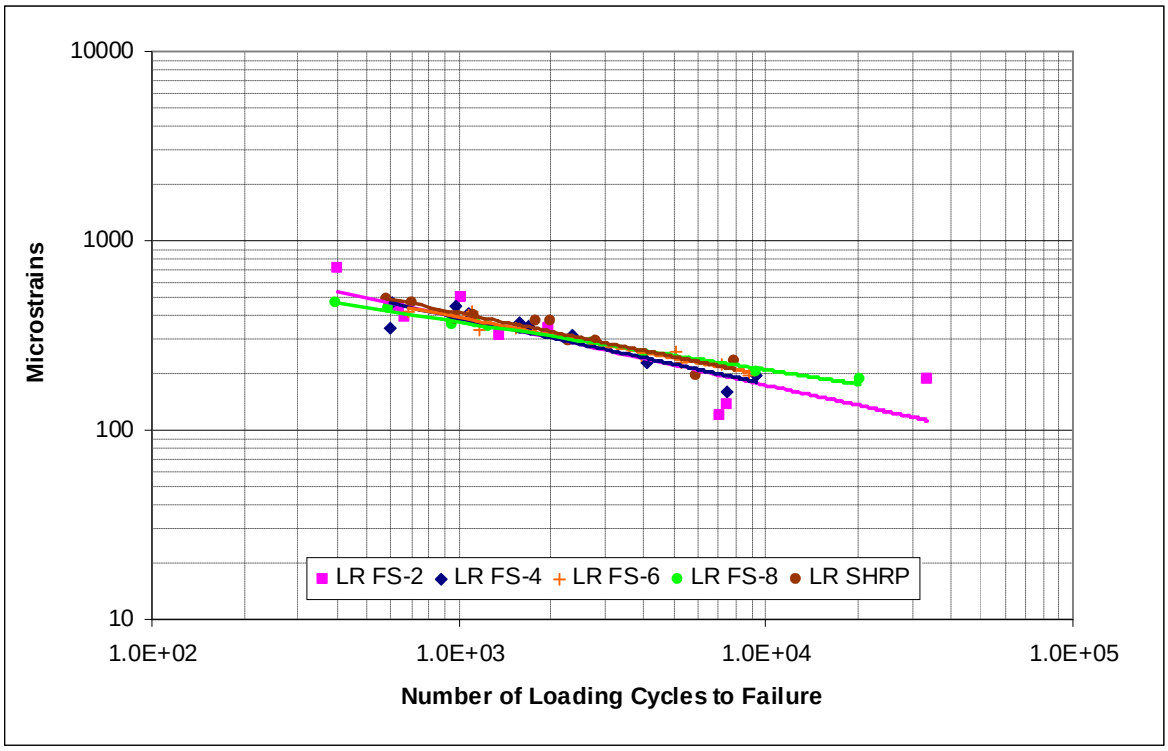


Figure 91: Fatigue lines of LR mixtures manufactured by different methods

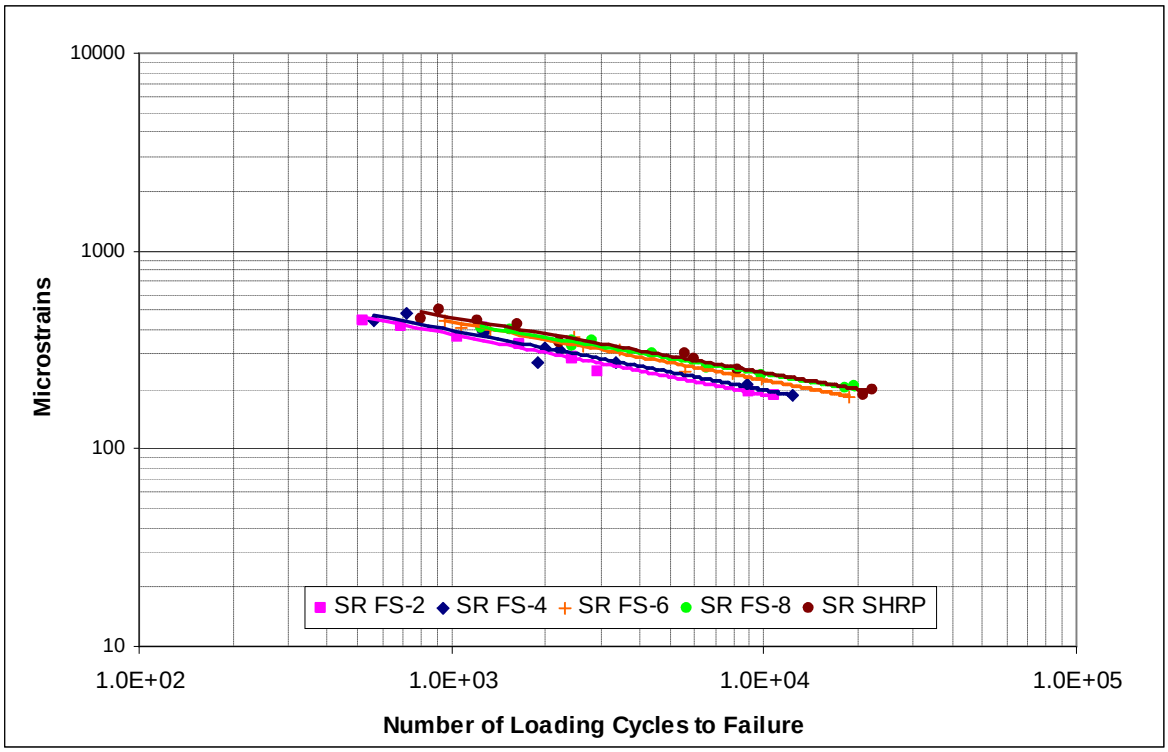


Figure 92: Fatigue lines of SR mixtures manufactured by different methods

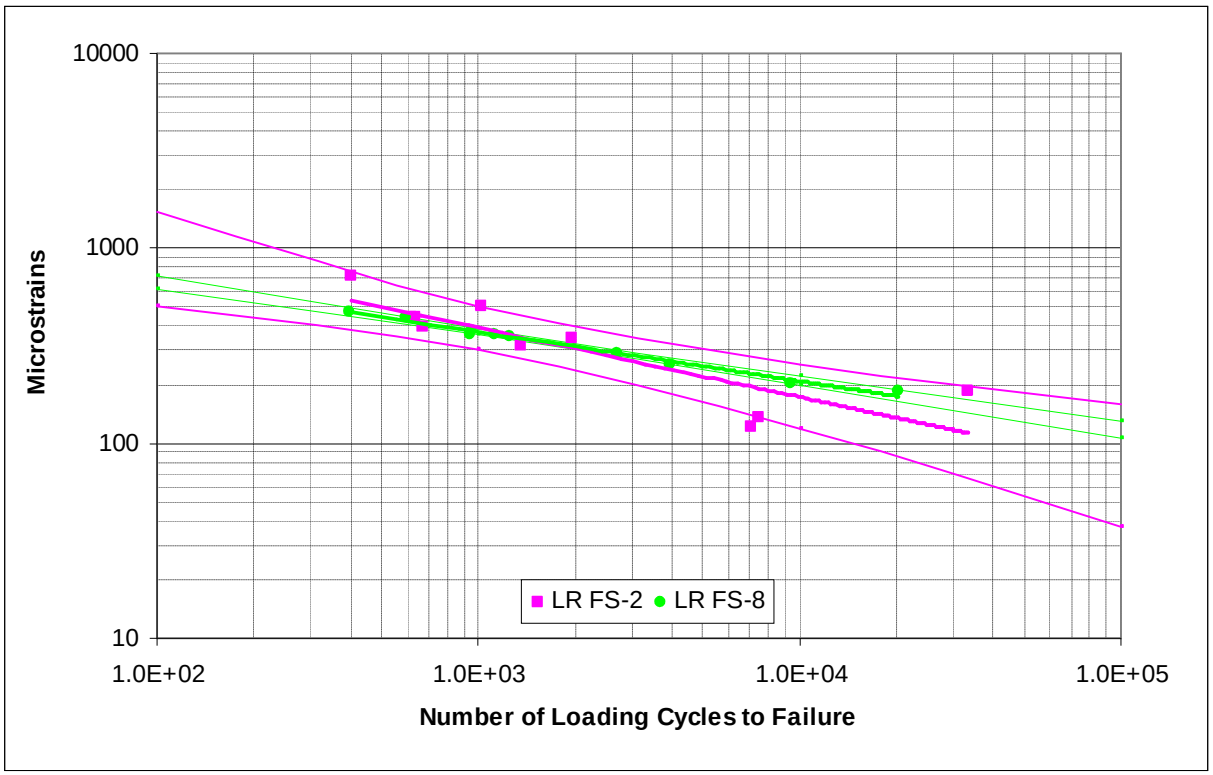


Figure 93: Fatigue lines with boundaries of 95% confidence interval of LR FS-2 and LR FS-8 mixtures

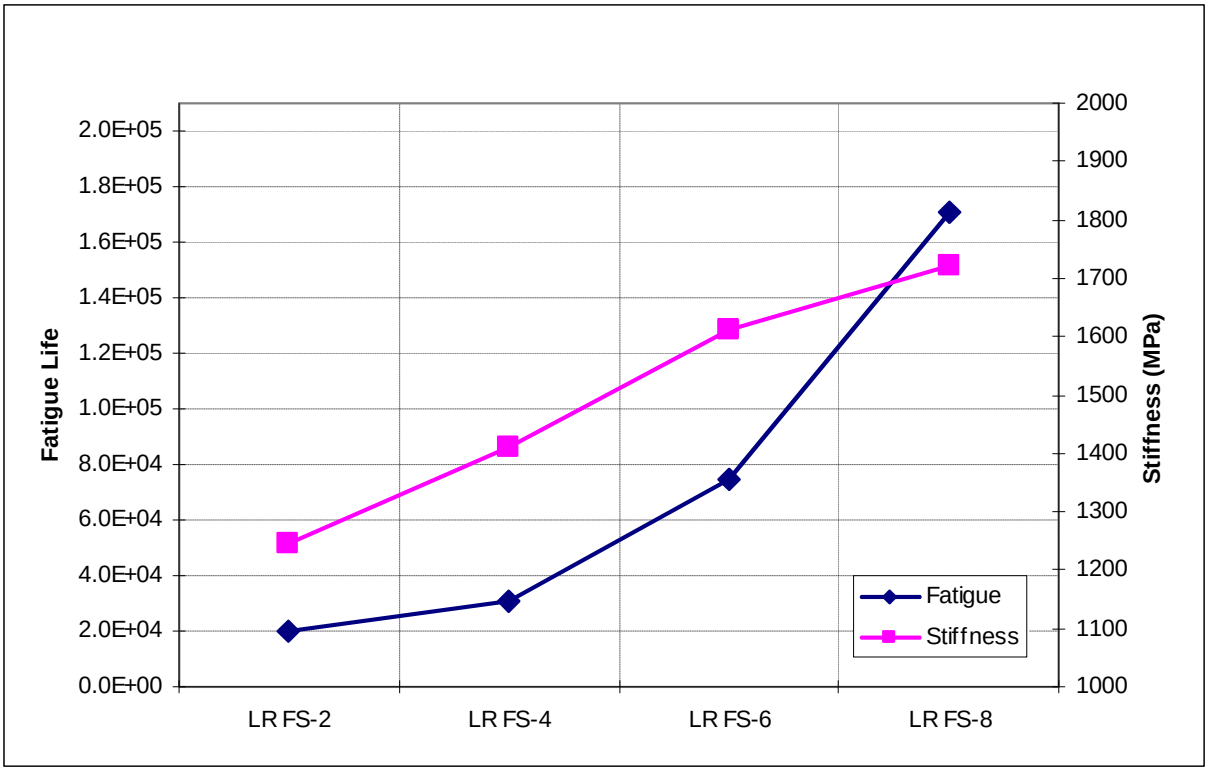


Figure 94: Fatigue life at 100 microstrain and stiffness versus different mixing time of LR mixtures

