# WARM MIX ASPHALT vs. HOT MIX ASPHALT: FLEXURAL STIFFNESS AND FATIGUE LIFE EVALUATION

By

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## DECLARATION

By submitting this thesis electronically, I declare that the entirety of the work contained therein is my own, original work, that I am the authorship owner thereof (unless to the extent explicitly otherwise stated) and that I have not previously in its entirety or in part submitted it for obtaining any qualification.

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# SUMMARY

The UNFCCC (United Nations Framework Convention on Climate Change), enabled by the Kyoto Protocol, set enforced responsibilities on industrialised countries to reduce the amount of emissions (greenhouse gases) produced. This global call for the reduction of greenhouse gas emissions ensured that the manufacturing sector commit to emission reduction.

The asphalt industry has embarked on a quest to find alternative methods of producing and constructing asphalt mixes which will release less greenhouse gasses into the atmosphere. These new methods include the reduction in production and construction temperatures which in turn will reduce the amount of greenhouse emissions produced. These new methods introduced the concept of warm mix asphalt (WMA) to the alternative hot mix asphalt (HMA).

To produce a WMA mix at lower temperatures the binder needs to be in a workable state so to effectively coat the aggregate and produce a good quality mix. WMA technologies have been developed to enable production of mixes at lower temperatures (effectively reducing emissions) whilst retaining the required binder viscosity and properties needed to produce a quality mix. The question which needs to be answered is whether the performance of these WMA mixes can compare with that of HMA mixes.

In this study several WMA mixes (with different WMA technologies) are evaluated against their equivalent HMA mixes in terms of fatigue life and flexural stiffness. Phase angle results were also considered. Flexural stiffness is a mix property which is dependent on loading time and temperature. It is used to measure the load spread ability of a mix and also influences fatigue behaviour. Fatigue cracking occurs in the material as a result of repeated cyclic loading.

The evaluation and analysis conducted in this study show that WMA mixes can compare favourably and even exceed that of HMA mixes in certain cases, although some WMA mixes resulted in lower fatigue life or flexural stiffness than its corresponding HMA mixes, which could be attributed to differences in mix components and variables.

In this study a literature study, methodology, laboratory test results, a comparison of mix results and conclusions and recommendations are made.

## OPSOMMING

Die UNFCCC (United Nations Framework Convention on Climate Change) was in staat gestel deur die Kyoto Protocol om verantwoordelikhede op geïndustrialiseerde lande te forseer om die hoeveelheid van nadelige kweekhuisgasse wat geproduseer word te verminder. Hierdie globale oproep tot die vermindering van kweekhuisgasse verseker dat die vervaardigingsektor hulself verbind tot emissie vermindering.

Die asfalt industrie het begin met 'n soektog na alternatiewe metodes van vervaardiging en die bou van asfaltmengsels wat minder kweekhuisgasse sal vrystel in die atmosfeer. Hierdie nuwe metodes sluit die vermindering in produksie en konstruksie temperature in wat op sy beurt die hoeveelheid kweekhuisgasse geproduseer verminder. Hierdie nuwe metodes het die konsep van warm mengsel asfalt (WMA) bekendgestel teenoor die alternatiewe 'hot' mengsel asfalt (HMA).

Om 'n WMA mengsel te produseer by laer temperature, moet die bindmiddel in 'n werkbare toestand wees om die aggregaat heeltemal te bedek en 'n goeie gehalte mengsel te produseer. WMA tegnologie is ontwikkel om die produksie van mengsels teen laer temperature te realiseer (vermindering die uitlaatgasse), terwyl die vereiste bindmiddel viskositeit en eienskappe wat nodig is om 'n kwaliteit mengsel te produseer behou word. Die vraag wat beantwoord moet word, is of die prestasie van hierdie WMA mengsel kan vergelyk word met dié van HMA mengsel.

In hierdie studie is 'n paar WMA mengsels (met verskillende WMA tegnologie) geëvalueer teen hul ekwivalent HMA mengsels in terme van vermoeiing en buig styfheid. Fase hoek resultate is ook in ag geneem. Buig styfheid is 'n mengsel eienskap wat afhanklik is van die laai tyd en temperatuur. Dit word gebruik om die las verspreiding vermoë van 'n mengsel te meet en beïnvloed ook vermoeiing gedrag. Vermoeidheid krake kom voor in die materiaal as gevolg van herhaalde sikliese laai.

Die evaluering en ontleding in hierdie studie toon dat WMA mengsels goed vergelyk en selfs in sekere gevalle meer as dié van HMA mengsels, hoewel sommige WMA mengsels laer vermoeidheid lewe of buig styfheid as die ooreenstemmende HMA mengsels gewys het, wat toegeskryf kan word tot verskille in mengsel komponente en veranderlikes.

In hierdie studie word 'n literatuurstudie, metodiek, laboratorium toets resultate, 'n vergelyking van die mengsel resultate en gevolgtrekkings en aanbevelings gemaak.

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## LIST OF ABBREVIATIONS

| | |
|---|---|
| AE-2 | Asphalt Elastomer 2 |
| AP-1 | Asphalt Plastomer 1 |
| ASTM | American Society for Testing and Materials |
| BRD | Bulk Relative Density |
| CAIR | Clean Air Interstate Rule |
| CO | Carbon Monoxide |
| $CO_2$ | Carbon Dioxide |
| CMA | Cold Mix Asphalt |
| DAT | Dispersed Asphalt Technology |
| EPDM | Ethylene Propylene |
| ERR | European Roads Review |
| ET | Emulsion Technology |
| EU | European Union |
| EVA | Ethyl-Vinyl-Actetate |
| FT | Fatigue Test |
| GHG | Greenhouse Gas |
| HMA | Hot Mix Asphalt |
| HWMA | Half-Warm Mix Asphalt |
| IPC | Industrial Process Controls |
| LEA | Low Energy Asphalt |
| LEAB | Low Energy Asphalt Concrete |
| LT-Asphalt | Low Temperature Asphalt |
| LVDT | Linear Variable Differential Transformer |
| MST | Mixture Stiffness Test |
| NA | National Asphalt |
| NCDOT | North Carolina Department of Transportation |
| NOx | Nitrous Oxide |
| PAH's | Polycyclic Aromatic Hydrocarbons |
| PG | Performance Grade |

| | |
|---|---|
| PMB | Polymer–Modified Binders |
| PVC | Polyvinyl Chloride |
| RA | Reclaimed Asphalt |
| REACH | Registration, Evaluation, Authorization and Restriction of Chemicals |
| SBR | Styrene-Butadiene-Rubber |
| SBS | Styrene-Butadiene-Styrene |
| SEAM | Sulphur Extended Asphalt Modifier |
| SGC | Superpave Gyratory Compactor |
| SIS | Styrene-Isoprene-Styrene |
| SMA | Stone Mastic Asphalt |
| $SO_2$ | Sulphur Dioxide |
| SUCM | Stellenbosch University Compaction Mould |
| TLA | Trinidad Lake Asphalt |
| UNFCCC | United Nations Framework Convention on Climate Change |
| UTM | Universal Testing Machine |
| VFB | Voids Filled with Binder |
| VMA | Voids in the Mineral Aggregate |
| VOC’s | Volatile Organic Compounds |
| VTM | Voids in the Total Mix |
| WMA | Warm Mix Asphalt |

# CHAPTER ONE

# INTRODUCTION

## 1.1 PREDICAMENT OF THE ASPHALT INDUSTRY

The asphalt industry currently faces challenges concerning the production and construction of asphalt mixes. Hot mix asphalt (HMA) has been used for years by the asphalt industry during flexible pavement design to provide the surface and base layers which form the fundamental components of the road. Over the years of working with HMA the asphalt industry has established that HMA mixes are reliable and satisfy the required performance criteria for roads.

In order to produce these HMA mixes the bitumen and aggregate have to be heated to very high temperatures to ensure that most of the moisture is evaporated from the aggregate and also to reduce the bitumen viscosity for good coating. This makes it possible to produce an asphalt mix with high workability and compactability, but with it comes some negative consequences.

Heating the aggregate and bitumen to these high temperatures, (typically ranging from 135° C – over 180° C depending on the conditions and binder types), requires a great deal of energy and fuel consumption.

Additionally, heating the bitumen and aggregate to such high temperatures also releases toxic fumes and greenhouse gas emissions (GHG's) which are harmful to the environment as well as the health of the workers and people that are exposed to these toxic fumes. The emissions (GHG's) include carbon dioxide ($CO_2$), sulphur dioxide ($SO_2$), carbon monoxide (CO) and nitrous oxide (NOx) amongst others which contribute to global warming. The toxic fumes make working conditions difficult and detrimental to the workers' health.

The Kyoto Protocol signed on 11 December 1997 in Kyoto, Japan, enabled the United Nations Framework Convention on Climate Change (UNFCCC or FCCC) to set enforced responsibilities on the industrialised countries to reduce the amount of emissions produced in the form of greenhouse gases. This protocol was officially enforced from 16 February 2005 with the purpose of accomplishing the stabilisation of GHG concentrations in the atmosphere at a safe and acceptable level. The Kyoto protocol established that the required percentage reduction in GHG emissions was 5.2% of the 1990 levels from 2008 – 2012. (Kyoto Protocol, 2012)

The United Nations Climate Change Conferences were held in 2009 in Denmark, in 2010 in Mexico and in 2011 in South Africa. At the last conference in 2011 a treaty was agreed upon which was legally binding upon all countries. The agreement would be enforced by 2020. (Post-Kyoto Protocol negotiations on greenhouse gas emissions, 2012)

## 1.2 PROPOSED SOLUTION TO THE PREDICAMENT

The asphalt industry in South Africa, as with the roads industries in many other countries, has embarked on a quest to find alternative mix types to investigate and evaluate against the HMA mixes as benchmark. These alternative mixes must be produced at lower temperatures than the HMA so as to effectively lower the energy consumption and the emissions and toxic fumes during production and construction.

To lower the production temperature of an asphalt mix is potentially dangerous since the binder viscosity needs to be in a workable state so to be able to effectively coat the aggregate and produce a good quality mix.

Mixes produced at lower temperatures have become known as warm mix asphalt (WMA) which incorporates a technology into the binder which enables it to reach the same or similar viscosity level achieved with HMA at high temperatures but at a reduced production temperature. Decreasing the production temperature of an asphalt mix brings great benefits. Therefore it is a sensible proposed solution to the 'predicament'. Benefits include:

- Reduced GHG emissions
- Reduced toxic fumes which means improved working conditions and health
- Reduced fuel and energy consumption which is more economical and sustainable in terms of depletion of Earth's resources
- More recycled materials can be used in WMA than in HMA
- Reduced rate of cooling which allows for longer mix and hauling distances
- Reduced compaction energy required
- Allows for paving in cooler temperatures whilst obtaining the target density

Even though WMA seems to offer more benefits than HMA, one needs to look at the potential challenges and difficulties associated with WMA. The production temperature of an asphalt mix is a vital parameter and influences the binder viscosity, workability and compactability of the mix and the amount of moisture remaining in the aggregate. Reducing the production temperature as with WMA mixes, raises some concerns regarding performance issues, of which potential moisture and rutting damage are the main ones. These concerns are related to the potential poor dryness of the aggregate and the fact that the resultant binder may be poor.

### 1.3 WARM MIX ASPHALT TECHNOLOGIES AND MIXES

Since the mid 1990's, Europe started producing new WMA technologies with the aim of forming a safer, healthier and better working conditions as well as cutting back the emissions generated. The first WMA technologies that would reduce the production temperature of HMA mixes, materialized in the late 1990's. There are several WMA technologies that have been developed since then and that are available on the market.

The different types of WMA technologies available can be divided into two main categories namely additive and foaming technologies, which in turn can each be divided into two sub-categories.

The first type of additive technology is organic additives which lower the viscosity of the binder at working temperatures and harden at service temperatures.

Chemical additives are the second type of additive technology. They work at the microscopic interface of the binder and aggregate to control and reduce internal friction when the mix is being mixed and compacted.

Foaming technologies are split into foaming admixtures and free water systems. Foaming admixtures use material (aggregate) which has moisture present in order to produce steam and create foam.
Free water systems use a foaming nozzle in the mixing process to incorporate moisture and create foam.

Figure 1.1 below displays the main types of WMA technologies available today as well as two examples of each type. The three WMA technologies highlighted in green on Figure 1.1 below are the three types of WMA technologies which are investigated in this study, namely Rediset, Sasobit and Foamtech. (Astec Double Barrel™ Green System)

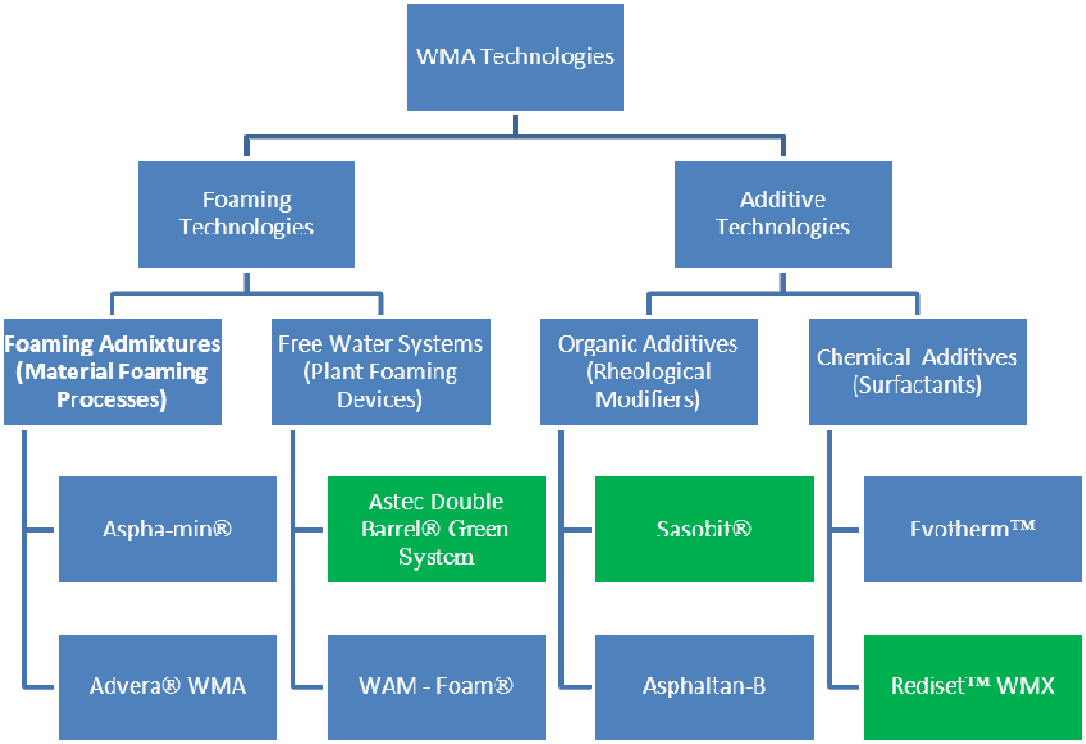


**Figure 1.1 WMA Technology Products**

## 1.4 METHOD FOR EVALUATING WMA vs. HMA

Evaluating WMA performance against HMA as a benchmark requires the determination of the engineering properties as well as the performance criteria to evaluate these mixes. The global approach to WMA technology is that it should perform at least as well as HMA, if not better, making these evaluations important. In this study flexural stiffness as a mix property and fatigue life as a performance condition are used when evaluating WMA mixes against HMA mixes. Performance can be evaluated in terms of material a) 'response' e.g. flexural stiffness and b) 'damage' e.g. fatigue cracking. This enables the comparison between HMA and WMA.

Flexural stiffness is a mix property which is dependent on loading time and temperature. The higher the flexural stiffness, the higher the load spreading ability of the mix, thus reducing the stressed transferred to the underlying layers. Flexural stiffness also influences the fatigue behaviour of the asphalt mixture.

The flexural stiffness is obtained from the LVDTs mounted on the beam in a four point beam test setup, and is used to produce a master curve for each mix. A master curve represents the flexural stiffness of the mixture over different frequencies (loading times) at a fixed reference temperature and thus the visco-elastic behaviour is determined. In this study the master curve is used to evaluate the flexural stiffness of the WMA mixes against the HMA mixes.

Damage that occurs in the bound WMA material as a result of repeated cyclic flexural loading is defined as fatigue cracking. The number of allowable load repetitions at a certain level of resultant tensile strain at the bottom of the asphalt pavement layer, is evaluated when considering the fatigue life of a mix. The fatigue life will be the number of load repetitions required to reduce the initial flexural stiffness by 50%. Two methods of evaluating the fatigue life of the mixes are used in this study namely, the Wohler approach (strain versus load repetitions) and the Van Dijk W (1977) approach (cumulative dissipated energy versus load repetitions).
Phase angle index values, measured during, are also used to evaluate the mixture behaviour under different environmental conditions.

## 1.5 PURPOSE AND OBJECTIVE OF STUDY

In 2008, the first WMA trial was launched from Durban by the WMA Interest Group in association with National Asphalt, eThekwini municipality and WMA technology suppliers. The first trial was run in November 2008 along the Brackenhill Road, the second trial on May/June 2009 along the Leichester Road. This research study forms part of the third and final trial performed on October/December 2010 along the Higginson Highway.

Both the first and second trials proved that WMA can successfully be produced and compacted at temperatures 20° C lower than those used for HMA. The goal of the third trial was to push boundaries by:

- Reducing the production and paving temperatures further
- Utilizing polymer-modified binders in the WMA mixes
- Achieving performance and quality criteria with WMA equal or above the conventional HMA
- Increasing the amount of reclaimed asphalt (RA) contents in the mixes
- Providing the opportunity to produce and compact both surface and base mixes

The researcher embarked on a laboratory evaluation of several WMA mixes to identify the relative fatigue performance and flexural stiffness of the mixes of the third trial. The laboratory evaluation is carried out using the IPC Four-Point Beam Fatigue Apparatus. To figure out the WMA performance these engineering properties and performances of WMA mixes (also called trial mixes) were assessed against the HMA mixes (also called control mixes). The objectives of this researcher include:

- To determine the performance criteria i.e. flexural stiffness and fatigue performance, of the WMA and HMA mixes
- To analyse the performance criteria of the WMA mixes and at the same time take notice of and compare the different mix variables used for the WMA mix recipes. (RA content, binder type, WMA technology used) This will show the effect these variables have on mix performance.
- To evaluate the WMA mixes against HMA mixes (as the benchmark) in terms of the performance criteria mentioned in the first point.
- To obtain the phase angle index of the WMA and HMA mixes, allowing for the investigation of the visco-elastic characteristics and behaviour of the WMA mixes compared to those of HMA mixes.
- To draw meaningful conclusions and recommendations from the results and comparisons made between WMA mixes and HMA mixes.

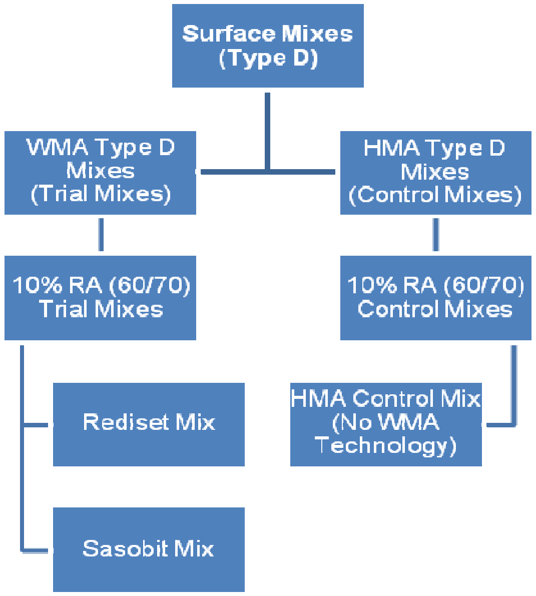


**Figure 1.2 Surface (Type D) Mixes for Evaluation in Research Study**

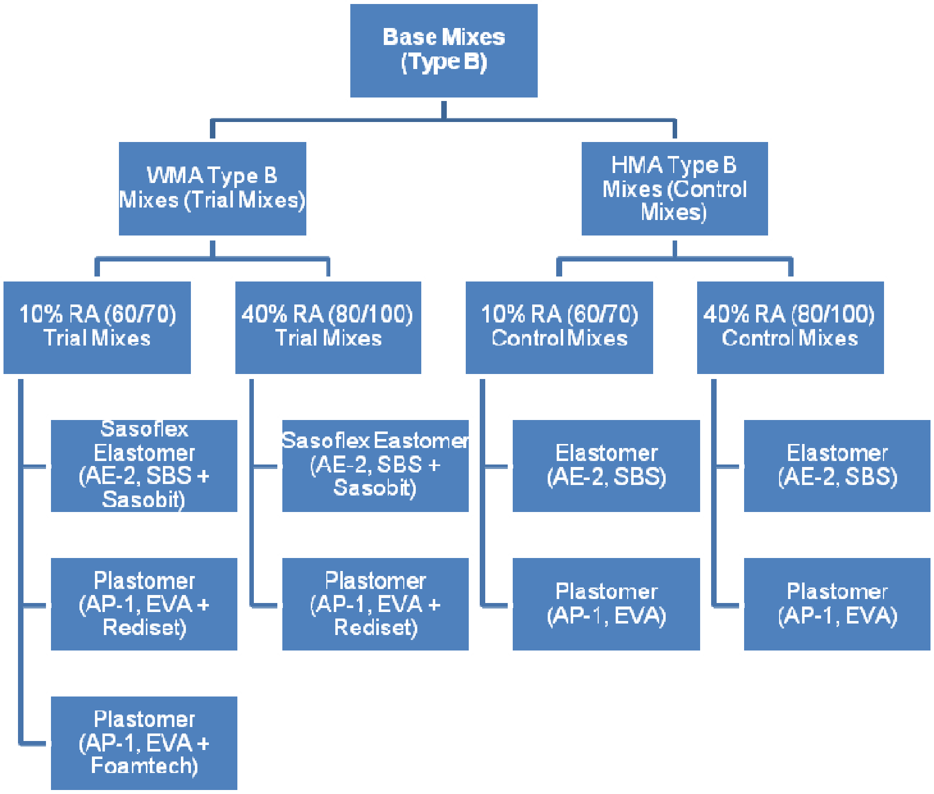


**Figure 1.3 Base (Type B) Mixes for Evaluation in Research Study**

Figure 1.2 and 1.3 above display the different mixes considered for evaluation for the surface (type D) and base (type B) mixes respectively. For a detailed description of these mixes refer to Table 3.1 in Chapter 3.

## 1.6 LIMITATIONS OF STUDY

This research study is limited in the following aspects:

- The data of this study was limited to the combinations of WMA mixes that was produced during the time of the investigation.
- The mixes that were produced can be seen on Figure 1.2 and Figure 1.3 above.

## 1.7 SCOPE OF STUDY

This research study is split into four main sections:

- **Chapter 2** – Research literature study which explains the principles in asphalt production as well as performance related aspects and environmental considerations regarding the subject at hand.
- **Chapter 3** – Methodology which describes and demonstrates the laboratory activities including the mixing, compaction, cutting, testing and evaluation of the mix beams.
- **Chapter 4** – Laboratory results and analysis which present the data and results obtained from laboratory testing of the mixes and analyses them. The WMA mix results are compared to their corresponding HMA mix results as benchmark to evaluate their performance against each other.

- **Chapter 5** – Conclusions which are drawn from the evaluation and analysis of the test results found in chapter 4. Recommendations are also made.

# CHAPTER TWO

# LITERATURE STUDY

## 2.1 INTRODUCTION

An asphalt mixture fundamentally consists of coarse aggregate, fine aggregate, filler, and bitumen as the binder. The bitumen binder could either be a conventional or polymer-modified binder. There are also some air-particles trapped inside the mixture, called voids, representing the void content of the mixture.

Asphalt mixture types are classified by the production temperature as shown below in Figure 2.1. The temperature ranges above 135 ℃ for HMA, 100-135 ℃ for WMA, 30-100 ℃ for HWMA (Half-Warm Mix Asphalt) and below 30 ℃ for CMA (Cold Mix Asphalt).

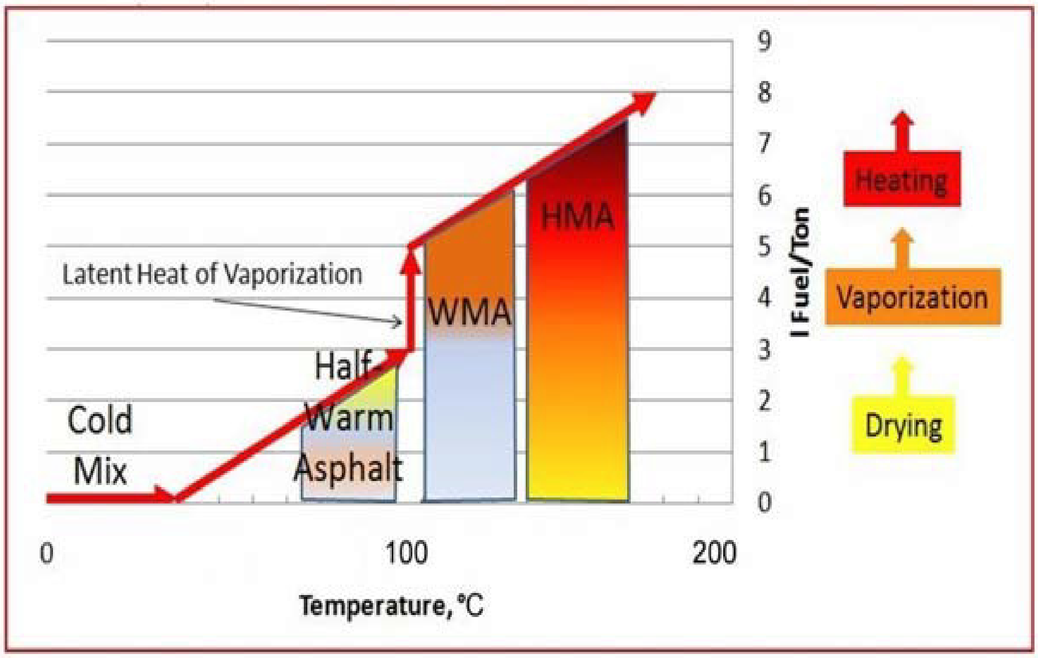


**Figure 2.1 Classification of Asphalt Mixture Types According to Production Temperature and Fuel Usage (D' Angelo et al, 2008)**

There is another component incorporated into WMA which makes it different from HMA, called WMA technologies. The intent of the WMA technologies is to lower the production temperature of the WMA mix while maintaining an equal or greater performance than that of the HMA mix produced at higher temperatures. These WMA technologies make it possible to reduce the binder viscosity at lower temperatures than usually achieved with HMA production. Seeing that the bitumen does not need to be heated to such high temperatures to ensure that the bitumen is at a workable level, a lower production temperature is achieved.