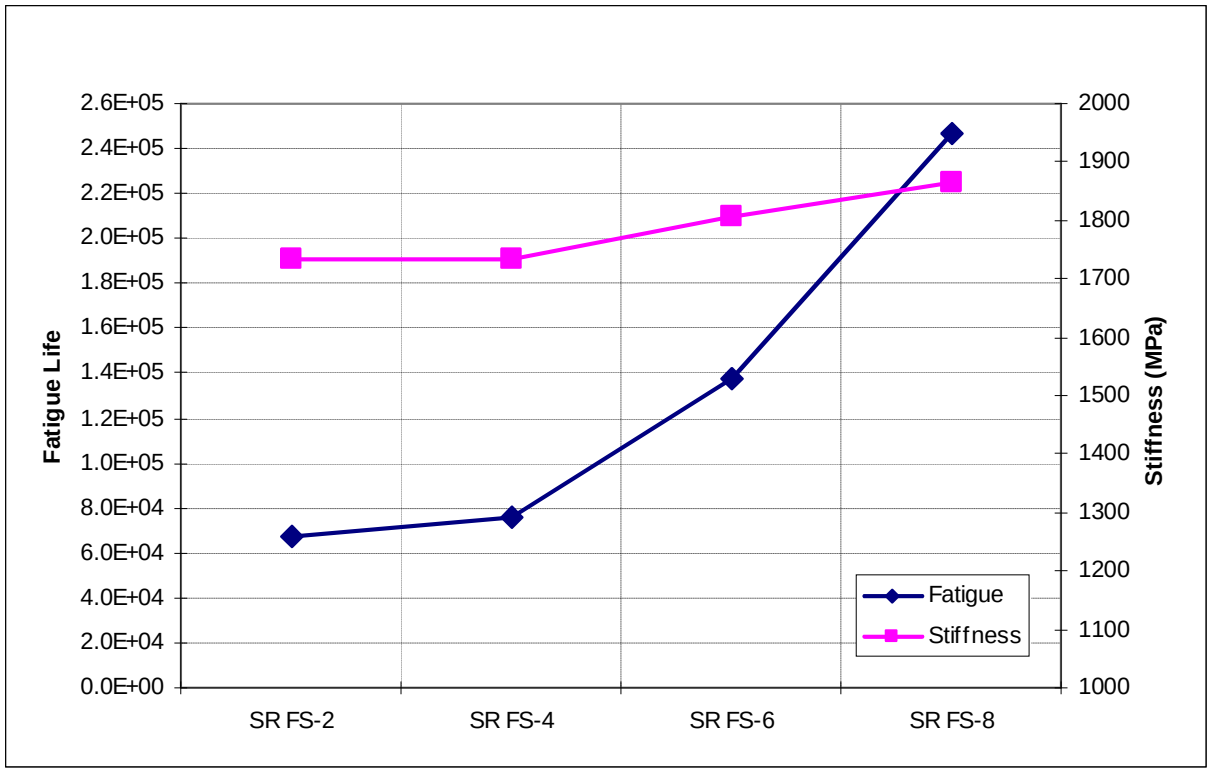


Figure 95: Fatigue life at 100 microstrain and stiffness versus different mixing time of SR mixtures

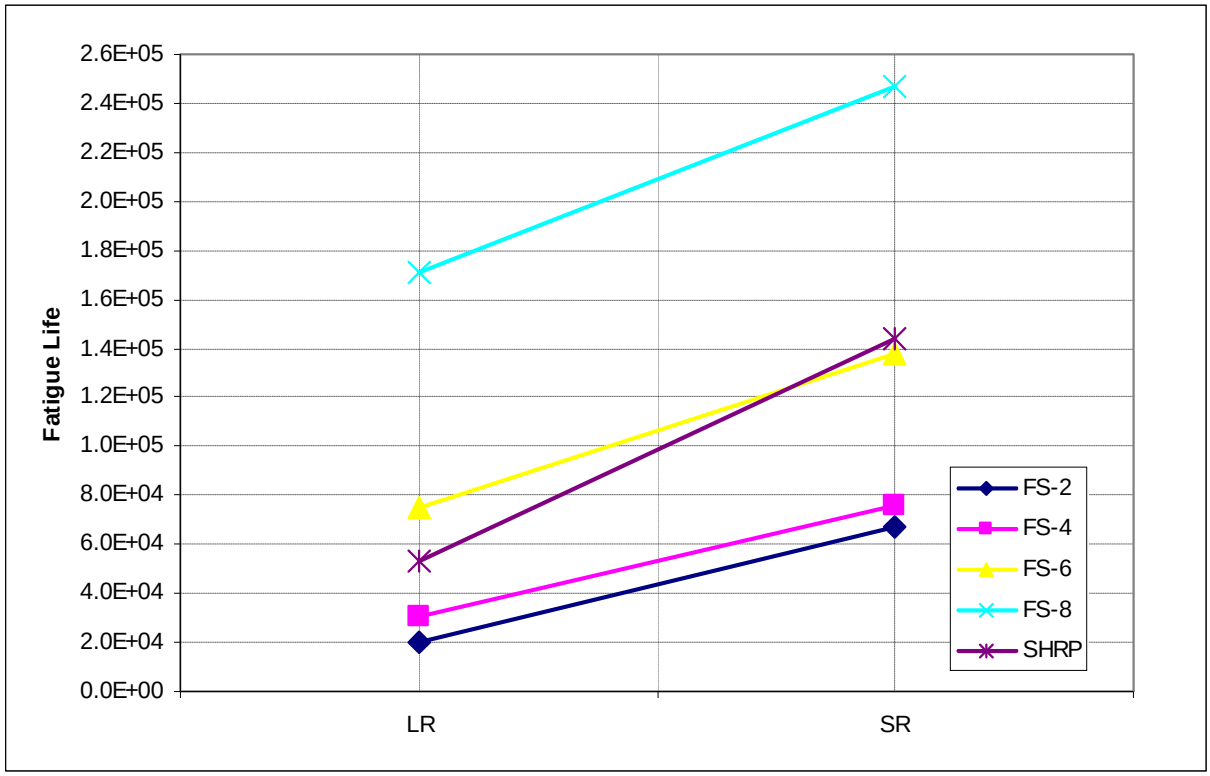


Figure 96: Relation between RAP sizes and fatigue life at 100 microstrain of recycled mixtures manufactured by different mixing methods

8 Effects of mixing methods on permanent deformation of hot recycled asphalt mixtures

8.1 Introduction

This chapter studies the effect of different mixing methods on resistance to permanent deformation of recycled mixtures. The material preparation is the same as that in Chapter 6. Only large RAP material is used in this experiment. The resistance to permanent deformation of recycled mixtures is determined by repeated loading axial test . To eliminate the effect of air void content, the resistances to permanent deformation of recycled mixtures are compared based on rutting characteristic after densification stage.

8.2 Materials preparation and testing plan

The materials for determining the resistance to permanent deformation of hot recycled mixtures are summarized in Table 53. Recycled mixtures are manufactured by two different methods, field simulation (FS) and the SHRP method. Only large size of RAP is used in this experiment. The proportion of RAP is also 40%. In FS method, RAP/superheated virgin aggregate varies from 2 to 8 minutes. There are also two control mixtures presenting the "Black Rock" and "Complete Blending" cases. The manufactures of theses mixtures are similar to the procedures in Section 6.3.1.

		RAP/Virgin aggregate mixing duration (minutes)			
LR	FS	2	4	6	8
		×	×	×	×
	SHRP	×			

Table 53: Test plan to study the effects of different mixing methods on resistance to permanent deformation

The resistance to permanent deformation is determined following the procedure in DD 226:1996. The test is conducted at 40^{o}C and under repeated axial dynamic load conditions. Each load pulse comprises of 1 second for load application and 1 second for the rest period. The magnitude of stress level is 100 kPa. The number of load applications that the specimen will experience is 3600. Similar to stiffness test, permanent deformation determination is implemented 15 days after the day of compaction. After manufacture, specimens are stored in a cabinet at a temperature of 20^{o}C. Before testing, specimen is

conditioned at testing temperature for at least 8 hours. In addition, to minimize the friction between surfaces of specimen and testing plates, surfaces of specimen are coated evenly and thinly with silicone grease and graphite flakes. Figure 97 illustrates the schematic of RLAT test to determine the resistance of mixture to permanent deformation.

During the test, accumulated vertical deformations are recorded after each load application. Permanent deformation is then plotted against number of loading applications that the specimen experiences. Permanent deformation patterns of recycled mixtures manufactured by different mixing methods are compared to each other to study the effects of mixing methods on deformation resistance. The deformations of recycled mixtures are also compared to those of control asphalt mixtures to study how different the properties of recycled mixtures are to those assumed in the design process.

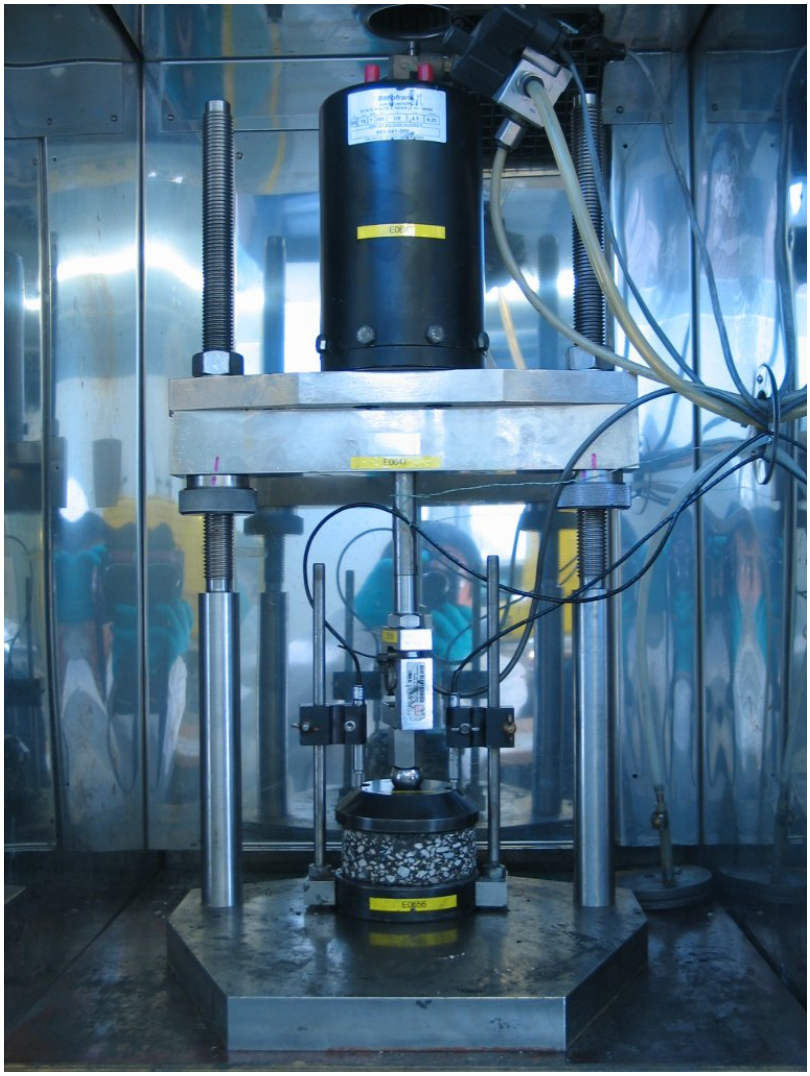


Figure 97: Schematic of RLAT test to determine resistance to permanent deformation

8.3 Results and discussion

The permanent deformation behavior of asphalt mixture under creep test conditions is normally divided into three stages (Bernasconi and Piatti, 1978):

- Primary stage: in this stage, the volume of specimen under the load decreases. This will consequently cause an increase in the density. The primary stage is also called densification in the other literature (Bahuguna et al., 2006). During this stage, although the accumulation of vertical strain increases rapidly, the permanent deformation per each loading cycle decreases.
- Secondary stage: the secondary stage starts when the permanent deformation per loading cycle reaches approximately constant value. In this stage, the volume decreases due to the load will be equal to the volume increases in the adjacent areas. This stage represents the shear deformation and is considered to be the primary deformation behavior of asphalt mixture (Sousa et al., 1991).
- Tertiary stage: the vertical strain per loading cycle increases rapidly again to failure.

However, under the condition of repeated load axial test with a total of 3600 loading cycles, the results just represent the densification and a part of the secondary stage. Figure 98 is an example of the permanent deformation versus the number of load application of LR FS-2 mixture. The data shows that the primary stage, or densification, occurs during the first 2000 cycles. During this stage, accumulated permanent deformation increases rapidly. On the contrary, during the secondary stage (after 2000^{th} load application), the accumulated vertical deformation has a linear relationship with the number of loading cycles.

The effect of air void content on permanent deformation has been found in previous literature (Sousa et al., 1991). Air void content plays a very important role in the primary stage or densification. In this experiment, generally under 3600 loading applications, the test data shows that deformation caused by densification accounts for a considerable part. If the permanent deformations at the 3600^{th} load application are used for the purpose of comparison, the result might be tremendously dependent on the air void content. In addition, the air void contents of testing specimens are always hard to control even in

laboratory manufacture. The permanent deformations and air void contents data is summarized in Table 54.

	Sample Number	Air Void (%)	Deformation (%)
LR FS-2	1	4.12	3.20
	2	4.73	3.05
	3	5.18	2.64
	4	6.77	5.18
	5	6.40	3.53
LR FS-4	1	5.38	4.19
	2	5.50	3.86
	3	5.54	3.58
	4	5.50	3.20
	5	6.07	3.19
LR FS-6	1	5.38	4.00
	2	5.83	3.12
	3	4.40	3.18
	4	3.91	3.61
	5	4.93	3.91
LR FS-8	1	5.46	3.28
	2	5.58	3.29
	3	5.42	3.24
	4	5.83	2.82
	5	6.36	3.00
LR SHRP	1	7.58	2.74
	2	4.20	2.81
	3	4.89	3.42
	4	4.77	4.03
	5	5.14	3.83
CB	1	3.26	2.67
	2	4.32	2.74
	3	4.12	2.29
	4	3.30	3.51
	5	3.59	3.50
BR	1	5.79	4.34
	2	6.24	4.27
	3	6.20	4.54
	4	5.38	4.77
	5	6.93	4.85

Table 54: Permanent deformation data of control and recycled specimens manufactured by different mixing methods

However, air void content will have insignificant effects on secondary stage as the deformation in this stage occurs without volume change. Therefore, the coefficient of the linear relationship between permanent deformation and number of load application in secondary stage can be used as a rutting indicator. The higher the value of the rutting

indicator, the lower the resistance to permanent deformation. For hot recycled asphalt mixtures, comparisons between rutting indicators might reveal the effects of mixing efforts on the resistance to permanent deformation. As all the mixture variables are deliberately controlled the same, the hypothesis is under mixing effort, rutting indicator might be altered in relation with the incorporation between RAP and virgin binder. Actually, rutting indicator will increase unless under mixing effort, integration between RAP and virgin binder is enhanced and vice versa.

The rutting indicators of control and recycled mixtures manufactured by different mixing methods are shown in Figure 99 and Table 55. Rutting indicator is the coefficient of the equation expressing the linear relationship between accumulated permanent deformation and number of load cycles after 2000^{th} load applications. The results indicate that RAP/superheated virgin aggregate mixing duration significantly affects the resistance to permanent deformation of recycled mixtures. The longer the mixing time, the less the susceptibility of recycled mixtures to permanent deformation under repeated loading conditions. For 2 minutes mixing duration, there is a proportion of the rutting indicators that are close to that of the BR case. On the contrary, rutting indicators of recycled mixture mixed for 8 minutes are close to those of the CB case (Figure 99). This is because the longer the mixing time, the more integration between RAP and virgin binder results in the increase of mixture stiffness. In addition, as recycled mixture become more homogeneous, rutting indicator variation also decreases. The coefficient of variation substantially decreases from 49% to 10% once the mixing time is increased from 2 to 8 minutes.

The data also indicates that mixing method significantly affects the resistance to permanent deformation of recycled mixtures. Recycled mixture manufactured by the SHRP method generally has better resistance to permanent deformation than those of FS mixtures (Figure 99). However, even in favourable conditions that never exist in the asphalt production industry, for instance, 2 hour preheating RAP at 110^{o}C of SHRP or 8 minutes mixing time in field simulation (FS) method, the resistance to permanent deformation of recycled mixture never reaches that of the complete blending (CB) mixture.

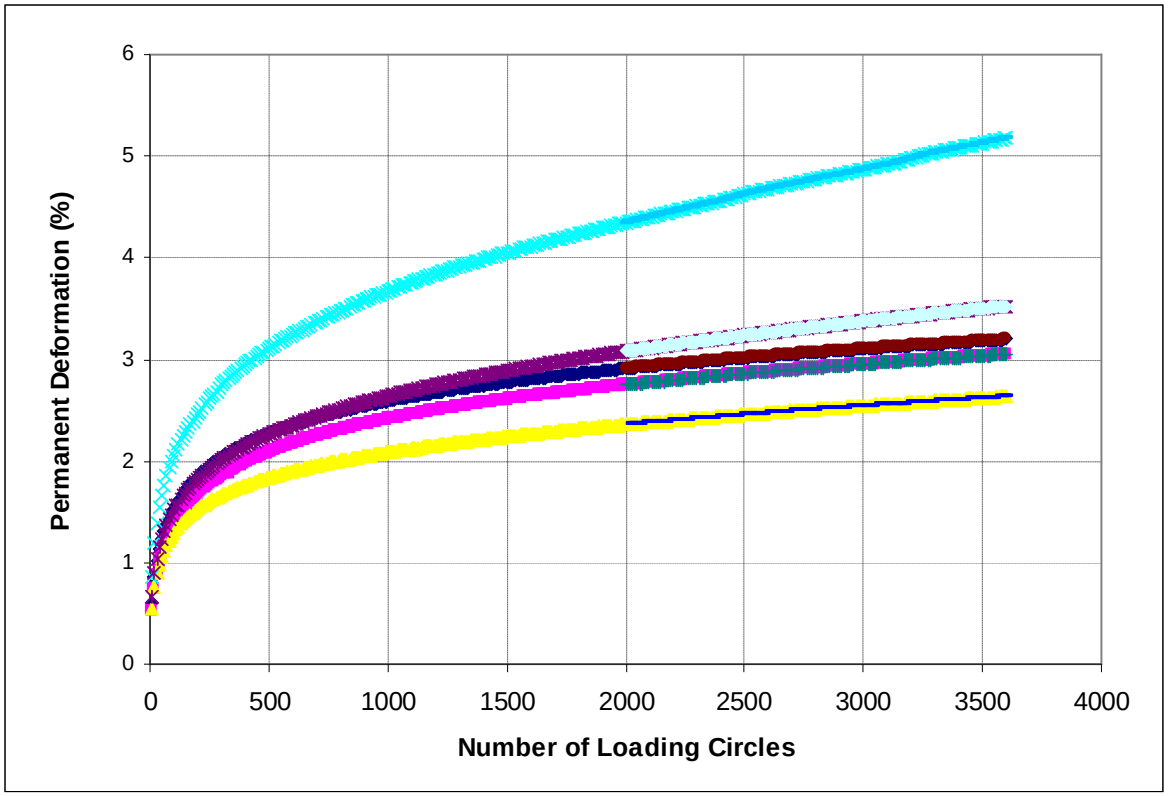


Figure 98: Permanent deformation versus number of loading application of LR FS-2 specimens