These WMA technologies can be split into two main types namely additive and foaming technologies. Furthermore, the additive technologies can be split into organic (rheological) and chemical (surfactants) additives. The foaming technologies can also be split into two categories namely foaming admixtures (material foaming process) and free water systems (plant foaming devices). These foaming technologies use water to foam the bitumen and hence improve the workability and viscosity of the bitumen.

The aim with this literature study is firstly to investigate the influence that the different mix components have on the performance of the mixture. The focus will be on how the WMA technologies (Sasobit, Rediset and Foamtech) influence the binder and mixture properties and how these compare to the properties of the HMA mixes. The performance considerations used to evaluate the WMA mixes against the HMA mixes will also be investigated.

The Asphalt Institute (2007) states that the main requirements or performance criteria needed for asphalt mix design (applies to both HMA and WMA mix design) are:

- Resistance to permanent deformation
- Fatigue resistance
- Low-temperature cracking
- Moisture resistance
- Durability
- Skid resistance
- Workability

This focus will be on the fatigue resistance, flexural stiffness (which is a function of load spread ability and permanent deformation) and phase angle index (to analyse the visco-elastic behaviour of mix). These are the performance criteria selected to be used to evaluate the WMA mixes against the HMA mixes (as benchmark).
Lastly, the environmental considerations with regards to WMA will be investigated by looking at reduced emissions, increased RA usage, reduced energy and fuel usage and improved working conditions in comparison with HMA mixes.

It is very important to understand the different components of a mixture and how they affect the performance of the mixture. If this is known, clear decisions can be made when proportioning the different components in the mix design, thus enhancing the performance properties of the mixture to meet the criteria desired. Different mixture components and their influence on the mix performance will now be investigated.

## 2.2 MIXTURE COMPONENTS AND MIXTURE PERFORMANCE INFLUENCE

In this part of the literature study each mix component is described individually; investigating the influence it has on the performance of the mix, as well as what the mix component consists of.

Essentially, a WMA mix consists of 4 components:

- Aggregate
- Binder (conventional or polymer-modified)
- WMA Technologies (additives or foaming process)
- Air Voids (void content)

### 2.2.1 Aggregate

Aggregate is defined (by the American Society for Testing and Materials.(ASTM D 8, 2003)) as *"a granular material of mineral composition such as sand, gravel, shell, slag, or crushed stone, used with a cementing medium to form mortars or concrete or alone as in base courses, railroad ballasts, etc."*

Aggregate can generally be described as the rigid, static mineral material component of the mixture, which provides a stable, structural skeleton to the mixture. This mechanically stable skeleton/framework primarily contributes to the load-supporting capacity of the pavement mixture. Consequently, the performance of a mixture is heavily influenced by the aggregate.

Aggregate is the main component of an asphalt mix, generally comprising 90-95% by weight and 75-85% by volume as stated by the Asphalt Institute (2007). Accordingly, it can be understood that the aggregate has a significant influence on the mixture performance since the mixture consists mostly of aggregate.

Aggregates consist of various graduated sized materials. Brown et al (1996) classify these different sized aggregates as coarse and fine aggregate as well as filler according to their size. The coarse aggregate is described as particles retained on a No. 4 sieve (4.75 mm), fine aggregate as particles passing the No. 4 sieve (4.75 mm) but retained on the No. 200 sieve (0.075 mm) and the mineral filler as at least 70% of the material passing the No. 200 sieve (0.075 mm).

Jackson et al (1962) describe and explain these three aggregate categories with regard to their influence on mixture performance:

Firstly, coarse aggregate contributes to the stability of the mixture due to the shape and surface texture of the aggregate particles. Ideally, the coarse aggregate should be a hard, angular stone with a rough surface texture, like crushed stone. Consequently this results in the aggregate particles interlocking with each other providing frictional resistance to displacement, therefore increasing the stability of the mixture.

Secondly, while fine aggregate also contributes to the stability of the mix, it also reduces the air voids in the coarse aggregate. The particle texture is essential with regards to the stability of the mixture, the rougher the surface texture, the higher the stability of the mixture. The coarser particles (those passing the 2.36 mm sieve but retained on the 0.60 mm sieve) provide the mortar with a sandpaper texture, thus resulting in good non-skid properties to the pavement. The finer particles (those passing the 0.60 mm sieve but retained on the 0.075 mm sieve) increase the surface area of aggregate in the mixture, which results in providing the mixture with the required durability. It should be noted that balancing the grading of the fine aggregate is very important, in order to provide both the non-skid and binder carrying properties required.

Thirdly, the filler acts as a final air void filling material and also stiffens the binder film on the aggregate particles. Hydrated lime and other active fillers can also increase the stability of the mixture. In suitable materials for fillers at least 65% or more should pass the 0.075 mm sieve. The fractional air voids in the filler have been shown by

Ridgen (1947) to play a major role in the behaviour of the filler and are a key parameter in the rheological properties of the mastic. The fractional air voids in the filler are filled up with the binder to form a 'fixed' mastic and the leftover binder is the 'free' binder which becomes a measure of the fluidity of the mix. Adding too little binder to the filler will only fill some of the air voids and result in a dry, rigid mix which will be impractical to work with. Adding too much binder to the filler will fill up all the voids and result in a fluid quality to the mixture. (Heukelom, 1965)
Ridgen (1947) suggested that the main factor defining the consistency of filled systems is the percentage 'free' binder. He also stated that changes in the mix viscosity are dependent on the fractional air voids in the filler, and not on any other binder or filler characteristics. Faheem et al (2011) concluded in their research study that the fractional air voids of fillers are critical for defining the influence on mixture performance.

The Aggregate Handbook, published by the National Stone, Sand and Gravel Association, states: *"The ideal aggregate has proper particle size and grading, is strong and tough, and consists of angular, nearly equidimensional (cubical) particles with moderately low porosity. The surface of the aggregate is clean, rough, and hydrophobic, which means it has an affinity for asphalt rather than water."*

However, this alone is not enough to meet the criteria. To determine the suitability of aggregates for use in WMA/HMA the following material characteristics are evaluated:

#### 2.2.1.1 Maximum Particle Size and Gradation

Brown et al (1996) indicate that maximum particle size in a mixture is vital to ensure good performance. If the maximum particle size is too large, workability and segregation may be a problem; if it is too small, the mixture may be unstable. An increase in the use of large stone mixes has been seen in recent years. This is done to minimize the rutting potential of the mixture. The large stone sizes increase the volume concentration of the aggregate in the mixtures, thus reducing both the design binder content and cost of the mixture. These mixtures are more resistant to rutting, but using maximum aggregate size greater than 25.4 mm often results in segregation.

Gradation refers to the distribution of particle sizes expressed as a percentage of the total weight. The gradation of an aggregate can be represented graphically by a gradation curve. Brown et al (1996) indicate that gradation may be the most important property of an aggregate affecting almost all of the important properties of a mixture including: stiffness, stability, durability, permeability, workability, fatigue resistance, frictional resistance and resistance to moisture damage.

It would seem sensible that the gradation having maximum density is best, since it provides increased stability to the mixture, by means of reducing the voids in the aggregate. However, Brown et al (1996) recommend that caution should be taken since there needs to be sufficient air void space to allow enough binder to provide an adequate film thickness to ensure maximum durability, while also leaving some air void space in the mixture to avoid bleeding and rutting. Higher density aggregate gradations are more sensitive to minor changes in the binder content. Minimum voids in the mineral aggregate (VMA) requirements have been suggested to ensure that the right balance is maintained.

#### 2.2.1.2 Particle Shape and Surface Texture

The Asphalt Institute (2007) defines particle shape as the form and contour of the individual aggregate particles. (Angular or round; cubic or flat/elongated) Surface texture is defined as the extent of roughness of the aggregate particle surface. Particle shape affects the compaction that is needed to obtain the desired density as well as the strength characteristics and workability of the pavement mixture.

Brown et al (1996) recommend that the aggregate particles should be cubical instead of flat/elongated.

The Asphalt Institute (2007) explains that flat/elongated particles will result in breakage during compaction. This leaves the aggregate particles with uncoated surfaces, thus reducing strength. Furthermore, they are also susceptible to segregation. Surface texture also affects the compatibility, workability and strength of mixtures.

#### 2.2.1.3 Toughness/Hardness

Aggregates go through several processes from production and placing, to compaction of the pavement mixture. Brown et al (1996) recommend that aggregates should be hard and tough in order to resist all the wear and degradation caused by these processes. The Asphalt Institute (2007) advises that aggregates at or near the pavement surface are subjected to abrasion under traffic loads, hence requiring more toughness than aggregates in the lower layers. Aggregate toughness is measured by its ability to resist degradation and wear.

#### 2.2.1.4 Durability/Soundness

Durability and soundness are also known as the freeze-thaw resistance and weathering resistance of the aggregate.

The Asphalt Institute (2007) defines the freeze-thaw resistance as the aggregate’s ability to resist degradation caused by cycles of freezing and thawing when the aggregate is in a saturated condition. When the absorbed water transforms into ice, internal expansive forces develop in the voids of the aggregate. Weathering resistance refers to the aggregate’s ability to withstand volume changes and degradation which occur during cyclic wetting and drying.

Brown et al (1996) state that once the aggregate is incorporated into the mixture, freezing/thawing should not be a problem, since the aggregates are coated with a thin film of binder, which should prevent significant aggregate moisture absorption during the life of the mixture.

In general, HMA mixes have thicker binder films which coat the aggregate particles, than the WMA mixes. This transpires from the higher production temperatures of HMA mixes, which vaporize the moisture in the aggregate voids, resulting in more air voids in the aggregate. The moisture in the aggregates of the WMA mixes which did not evaporate could hinder the bonding of the binder with the aggregate particles and could result in stripping taking place. This could increase the amount of absorption, which could decrease the freeze-thaw and weathering resistance for WMA mixes. HMA mixes with the thicker binder films will be more protected against absorption and hence increase the freeze-thaw and weathering resistance.

### 2.2.1.5 Pore Structure, Porosity and Absorption

The Asphalt Institute (2007) defines pore structure as the configuration and characteristics of voids in an aggregate particle. Voids in the aggregate particle can either be impermeable, which means the voids are isolated or encapsulated within the aggregate particles, or permeable, where the voids are interconnected and open to the surface.

The total volume of voids in the aggregate particle is defined as the porosity. Higher porosity results in lesser aggregate strength and lower density/specific gravity. A test was developed by Ridgen (1947) to measure the void content of dry, compacted filler which was later modified by Anderson (1987). This void content will fill up and hold the binder and represents the minimum volume available in the filler to hold the binder. When all the voids have been filled, the excess binder becomes 'free binder' which is the binder available to lubricate the filler-binder mixture (also called mastic). The voids in the filler relate to the stiffening potential of the mastic, as shown by Anderson (1987), Khandal (1981) and Cooley et al (1998). The higher the filler void content, the more binder will be absorbed, resulting in less 'free binder' and a higher stiffening effect of the mastic.

The intake of liquid into the voids of an aggregate particle is defined as the absorption. High absorption usually indicates a large volume of permeable voids, resulting in the aggregate absorbing binder. Consequently, additional binder needs to be added to the paving mixture to compensate for the binder absorbed by the aggregate.

When producing HMA the aggregate is heated to high temperatures which vaporize the moisture located in the voids from the aggregate resulting in dry aggregate with higher voids. WMA production reduces the temperature to which the aggregate is heated which results in some moisture remaining in the voids and on the aggregate. This moisture could interfere with the bonding of aggregate and binder, which could result in failure of the mix. The incomplete dryness of the aggregate also reduces the available voids in the aggregate since the remaining moisture takes up some voids. The fact that WMA has fewer voids than HMA will result in less binder being absorbed into the voids and more 'free binder' will be available which in turn leads to a reduced stiffening effect of the mastic.

### 2.2.1.6 Cleanliness/Deleterious Materials

The Asphalt Institute (2007) defines deleterious materials as any substance in the aggregate that is detrimental to or diminishes the necessary properties of the mixture. Examples of deleterious materials are clay and other surface coatings on aggregate particles, clay lumps, soft or weak particles and organic material. Aggregate cleanliness describes the level of surface coatings on an aggregate, which can affect the bond or adhesion of the binder to the aggregate.

### 2.2.1.7 Affinity for Water or Binder

Brown et al (1996) indicate that aggregates either has a greater affinity for water, called hydrophilic and is usually acidic in nature, or it will have a greater affinity for binder, in which case it is called hydrophobic and is usually basic in nature.

When water comes into contact with the aggregate surface, the surface becomes electrically charged and the nature of this charge significantly affects the adhesion between aggregate and binder and its resistance to moisture damage.
When the charge is negative the aggregate has a greater affinity for binder and when positive, a greater affinity for water. Hydrophilic aggregates in a pavement mixture, which is exposed to water, result in the binder film on these aggregate particles becoming detached or stripped.

### 2.2.2 Binder

The terms binder, bitumen and asphalt are used in different countries to refer to the same thing, but to avoid confusion only binder will be used to describe the bitumen or asphalt binder in this study. The Asphalt Institute (2007) describes binder as viscous liquids or solids mainly consisting of hydrocarbons and their derivatives, which are soluble in carbon disulphide. At room temperature the binder is substantially non-volatile but gradually softens when heated. Binder is also described as a visco-elastic material, which means the binder behaviour changes with change in temperature or loading time. This will be discussed in more detail later.

#### 2.2.2.1 Binder properties and characteristics

The Asphalt Institute (2007) identifies three properties or characteristics of binders which are important:

**a) Consistency**

Consistency is defined as the characteristic which describe the viscosity or degree of fluidity of the binder at any particular temperature. Binders are characterized by their consistency or ability to flow at different temperatures. Consistency varies with temperature; therefore it is essential to define either an equivalent temperature, or consistency, when comparing the temperature-consistency characteristics of different binders with each other.

During the mixing process a thin film of binder coats the aggregate particles. Exposure of this thin film of binder to the air, at elevated temperature, results in the binder hardening, which means the consistency or viscosity of the binder increases. Carelessly overheating the binder during mixing can result in damage through binder hardening, for example the asphalt pavement may experience early cracking failures, shortening the pavement life significantly.

**b) Purity**

Binders consist almost entirely of bitumen which dissolves in carbon disulphide. Usually more that 99.5 % of a binder is soluble in carbon disulphide.

**c) Safety**

When a binder has been heated to a high enough temperature (called the “flash point”) it releases fumes that flash in the presence of a spark or open flame.
Another safety hazard occurs when there is water or moisture present in the binder, resulting in the binder foaming when heated in the mixing process. This is due to the water or moisture becoming steam when heated, causing the binder to foam.

### 2.2.2.2 Binder Behaviour

As stated earlier, binder is often defined as a visco-elastic material, where it acts as a viscous liquid at high temperatures or/and under long duration loading; and as an elastic solid at low temperatures and/or under short duration loading. Evidently, it can be indicated that the behaviour of the binder changes with temperature and time of loading. Therefore, under high temperatures but loaded in a short period, the binder may exhibit the same flow as when it is loaded over a longer period under lower temperatures. The Asphalt Institute (2007) defines this concept as the time-temperature superposition and this applies to linear visco-elastic materials.

To understand the behaviour of binder at different temperatures, it is investigated at three conditions, namely:

- High temperatures and long duration loading
- Low temperatures and short duration loading
- Intermediate temperatures

Another important behaviour of binder which should be considered is called ageing or hardening and this occurs over a long period of time.

#### a) High Temperature and Long Duration Loading

Sabita Manual 2 (2007) and The Asphalt Institute (2007) both explain that when the binder is subjected to hot conditions (summer temperatures) or sustained loads (for example slow moving trucks); it acts like a viscous liquid. Under these conditions, the binder will undergo plastic deformation, which is irreversible

The Asphalt Institute (2007) defines viscosity as the physical material characteristic used to describe the resistance of liquids to flow.
Sabita Manual 2 (2007) describes that when a liquid flows, the adjacent molecules slide past each other creating frictional or resistive forces between them which are related to relative velocity of sliding. Viscosity is defined as the relationship between this resistive force and relative velocity of sliding.
Binders usually exhibit a linear relationship between rate of shear strain (relative velocity) and shear stress (resistive force) as illustrated in Figure 2.2. Referring to the figure, it can be noted that with Newtonian fluids, the viscosity (µ) remains constant, regardless of shear rate. Examples of Newtonian fluids are water, air and binder (greater than 60 °C).
The Asphalt Institute (2007) indicates that some binders, particularly modified binders, display non-Newtonian behaviour. “Shear thinning” may occur in some binder materials, by a decrease in viscosity as shear rate increases, also illustrated in Figure 2.2.
Less frequently, another non-Newtonian behaviour that may occur is called “shear thickening”, and is also illustrated in Figure 2.2, the viscosity increases as the shear rate is increased.

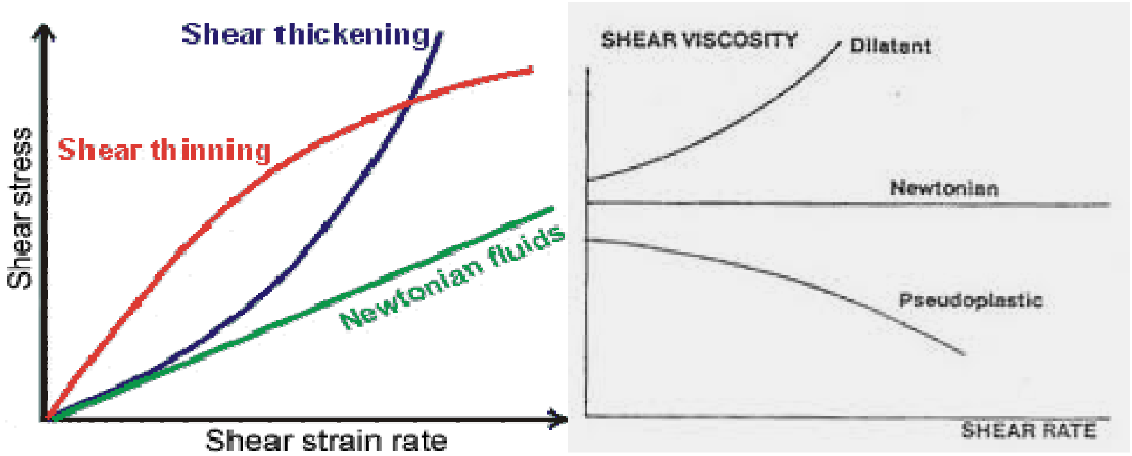


**Figure 2.2 Behaviour of Binders as Shear Rate Changes**

Sabita Manual 2 (2007) explains that pavements bound with binder, which is subject to high temperatures and repeated load applications, will tend to rut at a rate dependent on the temperature and rate of loading. This behaviour of the binder can be countered by the interlocking action of the aggregate particles, which helps in resisting permanent deformation.

### b) Low Temperatures and Short Duration Loading

As expected, binder subjected to low temperatures (winter conditions) or rapidly applied loads (fast moving trucks), behaves as an elastic solid. To understand elastic solid behaviour more clearly, The Asphalt Institute (2007) recommends that a rubber band be considered; when subjected to a load the band deforms, and after unloaded the band returns to its original shape. Elastic solids may break if subjected beyond the material capacity or strength. Binders become too brittle at low temperatures and crack when loaded, as can be seen in asphalt pavements during cold weather.
The Asphalt Institute (2007) and Sabita Manual 2 (2007) explain that the binder which cements the aggregate, shrinks as the temperature decreases, resulting in a build-up of stresses. When these internal stresses exceed the binder strength the surface between the aggregates will break, and hence a crack starts forming.

### c) Intermediate Temperatures

Binder essentially displays visco-elastic behaviour at intermediate temperatures, meaning that when heated, the binder will act as a lubricant (viscous liquid), coating the aggregate and compacts tightly, forming a smooth, dense surface. On the other hand, when cooled, the binder acts as the glue holding the aggregate together in a solid matrix.

### d) Oxidative Ageing

When an asphalt mixture is exposed to oxygen in the environment, oxidation of the binder molecules occurs, which results in a change in the structure and composition of the binder molecules. According to Sabita Manual 2 (2007), this results in an increase in viscosity, as well as hardening and a loss of flexibility. This reaction occurs because bitumen binders are composed of organic materials. The Asphalt Institute (2007) and Sabita Manual 2 (2007) state that as oxidation occurs, the binder

becomes more brittle and thus eventually results in oxidative hardening. This happens at a slow rate in pavement, although there are a few exceptions.
Firstly, at warmer climates or warmer seasons it occurs faster.
Secondly, premature oxidative hardening might occur if the asphalt pavement has been improperly compacted. Inadequate compaction leads to a higher percentage of interconnected air voids in the asphalt pavement, which allows for air (oxygen) to penetrate the asphalt mixture, resulting in more oxidative hardening early in the pavement's life.

The Asphalt Institute (2007), Sabita Manual 2 (2007) and Brown et al (1996) indicate that substantial oxidative hardening happens before the asphalt mixture is placed. This occurs at the mixing facility when heated aggregate is mixed with hot binder and maintained at high temperatures for a while. The forming thin film of binder coating the aggregate is exposed to air at high temperatures, which allows for oxidative hardening to occur faster.

All the above applies to HMA oxidative hardening and is not necessarily true for WMA. The number of voids in the mixture will influence the rate at which ageing will occur, since the voids allow entry of air, water and light. Two main factors influence ageing of a mixture according to Bahla & Hanz (2011), namely temperature and viscosity. As the viscosity increases any new surfaces exposed to oxidative hardening will decrease, resulting in reduced ageing. The lower the temperature, the higher the viscosity and hence these two factors go hand in hand.

With the production of WMA the lower temperatures will increase the viscosity and hence reduce the ageing which can occur. The WMA technologies used enable a reduced viscosity at lower temperatures which are closer to ambient temperatures. The higher temperatures associated with HMA production will reduce the binder viscosity and hence increase the ageing. The higher voids in HMA mixes will also lead to increased ageing of the binder. The resultant bitumen in the WMA mixture will be less aged (more elastic) compared with HMA. Accordingly, when WMA is compacted a wider compaction window is available than that achieved with HMA, resulting in more passes of the compactors, and hence higher densities can be achieved even under cooler weather conditions.

Physical hardening can also occur when the pavement is exposed to low temperatures for long periods, due to the binder continuing to shrink and harden.

Brown et al (1996) and Sabita Manual 2 (2007) report that the following factors contribute to the ageing of an asphalt mixture during the mixing process and over its service life:

### i. Oxidation

This has been described in detail above and is the greatest contributor to the ageing of the binder.

### ii. Volatilization

This is the evaporation of lighter constituents from binder, influenced mainly by temperature.

### iii. Polymerization

Molecules that are alike tend to combine and form larger molecules, resulting in progressive hardening, which is called polymerization.

### iv. Thixotropy

Due to the formation of a structure within the binder over a long time, progressive hardening called thixotropy may occur.

### v. Syneresis

This is defined as an exudation reaction where the thin oily liquids are exuded to the binder film surface. Eliminating these oily constituents results in the binder hardening.

### vi. Separation

This is the removal of the oily constituents, resins, or asphaltenes from the binder. These oily constituents can be selectively absorbed by some porous aggregates.

### 2.2.2.3 Types and Grades of Bitumen

According to Sabita Manual 2 (2007) the two main types of binders are conventional (or penetration grade) and modified (or polymer-modified) bitumen.
Other types include cutback bitumen, bitumen emulsions and bitumen rubber. These will not be discussed further since only the main two types of binders are considered for the research done.

- **Conventional Binders**

Conventional binders are penetration grade bitumens, which are characterized by their penetration achieved during the penetration test. Penetration grade bitumen is usually the primary binder used as base bitumen for manufacturing other binders, like modified binders, cutback bitumen or bitumen emulsions. Table 2.1 shows some of the grades of penetration grade bitumen most widely used and available.

**Table 2.1 Conventional Binder Types**

| Conventional Binder Types | | |
|---|---|---|
| Type of Bitumen | Penetration Grade | |
| | ASTM D946-09 | EN 12591-2009 |
| Penetration Grade Bitumen | 40/50 | 20/30 |
| | 60/70 | 30/45 |
| | 85/100 | 35/50 |
| | 120/150 | 40/60 |
| | 200/300 | 50/70 |
| | | 70/100 |
| | | 100/150 |
| | | 160/220 |

- **Modified Binders**

Modified binders can also be referred to as polymer–modified binders or PMB's. The Asphalt Institute (2007) reports through several surveys, that there are certain benefits in using PMB mixtures to extend the pavement's service life. There are some that also state that using PMB mixtures reduces maintenance costs significantly. Three of the main reasons to use PMB's are:

- To increase the mixture's resistance to rutting of mixture.
- To increase resistance to thermal cracking of mixture
- To increases durability of mixture.

It is possible for modified binders to be manufactured by chemical modification, but polymer modification is the most widely used method.
Polymers consist of smaller molecules (monomers) that are chemically polymerized to form long molecular chains.
The Asphalt Institute (2007) specifies two broad classes of polymers used in the modification of binders; namely polyolefins and styrenic polymers.

As a result of polymerisation of molecules containing a simple double bond or olefin becomes polyolefins. Polyethylene, polypropylene and ethylene vinyl acetate are examples of polyolefins. Co-polymerization of polystyrene with other small molecules results in styrenic polymers, usually butadiene.

When polymers are stretched (strained or stressed) with enough force, they either exhibit plastic or elastic behaviour. Polymers that display plastic behaviour are classified as plastomers (plastics) and will yield under the force and stay stretched out when the force is released. According to Brown et al (1996) these polymers exhibit quick early strength on loading but may fracture under strain

Polymers that display elastic behaviour are classified as elastomers (elastics or rubber) and will yield, but when the force is released they will return to their original shape. Brown et al (1996) explain that these polymers add very little strength to the binder until they are stretched. However their tensile strength increases with elongation.

Usually most polyolefins behave as plastomers and styrene-butadiene copolymers behave as elastomers. When elastomers are used to modify binders, this usually results in a more flexible and resilient pavement. Plastomers usually increase the stiffness moduli of the pavement.

However, it is important to note that these results are very dependent upon the concentration, molecular weight, molecular structure and chemical composition of the specific polymer. Other factors which are equally important are the crude source, refining process and grade of the neat bitumen. The different types of elastomers and plastomers are displayed in Figure 2.3 below. Elastomers and plastomers will now be explained in further detail.