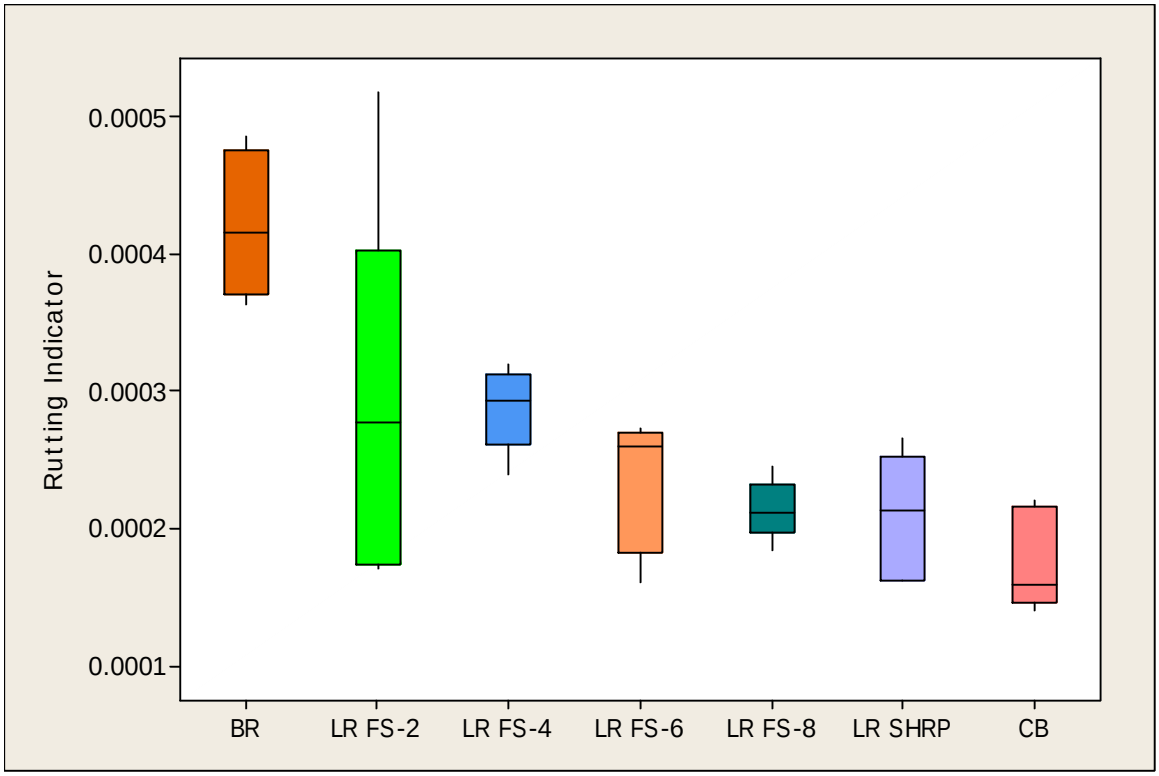


Figure 99: Inter-quartile rutting indicator ranges of control and recycled specimens manufactured by different mixing methods

	Rutting Indicator (s^{-1})					Mean	SD	COV (%)
LR FS-2	5.18E-04	2.78E-04	1.78E-04	2.87E-04	1.71E-04	2.86E-04	1.40E-04	49.08
LR FS-4	3.06E-04	3.20E-04	2.93E-04	2.40E-04	2.83E-04	2.88E-04	3.05E-05	10.58
LR FS-6	2.61E-04	2.03E-04	1.61E-04	2.74E-04	2.67E-04	2.33E-04	4.91E-05	21.06
LR FS-8	1.84E-04	2.12E-04	2.20E-04	2.10E-04	2.46E-04	2.15E-04	2.21E-05	10.32
LR SHRP	2.39E-04	2.13E-04	2.66E-04	1.62E-04	1.62E-04	2.40E-05	5.48E-06	22.83
CB	2.21E-04	2.13E-04	1.60E-04	1.53E-04	1.40E-04	1.77E-04	3.70E-05	20.83
BR	4.16E-04	3.64E-04	3.79E-04	4.86E-04	4.65E-04	4.22E-04	5.29E-05	12.54

Table 55: Rutting indicator data of control and recycled specimens manufactured by different mixing methods

9 Conclusions and recommendations for future research

9.1 Conclusions

The principal conclusions which can be drawn from the literature review include:

- The philosophy of available viscosity mixing equations assumes that aged binder and virgin binder are completely blended. The question is whether this assumption actually occurs in the recycled asphalt production process. Otherwise, the mechanical properties of recycled asphalt mixture would be deviated from expected.

- The result estimated by available viscosity mixing equations is normally not really close to the actual value. These viscosity mixing equations can provide an approximate value. Trial experiments with increment proportions of RAP or virgin binder in the blend should be used to obtain the accurate value.

- The current laboratory mixing methods indicate shortcomings as these methods could not depict the mixing mechanism that occurs in the asphalt mixing plant. Laboratory procedure allows RAP to be preheated for a long duration at high temperature before mixing with virgin material. On the contrary, RAP at ambient temperature is mixed with superheated virgin aggregate for short time, maximum 90 seconds in the asphalt mixing plant. The extensive RAP preheating time at high temperature might coincidentally enhance the interaction between RAP and virgin binder. The question is whether the asphalt mixing plant could generate the recycled mixture with the same homogeneity as that manufactured in the laboratory.

- RAP material used in laboratory is normally processed to less than ½ or 1 inch. However, there is a wide range of RAP sizes that have been used in the highway industry. The sizes of RAP used in practice are sometimes considerably bigger than that used in the laboratory.

- The diffusion pattern is supposed to be the same for the whole recycled mixture. The diffusion model assumes that single RAP aggregate particles coated by RAP binder are covered by virgin binder. Virgin binder starts to diffuse into RAP binder. The diffusion is long term and affected by many factors, for instance, temperature,

bitumen thickness, and chemical composition of bitumen. The diffusion model does not take into account the effect of RAP lump and existence of virgin aggregate.

The principal conclusions which can be drawn from the experimental work presented in this thesis include:

- Grunberg and Nissan equation proves to be the most efficient rule for predicting the viscosity of bitumen blends. Using Grunberg and Nissan equation, if interaction parameter G_{12} is properly determined for each specific bitumen blend, the viscosity could be predicted within 10% of the actual values. The other viscosity mixing rules using one universal interaction parameter G_{12} generally generate considerably high residual errors. For instance, the predicted viscosities by Arrhenius equation (ASTM D4887) are within approximately 30% of the actual values and 50% for DLV method. Therefore, the interaction parameter G_{12} should be determined for each specific bitumen blend. The fact that one constant value of G_{12} is used universally would result in substantial errors in viscosity estimation.

- There are reciprocal relationships between mixing effort, homogeneity, and mechanical properties of recycled mixtures. The mutual relationships between mixing effort and homogeneity, or homogeneity and mechanical properties, could not be evaluated in a quantitative manner. On the contrary, the relationship between mixing effort and mechanical properties could be quantified.

- The laboratory mixing method conventionally used to prepare recycled asphalt specimens tends to overestimate the mechanical properties of recycled asphalt mixtures. The long RAP preheating time that never exists in the industry coincidentally enhances the incorporation between RAP and virgin binder. The long RAP preheating time also slightly alters the properties of RAP binder. Using this method, the effect of RAP size is negligible.

- The newly developed laboratory mixing method provides a better means of describing the mixing mechanism between RAP and virgin material in the industrial asphalt mixer. The mixing mechanism is expressed as follows:
  - Virgin aggregate is superheated to required temperature

- RAP material is heated up and softened by the thermal energy transferred from superheated virgin aggregate. In this step, RAP materials start to disintegrate and are distributed all over the mixture under mechanical mixing
- RAP/virgin aggregate blend is mixed with virgin binder. In this step, besides the fact that RAP disintegration and distribution still progress, there is incorporation or rejuvenation between RAP and virgin binder.

❖ The newly developed method allows the effect of mixing time on homogeneity level to be investigated. This method also allows the effects of RAP sizes on quality of recycled mixture to be studied. In addition, the use of colour binder helps to position accurately the location of RAP binder, virgin bitumen and aggregate. The surface analysis of slices from top to bottom clearly depicts 3D distribution of RAP materials in recycled mixture.

❖ Measuring stiffness values of a cylindrical specimen in different orientations indirectly expresses the heterogeneity of recycled mixtures. The variation in stiffness values at different measured directions will be substantial for heterogeneous mixtures and relatively minor in the case of recycled mixtures that are homogeneous.

❖ The RAP superheated virgin aggregate mixing duration should be longer than a critical duration in which all the bitumen bonds in RAP lumps are deactivated. Hence, mechanical mixing will separate RAP lumps and enhance the interaction or rejuvenation between RAP and virgin binder. In this situation, the more efficient the mechanical mixing, the higher level of homogeneous recycled asphalt mixtures are manufactured. Otherwise, the effect of mechanical mixing can only distribute the RAP material all over the mixture. This situation is exaggerated if large RAP sizes are used. As an inconsiderable proportion of RAP binder can be rejuvenated by virgin binder, the recycled asphalt mixture will possess the properties of the Black Rock mixture.

❖ The increase in mixing duration significantly improves the homogeneity level of recycled mixture. The homogeneity level is also substantially affected by the sizes of RAP material. For the same mixing effort, the mixtures composed of small RAP

are generally more homogeneous than those made from large RAP. The more homogeneous the recycled mixture, the more interaction between RAP and virgin binder. Therefore, recycled mixtures become stiffer and thus have better resistance to permanent deformation and fatigue failure. A slightly linear increase in stiffness can result in an exponential increase in fatigue life of the recycled mixture.

- Although increase of mixing duration has positive effects on the homogeneity, the complete blending between RAP and virgin binder assumed in the design process would never exist in the production of recycled asphalt mixtures. Qualitatively, even at favourable conditions of extremely long mixing time compared to that in the real asphalt mixing plant, a considerable proportion of RAP still exists as lumps. Quantitatively, as RAP binder is not completely blended with virgin binder, the stiffness values, resistance to permanent deformation, and fatigue life of recycled asphalt mixture are considerably poorer than those of the Complete Blending mixture. Therefore, the design methodology for recycled asphalt mixture tends to overestimate the performance of hot recycled asphalt mixture.

9.2 Recommendations for future research

The mechanical mixing characteristic substantially affects the homogeneity and mechanical properties of hot recycled asphalt mixture. However, the mechanical mixing characteristic of a real asphalt mixer is quite different from that found in the laboratory. The movement of material in the laboratory mixer is primarily horizontal. On the contrary, in asphalt mixing plants, this includes not only horizontal but also vertical movement. The mixing efficiency of a real industry mixer might be totally different from that of a laboratory mixer. Therefore, research should be carried to validate the finding of the laboratory work.

The mixing condition in laboratory work is also different from the field. The mixing process in this research occurs under conditions of no moisture content. However, in the industry, RAP materials with different moisture contents are mixed with superheated virgin aggregate. The mixing process between RAP and virgin aggregate might occur under extremely hot and steamy conditions. This might alter the properties of RAP and virgin binder. Therefore, different mixing conditions should be considered in future studies. In addition, considering the whole service life, recycled asphalt pavement has to work in different climatic conditions, for instance under the effects of frost and moisture. Therefore,

low temperature cracking resistance and long term durability of recycled asphalt mixture should be also considered in future research.