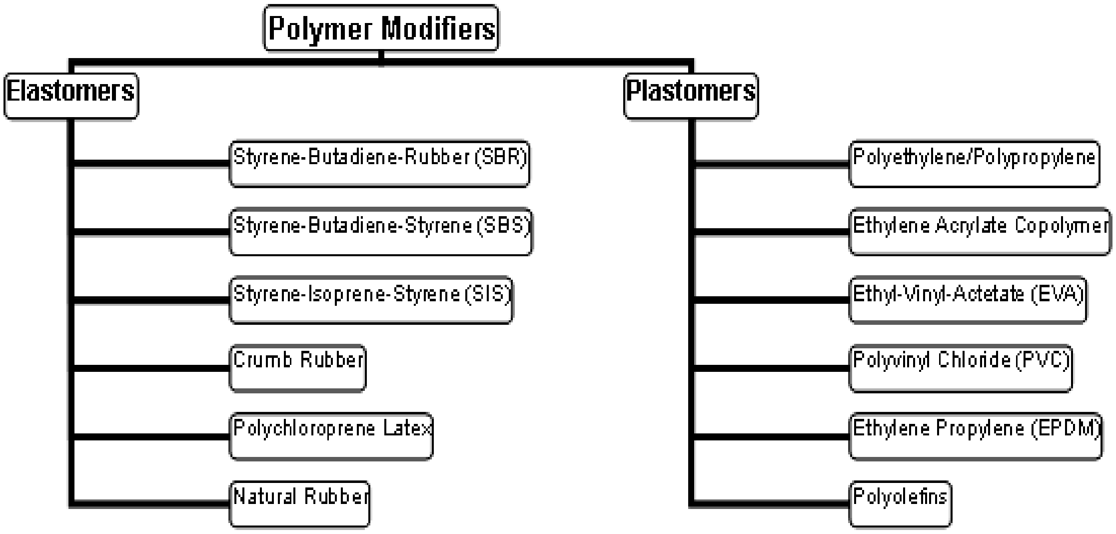


**Figure 2.3 Different Types of Elastomers and Plastomers Available**

### a) Elastomers

According to the Asphalt Institute (2007), butadiene is the most widely used co-monomer to produce styrenic polymers.
Sabita Manual 2 (2007) indicates that there are three types of elastomers used in South Africa:

- Styrene-Butadiene-Rubber (SBR) latex
- Styrene-Butadiene-Styrene (SBS)
- Rubber Crumb

The Asphalt Institute (2007) explains that SBR is produced by random polymerization of styrene and butadiene. The applications of SBR in South Africa include cold applied binder emulsion in chip seals and micro surfacing, and hot applied binder in chip seals and HMA.

SBS is produced by polymerization of styrene and butadiene in discrete, connected blocks. The Sabita Manual 2 (2007) and The Asphalt Institute (2007) indicate that SBS is the most widely used modifier in agencies. They continue by describing the potential benefits of SBS as follows:

- It helps to reduce permanent deformation or rutting of asphalt pavements.
- It helps to reduce low temperature cracking and fatigue.

Crumb rubber is reclaimed rubber primarily obtained from discarded tires. Brown et al (1996) indicate two processes by which crumb rubber is used, namely the wet and dry process. The wet process blends the crumb rubber with the binder before incorporating the binder into the project. The dry process mixes the crumb rubber with the aggregate before mixing it with the binder.

If an elastomer is used to modify the binder used in producing WMA, the resulting mixture will be more flexible and have improved strength and fatigue resistance, but because WMA is produced at lower temperatures the binder in the mix will age less and result in a more elastic mixture. One should take care when using elastomer modified binder with WMA technologies to produce a mixture which can be too elastic and susceptible to rutting and permanent deformation.

**b) Plastomers**

According to The Asphalt Institute (2007), polyolefin polymers will add to the stiffness of the binder at high temperatures but do not have elastic characteristics of styrenic polymers. Polyethylene and ethylene vinyl acetate (EVA) are most broadly used to modify binders. The main reason plastomers are used to modify binders, is to help reduce permanent deformation or rutting of asphalt pavements.

The more elastic mixture, due to less ageing of the binder when producing WMA at lower temperatures, should be alarming, since this increases the susceptibility to rutting and permanent deformation which opposes the aim of the plastomer modified binders. However, the WMA will rely more on the increased rut resistance, stiffness and viscosity achieved by the plastomer. In South Africa, EVA is most commonly used. The ethylene part of EVA improves the high temperature properties of the binder, and the vinyl acetate improves the low temperature properties.

### 2.2.3 WMA Technologies

Using polymer-modified binders in the production of HMA helped to improve the performance of the asphalt pavement, but a problem surfaced when WMA was introduced. WMA is to be produced and compacted at lower temperatures than HMA but still perform comparably to the HMA. Simply modifying the binder with polymers will only improve the performance of the mixture at high temperatures and this alone will not be enough to lower the production and compaction temperatures and still achieve equal or better performance than HMA mixes. Thus WMA technologies were developed to create an additive or process which would reduce the production/compaction temperatures of the mix and still maintain the desired performance criteria required.

WMA technologies generally reduce the binder viscosity and provide complete coating of the aggregate at lower temperatures. According to the European Roads Review 18 (ERR, 2011) these WMA technologies can reduce production temperatures by as much as 40%. WMA technologies are classified by type with regard to how they are implemented. Two main types of WMA technologies are classified, namely foaming technologies and additive technologies.

Foaming technologies incorporate small amounts of water into the hot binder and can be further classified by how they incorporate the water to foam the binder. Two main types of foaming technologies are free water systems and foaming admixtures.
Free water systems use a foaming nozzle, a series of nozzles or some other mechanism to introduce the water required to foam the binder. Foaming admixtures use a delivery system, like damp aggregate or hydrophilic material, to incorporate the water needed to foam the binder. When the water makes contact with the hot binder it turns into steam (disperses) and expands by a factor 1.673, resulting in an expansion of the binder phase and corresponding reduction in the mixture viscosity.

Additive technologies can also be further classified into two general types, namely surfactants (chemical additives) or rheological modifiers (organic additives).
Organic additives, usually some type of wax like Fischer-Tropsch wax, help to reduce the viscosity of the binder (and mixture) at temperatures above the melting point of wax. The type of wax to be used should have a melting point which is higher than the experienced in-service temperatures, to avoid or reduce permanent deformation and to minimize embrittlement of asphalt at low temperatures. Chemical additives (surfactants) work at the microscopic interface of the aggregates and binder. In essence, chemical additives make the binder “wetter” so it can more easily coat and lubricate the aggregate particles.
The different products available under the two types of WMA technologies, namely foaming technologies and additive technologies can be seen in Table 2.2 below and will now be discussed.

**Table 2.2 Different WMA Technology Products Available**

| Foaming Technologies | | Additive Technologies | |
|---|---|---|---|
| **Foaming Admixtures** | **Free Water Systems** | **Organic Additives** | **Chemical Additives** |
| Aspha-min® | Astec Double Barrel® Green System | Sasobit® | Evotherm™ |
| Advera® WMA | WAM-Foam® | Asphaltan-B | Rediset™ WMX |
| Low Energy Asphalt (LEA) | Terex® Warm Mix Asphalt System | Licomont BS 100/Sübit | Cecabase® RT |
| Low Energy Asphalt Concrete (LEAB) | Ultrafoam GX™ | 3ELT/Ecoflex | |
| ECOMAC | AquaBlack™ WMA System | TLA-X Warm Mix | |
| LT-Asphalt | Accu-Shear™ | Shell Thiopave™ | |

#### 2.2.3.1 Foaming Technologies

As stated previously foaming technologies are classified further according to how they incorporate the water to foam the binder. Therefore this section is split into two parts namely Free Water Systems and Foaming Admixtures.

#### A. Free Water Systems

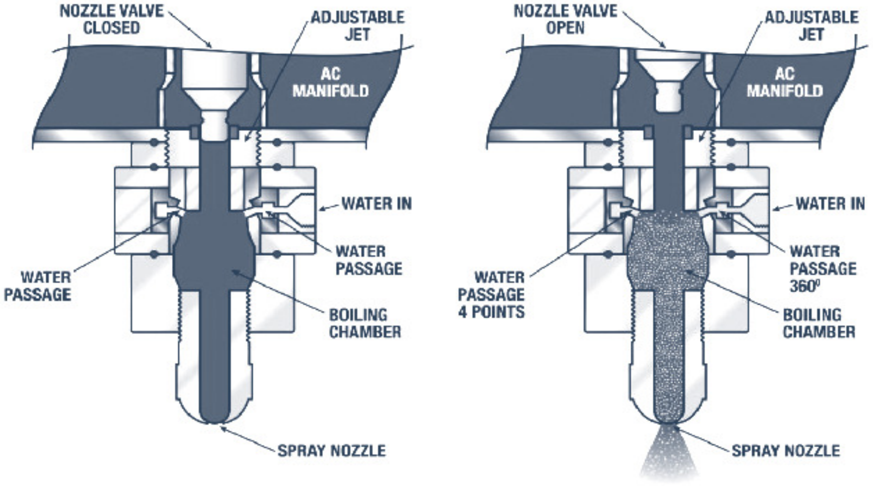
ERR (2011) describe free water systems as plant foaming devices which can be mounted on batch plants and continuous plants. These systems inject a small amount of water (1-3 % by weight of the binder) into the liquid binder before it is incorporated into the aggregate. When the water makes contact with the hot binder it vaporizes and expands to 1700 times its liquid volume. This causes the binder to expand by 5-10 %, thus increasing the volume, which in turn reduces the mass viscosity of the liquid binder and therefore improves the coating of the aggregate particles. Typical production temperatures range from 121 – 135 ° C when using mechanical foaming systems. Financially this system is beneficial since it is a once off capital cost to the owner.

Free water systems or plant foaming devices which have been developed include Astec Double Barrel® Green System, WAM-Foam® Terex® Warm Mix Asphalt System, Ultrafoam GX™, AquaBlack™ WMA System, Accu-Shear™, Meeker Mix System and Almix WMA System. The two most widely used and available systems are the WAM-Foam® and Astec Double Barrel® Green System, the latter being the system which was used to produce the Foamtech mixtures which were tested in the laboratory for this thesis. The different systems/devices will now be discussed in further detail.

***Astec Double Barrel® Green System***

Astec Industries developed a foaming system which uses a multi-nozzle foaming device to microscopically foam the binder. The device is made up out of a system of various valves, mixing chambers and nozzles. A hot oil jacket surrounds the entire system. Within the system each nozzle intimately mixes the water and binder within itself. To allow for expansion of the binder, each nozzle has a small region which is open to the atmosphere within an asphalt binder plenum. The foamed binder is then injected via the plenum into the mixing chamber of the drum or within a delivery pipe that supplies the mixing chamber. The nozzles can all be controlled by the computer, which makes it possible to set the number of nozzles needed based on production rate. A positive displacement pump, whose speed varies based on the asphalt pump speed, regulates the water being supplied to the system. Figure 2.4 presents an illustration of a typical nozzle and Figure 2.5 the multi-nozzle foaming manifold.

According to D'Angelo et al (2008), about 0.5 kg of water per metric ton of mixture is supplied through the nozzles, causing the binder to expand by roughly 18 times. Typical production temperatures are 135° C and the placing or compaction temperature as low as 115° C. The foaming technology which is investigated throughout this thesis, namely Foamtech, was produced and incorporated into the mixture using the Astec Double Barrel Green System.



FOAM NOZZLE CLOSED

FOAM NOZZLE OPEN

**Figure 2.4 Illustration of the Astec Nozzle (Brock, 2007)**

**Figure 2.5 Multi-Nozzle Foaming Manifold of Astec (Brock, 2007)**

### *WAM-Foam®*

A process was developed by Shell Bitumen in 1996 whereby hard and soft bitumen binder components are blended in order to reduce production temperatures. Collaboration with Kolo-Veidekke in Norway resulted in the development of the WAM-Foam process. Soft binder is typically 20-30% of total binder content. Coating the coarse aggregate with soft binder should satisfy the demand of any binder absorption of the coarse aggregate that may not otherwise occur with a stiffer binder at lower temperatures. Foaming the hard binder is achieved by adding ambient temperature water at a rate of 2-5% by mass of the hard binder fraction. According to Prowell and Hurley (2006), mixtures produced using WAM-Foam® have been placed/compacted at temperatures as low as 80℃, with a reduction in compaction temperatures of 50-60° C. It is also observed that a once-off plant modification is required for the foaming, estimated at $50,000 - $70,000, with no additional costs thereafter.

### *Terex® Warm Mix Asphalt System*

The Terex™ WMA System uses patented foamed-asphalt technology established in 1998, which uses a patented single expansion chamber to provide consistent asphalt binder/water mixture at any desired production rate.

The system produces foamed binder outside the rotating drum and then injects it immediately into the mixing chamber of the drum, allowing for even coating of the aggregate particles.

### *Ultrafoam GX™*

Ultrafoam GX™ WMA (also referred to as Green Machine) uses only the head (pressure) or energy of the pump which supplies the binder and water, which results in a simple yet reliable method for injecting steam into the foaming process. The binder and water can be introduced at varying flow rates, temperatures and pressures since there is no need for a powered mixing device.

Ultrafoam GX™ uses a patented design which uses a centrally located spring-loaded water valve which opens when water pressure is applied from behind the valve.

The binder can flow at various rates while the pressure of the fluid is kept constant, by means of a diaphragm plate located outside the nozzle. This results in the varying production rates of the binder and water ratio being well maintained and creates smaller steam bubbles, resulting in consistent binder foaming.

### *AquaBlack™ WMA System*

Maxam Equipment Inc. developed the AquaBlack™ WMA System which combines a centre convergence nozzle design with a patent-pending foaming gun to provide for efficient binder foaming.
Micro bubbles are produced and dispersed throughout the mixture with this system and the bubbles are retained throughout the mixing process, resulting in the asphalt mixture remaining workable for a longer time.

### *Accu-Shear™*

Stansteel developed the Accu-Shear™ WMA System which does not use water injection to produce foam as the previous systems do. The system forces the two fluids (binder and water) to mix together by means of a shearing process which uses a colloidal pump to drive the mixing action of the binder and water. According to Stansteel this mechanical blending of binder and water will increase the foaming action over simple water injection.

## Foaming Admixtures

Foaming admixtures or material foaming processes use specific materials which are water-bearing minerals to foam the binder as the mixing takes place. ERR (2011) identify two materials used as foaming admixtures namely moist sand and zeolite (a water-bearing mineral). When using moist sand the hot binder and coarse aggregate are first mixed together. Thereafter the moist sand, which contains a carefully controlled amount of moisture, is added, which causes the binder to expand.
Zeolite contains small amounts of water in its crystalline structure, which are released at high temperatures. According to ERR (2011), a reduction of 30-45° C in production temperatures has typically been seen.

When considering the cost associated with these processes, it has been found that the zeolite process requires modification of the plant to incorporate the material as well as the cost of the zeolite itself. Plant modification is required for the moist sand process as well as the use of an additive. Foaming admixtures or material foaming processes which have been developed and available for use include Aspha-min®, Advera® WMA, Low Energy Asphalt (LEA), ECOMAC, Low Energy Asphalt Concrete (LEAB®) and LT- Asphalt. The three most widely used processes are Aspha-min®, Advera® WMA and Low Energy Asphalt (LEA) and these will now be discussed in further detail.

### *Aspha-min®*

Aspha-min is a synthetic zeolite (water-bearing mineral) composed of alumino-silicates of alkalimetals which form silicate frameworks with large empty spaces in the structure that allow the presence of large cations, like sodium and calcium, and also large cation groups, like water molecules. Aspha-min has the following chemical formula:

$$M_{2/z}O \bullet Al_2O_3 \bullet x\ SiO_2 \bullet y\ H_2O$$

Inside the crystalline structure, the zeolite contains about 20% water, which is released by increasing the temperature. Zeolite releases small amounts of water in the form of very fine mist or water spray to create a controlled foaming effect, leading to a slight increase in binder volume and a reduction in binder viscosity.
According to D' Angelo et al (2008), 0.3% zeolite by weight of mixture is typically added to the mixture shortly before or at the same time the binder is added.

### *Advera® WMA*

According to D' Angelo et al (2008), PQ Corporation is producing a synthetic zeolite called Advera, similar to Aspha-min zeolite. Advera has a finer gradation than Aspha-min, with 100% passing the 0.075 mm (no. 200) sieve. Instead of simply blowing the Advera into the mixing chamber like a fibre, PQ Corporation is working on a process to blend Advera with the binder as it is being introduced into a plant.

### *Low Energy Asphalt (LEA)*

Low Energy Asphalt uses moisture contained in aggregates to foam the binder. The aggregate is split into two fractions, the coarse aggregate and sand-sized particles without fines, which should be about 60% of the total aggregate; and sand-sized particles with fines being the other 40%. The coarse aggregate, is heated to ± 150° C and mixed with total binder required for the mixture at normal binder temperatures. Just before mixing, about 0.5% (by weight of binder) of a coating and adhesion additive are added to the binder. The additive is designed to regulate the expansion of the foam and to act as an anti-stripping agent.
After the coarse aggregate is coated, the cold, wet fine aggregate is mixed in. Fine aggregate should ideally contain about 3% moisture. The moisture turns to steam when the fine aggregate comes into contact with the hot binder coated on the coarse aggregate, resulting in the binder foaming, which in turn results in the fine aggregate being encapsulated. Resulting mixture temperatures are less than 100° C.
Re-condensed residual moisture in the mixture, present in fine droplets, helps to maintain workability, even at low temperatures.

### *Low Energy Asphalt Concrete (LEAB)*

Low Energy Asphalt Concrete, which is actually a commercialization of the half-warm foam mix research conducted by Kim Jenkins, was developed by BAM in Netherlands.

It is the only process (other than ECOMAC) that does not heat at least a portion of the aggregate to temperatures above the boiling point of water. Virgin aggregate is heated to ± 95° C. Typically, 50% reclaimed asphalt (RA) is used in Netherlands for WMA and HMA. The RA is heated separately in a dryer drum to 110-115° C.

An amine-based additive, which is usually about 0.1% by weight of binder, is added to the binder immediately before mixing to promote coating and adhesion, but it also tends to extend the life of the foam, which increases workability. Foaming of the binder takes place in a nozzle. BAM uses a series of six nozzles, which are retractable, to manufacture LEAB when producing HMA. Energy savings of 40% with virgin mixes and 30% with mixes containing 50% RA were reported. (D' Angelo et al, 2008)

***ECOMAC***

Little is known about ECOMAC but it appears that a traditional cold mix is prepared using an emulsion. It is stored until ready to be laid, and is then warmed to improve the compaction and overall mechanical properties of the mixture.

***LT-Asphalt***

Low temperature asphalt uses a special foaming process in combination with about 0.5-1.0% of hydrophilic filler, which helps to hold and prevent latent moisture from foaming. Aggregates are heated to 90° C. Special nozzles are used to foam a special penetration-graded binder which is then mixed with aggregates along with the hygroscopic filler.

### 2.2.3.2 Additive Technologies

As mentioned previously all the WMA technologies discussed so far use water in some way to foam the binder. This raised concern of an increased potential of moisture susceptibility of the warm mix asphalt and therefore alternative WMA technologies that use additives, have been developed. Furthermore, the additive technologies can be classified under two broad types, namely organic additives (also called rheological modifiers) and chemical additives (also called surfactants). These two types of additives will now be discussed further.

### A. Organic Additives (Rheological Modifiers)

Organic additives are long-chain waxes that lower the viscosity of the binder at working temperatures and then harden at service temperatures. According to ERR (2011) some of these waxes have been used in HMA production to help with compaction, but these waxes are also effective at lower temperatures, allowing energy savings in production. Most hydrocarbons and polymers have a flexible backbone chain of carbon atoms. The carbon chain length is related to the molecular weight of the molecule and is denoted as $C_x$. (The x denotes the length of the carbon backbone chain and the C represents the carbon atom) Organic additives are generally waxes with melting points higher than 70° C and molecular sizes greater than $C_{45}$. The longer the carbon chain length the higher the melting point tends to be.

D’ Angelo et al (2008) indicate four different organic additives used in Europe namely Sasobit®, Asphaltan-B, Licomont BS 100 or Sübit and 3ELT or Ecoflex. Sasobit® is by far the most widely and extensively used organic additive in the world and is the organic additive which was investigated and tested in this thesis. These are all different wax type additives and will now be discussed further.

***Sasobit®***

Sasobit® has the ability to lower the viscosity of the binder during the mixing and compaction/paving process, which is why Sasobit® is often described as an “asphalt flow improver”. This allows working temperatures to be reduced by 18-54° C. Sasobit® is a Fischer-Tropsch paraffin wax, which is produced by treating hot coal with steam in the presence of a catalyst. It consists of long-chain aliphatic hydrocarbon waxes with melting point above 98° C. At lower temperatures they have a high viscosity and at higher temperatures it has a low viscosity. (Prowell, 2007) When incorporated into the binder, the Fischer-Tropsch wax will solidify into regularly distributed, microscopic, stick-shaped particles when temperatures reach between

65-115° C. These particles form a crystalline network structure in the binder which leads to improved stability, and higher viscosity at in-service pavement temperatures. Molecular lengths of the linear Sasobit® hydrocarbon molecule range from $C_{40}$ – $C_{120}$. The smaller crystalline structure of Fischer-Tropsch wax when compared to microcrystalline bituminous paraffin waxes, show reduced brittleness at low temperature.

There are a number of methods to incorporate Sasobit® into the binder or asphalt mixture. It can be pre-blended with the binder, added in-line with the binder in a molten state or added during the mixing process as a pellet. Figure 2.6 and 2.7 show two forms of Sasobit®, namely flakes and pellets. Figure 2.8 and 2.9 show the pneumatic feed to the mixing chamber.

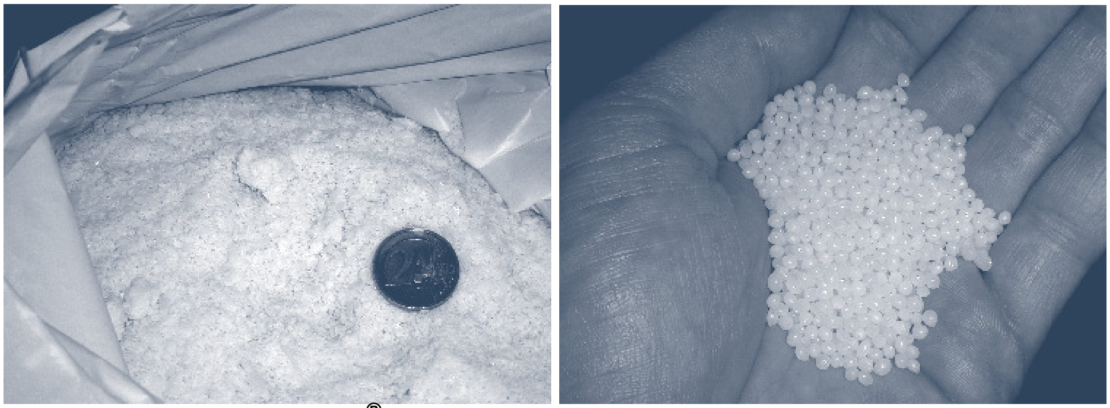


**Figure 2.6 and 2.7 Sasobit® Flakes (left) and Pellets (right) (Hurley & Prowell, 2005)**

**Figure 2.8 and 2.9 Sasobit® Pneumatic Feed to Mixing Chamber (Hurley & Prowell, 2005)**

According to D' Angelo (2008) the addition rates of Sasobit® should not be higher than 3% of total binder mass because of the stiffening effect at low temperatures. They also report that in Germany, 2.5% is typically added to the binder and in the USA, 1-1.5% is typically added.
Since 1997, more than 142 projects, totalling more than 10 million tons of mixture, have been paved using Sasobit®.

A new technology, developed by Sasol, is the combination of modification of Sasobit® plus SBS polymers with a patented cross-linking agent as well as a technology for transportable Super Concentrates, which enhances the high-temperature performance grade (PG) while minimizing the effect on the low temperatures PG. (Hurley & Prowell, 2005)

This ability of Sasobit® to be combined with polymers and reach the target specifications of a polymer-modified binder while still maintaining the advantages of WMA, has led to the development of Sasoflex.
Sasoflex is a compound of a plastomer (Sasobit®) and an elastomer (SBS), made possible through the patented chemical cross-linking agent.
The plastomer part of the compound reduces the viscosity of the binder at working/paving temperatures, and at in-service pavement temperatures it stiffens the binder. The elastomer part maintains the flexibility of the binder at low temperatures.

Typical benefits and results which have been found through investigation and laboratory testing of mixes produced with Sasobit® and Sasoflex include: (Hurley & Prowell, 2005)

- Improved compact-ability in Superpave Gyratory Compactor (SGC) and vibratory compactor at temperatures as low as 80° C.
- An overall reduction in air voids, with an average reduction of up to 0.87%.
- The addition of Sasobit® does not affect the resilient modulus of the mixtures.
- The addition of Sasobit® does not increase the rutting potential as other additives may do. Rutting potential did however increase as mixing and compaction temperatures decreased, which may be related to the anti-ageing properties of Sasobit® as well as the decreased ageing of the binder at lower temperatures.
- Lower compaction temperatures may increase the potential for moisture damage.
- Lower plant mixing temperatures can result in a 30% reduction in fuel energy consumption.
- Working temperatures decreased by 18-54° C.

#### *Asphaltan-B*

Asphaltan-B is a refined Montan wax blended with a fatty acid amide. Montan wax is a fossilized plant wax which consists of a combination of nonglyceride long-chain carboxylic acids esters, free long-chain organic acids, long-chain alcohols, ketones, hydrocarbons and resins. The melting point is between 82-95° C. Montan wax is produced by solvent extraction of certain types of lignite or brown coal. Montan wax is also used to make shoe and car polishes and paints and as a lubricant for moulding paper and plastics.

#### *Licomont BS 100/Sübit*

Licomont BS 100 is a fatty acid amide which is produced by reacting amines with fatty acids. The typical melting point lies between 141-146° C. Fatty acid amides have been used for several years as a viscosity modifier in asphalt. Licomont BS 100 is one form commercially used in WMA in Germany. Sübit is a binder modified with fatty acid amides. The fatty acid amides used to modify binders, come from the chemical family of N, N-Ethanol bistearin amides and have a low molecular weight.

### *3ELT/Ecoflex*

3ELT/Ecoflex is a proprietary process developed by Colas in France.