The material used in this research is primarily Dense Bitumen Macadam (DBM). The gradation of DBM conforms to continuous-graded theory. Therefore, there will be a substantial proportion of RAP materials existing as agglomerate after crushing. These RAP lumps will restrain the interaction between RAP and virgin binder. However, the situation might be different with material using gap-graded aggregate. Future research should take into account the effect of aggregate grading on the incorporation between RAP and virgin binder.

As the complete blending between RAP and virgin material assumed in the design process would never exist in the recycled asphalt production process, a new design method that involves the partial blending between RAP and virgin binder should be considered in future research.

Experiments in this thesis were carried out primarily at a macro scale level. However, the micro scale level has not been taken into account. How virgin binder diffuses into and recovers the properties of aged binder are not covered by this thesis. Once virgin binder is in contact with RAP binder, the rejuvenation or diffusion progresses with time. The rejuvenation might be influenced by many factors, for instance, temperature, or chemical composition of bitumen binder, the presence of filler or proportion of filler in the filler mastic. As a result, the effect of diffusion process on mechanical properties of recycled asphalt mixture should be considered in future research.

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Appendix A

Zero shear viscosity extrapolation data

Table A-1: Cross model parameters of Mix A (blends of different proportion of RAP binder and 160/220 Pen) at different temperatures

Temperature (^{o}C)	RAP %	η_{∞} (Pa.s)	η_{o} (Pa.s)	k	m	R square
20	0	8.3E-06	6.9E+04	0.668	0.440	0.998
	19.2	7.4E-04	1.5E+05	1.173	0.446	0.993
	41.9	1.7E-07	3.3E+05	1.516	0.573	0.992
	59.8	4.0E-07	6.2E+05	2.036	0.639	0.988
	80	4.4E-08	1.5E+06	3.950	0.717	0.993
	100	8.3E-06	2.8E+06	5.891	0.821	1.000
25	0	4.4E-08	2.5E+04	0.601	0.332	0.997
	19.2	2.3E-08	5.1E+04	0.762	0.400	0.997
	41.9	5.8E-09	1.2E+05	1.145	0.444	0.997
	59.8	3.7E-12	2.6E+05	1.909	0.470	0.960
	80	2.8E-06	5.2E+05	2.158	0.598	0.986
	100	3.0E-05	1.1E+06	3.236	0.715	0.992
30	0	1.4E-07	9.9E+03	0.492	0.302	1.000
	19.2	1.7E-08	1.9E+04	0.691	0.326	1.000
	41.9	1.0E-04	4.4E+04	0.922	0.392	0.995
	59.8	2.2E-08	9.4E+04	1.405	0.403	0.999
	80	2.5E-08	2.6E+05	2.458	0.440	0.992
	100	3.6E-11	4.4E+05	2.564	0.542	0.994
35	0	1.7E-06	3.3E+03	0.301	0.316	1.000
	19.2	9.7E-05	6.9E+03	0.453	0.325	1.000
	41.9	1.3E-06	1.8E+04	0.904	0.310	1.000
	59.8	1.0E-04	3.5E+04	1.080	0.367	0.989
	80	1.4E-07	8.9E+04	1.639	0.398	0.997
	100	1.4E-07	2.0E+05	2.535	0.435	0.997
40	0	1.0E-04	1.3E+03	0.135	0.416	0.998
	19.2	9.6E-05	2.5E+03	0.224	0.405	0.999
	41.9	1.0E-04	6.3E+03	0.556	0.328	1.000
	59.8	1.8E-06	1.4E+04	0.919	0.322	1.000
	80	8.2E-10	3.6E+04	1.439	0.346	0.999
	100	3.8E-07	7.7E+04	1.943	0.380	0.997
45	0	1.0E-04	5.4E+02	0.077	0.490	0.993
	19.2	1.0E-04	1.1E+03	0.198	0.358	0.999
	41.9	9.8E-05	2.4E+03	0.367	0.339	0.999
	59.8	2.0E-08	5.1E+03	0.618	0.318	1.000
	80	1.0E+04	1.3E+04	1.017	0.334	1.000
	100	4.2E-09	3.1E+04	1.653	0.336	1.000
50	0	1.0E-04	2.6E+02	0.051	0.522	0.992
	19.2	1.0E-03	4.7E+02	0.073	0.526	0.997
	41.9	9.8E-05	1.0E+03	0.207	0.395	0.999
	59.8	3.9E-09	2.0E+03	0.390	0.339	0.999
	80	8.2E-06	5.4E+03	0.838	0.306	1.000
	100	2.1E-07	1.2E+04	1.233	0.320	1.000
55	0	1.3E-07	1.2E+02	0.051	0.404	0.911
	19.2	1.8E-06	2.2E+02	0.052	0.534	0.976
	41.9	1.0E-04	4.5E+02	0.133	0.430	1.000
	59.8	9.8E-05	8.3E+02	0.230	0.392	1.000
	80	2.1E-06	2.0E+03	0.368	0.390	1.000
	100	3.7E-07	4.4E+03	0.724	0.343	1.000
60	0	9.9E-05	6.4E+01	0.003	1.402	0.145
	19.2	1.0E-04	1.1E+02	0.009	1.072	0.950
	41.9	5.2E-07	2.1E+02	0.102	0.403	0.992

	59.8	1.0E-04	3.9E+02	0.133	0.461	0.999
	80	6.6E-06	8.5E+02	0.228	0.451	0.993
	100	2.6E-07	1.9E+03	0.502	0.385	1.000
	0	NA	3.5E+01	NA	NA	0.196
	19.2	NA	6.1E+01	NA	NA	0.622
65	41.9	8.3E-07	1.0E+02	0.039	0.608	0.997
	59.8	1.0E-05	1.9E+02	0.070	0.567	0.983
	80	1.0E-04	4.2E+02	0.175	0.434	0.995
	100	1.7E-07	8.5E+02	0.390	0.337	0.999
	0	NA	2.1E+01	NA	NA	0.366
	19.2	NA	3.4E+01	NA	NA	0.175
70	41.9	9.0E-08	5.5E+01	0.024	0.668	0.928
	59.8	1.0E-04	9.5E+01	0.019	0.910	0.891
	80	1.4E-05	2.1E+02	0.143	0.402	0.998
	100	3.6E-05	4.0E+02	0.268	0.357	0.999
	0	NA	1.3E+01	NA	NA	0.294
	19.2	NA	2.0E+01	NA	NA	0.125
75	41.9	NA	3.2E+01	NA	NA	0.298
	59.8	4.8E-08	5.3E+01	0.008	1.124	0.862
	80	9.5E-08	1.1E+02	0.078	0.507	0.991
	100	5.0E-09	2.1E+02	0.295	0.284	0.999
	0	NA	7.9E+00	NA	NA	0.446
	19.2	NA	1.2E+01	NA	NA	0.605
80	41.9	NA	1.8E+01	NA	NA	0.778
	59.8	1.0E-05	3.1E+01	0.007	1.166	0.722
	80	4.7E-09	5.8E+01	0.049	0.524	0.798
	100	9.7E-06	1.0E+02	0.133	0.421	0.997

Table A-2: Cross model parameters of Mix B (blends of different % RAP binder and 100/150 Pen) at different temperatures

Temperature (^{o}C)	RAP %	η_{∞} (Pa.s)	η_{o} (Pa.s)	k	m	R square
	0	3.5E-06	2.3E+05	1.435	0.537	0.997
	19.7	1.1E-08	3.6E+05	1.720	0.585	0.994
20	41.9	9.1E-09	5.9E+05	2.001	0.678	0.994
	60.1	1.8E-05	9.4E+05	2.782	0.724	0.995
	80.9	2.4E-07	2.1E+06	5.161	0.731	0.993
	100	2.0E-08	2.8E+06	5.891	0.821	1.000
	0	4.4E-08	8.7E+04	1.136	0.438	0.998
	19.7	1.4E-08	1.8E+05	1.967	0.423	0.992
25	41.9	8.0E-09	2.6E+05	1.797	0.525	0.997
	60.1	3.1E-06	4.0E+05	2.204	0.571	0.994
	80.9	1.1E-08	7.5E+05	2.791	0.620	0.991
	100	5.4E-07	1.1E+06	3.235	0.715	0.993
	0	4.9E-08	3.1E+04	0.883	0.361	0.999
	19.7	1.0E-04	5.8E+04	1.087	0.421	0.997
30	41.9	2.0E-09	1.0E+05	1.546	0.418	0.999
	60.1	7.0E-09	1.7E+05	2.038	0.429	0.995
	80.9	7.7E-09	3.4E+05	2.664	0.477	0.996
	100	3.1E-10	4.4E+05	2.564	0.542	0.994
	0	1.0E-04	1.1E+04	0.622	0.341	1.000
	19.7	1.5E-07	2.1E+04	0.914	0.348	0.999
35	41.9	1.0E-04	3.7E+04	1.099	0.387	0.992
	60.1	1.0E-04	6.0E+04	1.382	0.405	0.995
	80.9	2.2E-08	1.2E+05	1.816	0.424	1.000
	100	1.4E-07	2.0E+05	2.535	0.435	0.997
	0	8.7E-08	3.6E+03	0.339	0.368	1.000
	19.7	7.3E-09	7.1E+03	0.555	0.350	1.000
40	41.9	2.2E-06	1.3E+04	0.893	0.329	1.000
	60.1	1.6E-08	2.2E+04	1.170	0.338	1.000
	80.9	1.0E-04	4.7E+04	1.415	0.388	0.994
	100	3.8E-07	7.7E+04	1.943	0.380	0.997
	0	9.8E-05	1.4E+03	0.206	0.403	0.999
	19.7	3.1E-07	2.7E+03	0.392	0.333	0.999
45	41.9	9.3E-07	4.7E+03	0.556	0.340	1.000
	60.1	1.0E-04	7.6E+03	0.649	0.372	1.000
	80.9	1.5E-07	1.8E+04	1.125	0.338	1.000
	100	4.2E-09	3.1E+04	1.653	0.336	1.000
	0	7.0E-06	5.7E+02	0.123	0.454	0.998
	19.7	9.8E-05	1.0E+03	0.225	0.383	1.000
50	41.9	1.0E-04	1.9E+03	0.335	0.365	0.999
	60.1	1.0E-04	2.9E+03	0.430	0.373	1.000
	80.9	9.8E-05	6.3E+03	0.649	0.368	1.000
	100	2.1E-07	1.2E+04	1.233	0.320	1.000
	0	9.8E-05	2.6E+02	0.060	0.538	0.990
	19.7	9.9E-05	4.5E+02	0.128	0.440	0.999
55	41.9	9.9E-05	7.7E+02	0.193	0.419	1.000
	60.1	2.5E-06	1.3E+03	0.354	0.344	0.999
	80.9	8.1E-07	2.7E+03	0.492	0.352	1.000
anh	100	3.7E-07	4.4E+03	0.724	0.343	1.000
	0	9.8E-05	1.2E+02	0.021	0.778	0.994
	19.7	1.0E-04	2.1E+02	0.071	0.505	0.994
60	41.9	1.0E-04	3.4E+02	0.065	0.653	0.981