### *TLA-X Warm Mix*

Trinidad Lake Asphalt (TLA) is composed of soluble binder mineral matter and other minor components (mostly water) and occurs naturally as an asphalt emulsion in its crude state. It is mined from a lake deposit in a semisolid form and processed to remove moisture. Benefits include:

- Ability to blend in homogeneously with most binders
- Provides excellent adhesion when used as binder
- Maintains high level of stability in paving mixes
- Provides high resistance to cracking and permanent deformation

Lake Asphalt of Trinidad and Tobago (1978) Limited developed TLA-X, which is a unique combination of rheology modifying agents and TLA.

### *Shell Thiopave™*

Shell Thiopave™, (previously known as Sulphur Extended Asphalt Modifier – SEAM) which is based on sulphur-extended asphalt technology, is a patented asphalt mix additive. It can replace up to 25% of the binder in an asphalt mixture and is added to the asphalt mixture as a solid pellet.

An organic additive is also included in Shell Thiopave™ which performs as a compaction agent, allowing Thiopave™ to act as both a binder extender and an asphalt mixture modifier.

Towards the end of the mixing process, after the addition of the binder, Shell Thiopave™ is usually added pneumatically directly into the mixing drum. During the mixing process the mixer temperature should be closely controlled at 140±5° C, which will melt the Thiopave™ quickly, and inside the drum mixer the shearing action allows the sulphur to thoroughly disperse into the asphalt mixture in a short time span.

## B. Chemical Additives (Surfactants)

As stated earlier, chemical additives do not change the viscosity of the binder as organic additives or foaming technologies do, but instead they work as surfactants at the microscopic interface of the aggregate and binder. When the asphalt mixture is subject to high shear rates (during mixing) and high shear stresses (during compaction) the chemical additives control and reduce the internal friction.

According to ERR (2011) the chemical additives also lower the surface tension of the liquid binder resulting in improved binder ability to compact and coat the particles at lower temperatures. They also state that a reduction of as much as 30-40°C in production and placement/compaction temperatures can be achieved. A potential concern for using chemical additives is that they can increase the unit material cost, which should be considered.

Chemical additives that have been developed and are available for use include Rediset™ WMX, Evotherm™ and Cecabase® RT and HyperTherm. Rediset™ WMX is the chemical additive which was investigated and tested for this thesis. The different chemical additives will now be discussed in further detail. A chemical additive not discussed in this report is HyperTherm, developed by LaFarge and used in Eastern Canada.

### *Evotherm™*

Evotherm™ was the first WMA technology developed in the United States. An emulsion is mixed with hot aggregates to produce a resulting mixture temperature of 85-115° C in the original process called Evotherm™ Emulsion Technology (ET). A chemical package designed to enhance adhesion, coating, compaction and workability of the asphalt mixture at lower temperatures, is used to produce the emulsion. There are different chemical packages available for different aggregate types. About 50% of the chemical package is derived from renewable resources. Most moisture in the emulsion evaporates as steam when it is mixed with the hot aggregates.
According to ERR(2011) a reduction in production and placement/compaction temperatures of 50-75° C is achievable when using Evotherm™, in comparison to HMA.

A new process was developed in 2005 called Evotherm™ Dispersed Asphalt Technology (DAT) which was introduced in 2007. The same chemical package used in Evotherm™ ET is diluted with a little water and then injected into the binder line just before the mixing chamber.
A major advantage of the Evotherm™ DAT process is that it reduces the shipping costs compared to those of the emulsion and allows the contractor to switch between WMA and HMA rapidly.

A third version of Evotherm™ has recently been developed and introduced by Ergon & Mathy Technology and Engineering Services, Inc. and marketed under the trademark name REVIX™, Evotherm™ 3G. This new version is a combination of waxes, surfactants, processing aids, polymers, acids and other material which will reduce frictional forces between aggregate and binder. The added benefit with this new version is that it requires absolutely no plant modifications.

### *Rediset™ WMX*

Akzo Nobel Surfactants developed Rediset™ WMX which is a combination of rheology modifiers and surfactants (cationic surface-active agents) and which is supplied in a solid form.
The surfactants improve the wetting of the aggregate surface through the binder and in particular provide “active adhesion” enabling the coating of damp aggregates, often encountered with lower drying temperatures. The adhesion promoter is both active and passive in order to provide good coating during mixing while ensuring extended life expectancy. The surfactants also provide an anti-stripping effect on the paving material, which reduces the need for liquid anti-stripping agents or hydrated lime. Figure 2.10 shows the Rediset™ in the solid form.

Rediset™ WMX is typically added during production through pneumatic conveying into the binder tank or directly into the mixing drum. Typical addition rates of Rediset™ WMX depend on the grade of bitumen used as the binder.
For a PG 76-22 or PG 82-22 graded bitumen, 2% by weight of binder is added. For a PG 70-22 graded bitumen, 1.75% by weight of binder is added. 1.5% by weight of binder should be added for all neat asphalt bitumen.

**Figure 2.10 Rediset™ WMX Pastilles (Prowell & Hurley, 2008)**

***Cecabase® RT***

CECA, a division of Arkema Group, developed Cecabase® RT in 2003. Cecabase® RT consists of patented chemical additives (made up of 50% renewable raw materials) which improves workability of asphalt mixtures at lower temperatures. The liquid additive can be injected directly into the binder line. It is suggested that 0.3-0.5% of Cecabase® RT liquid by weight of binder be added.

### 2.2.4 Void Content

Brown et al (1996) indicate that two parameters, namely the volume of voids in the mineral aggregate (VMA) and the voids in the total mix (VTM), are very important to determine the mix void content during the mix design process. These two parameters will now be discussed in further detail.

#### 2.2.4.1 Volume Of Voids In The Mineral Aggregate (VMA)

VMA is defined as the total volume of inter-granular void spaces between the aggregate particles in a compacted pavement mixture, and has a significant effect on the mixture performance.

According to Brown et al (1996), if the VMA is too large, the mixture may display stability problems and be too uneconomical to produce. If the VMA is too small, the mixture may suffer durability problems.

The more VMA in the aggregate the more space there is for the binder film coating the aggregate particles. The Asphalt Institute (2007) explains that as the binder film thickness increase, the durability of the mixture increases. Therefore, minimum VMA specifications are required in order to provide the mixture with an adequate binder film thickness, which will result in a durable asphalt pavement.

VMA has two components, namely the volume of voids filled with binder and the volume of air-voids remaining after compaction, as shown in Figure 2.11 below. The latter indicates the air-voids available for thermal expansion of the binder during hot weather and further slight compaction under traffic. The voids filled with binder are critical for durability of the mixture, as this together with aggregate gradation, determines the binder film thickness around each aggregate particle.

If the binder film thickness is inadequate, the binder will be oxidised faster (increased ageing of the binder), the film can be more easily penetrated by water, and the tensile strength of the mixture is negatively affected. Figure 2.11 and 2.12 illustrate the volumetric properties.

When producing HMA the aggregate is heated up to high temperatures which will vaporize the moisture located in the VMA, thus increasing the VMA. WMA production does not heat up the aggregate to such high temperatures resulting in some moisture still remaining in the VMA, thus WMA normally has less voids than HMA. This will result in HMA mixes having a thicker binder film coating the aggregate particles than the WMA mixes, since there is more air void space for the binder in the HMA mixes.

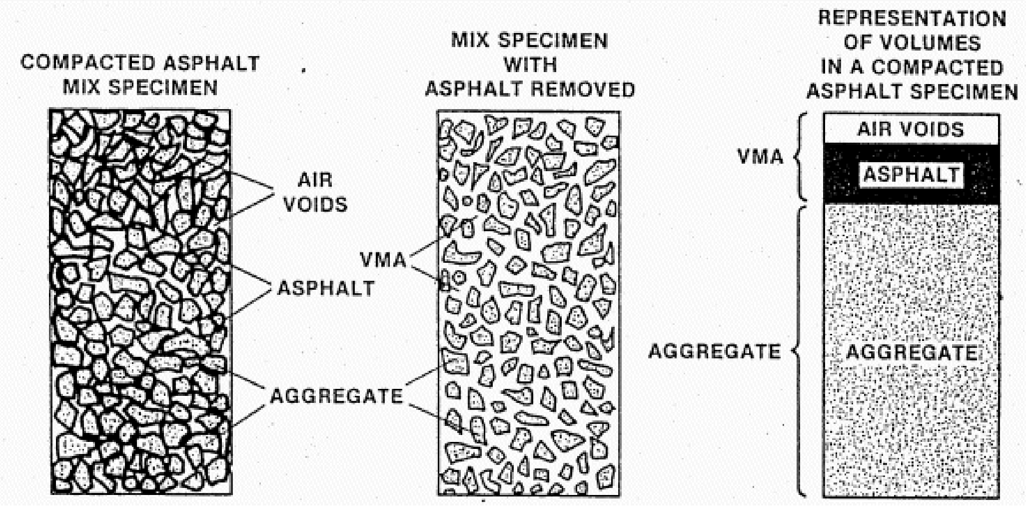
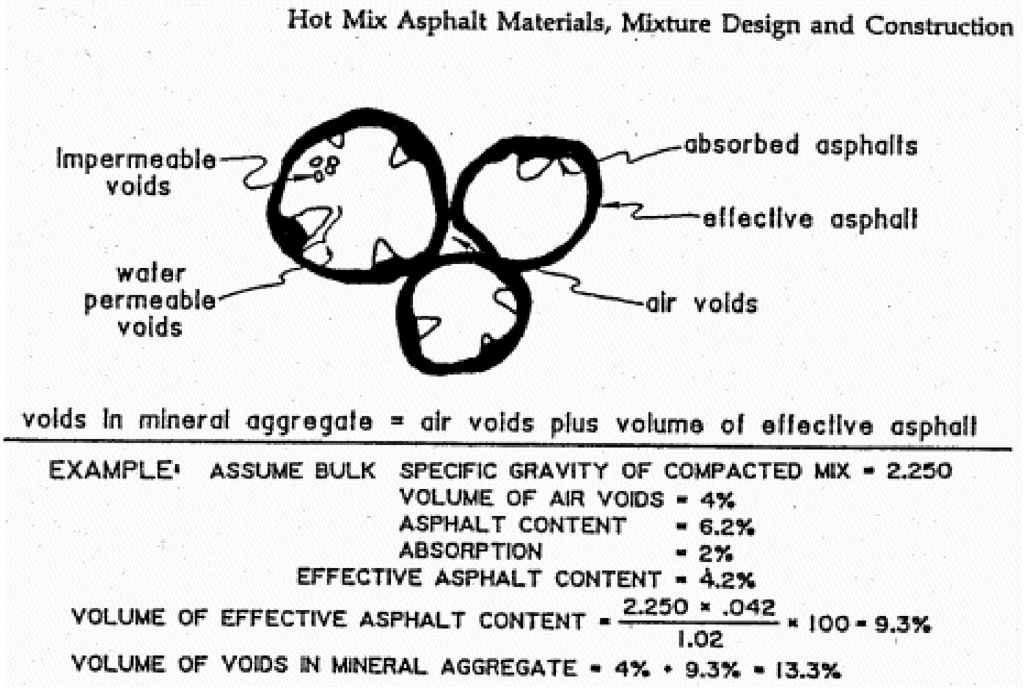


**Figure 2.11 Volumetric Properties of a Compacted Asphalt Mixture (NCDOT, 2012)**


Hot Mix Asphalt Materials, Mixture Design and Construction

voids in mineral aggregate = air voids plus volume of effective asphalt

EXAMPLE: ASSUME BULK SPECIFIC GRAVITY OF COMPACTED MIX = 2.250
VOLUME OF AIR VOIDS = 4%
ASPHALT CONTENT = 6.2%
ABSORPTION = 2%
EFFECTIVE ASPHALT CONTENT = 4.2%

$$\text{VOLUME OF EFFECTIVE ASPHALT CONTENT} = \frac{2.250 \times .042}{1.02} \times 100 = 9.3\%$$

VOLUME OF VOIDS IN MINERAL AGGREGATE = 4% + 9.3% = 13.3%

**Figure 2.12 Air Voids and Voids in the Mineral Aggregate (VMA) (NCDOT, 2012)**

#### 2.2.4.2 Voids In Total Mix (VTM)

The VTM is defined as the total volume of voids between the coated aggregate particles throughout a compacted mixture. Brown et al (1996) suggest that the VTM in the compacted mixture should be between 3-5%. A low void content minimizes the oxidative hardening of the binder film coating the aggregate particles and also minimizes the chance of water getting into the mixture, penetrating the thin binder film, and stripping the binder off the aggregates.

## 2.3 PERFORMANCE CONSIDERATIONS

It is vital to perform performance testing on WMA to predict the performance of the WMA before use and (in case of the research conducted in this thesis) to evaluate new materials and technologies, and design tools to improve the performance of the pavement mixtures. According to The Asphalt Institute (2007) performance testing of pavement mixtures can be divided into five general categories:

1) Modulus testing (Shear, dynamic and resilient modulus)
2) Creep testing (Static and dynamic creep)
3) Flexural beam fatigue testing
4) Empirical testing
5) Wheel tracking tests

It is important to differentiate between response and damage analysis for WMA. Response is resilient modulus which is the behaviour of the material under a single load. Damage analysis is the failing mechanisms like rutting or fatigue damage which is resultant of the material being subject to continued loading. For the purpose of the research conducted in this thesis, only the third type of testing was done on the mixture specimens. Testing was done to predict the fatigue life of the mixture as well as to determine the flexural stiffness of the mixture under different frequencies (loading times) over a range of varying temperatures. This resulted in the development of a master curve for each mixture.

Fatigue cracking and flexural stiffness will now be discussed in further detail.

### 2.3.1 Fatigue Cracking

Fatigue cracking is often called alligator cracking because of the closely spaced crack pattern being very similar to the pattern on the back of an alligator.

Fatigue cracking usually occurs when, due to repetitive axle load applications, the pavement has been stressed to the limit of its fatigue life. Brown et al (1996) indicate that loads which are too heavy for the pavement structure or when more repetitions of a specific load are applied than what was provided for in the design of the pavement, are often associated with fatigue cracking. Insufficient pavement thickness is also associated with fatigue cracking.

Brown et al (1996) also suggest that the development of potholes can be the result of fatigue cracking, as the individual pieces of the pavement are physically separated from the adjacent material and removed from the pavement surface by the action of the traffic. According to Brown et al (1996) some of the factors which influence the development of fatigue cracking are:

- Composition of structural section
- Binder consistency

- Binder content
- Binder age hardening
- Air voids and aggregate characteristics in the mixture
- The in-place properties of the untreated aggregates or bitumen-treated materials, and the in-place properties of the foundation soils
- Temperature
- Traffic

According to The Asphalt Institute (2007) several external factors which influence fatigue cracking in pavements include:

- Poor subgrade drainage
- Time of placement
- Method of compaction and placement of mixture

Air voids and binder stiffness also have a significant influence on fatigue resistance as explained below.
According to The Asphalt Institute (2007) if by design or lack of proper compaction the number of air voids increases in the pavement, the fatigue resistance of the pavement will be reduced severely. When a pavement contains a binder which ages or hardens significantly, resulting in higher pavement stiffness, a reduction in fatigue resistance will also occur.

Since HMA mixes generally have more voids because of the high production temperatures and thus are more susceptible to oxidative hardening of the binder than WMA mixes produced at lower temperatures, the fatigue life for WMA could be equal to or greater than that of HMA. There are several other factors that influence fatigue life as mentioned above which could give different results depending on the situation. Further research and evaluation should be done to validate these statements.

Using polymer-modified binders has been shown to improve fatigue resistance.
The Asphalt Institute (2007) also indicates that the thickness and strength characteristics of the pavement as well as the support of the underlying subgrade, have a significant influence when determining pavement life and preventing fatigue cracking. Thick, well-supported pavements bend less under loading, resulting in longer fatigue lives when compared to thin or poorly supported pavements. In general, thick pavements experience fatigue cracking that originates at the surface of the pavement and migrates downwards (called “top-down” cracking); and thin pavements experience fatigue cracking which starts at the bottom of the pavement and migrates to the surface (called “bottom-up” cracking).

In South Africa, “bottom-up” cracking is of most concern, since thin pavement layers are preferred to thick pavements. The tensile stress is the highest at the bottom of thin asphalt layers and spreads to the surface as one or more longitudinal cracks.

To determine the fatigue life of the mixes evaluated in this thesis, 4-point beam bending fatigue tests were conducted on the specimens. Repeated sinusoidal loads are applied at the third points of the specimen with the 4-point bending test device. The test can be conducted in two modes, namely constant stress mode and constant strain mode. The Asphalt Institute (2007) and Brown et al (1996) explain the difference between the two modes.

When using the constant stress mode, the applied load is repeated in cycles until the specimen fails to take more loads, or it breaks. The number of load cycles required for a specimen to fail or break is logged on a computer. Similar fatigue tests are done on specimens with different applied loads and results are plotted on a log-log graph. The general equation used for the fatigue model in the constant stress mode is given by:

$$N_f = k_1 \left(\frac{1}{\sigma}\right)^{n_1}$$

Where, $N_f$ = number of cycles to failure (fatigue life)

$\sigma$ = applied tensile stress (psi)

$k_1$, $n_1$ = experimentally determined regression coefficients (determined by fitting a power law regression function with the testing data on a log scale)

Specimens with higher stiffness generally perform better than specimens with lower stiffness when in the constant stress mode. Test results from this test mode are applicable to thick pavements.

When using the constant strain mode the constant strain in a specimen or deflection is maintained, but the applied load is allowed to decrease with increasing load cycles. Specimens do not usually break when tests are done in this mode. Failure is normally taken as the point where the applied load reaches a certain pre-selected percentage of the original or initial applied load. Failure is usually defined as 50% loss in initial flexural beam stiffness. Results are usually plotted on a log-log graph with the log of applied strain plotted against the log of cycles to failure.

The general equation used for the fatigue model in the constant strain mode is given by:

$$N_f = k_1 \left(\frac{1}{\varepsilon}\right)^{n_1}$$

Where, $N_f$ = number of cycles to failure (fatigue life)

$\varepsilon$ = tensile strain at the bottom of the specimen (inches/inch)

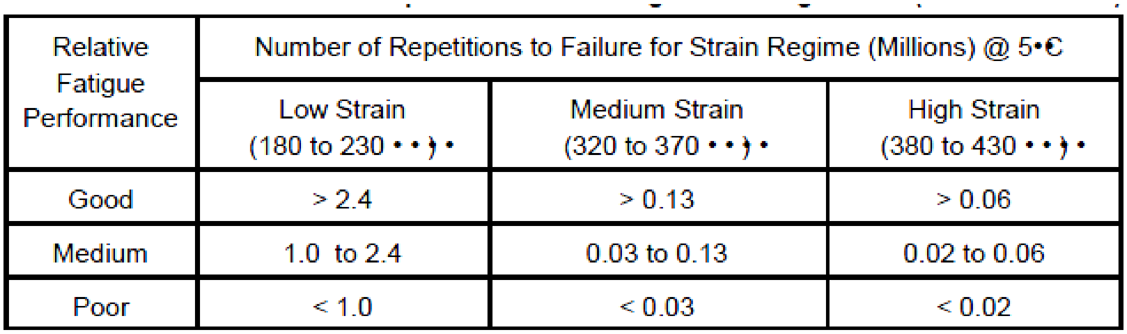
$k_1$, $n_1$ = same regression coefficients as the constant stress mode general equation

Specimens that are more flexible (lower stiffness) perform better in this mode of testing. Test results from this test mode are applicable to thin pavements (less than 50 mm).

As stated earlier, thin asphalt pavements are preferred in South Africa, which is why fatigue testing of specimens was conducted using the constant strain mode with a 50% loss in initial flexural stiffness defining the failure of the specimen.

Guidelines for fatigue evaluation of HMA are supplied by Taute et al (2001) and are displayed in Table 2.3 below. Since WMA is required to perform equally or greater than HMA, it is recommended that the HMA fatigue evaluation guidelines in Table 2.3 apply to WMA mixes. Fatigue tests were done at three different strain levels, namely low (160-200 με), medium (230-280 με) and high (300-380 με) strain levels. All fatigue tests were done at a temperature of 5° C. Fatigue tests on all mixtures were repeated three times at each strain level to control and validate the results.

**Table 2.3 Guidelines for Fatigue Evaluation via Four Point Bending Beam Testing (Taute et al, 2001)**



| Relative Fatigue Performance | Number of Repetitions to Failure for Strain Regime (Millions) @ 5•C | | |
|---|---|---|---|
| | Low Strain (180 to 230 • • ) • | Medium Strain (320 to 370 • • ) • | High Strain (380 to 430 • • ) • |
| Good | > 2.4 | > 0.13 | > 0.06 |
| Medium | 1.0 to 2.4 | 0.03 to 0.13 | 0.02 to 0.06 |
| Poor | < 1.0 | < 0.03 | < 0.02 |

By knowing the stresses and strains experienced by the pavement and the relationship between the stress/strain and the number of cycles to failure, the number of traffic loads to failure of the pavement can be estimated.

Brown et al (1996) state that it is impossible to accurately duplicate field conditions in the laboratory, thus the estimated failure determined by laboratory testing is not a good estimate of the actual applications to failure experienced in the field. These tests are therefore usually used to compare various mixtures and rank them in relative performance, as done in the laboratory testing of the research conducted in this thesis.

According to Medani & Molenaar (2000), several fatigue damage models are being used in asphalt pavement engineering today including the Wöhler approach, dissipated energy approach and fracture mechanics. Only the Wöhler approach and the cumulative dissipated energy approach, as formulated by Van Dijk & Visser (1977), will be used in this research study to evaluate the fatigue life of the mixes.

The traditional Wöhler approach has been described earlier when the constant strain mode equation was discussed. When beam testing with the four-point bending apparatus, the beam is placed under repeated flexure where the maximum flexural tensile strain takes place at the bottom of the beam. The number of load repetitions to failure is related to the tensile strain at the bottom of the beam which can be expressed as the equation above for constant strain mode.

The dissipated energy approach is independent of the loading conditions during the test which include loading frequency, rest periods, mode of loading, temperature, type of test method used and the type of binder used. Van Dijk and Visser (1977) illustrate that the cumulative dissipated energy per volume to fatigue failure can be formulated as follows:

$$W_N = A(N_f)^Z$$

Where, $W_N$ = total cumulative dissipated energy per volume (J/m$^3$ or MPa)

$N_f$ = number of load repetitions to failure

A, Z = experimentally determined coefficients

This model links the cumulative dissipated energy to the number of load repetitions to failure. By fitting a power law function along the test data points on a log scale, the coefficients A and Z can be determined.

Both these fatigue damage approaches will be used in a comparative manner to evaluate the mixes in this research study.

### 2.3.2 Flexural Stiffness

Permanent deformation of an asphalt mixture is a function of the flexural stiffness of the mixture; since as the flexural stiffness of a mixture is increased, the resistance to permanent deformation (like rutting) is increased. Excessive increase of the stiffness however results in reduced fatigue resistance, especially in thin asphalt layers, which should be avoided.

Flexural stiffness is more dependent on loading time and temperature than stress. The stiffness of an asphalt mixture is either elastic or viscous, depending on the loading time and temperature.
According to Read et al (2003) elastic stiffness occurs under conditions of short loading times or low temperatures, while at high temperatures or under longer loading times viscous stiffness will occur.

Two of the main factors which influence the load spreading ability of the pavement layers are mixture stiffness and layer thickness. A mixture with higher flexural stiffness will withstand loads as well as reduce the stress carried over to the underlying layers, as opposed to a lower stiffness mixture. Thus, as mixture stiffness increases so does its ability to spread the load to underlying layers in the pavement. Mixture stiffness also defines the cohesiveness and adhesiveness of asphalt materials and influences the fatigue behaviour of the mixture.

Flexural stiffness of mixtures was predicted by testing specimens with the 4-point bending beam test. Specimens were subjected to repeated (cyclic) load applications under varying loading times (frequencies) over a series of selected temperatures. Jenkins (2000) suggested a series of test temperatures that range from 5° C to 25° C, at intervals of 5° C, and frequencies of 0.5 Hz, 1 Hz, 2 Hz, 5 Hz and 10 Hz for Half-Warm mixes, which we adopted for WMA.
Each test was run for 300 load cycles and then terminated since it was sufficient to provide data to plot the master curve. A master curve is developed with frequency

sweeps of flexural stiffness values obtained from the test by varying frequencies and temperatures.

According to Jenkins (2000) a master curve defines stiffness by shifting the stiffness modulus (as an ordinate) horizontally with respect to loading time/frequency (as the abscissa) for various temperatures to a reference temperature. Consequently, one is able to determine a mixture stiffness value at a frequency and temperature from a given test range of that mixture.
Two master curves were developed for each mixture to control and validate the test results.

## 2.4 ENVIRONMENTAL CONSIDERATIONS

The United Nations' Brundtland Commission defines sustainable development as: "development that meets the need of the present without compromising the ability of future generations to meet their own needs." Sustainable development involves three interdependent areas namely economic development, social development and environmental protection as shown in Figure 2.13.

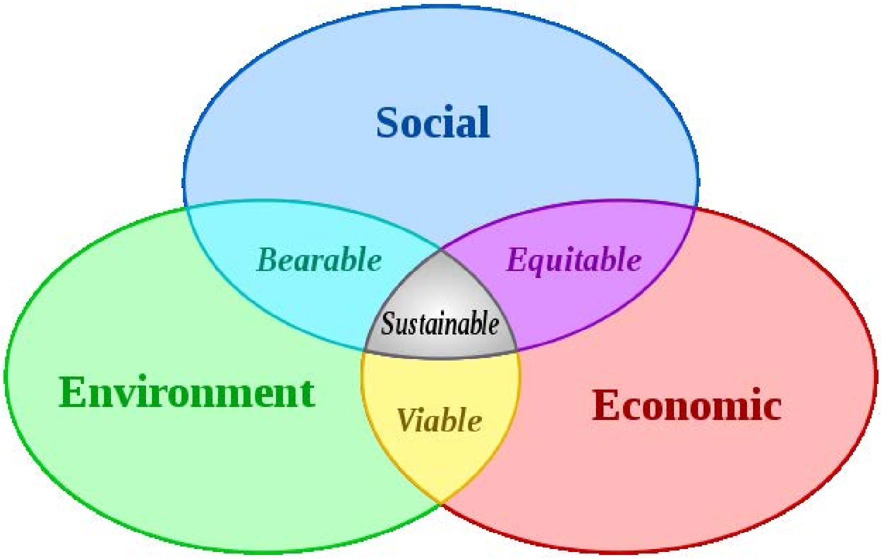


**Figure 2.13 The Three Interdependent Areas of Sustainable Development (Google search for "sustainable development pictures")**

Producing and compacting HMA has shown to be unsustainable since the $CO_2$–emissions which are released, when heating the asphalt mixtures to very high temperatures, are negatively impacting our environment. This has led to the development of WMA which reduces the production and compaction temperatures. This resulted in benefits including reduced emissions, reduced energy and fuel (raw materials) usage, paving benefits, the possibility of increased recycling and improved working conditions while still meeting development needs. WMA is therefore consistent with the ideals described by sustainable development and is thus embraced.