	60.1	2.6E-08	5.3E+02	0.178	0.415	0.999
	80.9	1.0E-06	1.0E+03	0.454	0.589	0.980
	100	1.2E-07	1.9E+03	0.502	0.349	1.000
	0	1.2E-09	6.6E+01	0.020	0.636	0.862
	19.7	2.3E-14	1.0E+02	0.036	0.581	0.968
65	41.9	1.0E-04	1.8E+02	0.085	0.472	0.991
	60.1	1.0E-04	2.5E+02	0.096	0.513	0.992
	80.9	9.9E-05	5.2E+02	0.205	0.404	0.998
	100	1.7E-07	8.5E+02	0.390	0.337	0.999
	0	9.5E-05	3.6E+01	0.010	0.670	0.701
	19.7	4.2E-06	5.6E+01	0.045	0.489	0.964
70	41.9	6.2E-09	1.0E+02	0.149	0.268	0.966
	60.1	2.3E-07	1.3E+02	0.067	0.532	0.974
	80.9	1.0E-04	2.5E+02	0.101	0.052	0.997
	100	3.6E-05	4.0E+02	0.268	0.357	0.999
	0	NA	2.1E+01	NA	NA	0.267
	19.7	NA	3.0E+01	NA	NA	0.804
75	41.9	9.5E-07	4.9E+01	0.008	1.103	0.927
	60.1	7.7E-06	7.1E+01	0.049	0.532	0.970
	80.9	1.0E-04	1.3E+02	0.067	0.556	0.983
	100	2.9E-09	2.1E+02	0.295	0.284	0.998
	0	NA	1.3E+01	NA	NA	0.182
	19.7	NA	1.9E+01	NA	NA	0.363
80	41.9	NA	2.9E+01	NA	NA	0.316
	60.1	7.1E-05	4.0E+01	0.014	0.935	0.870
	80.9	1.0E-04	7.0E+01	0.025	0.798	0.987
	100	9.7E-05	1.0E+02	0.133	0.421	0.997

Table A-3: Mix A – experiment and predicted viscosity (P) using different viscosity mixing equations at different temperatures

Temperature	Rap	Experiment	ASTM Predicted		G&N Predicted		Epps Predicted		DLV Predicted	
			Viscosity	Residue	Viscosity	Residue	Viscosity	Residue	Viscosity	Residue
	%		(P)	(%)	(P)	(%)	(P)	(%)	(P)	(%)
20	0	6.89E+05	6.89E+05	0.0	6.89E+05	0.0	6.89E+05	0.0	7.15E+05	3.8
	19.2	1.54E+06	1.40E+06	8.9	1.53E+06	0.1	1.31E+06	14.8	9.50E+05	38.2
	41.9	3.33E+06	3.23E+06	2.4	3.74E+06	12.8	2.90E+06	12.4	1.72E+06	48.3
	59.8	6.15E+06	6.26E+06	1.8	7.22E+06	17.4	5.62E+06	8.7	3.33E+06	45.9
	80	1.55E+07	1.32E+07	14.8	1.45E+07	6.3	1.23E+07	20.8	8.64E+06	44.2
	100	2.76E+07	2.76E+07	0.0	2.76E+07	0.0	2.76E+07	0.0	2.76E+07	0.0
25	0	2.50E+05	2.50E+05	0.0	2.50E+05	0.0	2.50E+05	0.0	2.60E+05	3.8
	19.2	5.07E+05	5.13E+05	1.3	5.36E+05	5.7	4.76E+05	6.0	3.46E+05	31.7
	41.9	1.18E+06	1.20E+06	2.6	1.29E+06	9.8	1.07E+06	8.9	6.31E+05	46.1
	59.8	2.63E+06	2.35E+06	10.8	2.51E+06	4.6	2.09E+06	20.8	1.24E+06	53.1
	80	5.19E+06	5.01E+06	3.4	5.24E+06	1.0	4.62E+06	10.9	3.26E+06	37.2
	100	1.06E+07	1.06E+07	0.0	1.06E+07	0.0	1.06E+07	0.0	1.06E+07	0.0
30	0	9.91E+04	9.91E+04	0.0	9.91E+04	0.0	9.91E+04	0.0	1.03E+05	3.9
	19.2	1.94E+05	2.05E+05	5.6	2.35E+05	20.8	1.89E+05	2.6	1.38E+05	29.1
	41.9	4.40E+05	4.84E+05	10.6	5.98E+05	36.7	4.25E+05	2.9	2.53E+05	42.3
	59.8	9.38E+05	9.54E+05	1.7	1.18E+06	25.3	8.37E+05	10.8	4.98E+05	46.9
	80	2.60E+06	2.05E+06	21.1	2.35E+06	9.3	1.88E+06	27.8	1.33E+06	48.9
	100	4.37E+06	4.37E+06	0.0	4.37E+06	0.0	4.37E+06	0.0	4.37E+06	0.0
35	0	3.33E+04	3.33E+04	0.0	3.33E+04	0.0	3.33E+04	0.0	3.47E+04	4.2
	19.2	6.91E+04	7.34E+04	6.2	7.10E+04	2.8	6.62E+04	4.1	4.76E+04	31.1
	41.9	1.77E+05	1.87E+05	6.0	1.78E+05	0.7	1.59E+05	10.1	9.21E+04	47.8
	59.8	3.47E+05	3.91E+05	12.8	3.72E+05	7.2	3.31E+05	4.5	1.93E+05	44.4
	80	8.87E+05	8.99E+05	1.3	8.69E+05	2.0	8.02E+05	9.5	5.60E+05	36.9
	100	2.05E+06	2.05E+06	0.0	2.05E+06	0.0	2.05E+06	0.0	2.05E+06	0.0
40	0	1.27E+04	1.27E+04	0.0	1.27E+04	0.0	1.27E+04	0.0	1.32E+04	4.2
	19.2	2.52E+04	2.79E+04	10.9	2.74E+04	8.7	2.50E+04	0.7	1.81E+04	28.0
	41.9	6.27E+04	7.10E+04	13.8	6.88E+04	10.3	5.94E+04	4.8	3.50E+04	43.9
	59.8	1.37E+05	1.48E+05	8.2	1.44E+05	4.9	1.24E+05	9.6	7.32E+04	46.5
	80	3.61E+05	3.40E+05	6.0	3.33E+05	7.9	3.00E+05	16.8	2.12E+05	41.3

	100	7.72E+05	7.72E+05	0.0	7.72E+05	0.0	7.72E+05	0.0	7.72E+05	0.0
45	0	5.39E+03	5.39E+03	0.0	5.39E+03	0.0	5.39E+03	0.0	5.62E+03	4.1
	19.2	1.10E+04	1.18E+04	6.9	1.09E+04	0.9	1.05E+04	4.9	7.68E+03	30.3
	41.9	2.44E+04	2.96E+04	22.2	2.63E+04	8.4	2.45E+04	1.1	1.47E+04	39.3
	59.8	5.09E+04	6.14E+04	20.6	5.45E+04	7.2	5.07E+04	0.4	3.06E+04	39.9
	80	1.32E+05	1.40E+05	5.4	1.29E+05	2.6	1.22E+05	7.5	8.75E+04	33.9
	100	3.15E+05	3.15E+05	0.0	3.15E+05	0.0	3.15E+05	0.0	3.15E+05	0.0
50	0	2.56E+03	2.56E+03	0.0	2.56E+03	0.0	2.56E+03	0.0	2.66E+03	3.9
	19.2	4.67E+03	5.37E+03	15.0	4.96E+03	6.2	4.79E+03	2.6	3.58E+03	23.4
	41.9	1.00E+04	1.29E+04	29.6	1.14E+04	14.3	1.07E+04	7.6	6.65E+03	33.3
	59.8	1.98E+04	2.58E+04	30.4	2.28E+04	15.2	2.14E+04	8.1	1.33E+04	32.8
	80	5.43E+04	5.63E+04	3.7	5.18E+04	4.6	4.95E+04	8.8	3.61E+04	33.5
	100	1.22E+05	1.22E+05	0.0	1.22E+05	0.0	1.22E+05	0.0	1.22E+05	0.0
55	0	1.24E+03	1.24E+03	0.0	1.24E+03	0.0	1.24E+03	0.0	1.29E+03	3.6
	19.2	2.21E+03	2.46E+03	11.7	2.20E+03	0.1	2.21E+03	0.3	1.69E+03	23.2
	41.9	4.52E+03	5.53E+03	22.8	4.65E+03	3.1	4.65E+03	3.2	3.00E+03	33.5
	59.8	8.31E+03	1.05E+04	26.1	8.82E+03	6.1	8.79E+03	5.8	5.68E+03	31.6
	80	1.96E+04	2.15E+04	9.9	1.92E+04	2.0	1.91E+04	2.5	1.43E+04	27.0
	100	4.39E+04	4.39E+04	0.0	4.39E+04	0.0	4.39E+04	0.0	4.39E+04	0.0
60	0	6.40E+02	6.40E+02	0.0	6.40E+02	0.0	6.40E+02	0.0	6.62E+02	3.4
	19.2	1.12E+03	1.22E+03	8.8	1.09E+03	3.2	1.10E+03	2.0	8.58E+02	23.7
	41.9	2.15E+03	2.63E+03	22.9	2.19E+03	2.3	2.22E+03	3.7	1.47E+03	31.2
	59.8	3.87E+03	4.80E+03	23.9	4.00E+03	3.4	4.04E+03	4.4	2.69E+03	30.4
	80	8.50E+03	9.48E+03	11.5	8.40E+03	1.2	8.43E+03	0.9	6.44E+03	24.3
	100	1.86E+04	1.86E+04	0.0	1.86E+04	0.0	1.86E+04	0.0	1.86E+04	0.0
65	0	3.47E+02	3.47E+02	0.0	3.47E+02	0.0	3.47E+02	0.0	3.58E+02	3.2
	19.2	6.13E+02	6.41E+02	4.6	5.81E+02	5.1	5.78E+02	5.6	4.58E+02	25.2
	41.9	1.05E+03	1.32E+03	26.8	1.14E+03	8.8	1.12E+03	7.3	7.64E+02	26.8
	59.8	1.88E+03	2.34E+03	24.6	2.02E+03	7.2	1.98E+03	5.3	1.36E+03	27.9
	80	4.17E+03	4.47E+03	7.2	4.04E+03	3.0	3.98E+03	4.5	3.10E+03	25.7
	100	8.46E+03	8.46E+03	0.0	8.46E+03	0.0	8.46E+03	0.0	8.46E+03	0.0
	0	2.08E+02	2.08E+02	0.0	2.08E+02	0.0	2.08E+02	0.0	2.14E+02	3.0
	19.2	3.40E+02	3.66E+02	7.7	3.34E+02	2.0	3.33E+02	2.2	2.69E+02	21.0