The main driving factor in the reduction of $CO_2$ and other greenhouse gasses worldwide, and consequently the development of WMA, is the Kyoto Protocol.
The Kyoto Protocol was adopted by a consensus of the third session of the United Nations Framework Convention on Climatic Change. It is designed to arrest greenhouse gas concentrations, which are believed by some to cause global warming. The Kyoto Protocol seeks to cut production of $CO_2$ by 5.2% of 1990 levels between 2008 and 2012. The European Union (EU) pledged a 15% reduction in CO2 emissions by 2010. Germany pledged a 25% reduction of 1990 levels which they achieved in 2005.

According to D'Angelo et al (2008) the four main benefits of WMA are:

a) Reduced emissions
b) Reduced energy and fuel usage
c) Paving benefits (including increased RA use)
d) Reduced worker exposure (Improved working conditions

These benefits and their impact on the environment will now be discussed in further detail.

### 2.4.1 Reduction In Emissions

According to D'Angelo et al (2008) typical expected reductions are 30-40% for carbon dioxide ($CO_2$) and sulphur dioxide ($SO_2$), 50% for volatile organic compounds (VOC's), 10-30% for carbon monoxide (CO), 60-70% for nitrous oxides ($NO_x$) and 20-25% for dust.
Actual reductions vary on a number of factors. WMA technologies that result in greater temperature reductions are expected to have greater emission reductions.

Sulphur dioxide ($SO_2$) and nitrogen oxide ($NO_x$) contribute to fine particles and $NO_x$ contributes to ground-level ozone, which are both associated with a variety of health problems. The United States Environmental Protection Agency issued the Clean Air Interstate Rule (CAIR) in March 2005, designed to significantly reduce both $SO_2$ by 73% and $NO_x$ by 61% of their respective 2003 levels, where most of the reductions are expected to come from the power plants.

### 2.4.2 Reduction In Energy Use

According to D'Angelo (2008) typical burner fuel usage reductions range from 20-35%. This reduction could be even higher (possibly 50% or more) with processes like Low-Energy Asphalt Concrete (LEAB) and Low-Energy Asphalt (LEA) in which the aggregates (or a portion thereof) are not heated above the boiling point of water (100° C).
It is estimated that if production temperatures are reduced by 28%, fuel consumption to heat and dry the aggregate will be reduced by 11%. For one WMA technology, where resulting mixing temperatures were less than 100° C, theoretical calculations showed that a 50% reduction in fuel usage to heat and dry the aggregate was found. The reductions could also be higher if burner tuning was done to allow the burner to run at lower settings.

### 2.4.3 Paving Benefits

The paving benefits resulting from WMA are divided into five benefits and will now be discussed.

The ability to pave in cooler temperatures and still achieve target density is the first benefit. D'Angelo et al (2008) report a case study in Germany where base; binder and Stone Mastic Asphalt (SMA) surface course were placed using Aspha-min®. Base course contained 45% RA. Ambient temperatures during placement ranged from -1 to 3° C and mixing temperatures for the WMA behind the paver ranged from 102-139° C. Better density results were obtained with the WMA than the HMA with the same or fewer roller passes. The ability to compact the mixture at lower temperatures is achieved by the reduction in viscosity of the binder.

The second benefit is that the mixture can be hauled for longer distances and still have sufficient workability to place and compact the mixture. This is achieved by the reduced rate of cooling of WMA and the reduced viscosity of WMA at lower temperatures.

According to D'Angelo et al (2008), Kolo Veidekke reported that WAM-foam® was stored in a silo for 48 hours and still had the ability to be placed and compacted afterwards. In Australia, HMA containing Sasobit® was reported to be hauled for up to 9 hours and the material was still able to be unloaded.

The third benefit is the possibility of compacting the mixture with less effort, assuming typical conditions. D'Angelo et al (2008) indicate that several studies provide data to show that WMA technologies act as compaction aids and reduce the required compaction effort.

The possibility of incorporating higher percentages of reclaimed asphalt (RA) at reduced temperatures is the fourth benefit and has a significant effect on the environment since increased use of RA means more recycling and that fewer raw material sources are being depleted. WMA mixes with higher percentages of RA may be beneficial in two ways.
Firstly, the viscosity reduction will aid in the compaction.
Secondly, lower production temperatures which result in the decreased ageing of the binder may help compensate for the aged RA binder (similar to using a softer binder grade).
D'Angelo et al (2008) indicate several case studies which used higher percentages of RA. In Germany 45% RA was used in base course. In Netherlands both LEAB and HMA are produced with 50% unfractioned RA. Also In Germany, trials have been conducted with 90-100% RA using Aspha-min® zeolite and Sasobit®. Overall, RA usage in the US is higher than those of Germany, Belgium, Norway and France. According to Kolo Veidekke all mixes in Norway are made with 7-8% RA. The small percentage of RA used in Norway can be attributed to the fact that milling is not used extensively so the RA supply in Norway is limited. Colas reported an average recycling rate of 14% for its US-based operations compared to 3% in France. The Northern Europe operations of Colas averaged a recycling rate of 11%.

The fifth and final benefit is the ability to place thick lifts and open to traffic in a short time. WMA technologies can be used to facilitate deep patches (like repaving an

airport). According to D'Angelo et al (2008) Frankfurt Airport was repaved using Sasobit®, where 24 inches of HMA was placed in a 7.5 hours window. The runway reopened to jet aircraft at the temperature of 85° C.
This may have significant implications for trench patching or when rehabilitation strategies require multiple lifts to be paced in the same night.

### 2.4.4 Reduced Worker Exposure (Improved Working Conditions)

In June 2007, a new European Union regulation called Registration, Evaluation, Authorization and Restriction of Chemicals (REACH) was implemented. This regulation requires chemical suppliers to provide information to workers on potential exposure and to set derived non-effect levels.

Implementation of engineering controls on asphalt pavers in 1997, which removes fumes from the immediate area surrounding the paver and screed operator, was an important step to improve working conditions. Research shows a strong correlation between production temperatures and asphalt fume production. According to D'Angelo et al (2008) French, German and Italian data indicated a reduction in worker exposure when placing WMA. All the exposure data for HMA were below the current acceptable exposure limits.

Data presented by the Bitumen Forum shows a 30-50% reduction in asphalt aerosols/fumes and polycyclic aromatic hydrocarbons (PAH's).

Lower mixing and placing temperatures reduces the fumes which workers are exposed to and also provides for a cooler, more comfortable working environment. These improved working conditions when placing WMA can lead to higher quality work, increased productivity and greater employee retention.

# CHAPTER THREE

# METHODOLOGY

## 3.1 INTRODUCTION

In this chapter there is a description of the procedures and activities followed during the laboratory work done for this thesis. This investigation forms part of the 3rd WMA trial conducted on the Higginson Highway located in Durban. Table 3.1 show the target mixing and compaction temperatures for the different mix types tested.

**Table 3.1 Target Mixing and Compaction Temperatures**

| **Type D (Surface Mix Type) Mixes** | | | |
|---|---|---|---|
| **Unmodified 60/70 Binder** | **Target Temperature** | | **Details** |
| | **Mixing** | **Compaction** | |
| 10% RA Control | 160° C | 135° C | No WMA Technology |
| 10% RA, 1.5% Rediset | 125° C | 110° C | Surfactant & Modifier |
| 10% RA, 1.5% Sasobit | 125° C | 110° C | Fischer Tropsch Wax |
| **Type B (Base Mix Type) Mixes** | | | |
| **Modified 80/100 Binder** | **Mixing** | **Compaction** | **Details** |
| 40% RA Control, AE-2 | 155° C | 135° C | AE-2 (Elastomer) |
| 40% RA ,1.5% Sasoflex, AE-2 | 140° C | 120° C | AE-2 (Elastomer) |
| 40% RA Control, AP-1 | 155° C | 135° C | AP-1 (Plastomer) |
| 40% RA ,1.5% Rediset, AP-1 | 140° C | 120° C | AP-1 (Plastomer) |
| **Modified 60/70 Binder** | **Mixing** | **Compaction** | **Details** |
| 10% RA Control, AE-2 | 165° C | 145° C | AE-2 (Elastomer) |
| 10% RA,1.5% Sasoflex, AE-2 | 145° C | 120° C | AE-2 (Elastomer) |
| 10% RA Control, AP-1 | 165° C | 145° C | AP-1 (Plastomer) |
| 10% RA,1.5% Rediset, AP-1 | 145° C | 120° C | AP-1 (Plastomer) |
| 10% RA,1.5% Foamtech, AP-1 | 145° C | 120° C | AP-1 (Plastomer) |

The production of these mixes and the testing of specimens are separated into two separate stages since these where done in two stages at two different locations, namely the plant stage and the laboratory stage.

The plant stage took place at the National Asphalt (NA) plant site in Durban near Pinetown in the eThekwini municipality. The general mix used for the production of slabs was the same mix used along Higginson Highway. The plant stage included the following:

- The production of the different mix types
- The compaction and preparation of slabs
- Fundamental mix tests and evaluation
- The cutting of the slabs
- The labelling and packaging of the slabs

The procedures and flow of activities for the plant stage are illustrated in Figure 3.1.

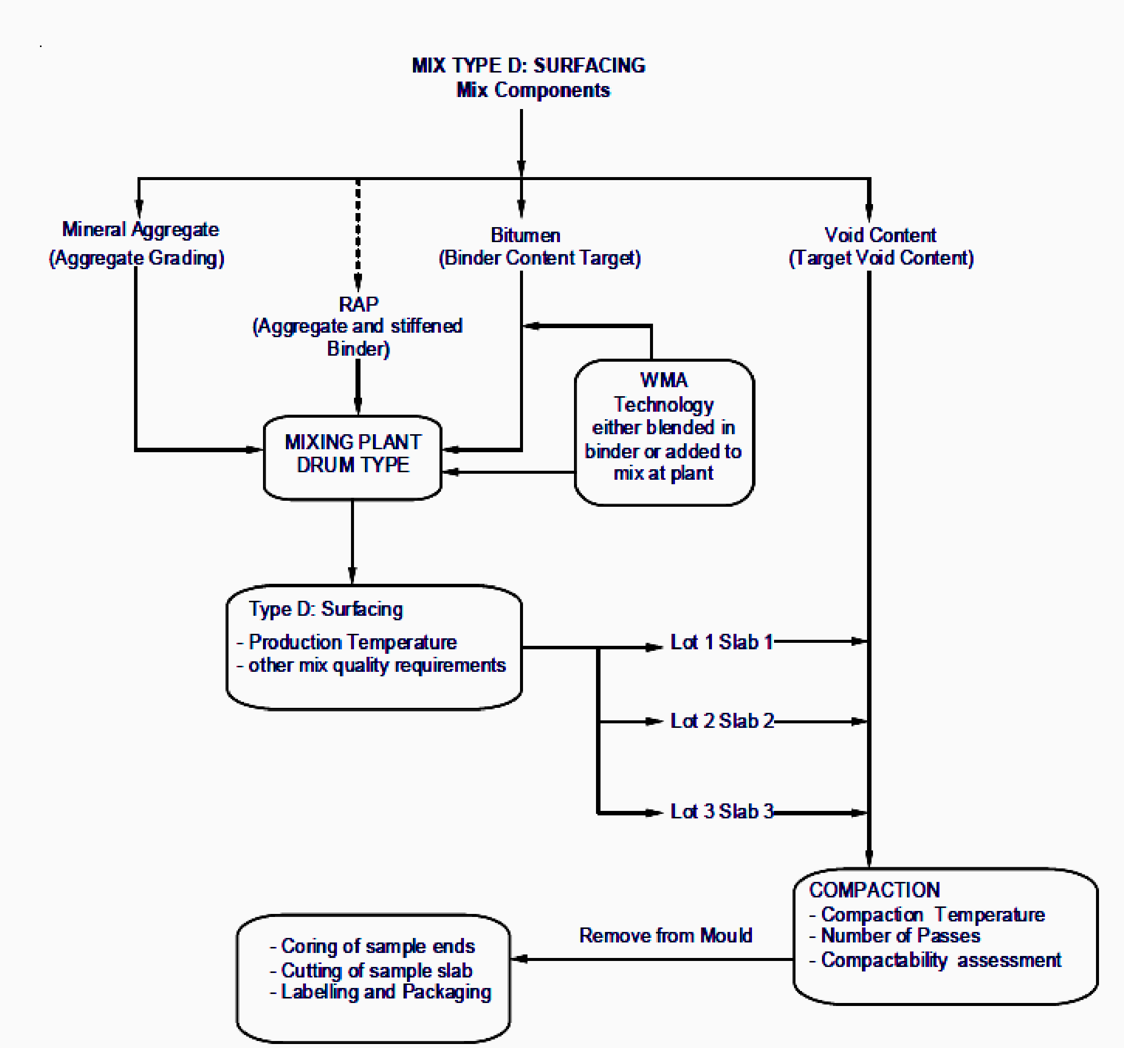


**Figure 3.1 Layout of the Procedures and Activities for the Plant Stage (Mbaraga, 2011)**

The laboratory stage was executed at the Pavement Engineering laboratory section of Stellenbosch University, and included the following:

- The unpacking and visual inspection of the slabs
- Cutting the beam specimens out of the slabs to required dimensions
- Bulk relative density tests for each specimen
- The labelling of specimens and selecting specimens for testing
- Storage of specimens
- Testing the specimens with the 4-point fatigue beam apparatus
- Acquiring of results

## 3.2 MIX PRODUCTION

For each mix, the components namely, the mineral aggregate and binder (also called the virgin materials) as well as the Reclaimed Asphalt (RA), were mixed in the plant at the required mixing temperatures listed in Table 3.1.
The WMA technology was either blended in the binder or added to the mix in the mixing plant depending on the WMA technology specification.

The mix produced in the mixing plant was then collected and divided into three different production lots where one slab per production slot was manufactured. Thus for each mix produced three slabs were manufactured.
Each mix produced was assessed for mix quality and viability for use. The target binder content for each mix was set at 5.0 -5.6 % for Type D surface mixes and 3.9 – 4.5 % for Type B base mixes.

## 3.3 SLAB COMPACTION

The following compaction method was used because of compactor availability and specifications. The Bomag 30, a small two-drum roller compactor, was used to compact the mixes. The existing Stellenbosch University Compaction Mould (SUCM) was adjusted to fit the width of the compactor drums and the length of the compactor. A Tel-Try thermometer was used to check the temperature at each production lot to ensure that the required compaction temperatures were met. The compactor specifications included the following:

- Speed of 2 km/hr
- A maximum acting force of 28 kN
- Drum diameter of 450 mm
- Drum width of 400 mm
- A tampering depth of ± 100 mm
- The ramp was at a slope of 30 °

These specifications resulted in the modification of Stellenbosch University Compaction Mould (Modified SUCM). The dimensions of the Modified SUCM metal mould are 770 mm long by 390 mm wide and 70 mm high, as shown in Figure 3.2 below.

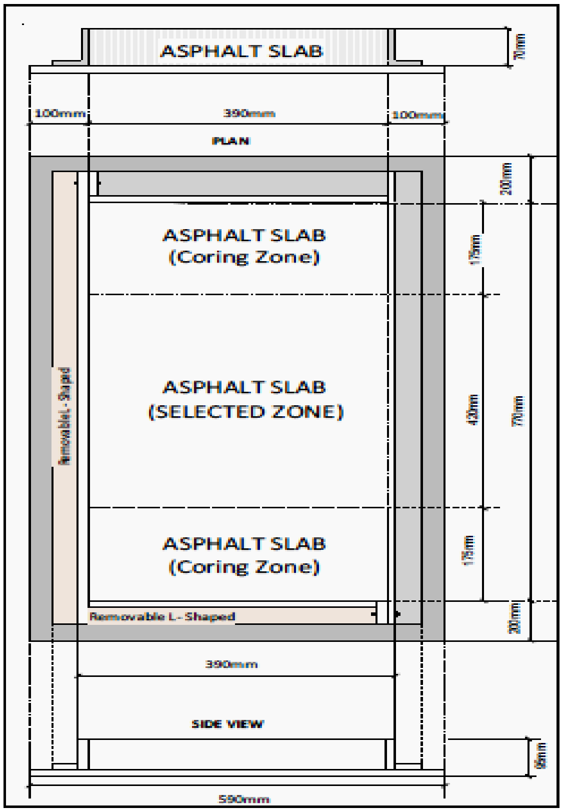


**Figure 3.2 The Metal Modified SUCM Details (Mbaraga, 2011)**

### 3.3.1 Compaction System

As stated above, the dimensions of the mould were increased to fit the compactor, but they were also modified to reduce variations in the slab by providing a wider compaction area. Mbaraga (2011) indicated that the Modified SUCM was a teamwork effort between Stellenbosch University and National Asphalt (NA).

An existing concrete floor, dimensions 3500 mm in length by 2000 mm width, was used to mount the modified SUCM. The mould was mounted by means of two mounting nuts at each end and two wooden planks on either side of the mould fastened along the length. These planks had dimensions of 3100 mm in length by 60 mm by 60 mm.

Besides preventing any side movement and confining the mix in the ramps, these two planks also suggested the direction for the compactor.

This compaction system was tested for efficiency and usability using HMA mixes, before compaction was done on the required mixes. The test run resulted in 35 passes being selected for all mixes being researched as well as a target void content of 4%.

### 3.3.2 Compaction Mould Assembling

As stated before, the compaction mould is mounted to the concrete floor by means of two nuts on each end of the mould. The following procedure was followed to assemble the compaction system: (Mbaraga, 2011)

- The removable L-shaped side of the compaction mould is connected to the mould by screwing back the nuts.
- Two wooden planks, with a groove on each side, are then fastened to each side of the compaction mould.
- The compaction mould is then checked for firmness both horizontally (sideways movement) and vertically (fastened to the concrete floor).
- A final test follows to check the general condition and stability of the compaction mould.

### 3.3.3 Placing Mix

The following procedure was followed to place the mix into the compaction mould: (Mbaraga, 2011)

- To prevent the slab from sticking to the mould surface and to ensure an easy removal of the slab after cooling down, a releasing agent (Sasol Wax™ BituGlide) is brushed onto the inner surfaces of the mould as well as the exterior sides at the ramps, and on the bolts and nuts.
- The on- and off-ramp areas of the compaction system are filed with the mix first.
- The mix temperature is checked before placing the mix in the mould to see if it satisfies the required criteria.
- The compaction mould is then filled with mix ensuring no segregation.
- To prevent direct compaction of the mould edges the mould is overfilled with about 200 – 210 kg of mix. (Extra caution should be taken by overfilling the mould by 15% over the mould capacity)
- After placing the mix the temperature is checked again to ensure satisfaction of required compaction temperature.

### 3.3.4 Compaction

The following procedure was followed to compact the mixes: (Mbaraga, 2011)

- Compaction is only directed to the mix and is started by running the compactor over the overfilled mould for 35 passes.
- The roller compactor was set on vibration.
- One pass represents the compactor moving from the start of the on-ramp to the end of the off-ramp and returning to the start.

Figure 3.3 below shows photographs of the actual compaction process at the plant.

**Figure 3.3 Photographs of the Compaction Process at the Plant (Mbaraga, 2011)**

### 3.3.5 Disassembling Mould & Slab Removal

After cooling down for long enough, after compaction has been completed, the mould can be removed from the compaction system. Two moulds were used to compact more slabs faster. The following procedure to disassemble the mould and remove the slab was followed: (Mbaraga, 2011)

- Removal of ramps
    - To induce a crack at the ends of the ramp a lift force is exerted to the ramp ends. (Extra caution should be taken not to lift the slab as well when doing this)
    - The existing interface between the ramps and the slab as well as the discontinuity established by the mould edges at this interface enabled an easy separation of slab and ramp without lifting the slab.

- Removal of Wooden Planks & L-Shaped Side
    - The bolts and nuts are loosened and removed from the wooden planks.
    - Slightly tapping the sides at each end in opposite direction to the mould enables the wooden planks to come loose so that they can be removed.

- The four nuts between the L-shaped plank and the mould side are loosened and removed.
- To lift and slide the L-shaped side, a small tap along with a slight lift is applied, enabling the disassembling of the L-shaped side from the mould.

- Removal of Slabs
  - A rigid, flat-surfaced wooden board with end handles is placed next to the mould where the L-Shaped side has been removed.
  - A thin scraper is placed between the slab and metal edge of the mould and a slight push to the outer area in direction of the wooden board is applied to release the slab from the mould edges.
  - The slab is now removed by sliding it from the mould onto the wooden board.

### 3.3.6 Slab Coring

Since the middle area of the slab is for cutting beam specimens for fatigue and flexural stiffness testing, coring was done at the extreme ends of the slab as shown in Figure 3.4 below. The cores gave an indication of the expected compact-ability of the slab and beam specimens.

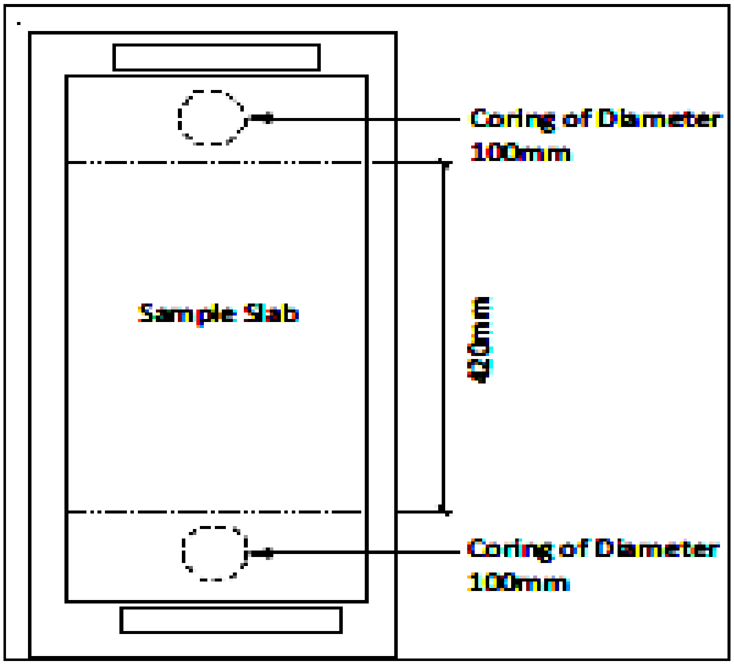


**Figure 3.4 Coring Zones on Compacted Slab (Mbaraga, 2011)**

## 3.4 SLAB SAWING, LABELLING AND PACKAGING

Slabs were sawn at the plant site to dimensions of 420 mm in length by cutting off the coring zones at each end. (The slab width is the internal width of the mould which is 390 mm)

The slabs were then labelled and packaged in order to transport them down from the plant site, situated in Durban, to the laboratory at Stellenbosch University for fatigue and flexural stiffness testing.

The labelling procedure worked as follows: WMA Technology / Slab Number / Front. Front point to the beginning side and direction of compaction.

### 3.4.1 Packaging of Slabs

The concern that cracks could be created during transportation needed to be addressed. The packaging of slabs was done in a manner so as to restrict the slab from moving around during transportation, and hence the problem was confined. Refer to Mbaraga (2011) for further details.

## 3.5 BEAM CUTTING & STORAGE

The slabs were transported down in couriers to Stellenbosch University where they were stored in a cold room which is set at a constant temperature of 10° C. A record of all slabs received was kept and each slab was visually inspected for cracks or any damage before a start was made with the cutting off of beams. The following procedure was followed to cut the beams:

- Target beam specimen dimensions of 400 mm length by 63 mm width by 50 mm height were decided on and dry cutting of the beams was preferred.
- A model of a typical beam used for testing with the IPC (Industrial Process Controls) 4-point beam fatigue testing apparatus was used to mark out the beams to be cut on the top surface of the slab, as shown in Figure 3.5 below. Four Beams were cut out of each slab.
- Beams were cut using a diamond sawing blade on a well aligned cutting table. A fixed measuring scale on the cutting table allows cutting up to 4 mm off the specimen.
- The beams could not always be cut exactly to target specifications and varied by 2-5 mm as the cutting blade is only accurate to 4 mm. Other factors which influenced the accuracy include the sawing blade being pushed sideways by the clamped specimen as the blade cuts through the specimen or because of frequent use the blade could start exhibiting a sideways movement while spinning. If the latter happens the blade should be taken off and refastened tightly or a new blade should be used.

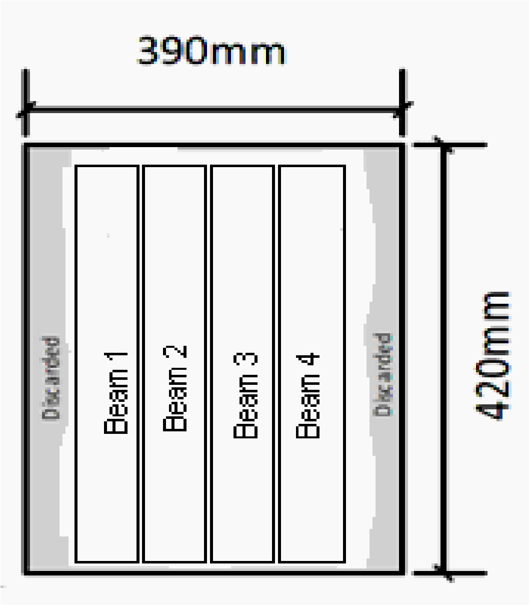


**Figure 3.5 Longitudinal Cutting of Beams (Mbaraga, 2011)**

## 3.6 BRD TESTING

After cutting the beam specimens, a Bulk Relative Density test was performed on each beam to determine the bulk relative density of each specimen. Rice density information was supplied with the slabs for each mix. With these two densities known, the void content of the specimen could be determined. The procedure to do this will now be explained:

- Each beam was first weighed after cutting and the weight recorded as A.
- The beam was then submerged in a water bath which was preset to 20° C and left to saturate for 5 minutes.
- The beam was then taken out and weighed under water using a scale with a tray hanging from it into another water bath. (Caution should be taken to ensure that no part of the tray hanging in the water touches the sides of the water bath and that the beam on the tray is totally submerged in the water when weighing the beam) This weight was recorded as C.
- Lastly, the beam was taken out the water bath and surface dried using paper towels and then weighed again. This weight was recorded as B.
- With the three recorded weights the bulk relative density of the beam specimen was calculated as follows:

$$\mathbf{BRD = A / (B-C)}$$

With A, B and C as described above

- The void content of the specimen was then calculated as follows:

$$\textbf{Void Content (\%)} = 100 - ((\text{BRD}/\text{Rice Density}) \times 100)$$

- After the BRD test the beam specimens were allowed to dry at room temperature.
- As soon as the moisture evaporated the beam specimens were labelled and placed in the cold room at 10° C on flat surface boards until it was time for them to be tested. Figure 3.6 shows two photos of how the beam specimens were labelled.