70	41.9	5.54E+02	7.15E+02	29.5	6.17E+02	11.8	6.12E+02	10.9	4.31E+02	22.0
	59.8	9.53E+02	1.21E+03	27.2	1.05E+03	10.0	1.04E+03	8.7	7.31E+02	23.3
	80	2.10E+03	2.20E+03	4.8	1.99E+03	4.9	1.97E+03	5.9	1.57E+03	25.3
	100	3.96E+03	3.96E+03	0.0	3.96E+03	0.0	3.96E+03	0.0	3.96E+03	0.0
75	0	1.28E+02	1.28E+02	0.0	1.28E+02	0.0	1.28E+02	0.0	1.31E+02	2.9
	19.2	2.00E+02	2.19E+02	9.8	1.90E+02	4.7	1.99E+02	0.2	1.63E+02	18.3
	41.9	3.16E+02	4.15E+02	31.7	3.32E+02	5.5	3.55E+02	12.9	2.56E+02	18.8
	59.8	5.33E+02	6.86E+02	28.6	5.51E+02	3.4	5.87E+02	10.0	4.24E+02	20.6
	80	1.07E+03	1.21E+03	13.5	1.05E+03	1.9	1.09E+03	1.9	8.77E+02	17.8
	100	2.13E+03	2.13E+03	0.0	2.13E+03	0.0	2.13E+03	0.0	2.13E+03	0.0
80	0	7.90E+01	7.90E+01	0.0	7.90E+01	0.0	7.90E+01	0.0	8.11E+01	2.6
	19.2	1.17E+02	1.29E+02	10.8	1.19E+02	2.2	1.18E+02	1.6	9.86E+01	15.3
	41.9	1.83E+02	2.30E+02	26.2	2.03E+02	11.2	2.00E+02	9.6	1.49E+02	18.7
	59.8	3.11E+02	3.64E+02	17.0	3.21E+02	3.2	3.16E+02	1.4	2.35E+02	24.5
	80	5.82E+02	6.10E+02	4.8	5.61E+02	3.6	5.53E+02	5.0	4.55E+02	21.8
	100	1.02E+03	1.02E+03	0.0	1.02E+03	0.0	1.02E+03	0.0	1.02E+03	0.0

Table A-4: Mix B – experiment and predicted viscosity (P) using different viscosity mixing equations at different temperatures

Temperature	Rap	Experiment	ASTM Predicted		G&N Predicted		Epps Predicted		DLV Predicted	
			Viscosity	Residue	Viscosity	Residue	Viscosity	Residue	Viscosity	Residue
	%		(P)	(%)	(P)	(%)	(P)	(%)	(P)	(%)
20	0	2.29E+06	2.29E+06	0.0	2.29E+06	0.0	2.29E+06	0.0	2.35E+06	2.5
	19.7	3.64E+06	3.74E+06	2.9	3.99E+06	9.5	3.63E+06	0.2	2.87E+06	21.3
	41.9	5.89E+06	6.50E+06	10.5	7.16E+06	21.7	6.20E+06	5.4	4.24E+06	27.9
	60.1	9.35E+06	1.02E+07	9.4	1.12E+07	20.2	9.76E+06	4.3	6.68E+06	28.6
	80.9	2.09E+07	1.72E+07	17.7	1.82E+07	12.5	1.66E+07	20.2	1.30E+07	37.5
	100	2.76E+07	2.76E+07	0.0	2.76E+07	0.0	2.76E+07	0.0	2.76E+07	0.0
25	0	8.67E+05	8.67E+05	0.0	8.67E+05	0.0	8.67E+05	0.0	8.89E+05	2.5
	19.7	1.84E+06	1.42E+06	22.7	1.54E+06	16.4	1.37E+06	25.2	1.08E+06	40.9
	41.9	2.65E+06	2.47E+06	6.6	2.79E+06	5.5	2.35E+06	11.2	1.61E+06	39.2
	60.1	4.03E+06	3.90E+06	3.1	4.40E+06	9.2	3.71E+06	7.9	2.54E+06	36.8
	80.9	7.46E+06	6.57E+06	11.9	7.10E+06	4.9	6.36E+06	14.8	4.98E+06	33.3
	100	1.06E+07	1.06E+07	0.0	1.06E+07	0.0	1.06E+07	0.0	1.06E+07	0.0
30	0	3.07E+05	3.07E+05	0.0	3.07E+05	0.0	3.07E+05	0.0	3.15E+05	2.7
	19.7	5.77E+05	5.18E+05	10.3	6.10E+05	5.7	4.98E+05	13.7	3.89E+05	32.5
	41.9	1.05E+06	9.34E+05	11.0	1.20E+06	14.6	8.78E+05	16.3	5.92E+05	43.6
	60.1	1.72E+06	1.51E+06	12.0	1.94E+06	12.9	1.42E+06	17.2	9.62E+05	44.1
	80.9	3.40E+06	2.63E+06	22.7	3.09E+06	9.3	2.53E+06	25.7	1.96E+06	42.4
	100	4.37E+06	4.37E+06	0.0	4.37E+06	0.0	4.37E+06	0.0	4.37E+06	0.0
35	0	1.05E+05	1.05E+05	0.0	1.05E+05	0.0	1.05E+05	0.0	1.08E+05	3.0
	19.7	2.14E+05	1.89E+05	11.7	1.92E+05	10.3	1.79E+05	16.2	1.37E+05	35.8
	41.9	3.65E+05	3.65E+05	0.0	3.74E+05	2.5	3.36E+05	7.8	2.19E+05	39.9
	60.1	5.96E+05	6.27E+05	5.2	6.42E+05	7.7	5.78E+05	3.1	3.77E+05	36.7
	80.9	1.22E+06	1.16E+06	4.6	1.18E+06	3.1	1.10E+06	9.6	8.36E+05	31.3
	100	2.05E+06	2.05E+06	0.0	2.05E+06	0.0	2.05E+06	0.0	2.05E+06	0.0
40	0	3.64E+04	3.64E+04	0.0	3.64E+04	0.0	3.64E+04	0.0	3.75E+04	3.1
	19.7	7.14E+04	6.64E+04	6.9	6.93E+04	2.9	6.25E+04	12.4	4.78E+04	33.0
	41.9	1.34E+05	1.31E+05	2.2	1.40E+05	4.4	1.19E+05	11.0	7.74E+04	42.2
	60.1	2.24E+05	2.28E+05	1.7	2.43E+05	8.5	2.08E+05	7.4	1.35E+05	39.7
	80.9	4.68E+05	4.31E+05	7.9	4.49E+05	4.0	4.05E+05	13.4	3.07E+05	34.4

	100	7.72E+05	7.72E+05	0.0	7.72E+05	0.0	7.72E+05	0.0	7.72E+05	0.0
45	0	1.39E+04	1.39E+04	0.0	1.39E+04	0.0	1.39E+04	0.0	1.43E+04	3.2
	19.7	2.69E+04	2.56E+04	4.5	2.52E+04	6.3	2.40E+04	10.8	1.83E+04	31.7
	41.9	4.74E+04	5.13E+04	8.1	4.98E+04	5.1	4.61E+04	2.8	3.00E+04	36.8
	60.1	7.56E+04	9.05E+04	19.8	8.80E+04	16.5	8.13E+04	7.7	5.31E+04	29.8
	80.9	1.81E+05	1.73E+05	4.0	1.70E+05	5.7	1.62E+05	10.5	1.23E+05	32.1
	100	3.15E+05	3.15E+05	0.0	3.15E+05	0.0	3.15E+05	0.0	3.15E+05	0.0
50	0	5.70E+03	5.70E+03	0.0	5.70E+03	0.0	5.70E+03	0.0	5.88E+03	3.1
	19.7	1.04E+04	1.04E+04	0.1	9.52E+03	8.7	9.71E+03	6.9	7.50E+03	28.1
	41.9	1.88E+04	2.06E+04	9.5	1.79E+04	4.7	1.84E+04	2.1	1.22E+04	35.3
	60.1	2.90E+04	3.59E+04	24.0	3.13E+04	8.2	3.21E+04	10.9	2.13E+04	26.6
	80.9	6.34E+04	6.79E+04	7.2	6.22E+04	1.9	6.31E+04	0.5	4.84E+04	23.7
	100	1.22E+05	1.22E+05	0.0	1.22E+05	0.0	1.22E+05	0.0	1.22E+05	0.0
55	0	2.59E+03	2.59E+03	0.0	2.59E+03	0.0	2.59E+03	0.0	2.67E+03	2.9
	19.7	4.45E+03	4.53E+03	1.7	4.50E+03	1.2	4.23E+03	4.9	3.34E+03	25.0
	41.9	7.72E+03	8.48E+03	9.9	8.42E+03	9.1	7.64E+03	1.0	5.21E+03	32.4
	60.1	1.27E+04	1.42E+04	12.1	1.41E+04	11.2	1.28E+04	0.9	8.75E+03	30.9
	80.9	2.70E+04	2.56E+04	5.2	2.55E+04	5.6	2.39E+04	11.5	1.87E+04	30.7
	100	4.39E+04	4.39E+04	0.0	4.39E+04	0.0	4.39E+04	0.0	4.39E+04	0.0
60	0	1.24E+03	1.24E+03	0.0	1.24E+03	0.0	1.24E+03	0.0	1.27E+03	2.7
	19.7	2.06E+03	2.11E+03	2.8	1.93E+03	6.2	1.98E+03	3.9	1.58E+03	23.2
	41.9	3.40E+03	3.86E+03	13.4	3.35E+03	1.5	3.47E+03	2.1	2.42E+03	28.8
	60.1	5.33E+03	6.31E+03	18.4	5.49E+03	3.1	5.68E+03	6.6	3.97E+03	25.5
	80.9	1.02E+04	1.11E+04	8.7	1.01E+04	0.6	1.03E+04	1.4	8.21E+03	19.5
	100	1.86E+04	1.86E+04	0.0	1.86E+04	0.0	1.86E+04	0.0	1.86E+04	0.0
65	0	6.59E+02	6.59E+02	0.0	6.59E+02	0.0	6.59E+02	0.0	6.76E+02	2.6
	19.7	1.01E+03	1.09E+03	7.9	1.04E+03	2.7	1.02E+03	1.1	8.28E+02	18.0
	41.9	1.78E+03	1.92E+03	8.2	1.78E+03	0.3	1.73E+03	2.3	1.24E+03	30.2
	60.1	2.54E+03	3.06E+03	20.2	2.83E+03	11.6	2.76E+03	8.5	1.97E+03	22.3
	80.9	5.21E+03	5.20E+03	0.3	4.95E+03	5.0	4.86E+03	6.8	3.91E+03	24.9
	100	8.46E+03	8.46E+03	0.0	8.46E+03	0.0	8.46E+03	0.0	8.46E+03	0.0
	0	3.63E+02	3.63E+02	0.0	3.63E+02	0.0	3.63E+02	0.0	3.72E+02	2.4
	19.7	5.61E+02	5.81E+02	3.7	5.61E+02	0.0	5.46E+02	2.5	4.50E+02	19.8