Figure 3.6 Beam Specimen Labelling

## 3.7 TEST PARAMETERS & PROCEDURE

The IPC (Industrial Process Controls) four point beam fatigue apparatus will now be described, followed by the testing parameters used for both fatigue & mixture stiffness tests and finally the testing procedure will be described.

A testing system should have the following 3 components to enable successful testing of the specimens: a loading device, an environmental chamber and a data and control acquisition system. Figure 3.7 below shows the testing system (with the three components) used for this research at the Pavement Engineering laboratory of Stellenbosch University.

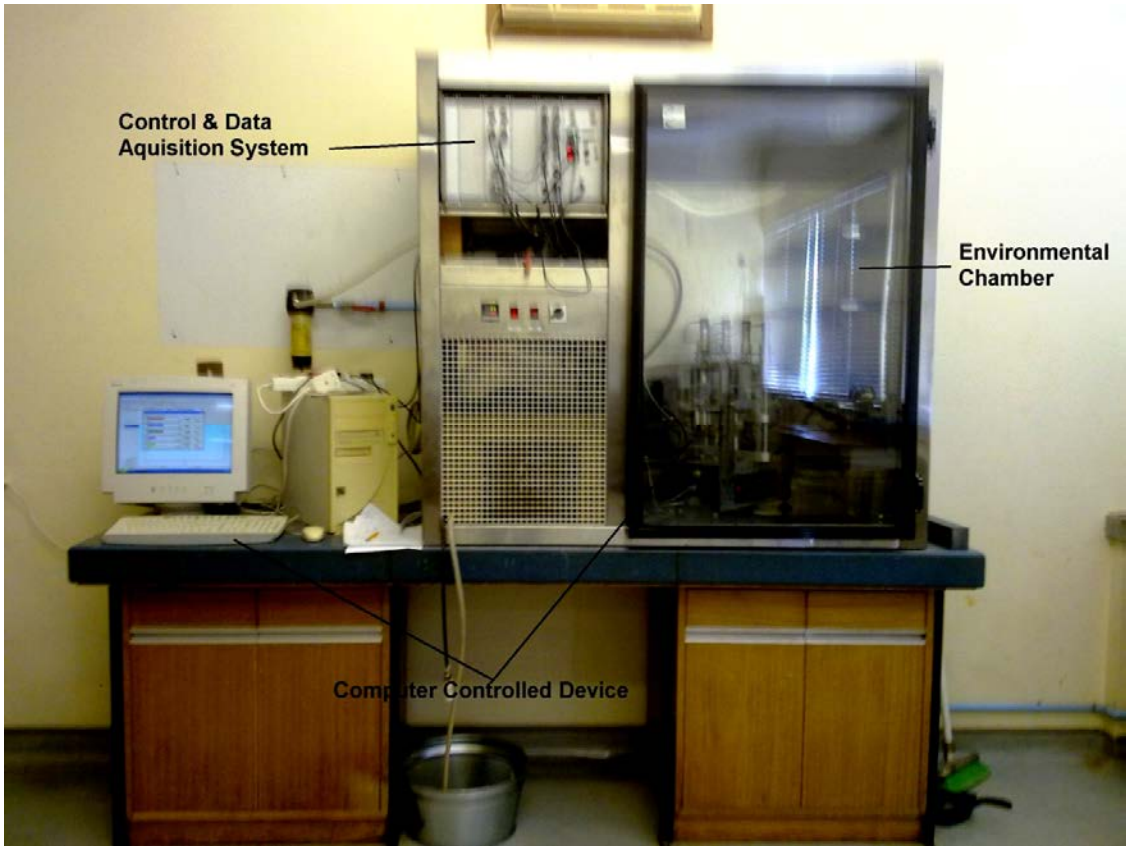


**Figure 3.7 Testing System**

Each of these components has requirements for a standard test and will now be described.

The loading device used should include a computer controlled loading component and a closed-loop. The function of the loading component is to carry out the commands received from the data & control acquisition system, adjusting and applying a load so that the beam specimen is subjected to a constant level of strain (set by the user) during each cycle. A schematic illustration of the four point bending beam testing apparatus can be seen in Figure 3.8 below. Note that the IPC actuator is located underneath and not above as Figure 3.8 shows. Figure 3.9 show a photograph of the computer linked with and controlling the loading component as well as a photograph of the loading component located inside the environmental chamber.

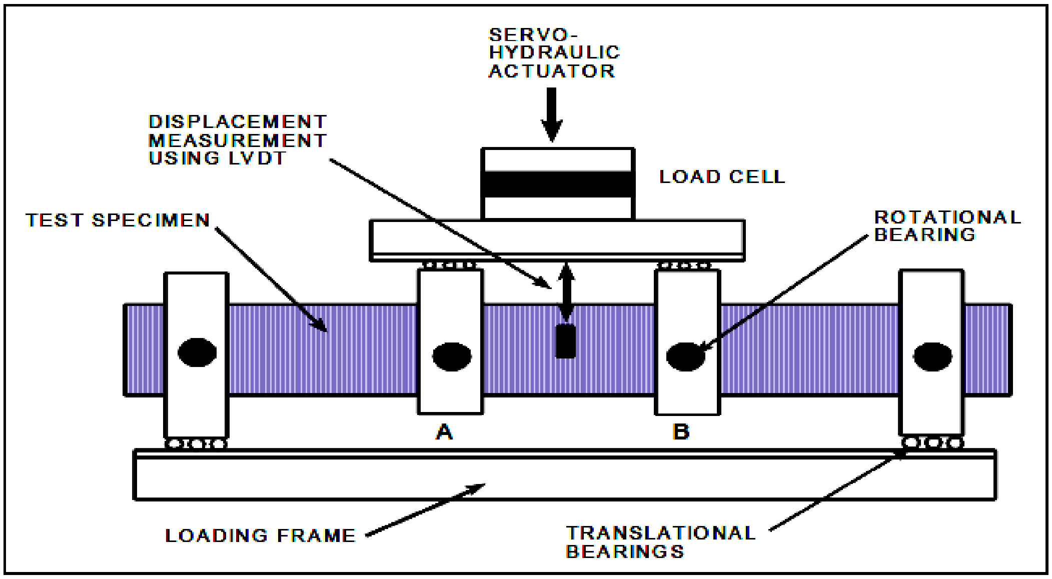


**Figure 3.8 Schematic Illustration of the Four Point Bending Beam Testing Apparatus (Taute et al, 2001)**

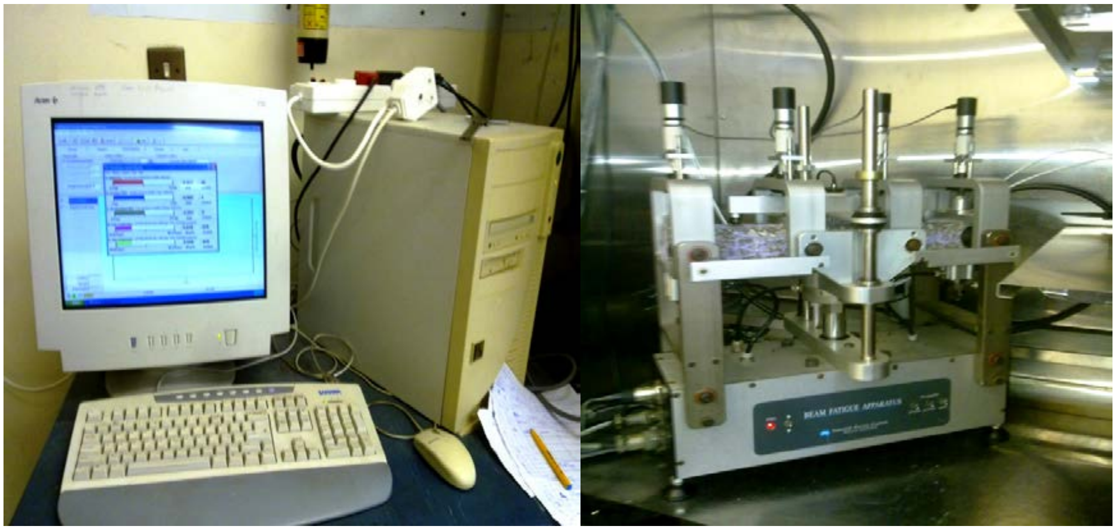


**Figure 3.9 Computer & Loading Component**

The environmental chamber should be able to maintain the desired temperature (set by the user) and also completely contain and surround the entire loading component, holding the specimen being tested, so as to control the specimen temperature.

There should also be a way for the testing system to check the temperature of a specimen inside the chamber to confirm that the specimen being tested has reached the desired testing temperature set. A round specimen has been placed inside the environmental chamber with two cables measuring the temperature at the core and the skin of the specimen. This information is sent to the computer where it can be displayed.

Figure 3.10 below shows a photograph of the temperature controls which are set by the user and beside it is a photograph of the round specimen with the two cables measuring the temperature, and the loading component which are both located inside the environmental chamber.

**Figure 3.10 Environmental Chamber**

The control & data acquisition system is the most important component of the testing system since this is the 'brain' of the system. It has several functions including the following:

- Record the load cycles
- Measure & record the applied load as well as adjusting the applied load to maintain constant strain
- Calculate & record the beam specimen deflection
- Calculate & record the strain in the beam specimen
- Calculate & record the following at each load cycle interval: the stiffness, maximum tensile strain & stress, phase angle, dissipated energy as well as the accumulated dissipated energy of the beam specimen being tested.

Figure 3.11 below shows a photograph of the data & control acquisition system responsible for the tasks listed above.

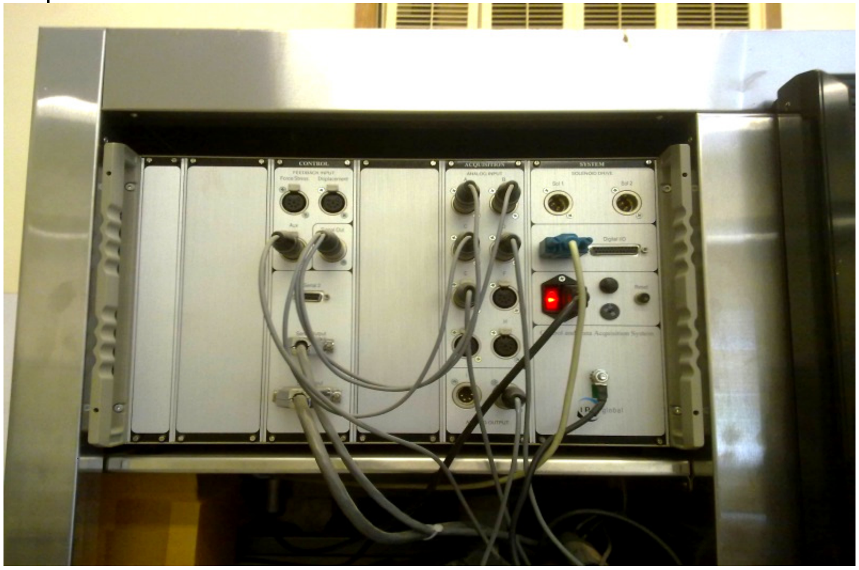


**Figure 3.11 Data & Control Acquisition System**

The formulas for calculating all these attributes will now be presented:

- Maximum tensile stress (Pa):

$$\sigma_t = \frac{(0.357P)}{(bh^2)}$$

With; P → applied load by actuator (N)
b → average beam specimen width (m)
h → average beam specimen height (m)

- Maximum tensile strain (m/m):

$$\epsilon_t = \frac{(12\delta h)}{(3L^3 - 4a^2)}$$

With; δ → maximum deflection at the centre of the beam specimen (m)
α → space between inside clamps (0.119 mm)
L → length of beam specimen between outer clamps (0.356 mm)

- Flexural stiffness (Pa):

$$S = \frac{\sigma_t}{\epsilon_t}$$

- Phase angle (degrees):

$$\varphi = 360fs$$

With; f → load frequency (Hz)
s → time lag between $P_{max}$ and $\sigma_{max}$

- Dissipated energy (J/m$^3$) per cycle:

$$D = \pi\sigma_t\epsilon_t \sin(\varphi)$$

- Cumulative dissipated energy (J/m$^3$):

$$\sum_{i=1}^{i=n} D_i$$

With; $D_i$ → D for the i$^{th}$ load cycle

- Initial stiffness (Pa):

$$S = Ae^{bn}$$

With; e → natural logarithm to the base of e
A, b → constants

- Cycles to failure:

$$n_{f,50} = \left[In\left(\frac{S_{f,50}}{A}\right)\right]/b$$

With; $S_{f,50}$ → 50% of the initial stiffness S
$S_{f,50}/A$ → 0.5

Before a test can be started the type of test should be decided on and subsequently the test parameters should be set. Two types of testing were done on beam specimens namely fatigue testing and mixture stiffness testing. For each test type the following parameters were set beforehand.

When performing a mixture stiffness test, 25 short tests in total are done on one beam specimen. These tests make up the 25 different pulse frequency and test conditioning temperature combinations achieved by combining 5 different pulse frequencies with 5 different conditioning temperatures, as described below. Also the conditioning cycle which is when the initial flexural stiffness of the beam specimen is measured and recorded should be decided on. This is the number of cycles allowed to pass to make sure that the specimen and loading device has regulated after starting as well as eliminating any measuring errors which could occur when the test is started. The total duration (number of cycles) for each test is also set. Conditioning time is also considered since it's very important that the specimen being tested is at the required test temperature. The loading mode and the strain level are also set. The parameters set for a mixture stiffness test include the following:

- Pulse frequencies → 0.5 Hz, 1 Hz, 2 Hz, 5 Hz and 10 Hz
- Conditioning temperatures → 5° C, 10° C, 15° C, 20° C and 25° C
- Conditioning cycle → initial flexural stiffness measured at the 50th cycle
- Conditioning time → 1 to 2 hours
- Loading mode → sinusoidal strain mode
- Strain level → 150 $\mu\varepsilon$ as testing strain level (300 $\mu\varepsilon$ peak to peak strain)
- Termination condition → 300 cycle for a complete mixture stiffness analysis

When performing a fatigue test, the parameters set are almost the same as for the mixture stiffness test, with a few exceptions. This test is a long test at one pulse frequency and test temperature. The initial flexural stiffness is measured at the set conditioning cycle after which the beam specimen will undergo cyclic loading until the specimen stiffness reaches the termination stiffness, which is set at half of the initial termination stiffness measured earlier. If the beam specimen does not reach the termination stiffness, a termination condition is set at the maximum cycles to be applied, after which the test is terminated. The parameters set for a fatigue test include the following:

- Pulse frequency → 10 Hz
- Conditioning temperature → 5° C
- Conditioning cycle → initial flexural stiffness measured at the 50th cycle
- Conditioning time → 1 to 2 hours
- Loading mode → sinusoidal strain mode
- Strain level → depending on whether a low, medium or high strain test is considered, the strain level will vary. At low strain level 180 – 230 Hz, at medium strain level 230 – 280 Hz and at high strain level 280 – 380 Hz were decided upon.

- Termination condition → 3 500 000 cycles

When all the test parameters have been decided on the test preparation and procedure can be started. The testing procedure which was followed will now be described:

- Set the environmental chamber to the desired conditioning temperature.
- Measure the height and width at four different positions along the length, as well as the length of the beam specimen, and input this data into the Universal Testing Machine (UTM) software program on the computer. Figure 3.12 below illustrates how the beam specimen measurements were taken.
- Slide the beam specimen into the loading device. Make sure the clamps are open before sliding the beam specimen and do so with caution to avoid damage to the apparatus and the beam specimen.
- Close the environmental chamber and allow the beam specimen to reach the conditioning temperature.
- Select and input the desired loading frequency, strain level, loading mode, conditioning cycles and termination conditions. (see the parameter values and description above)
- When the beam specimen has reached the conditioning temperature, the chamber is opened again and the clamps are fastened and the LVDT is put into position.
- Display the levels on the software program on the computer to see the reading for the actuator LVDT and the on-specimen LVDT. These levels should both be as close to 0 as possible before the test can start.
- First the actuator LVDT is adjusted with the lever on the bottom right of the loading apparatus as close to 0 as possible and then the on-specimen LVDT is adjusted by turning the circular knob in the middle of the top of the loading apparatus as close to 0 as possible.
- When both LVDT levels are set to 0, the two steel support braces on the side of the loading apparatus are taken off and the chamber door closed again.
- Once the conditioning temperature has regulated, the test may be started by clicking on the start button of the software program on the computer.
- The test data is displayed and can be saved and exported to excel.

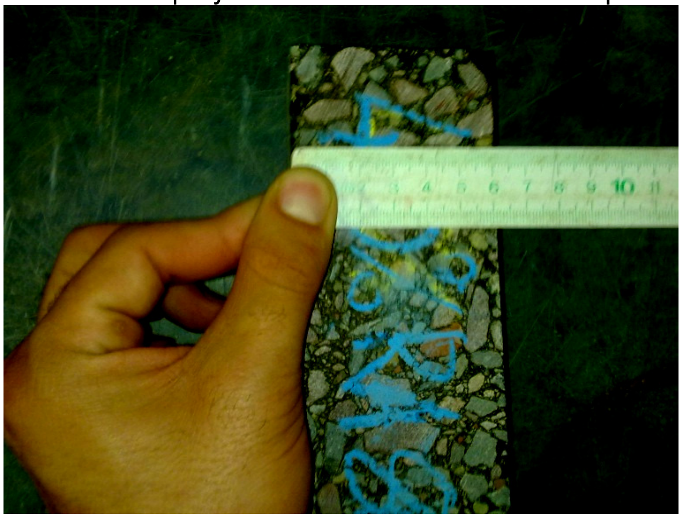


**Figure 3.12 Beam Specimen Measuring**

# CHAPTER FOUR

# LABORATORY TEST RESULTS & ANALYSIS

## 4.1 INTRODUCTION

In this chapter the data that has been obtained from laboratory testing is analysed and illustrated in figures and tables.

First there is a description of the analysis of the sieve data and additional mixture data. The test results for each mixture type are then displayed, evaluated and discussed. Then there is a description of the comparison of mixes. Phase angle results are then analysed with reference to the mixture behaviour.

## 4.2 MIX COMPONENT & FUNDAMENTAL MIXTURE DATA

The assessment of mixture quality and viability was done via testing at the plant site. The tests performed included binder testing, rice density and other density testing as well as several other mixture component evaluations. This procedure was vital since the findings and results obtained from the first plant run tests were used to make necessary adjustments to the mixture and plant in the mixture and plant calibration phase of the WMA trial.

HMA (control) mix specifications were used to evaluate the WMA (trial) mixes. The sieve data as well as mixture component and fundamental mixture data, will now be analysed.

### 4.2.1 Sieve Analysis

The sieve analysis data for each mixture type are presented in Tables 4.1 to 4.3 below. For each mixture type several mixtures were made. Table 4.1 to 4.3 give only the average values. For example, for Type D 10% there were four mixes made for the control (HMA) mixture but only the average value of the aggregate grading of all four mixes is displayed in Table 4.1.

The aggregate grading specification for a HMA surface and base mix is also given to see whether the mixes satisfy the specification. The HMA (control mix) aggregate grading specifications are used in the evaluation of WMA (trial) mixes.

## Table 4.1 Sieve Analysis Data for Type D 10% RA 60/70 Unmodified (Trial & Control) Mixes

| | Specification | | Type D 10% RA 60/70 Unmodified (Trial & Control Mixes) | | |
|---|---|---|---|---|---|
| Sieve Size (mm) | Min | Max | WMA Rediset (% Passing) | WMA Sasobit (% Passing) | HMA Control (% Passing) |
| 37.50 | 100 | 100 | 100 | 100 | 100 |
| 26.50 | 100 | 100 | 100 | 100 | 100 |
| 19.00 | 100 | 100 | 100 | 100 | 100 |
| 13.20 | 92 | 100 | 99 | 100 | 99 |
| 9.50 | 74 | 90 | 87 | 86 | 88 |
| 6.70 | 63 | 79 | 67 | 66 | 69 |
| 4.75 | 52 | 68 | 57 | 58 | 59 |
| 2.36 | 36 | 52 | 40 | 40 | 39 |
| 1.18 | 24 | 40 | 30 | 30 | 28 |
| 0.600 | 18 | 28 | 23 | 23 | 22 |
| 0.300 | 10 | 20 | 16 | 15 | 15 |
| 0.150 | 6 | 12 | 9 | 9 | 9 |
| 0.075 | 4 | 8 | 5.9 | 5.8 | 6.2 |

## Table 4.2 Sieve Analysis Data for Type B 40% RA 80/100 (Trial & Control) Mixes

| | Specification | | Type B 40% RA 80/100 (Trial & Control Mixes) | | | |
|---|---|---|---|---|---|---|
| Sieve Size (mm) | Min | Max | WMA AP-1 Rediset (% Passing) | HMA AP-1 Control (% Passing) | WMA AE-2 Sasoflex (% Passing) | HMA AE-2 Control (% Passing) |
| 37.50 | 100 | 100 | 100 | 100 | 100 | 100 |
| 26.50 | 100 | 100 | 100 | 100 | 100 | 100 |
| 19.00 | 80 | 100 | 95 | 98 | 98 | 96 |
| 13.20 | 60 | 80 | 80 | 85* | 84* | 81* |
| 9.50 | 51 | 71 | 65 | 71 | 68 | 67 |
| 6.70 | 44 | 64 | 52 | 57 | 54 | 52 |
| 4.75 | 36 | 56 | 44 | 49 | 47 | 45 |
| 2.36 | 28 | 44 | 31 | 36 | 34 | 32 |
| 1.18 | 20 | 34 | 24 | 27 | 26 | 24 |
| 0.600 | 15 | 27 | 19 | 22 | 21 | 20 |
| 0.300 | 10 | 20 | 14 | 16 | 15 | 15 |
| 0.150 | 6 | 12 | 9 | 10 | 10 | 10 |
| 0.075 | 2 | 6 | 5.8 | 6.5* | 6.2* | 6.2* |

*Note: * indicates that the values do not comply with the specification*

**Table 4.3 Sieve Analysis Data for Type B 10% RA 60/70 (Trial & Control) Mixes**

| | Specification | | Type B 10% RA 60/70 (Trial & Control Mixes) | | | | |
|---|---|---|---|---|---|---|---|
| Sieve Size (mm) | Min | Max | WMA AP-1 Rediset (%Passing) | WMA AP-1 Foamtech (%Passing) | HMA AP-1 Control (%Passing) | WMA AE-2 Sasoflex (%Passing) | HMA AE-2 Control (%Passing) |
| 37.50 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| 26.50 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| 19.00 | 80 | 100 | 97 | 98 | 98 | 95 | 97 |
| 13.20 | 60 | 80 | 80 | 82* | 82* | 82* | 84* |
| 9.50 | 51 | 71 | 64 | 64 | 70 | 68 | 70 |
| 6.70 | 44 | 64 | 51 | 50 | 59 | 54 | 55 |
| 4.75 | 36 | 56 | 44 | 41 | 51 | 46 | 46 |
| 2.36 | 28 | 44 | 31 | 27* | 35 | 31 | 32 |
| 1.18 | 20 | 34 | 23 | 20 | 25 | 23 | 23 |
| 0.600 | 15 | 27 | 17 | 15 | 18 | 17 | 17 |
| 0.300 | 10 | 20 | 13 | 12 | 13 | 13 | 13 |
| 0.150 | 6 | 12 | 9 | 8 | 9 | 9 | 9 |
| 0.075 | 2 | 6 | 6.1* | 5.2 | 6.2* | 5.7 | 5.7 |

*Note: * indicates that the values do not comply with the specification*

The data presented in Tables 4.1 to 4.3 above are illustrated below on Figure 4.1 to 4.3 to show whether the aggregate grading for each mix type satisfies the required specifications.

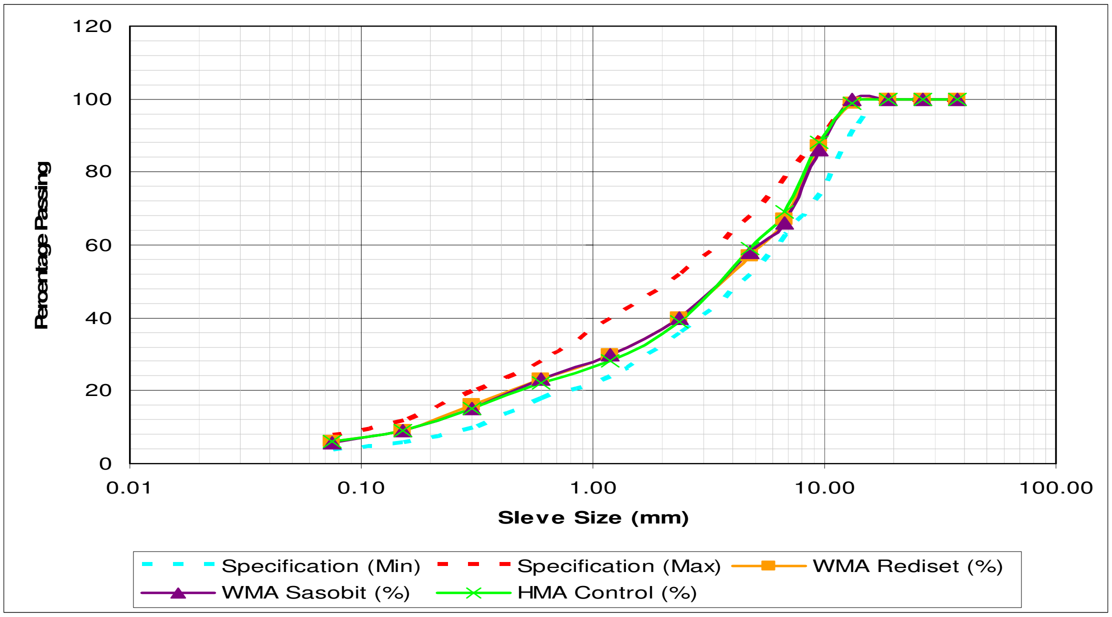


**Figure 4.1 Sieve Analysis Data for Type D 10% RA 60/70 Unmodified Mixes**

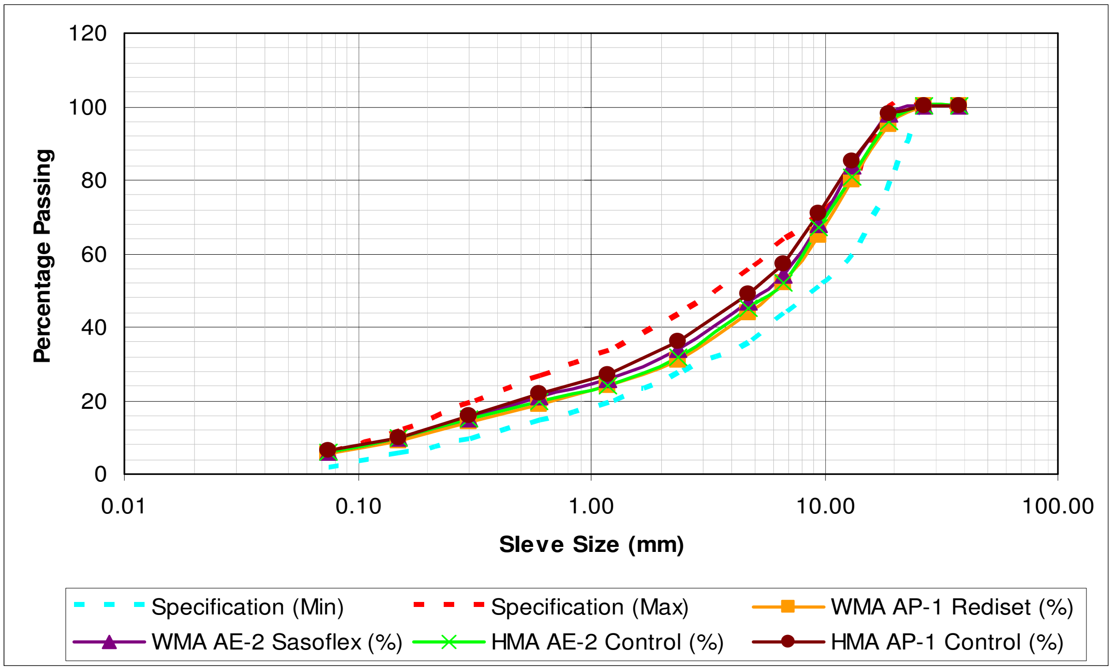


Figure 4.2 Sieve Analysis Data for Type B 40% RA 80/100 Modified Mixes

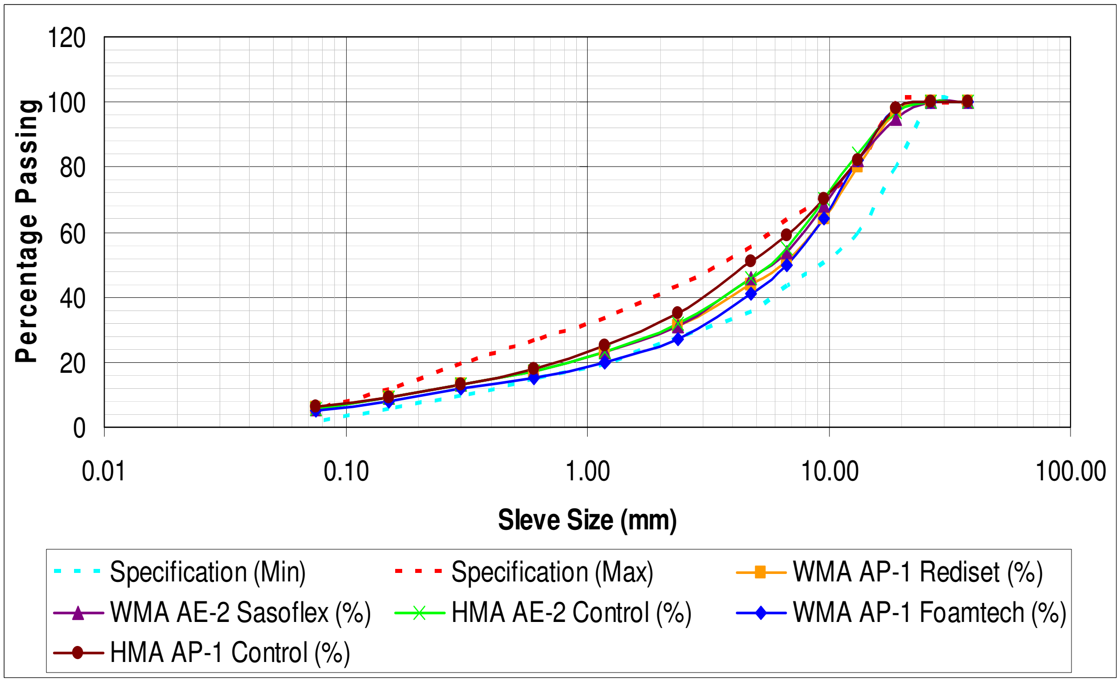


Figure 4.3 Sieve Analysis Data for Type B 10% RA 60/70 Modified Mixes

Following below in Table 4.4 the filler/bitumen ratio as well as the percentage of each aggregate size (coarse, fine and filler) used for each mixture type is presented.

**Table 4.4 Mix Component Details for all Mix Types**

| Type D 10% RA 60/70 | | | |
|---|---|---|---|
| **Mix Component** | **Control** | **Rediset** | **Sasobit** |
| **Filler/Bitumen Ratio (1.0 -1.5)** | 1.135 | 1.085 | 1.032 |
| **Coarse Aggregate (%)** | 57.5 | 56.7 | 56.3 |
| **Fine Aggregate (%)** | 31.4 | 32.5 | 32.8 |
| **Filler Content (%)** | 5.9 | 5.6 | 5.4 |

| Type B 40% RA 80/100 | | | | |
|---|---|---|---|---|
| **Mix Component** | **WMA AP-1 Rediset** | **HMA AP-1 Control** | **WMA AE-2 Sasoflex** | **HMA AE-2 Control** |
| **Filler/Bitumen Ratio (1.0 -1.5)** | 1.382 | 1.432 | 1.374 | 1.377 |
| **Coarse Aggregate (%)** | 53.3 | 48.3 | 50.2 | 53.0 |
| **Fine Aggregate (%)** | 37.0 | 41.1 | 39.5 | 36.7 |
| **Filler Content (%)** | 5.6 | 6.2 | 5.9 | 5.9 |

| Type B 10% RA 60/70 | | | | | |
|---|---|---|---|---|---|
| **Mix Component** | **WMA AP-1 Rediset (%)** | **WMA AP-1 Foamtech (%)** | **HMA AP-1 Control (%)** | **WMA AE-2 Sasoflex (%)** | **HMA AE-2 Control (%)** |
| **Filler/Bitumen Ratio (1.0 -1.5)** | 1.367 | 1.271 | 1.311 | 1.182 | 1.254 |
| **Coarse Aggregate (%)** | 53.8 | 56.7 | 47.2 | 51.7 | 51.3 |
| **Fine Aggregate (%)** | 36.0 | 34.3 | 42.3 | 38.2 | 38.8 |
| **Filler Content (%)** | 5.8 | 5.0 | 5.9 | 5.5 | 5.5 |

### 4.2.2 Fundamental Mixture Data

The fundamental mixture data was received from the plant laboratory and is presented in Table 4.5 on the next page.

## Table 4.5 Fundamental Mixture Data

**Type D 10% RA 60/70**

| Evaluation | Control | Rediset | Sasobit | Specification |
|---|---|---|---|---|
| Rice Density (kg/m$^3$) | 2466 | 2476 | 2471 | - |
| BRD (kg/m$^3$) | 2378 | 2370 | 2369 | - |
| Bitumen Content (%) | 5.2 | 5.1 | 5.3 | 5.0 -5.6 |
| Film Thickness (µm) | 8.1 | 7.7 | 8.2 | 5.0 µm min |
| Binder Absorption (%) | 0.3 | 0.5 | 0.5 | 0.5 max |
| Void Content (%) | 3.5 | 4.3 | 4.1 | 3.0 -6.0 |
| VMA (%) | 14.7* | 15.0 | 15.2 | 15.0 min |
| VFB (%) | 76.1* | 71.6 | 72.7 | 65-75 |

**Type B 40% RA 80/100**

| Evaluation | WMA AP-1 Rediset | HMA AP-1 Control | WMA AE-2 Sasoflex | HMA AE-2 Control | Specification |
|---|---|---|---|---|---|
| Rice Density (kg/m$^3$) | 2500 | 2483 | 2492 | 2489 | - |
| BRD (kg/m$^3$) | 2375 | 2387 | 2376 | 2388 | - |
| Bitumen Content (%) | 4.1 | 4.3 | 4.3 | 4.3 | 3.9 - 4.5 |
| Film Thickness (µm) | 6.7* | 6.6* | 6.7* | 6.9* | 8.0 µm min |
| Binder Absorption (%) | 0.3 | 0.2 | 0.3 | 0.3 | 0.5 max |
| Void Content (%) | 5.0 | 3.9 | 4.6 | 4.1 | 3.0 - 6.0 |
| VMA (%) | 13.6* | 13.5* | 13.8* | 13.4* | 14 min |
| VFB (%) | 63.4 | 71.3 | 66.5 | 69.7 | 65 - 75 |

**Type B 10% RA 60/70**

| Evaluation | WMA AP-1 Rediset (%) | WMA AP-1 Foamtech (%) | HMA AP-1 Control (%) | WMA AE-2 Sasoflex (%) | HMA AE-2 Control (%) | Specification |
|---|---|---|---|---|---|---|
| Rice Density (kg/m$^3$) | 2499 | 2495 | 2492 | 2489 | 2489 | - |
| Bulk Relative Density (kg/m$^3$) | 2384 | 2353 | 2400 | 2377 | 2389 | - |
| Bitumen Content (%) | 4.3 | 3.9 | 4.5 | 4.6* | 4.4 | 3.9 - 4.5 |
| Film Thickness (µm) | 7.1* | 7.8* | 7.2* | 7.9* | 7.6* | 8.0 µm min |
| Binder Absorption (%) | 0.4 | 0.1 | 0.4 | 0.5 | 0.3 | 0.5 max |
| Void Content (%) | 4.6 | 5.7 | 3.7 | 4.5 | 4.0 | 3.0 - 6.0 |
| VMA (%) | 13.6* | 14.4 | 13.3* | 14.1 | 13.5* | 14 min |
| VFB (%) | 65.9 | 60.5* | 72.3 | 68.2 | 70.5 | 65 - 75 |

*Note: * indicates that the values do not comply with the specification*

As can be seen from Table 4.5 above, none of the Type B mixes met the required minimum film thickness specification. This can be explained by looking at their VMA and VFB values. VMA signifies the volumetric space available for bitumen while VFB depicts the void spaces between the aggregate particles filled with bitumen. If the VMA of a mix is low it means that there is limited space for bitumen and the binder content will need to be low. Depending on the fines content, this could result in a low film thickness. On the other hand, a high VFB means more voids are filled with bitumen. As can be seen in Table 4.5 above, the Type B mixes all have VMA values that are smaller than their specified minimum which is why their film thicknesses are thinner than the specified criteria. Table 4.6 and 4.7 below provide a detailed analysis regarding the aggregate sizing used.

**Table 4.6 Cumulative Percentage of Aggregate Retained for Type D 10% RA 60/70 Mixes (Using Table 4.1 Data)**

| **Type D 10% RA 60/70 (Trial & Control Mixes)** | | | |
|---|---|---|---|
| **Sieve Size (mm)** | **WMA Rediset (%)** | **WMA Sasobit (%)** | **HMA Control (%)** |
| 37.50 | 0 | 0 | 0 |
| 26.50 | 0 | 0 | 0 |
| 19.00 | 0 | 0 | 0 |
| 13.20 | 1 | 0 | 1 |
| 9.50 | 13 | 14 | 12 |
| 6.70 | 33 | 34 | 31 |
| 4.75 | 43 | 42 | 41 |
| 2.36 | 60 | 60 | 61 |
| 1.18 | 70 | 70 | 72 |
| 0.600 | 77 | 77 | 78 |
| 0.300 | 84 | 85 | 85 |
| 0.150 | 91 | 91 | 91 |
| 0.075 | 94.1 | 94.2 | 93.8 |
| **Percentage Aggregate Types Contained in Mix** | | | |
| **Aggregate Type** | **WMA Rediset (%)** | **WMA Sasobit (%)** | **HMA Control (%)** |
| Coarse (%) | 43 | 42 | 41 |
| Fine (%) | 51.1 | 52.2 | 52.8 |
| Filler (%) | 5.9 | 5.8 | 6.2 |

As can be seen from Table 4.7 below the Foamtech mix has the highest percentage of coarse aggregate and the lowest of the fine and filler. This explains why the Foamtech mix had the highest void content of all the mixes since it had extra coarse aggregate and less fine and filler to fill up all the air voids.

## Table 4.7 Cumulative Percentage of Aggregate Retained for Type B 10% RA 60/70 and Type B 40% RA 80/100 Mixes (Using Table 4.2 and 4.3 Data)

**Type B 40% RA 80/100 (Trial & Control Mixes)**

| Sieve Size (mm) | WMA AP-1 Rediset (%) | HMA AP-1 Control (%) | WMA AE-2 Sasoflex (%) | HMA AE-2 Control (%) |
|---|---|---|---|---|
| 37.50 | 0 | 0 | 0 | 0 |
| 26.50 | 0 | 0 | 0 | 0 |
| 19.00 | 5 | 2 | 2 | 4 |
| 13.20 | 20 | 15 | 16 | 19 |
| 9.50 | 35 | 29 | 32 | 33 |
| 6.70 | 48 | 43 | 46 | 48 |
| 4.75 | 56 | 51 | 53 | 55 |
| 2.36 | 69 | 64 | 66 | 68 |
| 1.18 | 76 | 73 | 74 | 76 |
| 0.600 | 81 | 78 | 79 | 80 |
| 0.300 | 86 | 84 | 85 | 85 |
| 0.150 | 91 | 90 | 90 | 90 |
| 0.075 | 94.2 | 93.5 | 93.8 | 93.8 |

**Percentage Aggregate Types Contained in Mix**

| Aggregate Type | WMA AP-1 Rediset (%) | HMA AP-1 Control (%) | WMA AE-2 Sasoflex (%) | HMA AE-2 Control (%) |
|---|---|---|---|---|
| Coarse (%) | 56 | 51 | 53 | 55 |
| Fine (%) | 38.2 | 42.5 | 40.8 | 38.8 |
| Filler (%) | 5.8 | 6.5 | 6.2 | 6.2 |

**Type B 10% RA 60/70 (Trial & Control Mixes)**

| Sieve Size (mm) | WMA AP-1 Rediset (%) | WMA AP-1 Foamtech (%) | HMA AP-1 Control (%) | WMA AE-2 Sasoflex (%) | HMA AE-2 Control (%) |
|---|---|---|---|---|---|
| 37.50 | 0 | 0 | 0 | 0 | 0 |
| 26.50 | 0 | 0 | 0 | 0 | 0 |
| 19.00 | 3 | 2 | 2 | 5 | 3 |
| 13.20 | 20 | 18 | 18 | 18 | 16 |
| 9.50 | 36 | 36 | 30 | 32 | 30 |
| 6.70 | 49 | 50 | 41 | 46 | 45 |
| 4.75 | 56 | 59 | 49 | 54 | 54 |
| 2.36 | 69 | 73 | 65 | 69 | 68 |
| 1.18 | 77 | 80 | 75 | 77 | 77 |
| 0.600 | 83 | 85 | 82 | 83 | 83 |
| 0.300 | 87 | 88 | 87 | 87 | 87 |
| 0.150 | 91 | 92 | 91 | 91 | 91 |
| 0.075 | 93.9 | 94.8 | 93.8 | 94.3 | 94.3 |

**Percentage Aggregate Types Contained in Mix**

| Aggregate Type | WMA AP-1 Rediset (%) | WMA AP-1 Foamtech (%) | HMA AP-1 Control (%) | WMA AE-2 Sasoflex (%) | HMA AE-2 Control (%) |
|---|---|---|---|---|---|
| Coarse (%) | 56 | 59 | 49 | 54 | 54 |
| Fine (%) | 37.9 | 35.8 | 44.8 | 40.3 | 40.3 |
| Filler (%) | 6.1 | 5.2 | 6.2 | 5.7 | 5.7 |

## 4.3 TYPE D 10% RA 60/70 (UNMODIFIED) TEST RESULTS

For each mix type three slabs were compacted from which four beams per slab were sawn resulting in twelve beam specimens available for testing per mix type. The slabs were sawn following the procedure described in Section 3.5.

Two beams for each mix type were allocated for flexural stiffness testing and nine beams for fatigue testing. The left over beam was kept as a reserve in case a beam failed prematurely or any other problem occurred. The procedure for beam selection, as to which beam for which test and strain level, was done in an unbiased manner (completely random).

BRD testing was conducted on each beam after cutting them to calculate the void content for each beam. The BRD testing procedure described in Section 3.6 was followed.

Table 4.8 below gives beam specimen details for each mix type under the Type D 10% RA 60/70 unmodified mixes. The details include beam number and from which slab it was cut, beam dimensions, mass in air, void content (from BRD test results) as well as indicating which type of test was conducted on that particular beam. The abbreviations FT and FST, in the last column of Table 4.8 below, represent a Fatigue Test and a Flexural Stiffness Test respectively.

**Table 4.8 Beam Details for Type D 10% RA 60/70 (Unmodified) Mixes**

| Type D 10% RA 60/70 (Unmodified) Beam Specimens | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Mix Type** | **Slab No.** | **Beam No.** | **Width (mm)** | **Height (mm)** | **Length (mm)** | **Mass in Air (g)** | **Void Content (%)** | **Test Conducted** |
| **Control** | 1 | 1 | 63.0 | 51.5 | 400 | 3121.8 | 4.94 | FT @ 180 με |
| | | 2 | 61.5 | 50.3 | 399 | 2943.3 | 4.25 | FST |
| | | 3 | 60.3 | 51.5 | 399 | 2994.2 | 4.32 | FT @ 300 με |
| | | 4 | 62.8 | 52.3 | 400 | 3110.8 | 4.42 | FT @ 230 με |
| | 2 | 1 | 64.0 | 52.3 | 391 | 3154.1 | 4.87 | FT @ 230 με |
| | | 2 | 63.8 | 51.0 | 396 | 3167.0 | 4.35 | FT @ 300 με |
| | | 3 | 63.5 | 52.8 | 399 | 3223.2 | 4.54 | FST |
| | | 4 | 62.5 | 53.0 | 396 | 3140.6 | 4.55 | FT @ 180 με |
| | 3 | 1 | Extra Beam Never Tested! | | | | | |
| | | 2 | 63.0 | 50.0 | 397 | 3034.2 | 4.64 | FT @ 180 με |
| | | 3 | 63.0 | 52.3 | 397 | 3176.7 | 4.05 | FT @ 230 με |
| | | 4 | 62.8 | 50.5 | 398 | 3084.9 | 3.90 | FT @ 300 με |
| **Rediset** | 1 | 1 | 61.0 | 51.5 | 399 | 2968.0 | 6.68 | FT @ 180 με |
| | | 2 | 61.0 | 51.0 | 398 | 2982.3 | 5.42 | FT @ 230 με |
| | | 3 | 61.0 | 50.8 | 397 | 2970.9 | 5.25 | FT @ 300 με |
| | | 4 | 62.8 | 51.0 | 400 | 2968.0 | 6.68 | FST |
| | 2 | 1 | 63.0 | 51.0 | 399 | 3011.7 | 3.39 | FST |
| | | 2 | 61.5 | 52.0 | 399 | 3139.8 | 2.65 | FT @ 300 με |
| | | 3 | 61.0 | 50.3 | 398 | 3004.1 | 2.41 | FT @ 180 με |
| | | 4 | 61.8 | 50.0 | 397 | 2989.1 | 2.52 | FT @ 230 με |
| | 3 | 1 | Extra Beam Never Tested! | | | | | |
| | | 2 | 63.0 | 52.0 | 399 | 3201.4 | 3.54 | FT @ 300 με |
| | | 3 | 63.0 | 52.8 | 399 | 3191.9 | 3.73 | FT @ 230 με |
| | | 4 | 64.0 | 53.0 | 399 | 3205.3 | 3.86 | FT @ 180 με |
| **Sasobit** | 1 | 1 | 62.0 | 51.8 | 399 | 3023.4 | 4.05 | FST |
| | | 2 | 61.5 | 50.8 | 399 | 3012.7 | 3.47 | FT @ 300 με |
| | | 3 | 61.0 | 51.5 | 400 | 3044.8 | 3.75 | FT @ 230 με |
| | | 4 | 62.3 | 51.0 | 400 | 3073.7 | 3.95 | FT @ 180 με |
| | 2 | 1 | 62.8 | 53.5 | 398 | 3143.5 | 5.24 | FT @ 180 με |
| | | 2 | 63.3 | 52.5 | 394 | 3187.5 | 4.32 | FST |
| | | 3 | 62.3 | 53.8 | 398 | 3203.4 | 4.11 | FT @ 300 με |
| | | 4 | 63.3 | 53.8 | 399 | 3254.9 | 4.78 | FT @ 230 με |
| | 3 | 1 | Extra Beam Never Tested! | | | | | |
| | | 2 | 63.0 | 52.8 | 396 | 3084.1 | 5.15 | FT @ 230 με |
| | | 3 | 63.5 | 52.3 | 393 | 3087.0 | 4.88 | FT @ 180 με |
| | | 4 | 63.0 | 51.5 | 390 | 2993.8 | 5.06 | FT @ 300 με |

### 4.3.1 Flexural Stiffness Results

The parameters and procedure followed for flexural stiffness testing are described in Section 3.7. For each mix type two beams were evaluated for flexural stiffness. The flexural stiffness results for each mix type will first be analysed individually and then the representative result for each mix type will be selected and compared on one graph.

The results have been displayed as follows:

- Table 4.9 provides flexural stiffness results for Type D 10% RA 60/70 unmodified control (HMA) mix and Figure 4.4 illustrates the master curves.
- Table 4.10 provides flexural stiffness results for Type D 10% RA 60/70 unmodified Rediset (WMA) mix and Figure 4.5 illustrates the master curves.
- Table 4.11 provides flexural stiffness results for Type D 10% RA 60/70 unmodified Sasobit (WMA) mix and Figure 4.6 illustrates the master curves.
- Figure 4.7 compares the master curves for all the mix types under Type D 10% RA 60/70 unmodified mixes.