70	41.9	1.03E+03	9.88E+02	3.6	9.35E+02	8.8	8.96E+02	12.6	6.55E+02	36.1
	60.1	1.33E+03	1.53E+03	15.2	1.44E+03	9.0	1.38E+03	4.4	1.01E+03	23.5
	80.9	2.47E+03	2.51E+03	1.6	2.42E+03	2.0	2.35E+03	4.8	1.93E+03	22.1
	100	3.96E+03	3.96E+03	0.0	3.96E+03	0.0	3.96E+03	0.0	3.96E+03	0.0
75	0	2.11E+02	2.11E+02	0.0	2.11E+02	0.0	2.11E+02	0.0	2.15E+02	2.3
	19.7	3.02E+02	3.32E+02	10.0	3.06E+02	1.3	3.12E+02	3.3	2.59E+02	14.2
	41.9	4.88E+02	5.55E+02	13.7	4.89E+02	0.2	5.02E+02	2.9	3.73E+02	23.6
	60.1	7.13E+02	8.45E+02	18.5	7.46E+02	4.6	7.64E+02	7.1	5.69E+02	20.2
	80.9	1.29E+03	1.37E+03	5.9	1.26E+03	2.2	1.28E+03	0.9	1.06E+03	18.0
	100	2.13E+03	2.13E+03	0.0	2.13E+03	0.0	2.13E+03	0.0	2.13E+03	0.0
80	0	1.28E+02	1.28E+02	0.0	1.28E+02	0.0	1.28E+02	0.0	1.31E+02	2.1
	19.7	1.88E+02	1.92E+02	2.3	1.88E+02	0.2	1.82E+02	3.3	1.54E+02	18.1
	41.9	2.93E+02	3.05E+02	4.1	2.95E+02	0.8	2.79E+02	4.7	2.13E+02	27.1
	60.1	4.02E+02	4.44E+02	10.7	4.31E+02	7.2	4.06E+02	1.2	3.12E+02	22.4
	80.9	7.00E+02	6.84E+02	2.3	6.70E+02	4.3	6.45E+02	7.9	5.43E+02	22.4
	100	1.02E+03	1.02E+03	0.0	1.02E+03	0.0	1.02E+03	0.0	1.02E+03	0.0

Appendix B

ITFT data

Table B-1: ITFT data of LR FS-2 mixture at 20°C

Sample	Width (mm)	ϕ (mm)	E (MPa)	σ (kPa)	ε (μm)	N
S1	40	98	1096	100	187	33537
S2	40	98	854	300	720	402
S3	40	98	1849	400	443	622
S4	37	98	1309	250	392	670
S5	39	98	937	200	438	636
S6	42	98	1709	100	120	7054
S7	40	98	899	150	342	1960
S8	41	98	1515	100	135	7436
S9	42	98	1636	250	313	1356
S10	40	98	811	200	506	1018

Table B-2: ITFT data of LR FS-4 mixture at 20°C

Sample	Width (mm)	ϕ (mm)	E (MPa)	σ (kPa)	ε (μm)	N
S1	41	98	1052	100	195	9351
S2	39	98	1165	200	352	1678
S3	40	98	1376	300	447	971
S4	40	98	1523	350	471	610
S5	41	98	1346	150	228	4090
S6	42	98	1301	100	158	7516
S7	41	98	1390	250	369	1579
S8	42	98	1768	300	348	602
S9	43	98	1250	250	410	1075
S10	38	98	1299	200	316	2357

Table B-3: ITFT data of LR FS-6 mixture at 20°C

Sample	Width (mm)	ϕ (mm)	E (MPa)	σ (kPa)	ε (μm)	N
S1	41	98	1178	200	348	1544
S2	42	98	1823	300	337	1166
S3	42	98	1698	350	423	688
S4	41	98	1273	250	403	1080
S5	41	98	1638	200	250	3922
S6	41	98	1360	150	226	5303
S7	40	98	1195	150	257	5128
S8	40	98	1208	250	424	1098
S9	41	98	1832	200	224	7192
S10	40	98	1050	100	195	8748

Table B-4: ITFT data of LR FS-8 mixture at 20°C

Sample	Width (mm)	ϕ (mm)	E (MPa)	σ (kPa)	ε (μm)	N
S1	39	98	1649	150	186	20224
S2	41	98	1526	150	202	9354
S3	41	98	1516	350	473	399
S4	40	98	1691	300	364	946
S5	42	98	1435	250	357	1249
S6	40	98	1403	250	365	1131
S7	41	98	1637	200	250	3978
S8	40	98	1619	300	380	956
S9	40	98	1422	200	288	2714
S10	40	98	1623	350	442	592

Table B-5: ITFT data of SR FS-2 mixture at 20°C

Sample	Width (mm)	ϕ (mm)	E (MPa)	σ (kPa)	ε (μm)	N
S1	41	98	1413	200	290	2436
S2	41	98	1605	350	447	523
S3	40	98	1729	350	415	691
S4	40	98	1669	300	368	1046
S5	40	98	1532	250	335	1649
S6	40	98	1667	200	246	2950
S7	40	98	1587	150	194	8990
S8	40	98	1788	250	287	2437
S9	39	98	1665	150	185	10847
S10	40	98	1515	300	406	1261

Table B-6: ITFT data of SR FS-4 mixture at 20°C

Sample	Width (mm)	ϕ (mm)	E (MPa)	σ (kPa)	ε (μm)	N
S1	40	98	1616	250	317	2205
S2	41	98	1506	200	272	3377
S3	40	98	1565	300	393	1282
S4	41	98	1493	350	481	719
S5	41	98	1637	150	188	12325
S6	40	98	1448	150	212	8857
S7	41	98	1507	200	272	1884
S8	42	98	1581	300	389	1255
S9	41	98	1593	250	322	1984
S10	40	98	1606	350	447	565

Table B-7: ITFT data of SR FS-6 mixture at 20°C

Sample	Width (mm)	ϕ (mm)	E (MPa)	σ (kPa)	ε (μm)	N
S1	40	98	1544	300	398	1327
S2	39	98	1751	350	410	1072
S3	39	98	1566	250	327	2629
S4	40	98	1656	200	248	5617
S5	40	98	1681	150	183	18661
S6	39	98	1619	250	317	3471
S7	40	98	1683	300	365	2476
S8	40	98	1605	350	447	953
S9	40	98	1379	150	223	9802
S10	40	98	1705	200	240	7952

Table B-8: ITFT data of SR FS-8 mixture at 20°C

Sample	Width (mm)	ϕ (mm)	E (MPa)	σ (kPa)	ε (μm)	N
S1	38	98	1560	250	329	2445
S2	39	98	1609	200	255	6589
S3	40	98	1743	350	412	1250
S4	42	98	1514	150	203	18133
S5	40	98	1497	150	205	19370
S6	39	98	1704	250	301	4404
S7	41	98	1740	300	353	2437
S8	41	98	1734	300	355	2815
S9	39	98	1727	200	237	9840
S10	40	98	1808	350	397	1549

Table B-9: ITFT data of LR SHRP mixture at 20°C

Sample	Width (mm)	ϕ (mm)	E (MPa)	σ (kPa)	ε (μm)	N
S1	40	98	1535	350	467	709
S2	40	98	1528	300	402	1116
S3	40	98	1338	150	230	7945
S4	39	98	1379	200	297	2275
S5	40	98	1366	250	375	2001
S6	40	98	1356	250	378	1788
S7	41	98	1590	300	387	971
S8	41	98	1579	150	195	5966
S9	41	98	1470	350	488	578
S10	40	98	1376	200	298	2782

Table B-10: ITFT data of SR SHRP mixture at 20°C

Sample	Width (mm)	ϕ (mm)	E (MPa)	σ (kPa)	ε (μm)	N
S1	41	98	1450	300	424	1621
S2	41	98	1584	350	453	800
S3	40	98	1675	250	306	5587
S4	42	98	1634	200	251	8259
S5	39	98	1640	150	188	20869
S6	40	98	1539	150	200	22343
S7	40	98	1453	200	282	5940
S8	40	98	1481	250	346	2218
S9	40	98	1385	300	444	1218
S10	39	98	1437	350	499	913

Table B-11: ITFT data of BR mixture at 20°C

Sample	Width (mm)	ϕ (mm)	E (MPa)	σ (kPa)	ε (μm)	N
S1	39	98	744	100	276	1963
S2	39	98	655	250	782	414
S3	40	98	791	50	130	6885
S4	41	98	754	50	136	7062
S5	39	98	764	150	402	1612
S6	37	98	853	100	240	2672
S7	40	98	878	200	467	978
S8	39	98	818	200	501	930
S9	40	98	815	250	629	431
S10	41	98	919	150	335	2510

Table B-12: ITFT data of CB mixture at 20°C

Sample	Width (mm)	ϕ (mm)	E (MPa)	σ (kPa)	ε (μm)	N
S1	39	98	2185	350	328	2622
S2	39	98	1805	300	341	2842
S3	39	98	1918	250	267	9778
S4	39	98	2001	200	205	14064
S5	40	98	1708	150	180	37012
S6	39	98	1941	300	317	3460
S7	38	98	1738	150	177	33720
S8	39	98	1822	200	225	16648
S9	39	98	1850	250	277	6324
S10	38	98	1942	350	369	2024

Table B-13: ITFT data of CB-V mixture at 20°C

Sample	Width (mm)	ϕ (mm)	E (MPa)	σ (kPa)	ε (μm)	N
S1	40	98	1840	350	390	2267
S2	39	98	1873	400	438	1201
S3	40	98	1757	350	408	1774
S4	42	98	2025	300	304	4891
S5	40	98	2047	300	300	2936
S6	41	98	2251	250	228	12190
S7	40	98	2306	400	356	2497
S8	40	98	1754	200	234	20100
S9	40	98	2210	250	232	12239
S10	41	98	1984	200	207	28312