**Table 4.9 Flexural Stiffness Results for Type D 10% RA 60/70 (Unmodified) Control Mixes**

| **Flexural Stiffness for Type D 10% RA 60/70 Control Mix Beam 2 Slab 1 (MPa)** | | | | | |
|---|---|---|---|---|---|
| **Frequency (Hz)** | **5° C** | **10° C** | **15° C** | **20° C** | **25° C** |
| **0.5** | 11430.8 | 7946.7 | 4809.7 | 2516.9 | 1176.4 |
| **1** | 12532.5 | 9233.2 | 5964.3 | 3205.0 | 1578.2 |
| **2** | 13734.0 | 10307.7 | 6943.1 | 4260.0 | 2161.9 |
| **5** | 15172.8 | 12174.5 | 8777.4 | 5852.7 | 3302.4 |
| **10** | 16473.5 | 13579.2 | 10320.4 | 7432.7 | 4400.4 |
| **Flexural Stiffness for Type D 10% RA 60/70 Control Mix Beam 3 Slab 2 (MPa)** | | | | | |
| **Frequency (Hz)** | **5° C** | **10° C** | **15° C** | **20° C** | **25° C** |
| **0.5** | 10828.7 | 7709.5 | 4627.2 | 2453.4 | 1135.2 |
| **1** | 12017.3 | 8778.9 | 5735.3 | 3175.6 | 1509.0 |
| **2** | 13141.8 | 10183.9 | 7001.9 | 4108.6 | 2139.5 |
| **5** | 15176.1 | 12154.6 | 8893.8 | 5672.4 | 3150.9 |
| **10** | 16406.2 | 13797.8 | 10518.3 | 7236.6 | 4289.3 |

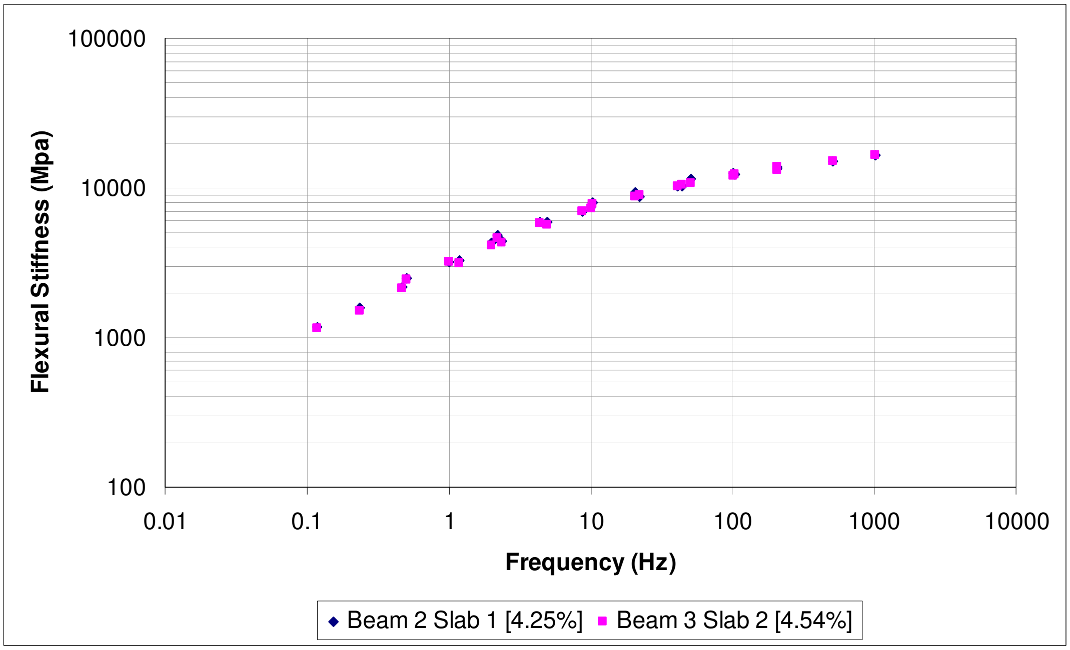


**Figure 4.4 Master Curves at Reference Temperature 20° C for Type D 10% RA 60/70 (Unmodified) Control Mix Beams [Void Content (%)]**

**Table 4.10 Flexural Stiffness Results for Type D 10% RA 60/70 (Unmodified) Rediset Mixes**

| **Flexural Stiffness for Type D 10% RA 60/70 Rediset Mix Beam 4 Slab 1 (MPa)** | | | | | |
|---|---|---|---|---|---|
| **Frequency(Hz)** | **5° C** | **10° C** | **15° C** | **20° C** | **25° C** |
| **0.5** | 8376.7 | 5249.4 | 2842.6 | 1450.8 | 692.6 |
| **1** | 9403.7 | 6332.4 | 3756.5 | 1905.2 | 943.9 |
| **2** | 10962.0 | 7400.2 | 4676.4 | 2554.3 | 1308.1 |
| **5** | 12932.2 | 9093.9 | 6199.8 | 3651.9 | 2139.4 |
| **10** | 14206.9 | 11044.1 | 7924.9 | 4909.8 | 2969.4 |
| **Flexural Stiffness for Type D 10% RA 60/70 Rediset Mix Beam 1 Slab 2 (MPa)** | | | | | |
| **Frequency(Hz)** | **5° C** | **10° C** | **15° C** | **20° C** | **25° C** |
| **0.5** | 10988.4 | 7398.1 | 4339.4 | 2370.2 | 1052.5 |
| **1** | 12130.9 | 8561.2 | 5421.1 | 3054.1 | 1349.8 |
| **2** | 13393.1 | 9922.5 | 6507.9 | 4057.4 | 1941.0 |
| **5** | 15029.3 | 11774.8 | 8466.9 | 5574.4 | 2856.1 |
| **10** | 16061.1 | 13550.0 | 10042.5 | 6993.8 | 3990.0 |

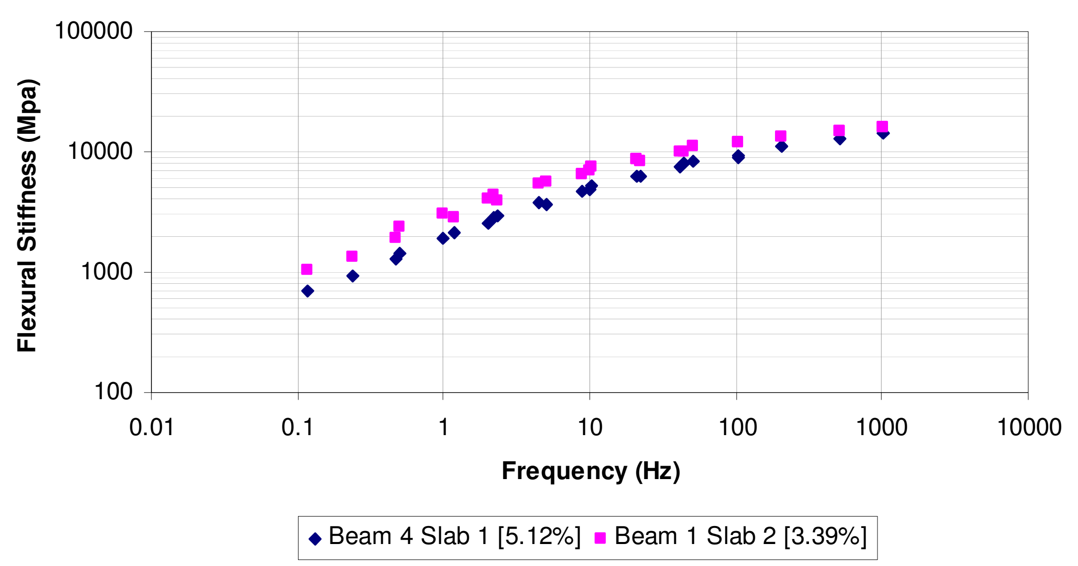


**Figure 4.5 Master Curves at Reference Temperature 20° C for Type D 10% RA 60/70 (Unmodified) Rediset Mix Beams [Void Content (%)]**

**Table 4.11 Flexural Stiffness Results for Type D 10% RA 60/70 (Unmodified) Sasobit Mixes**

| Flexural Stiffness for Type D 10% RA 60/70 Sasobit Mix Beam 1 Slab 1 (MPa) | | | | | |
|---|---|---|---|---|---|
| **Frequency(Hz)** | **5° C** | **10° C** | **15° C** | **20° C** | **25° C** |
| **0.5** | 10538.8 | 7005.0 | 4026.5 | 2258.5 | 1138.0 |
| **1** | 11495.3 | 8011.1 | 5082.1 | 2728.6 | 1380.4 |
| **2** | 12654.2 | 9549.4 | 6313.7 | 3631.8 | 1929.6 |
| **5** | 14308.5 | 11290.4 | 8175.6 | 5127.6 | 2931.7 |
| **10** | 15524.7 | 13000.5 | 9729.9 | 6640.6 | 4006.5 |
| **Flexural Stiffness for Type D 10% RA 60/70 Sasobit Mix Beam 2 Slab 2 (MPa)** | | | | | |
| **Frequency(Hz)** | **5° C** | **10° C** | **15° C** | **20° C** | **25° C** |
| **0.5** | 10714.7 | 7316.2 | 4447.3 | 2447.8 | 1223.9 |
| **1** | 11806.8 | 8382.1 | 5479.2 | 3079.7 | 1585.9 |
| **2** | 12850.1 | 9539.9 | 6424.2 | 3906.9 | 2135.5 |
| **5** | 14698.5 | 11417.0 | 8191.1 | 5368.0 | 3031.3 |
| **10** | 15943.0 | 13118.1 | 9864.8 | 6771.4 | 4104.2 |

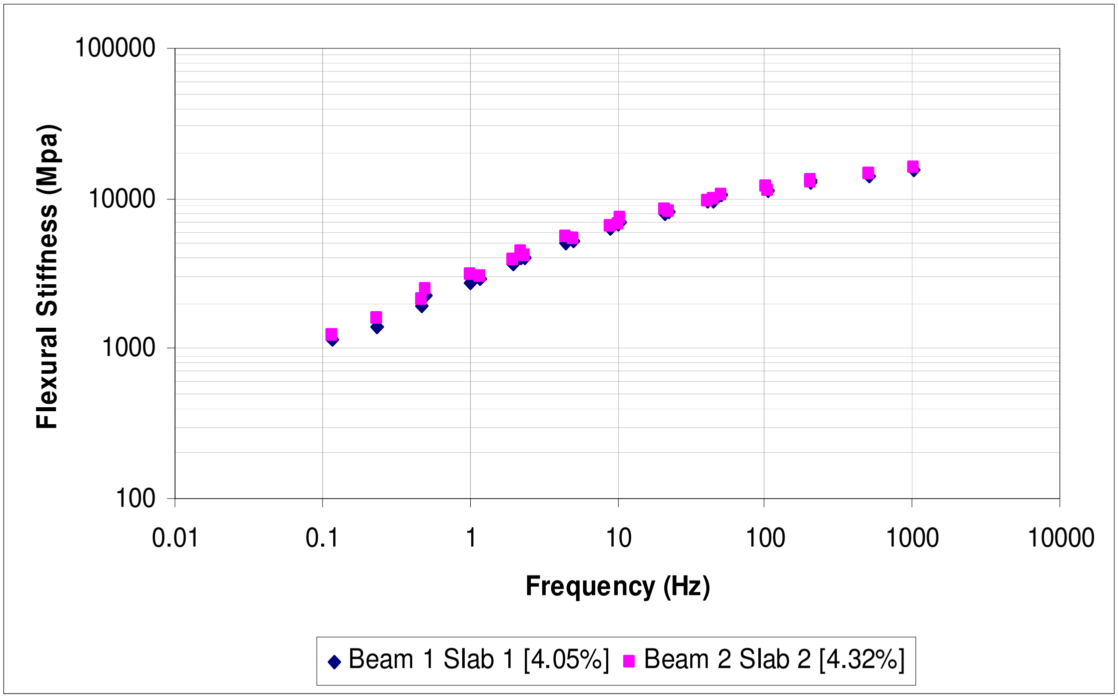


Figure 4.6 Master Curves at Reference Temperature 20° C for Type D 10% RA 60/70 (Unmodified) Sasobit Mix Beams [Void Content (%)]

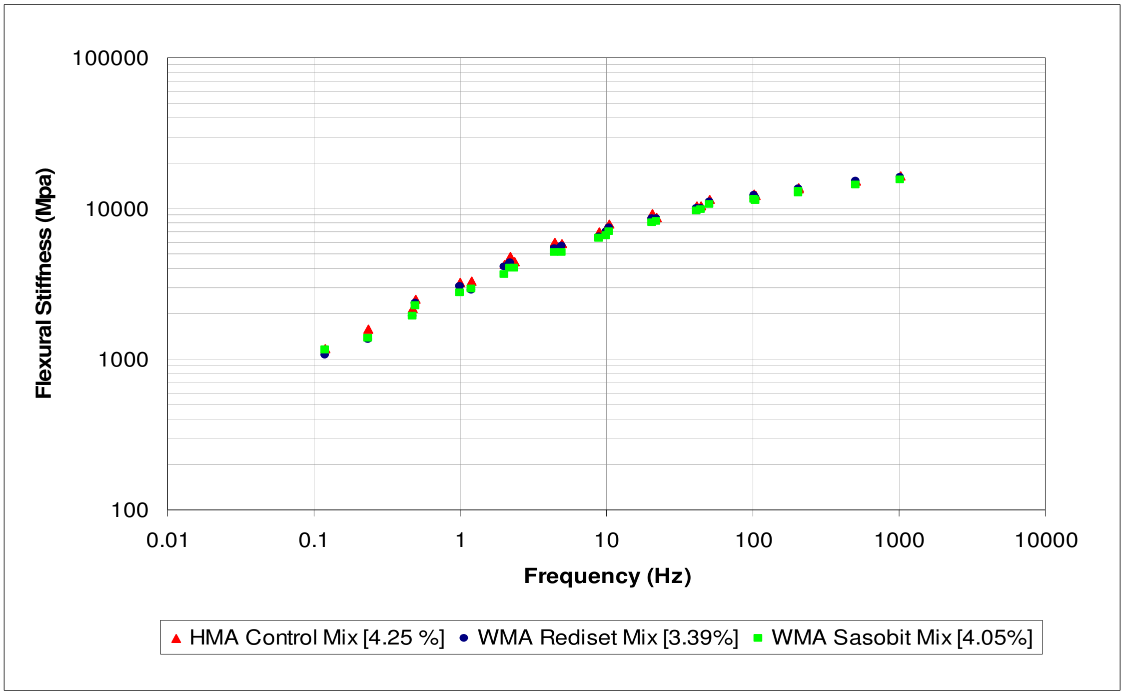


Figure 4.7 Master Curves at Reference Temperature 20° C for Type D 10% RA 60/70 (Unmodified) Trial and Control Mixes [Void Content (%)]

When looking at the master curves in the figures, the legend gives the void content of each beam tested, in square brackets. As can be seen from Figure 4.4 and 4.6 the control (HMA) and Sasobit (WMA) mix beams all have void contents which are close to 4% (which is the optimum void content) and they performed relatively similarly. Figure 4.5 displays two results which differ for the Rediset (WMA) mix. This is attributed to the void content difference between the two beams used for these tests [5.12% vs. 3.39%]. A more densely compacted beam will have less void content and result in a general higher flexural stiffness.

The method to select the representative result for each mix is to use the result of the beam which has a void content which is closest to 4% (optimum). For the control (HMA) mix, beam 2 from slab 1 (4.25%) was selected. For the Rediset (WMA) mix, beam 1 slab 1 (3.39%) was used and for the Sasobit (WMA) mix, beam 1 slab 2 (4.05%) was used. The representative results selected for each mix are compared on Figure 4.7. Looking at Figure 4.7 it can be seen that the Rediset and Sasobit (WMA) trial mixes compared well with the equivalent control (HMA) mix in terms of flexural stiffness. Flexural Stiffness provides an indication of rut resistance at higher temperatures (higher flexural stiffness values are better) and at low temperatures is an 'indicator' of fatigue resistance (lower flexural stiffness values are better). These three mixes yield a similar trend in flexural stiffness. Further fatigue analysis will be done when analysing the fatigue test results below.

### 4.3.2 Fatigue Results

The parameters and procedure followed for fatigue testing are described in Section 3.7 and Section 2.3.1. For each mix type nine beams were selected for fatigue evaluation since the guidelines for fatigue evaluation, indicated in the Interim Guidelines for the Design of Hot-Mix Asphalt in South Africa (Taute et al, 2001), recommend that a mix should be tested at three different strain regimes with a minimum of three beams for each strain regime.

Two fatigue characterization approaches are used to analyse the fatigue testing results. The first is Wöhler's fatigue relationship which relates the number of load repetitions to failure to the tensile strain. Secondly Van Dijk's (1977) cumulative dissipated energy model which correlates cumulative dissipated energy to the number of load repetitions to failure is considered as an alternative approach. Refer to Section 2.3.1 for the theory behind these two approaches considered.

For Type D 10% RA 60/70 unmodified mixes, the three strain levels at which the fatigue tests were performed included 180 με, 230 με and 300 με. Since the fatigue life of these mixes at 300 με strain level was relatively short, it was decided that testing them at a higher strain level (320 – 380 με) would result in losing beams to premature failure, and hence lower strain levels were selected than those recommended by Taute et al (2001) to ensure achievable results.

The results have been displayed as follows:

- Table 4.12 provides the fatigue results and evaluation for Type D 10% RA 60/70 mixes and Figure 4.8 and 4.9 illustrate the relative fatigue performance of these mixes with regards to the Wöhler and Van Dijk's approach respectively.

- Table 4.13 summarizes these two approaches by presenting the coefficients and $R^2$ values for each model.

### Table 4.12 Fatigue Results for Type D 10% RA 60/70 (Unmodified) Control and Trial Mixes

| Type D 10% RA 60/70 (Unmodified) Beam Specimens | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Mix Type** | **Slab No.** | **Beam No.** | **Void Content (%)** | **Initial Flexural Stiffness (MPa)** | **Strain Level [Peak to Peak] ($\mu\varepsilon$)** | **Number of Load Repetitions** | **Cumulative Dissipated Energy (MPa)** | **Average Phase Angle (Degrees)** |
| **Control** | 1 | 1 | 4.9 | 16650 | 180 | 2470600 | 102.396 | 4.52 |
| | 2 | 4 | 4.5 | 14447 | | 1696780 | 66.916 | 5.81 |
| | 3 | 2 | 4.6 | 16255 | | 4147059* | 138.818 | 6.00 |
| | 1 | 4 | 4.4 | 15808 | 230 | 925500 | 55.062 | 5.77 |
| | 2 | 1 | 4.9 | 15956 | | 403260 | 29.492 | 7.55 |
| | 3 | 3 | 4.0 | 15887 | | 627700 | 40.159 | 6.31 |
| | 1 | 3 | 4.3 | 15215 | 300 | 105890 | 11.021 | 6.24 |
| | 2 | 2 | 4.3 | 17114 | | 203060 | 24.357 | 6.38 |
| | 3 | 4 | 3.9 | 15868 | | 171850 | 23.028 | 8.21 |
| **Rediset** | 1 | 1 | 6.7 | 12273 | 180 | 2139310 | 89.847 | 7.69 |
| | 2 | 3 | 2.4 | 17362 | | 1864760 | 101.218 | 6.75 |
| | 3 | 4 | 3.9 | 13948 | | 1252950 | 48.303 | 6.10 |
| | 1 | 2 | 5.4 | 12140 | 230 | 224340 | 16.005 | 9.46 |
| | 2 | 4 | 2.5 | 16201 | | 1174010 | 98.240 | 5.90 |
| | 3 | 3 | 3.7 | 14904 | | 837830 | 56.826 | 6.50 |
| | 1 | 3 | 5.3 | 12888 | 300 | 103050 | 12.987 | 10.76 |
| | 2 | 2 | 2.6 | 17921 | | 243340 | 29.418 | 7.35 |
| | 3 | 2 | 3.5 | 16170 | | 245670 | 28.347 | 6.64 |
| **Sasobit** | 1 | 4 | 3.9 | 17210 | 180 | 1374170 | 64.898 | 5.99 |
| | 2 | 1 | 5.2 | 13113 | | 5173913* | 143.170 | 5.31 |
| | 3 | 3 | 4.9 | 14527 | | 1854390 | 72.573 | 5.11 |
| | 1 | 3 | 3.7 | 16275 | 230 | 325420 | 24.582 | 6.11 |
| | 2 | 4 | 4.8 | 14065 | | 1922080 | 131.411 | 6.95 |
| | 3 | 2 | 5.2 | 13693 | | 543840 | 36.058 | 5.16 |
| | 1 | 2 | 3.5 | 17131 | 300 | 155900 | 20.610 | 8.88 |
| | 2 | 3 | 4.1 | 14219 | | 451330 | 54.133 | 7.44 |
| | 3 | 4 | 5.1 | 14755 | | 208350 | 21.998 | 4.58 |

*Note: Values with * indicate an extrapolated point*

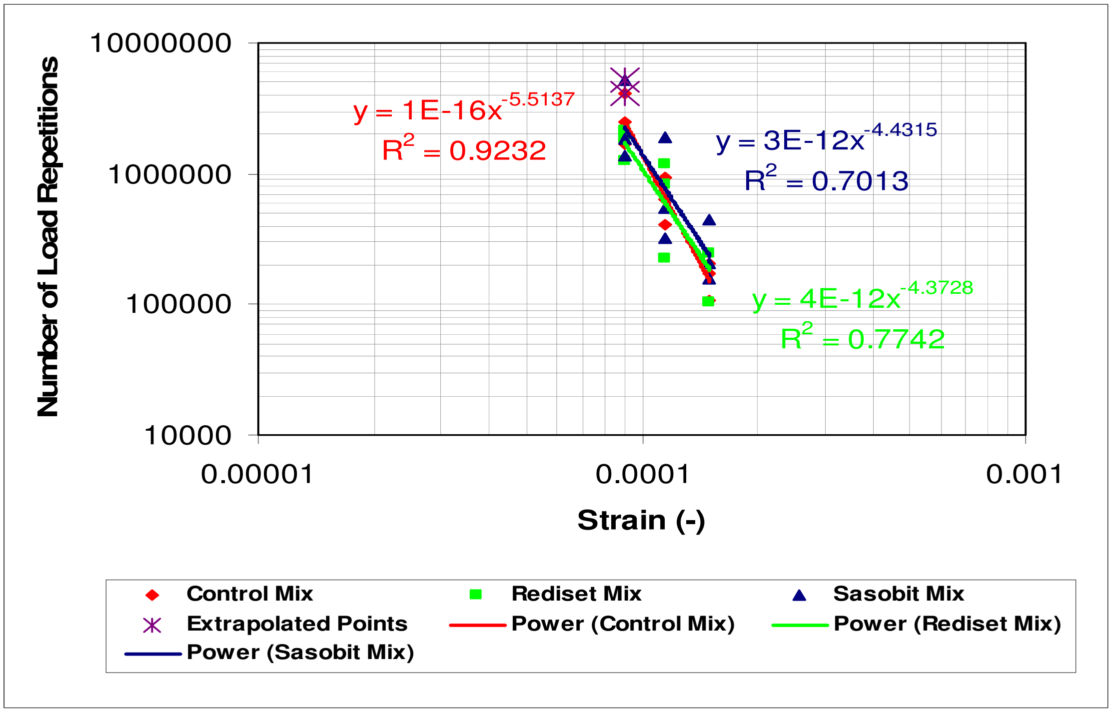


Figure 4.8 Strain vs. $N_f$ for Type D 10% RA 60/70 (Unmodified) Trial and Control Mixes

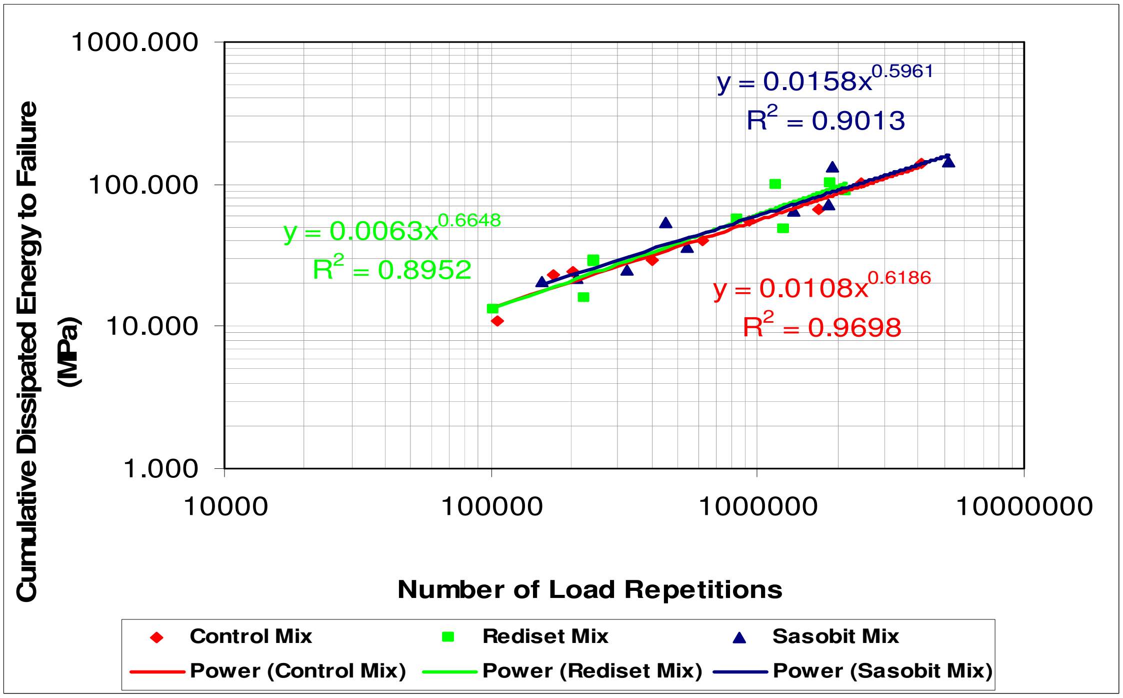


Figure 4.9 Cumulative Dissipated Energy vs. $N_f$ for Type D 10% RA 60/70 (Unmodified) Trial and Control Mixes

**Table 4.13 Fatigue Approach Comparison for Type D 10% RA 60/70 (Unmodified) Control and Trial Mixes**

| Type D 10% RA 60/70 Unmodified Mixes | | | | |
|---|---|---|---|---|
| **Wöhler's Approach** | | | | |
| **Mix Type** | **$k_1$** | **$k_2$** | **$R^2$** | **$N_f = k_1(1/\varepsilon)^{k2}$** |
| **HMA Control** | 1E-16 | -5.5137 | 0.923 | $N_f$ = 1E-16$(1/\varepsilon)^{5.5137}$ |
| **WMA Rediset** | 4E-12 | -4.3728 | 0.774 | $N_f$ = 4E-12$(1/\varepsilon)^{4.3728}$ |
| **WMA Sasobit** | 3E-12 | -4.4315 | 0.701 | $N_f$ = 3E-12$(1/\varepsilon)^{4.4315}$ |
| **Cumulative Dissipated Energy Approach** | | | | |
| **Mix Type** | **A** | **Z** | **$R^2$** | **$W_n = A(N_f)^Z$** |
| **HMA Control** | 0.0108 | 0.6186 | 0.970 | $W_n = 0.0108(N_f)^{0.6186}$ |
| **WMA Rediset** | 0.0063 | 0.6648 | 0.895 | $W_n = 0.0063(N_f)^{0.6648}$ |
| **WMA Sasobit** | 0.0158 | 0.5961 | 0.901 | $W_n = 0.0158(N_f)^{0.5961}$ |

Figure 4.8 and 4.9 portray a similar fatigue life for all three mixes. It can be said that for all intents and purposes, these two WMA mixes performed equivalent to the corresponding control (HMA) mix in terms of flexural stiffness and fatigue life performance.

## 4.4 TYPE B 40% RA 80/100 AE-2 (SBS) ELASTOMER TEST RESULTS

With regards to fatigue evaluation for the Type B 40% RA 80/100 AE-2 (SBS) elastomer mixes, three beams were selected for each strain regime. For the flexural stiffness test two beams for each mix were tested. Table 4.14 provides beam details for these mixes.

The same procedure was followed for the base (Type B) mixes, described in Section 4.3 above for the surfacing (Type D) mixes.

**Table 4.14 Beam Details for Type B 40% RA 80/100 AE-2 (SBS) Elastomer Mixes**

| Type B 40% RA 80/100 AE-2 (SBS) Elastomer Beam Specimens | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Mix Type** | **Slab No.** | **Beam No.** | **Width (mm)** | **Height (mm)** | **Length (mm)** | **Mass in Air (g)** | **Void Content (%)** | **Test Conducted** |
| **Control** | 1 | 1 | 61.5 | 51.5 | 399 | 3049.3 | 4.48 | FT @ 300 με |
| | | 2 | 62.0 | 52.5 | 400 | 3328.7 | 3.13 | FT @ 180 με |
| | | 3 | 61.5 | 51.5 | 397 | 3053.1 | 3.60 | FST |
| | | 4 | 62.0 | 52.0 | 399 | 3145.0 | 4.18 | FT @ 230 με |
| | 2 | 1 | 61.8 | 53.0 | 397 | 3108.4 | 3.38 | FT @ 200 με |
| | | 2 | 62.5 | 52.8 | 397 | 3227.8 | 2.65 | FT @ 300 με |
| | | 3 | 63.3 | 52.3 | 398 | 3161.9 | 2.91 | FST |
| | | 4 | 63.0 | 50.0 | 397 | 3015.9 | 3.31 | FT @ 230 με |
| | 3 | 1 | Extra Beam Never Tested! | | | | | |
| | | 2 | 63.8 | 51.8 | 399 | 3274.8 | 2.35 | FT @ 300 με |
| | | 3 | 65.0 | 52.0 | 399 | 3284.7 | 2.75 | FT @ 250 με |
| | | 4 | 64.0 | 52.0 | 399 | 3261.3 | 3.44 | FT @ 200 με |
| **Sasoflex** | 1 | 1 | 62.0 | 51.8 | 398 | 3093.0 | 4.55 | FT @ 180 με |
| | | 2 | 62.0 | 51.8 | 398 | 3040.1 | 3.18 | FT @ 230 με |
| | | 3 | 62.0 | 51.8 | 400 | 2923.3 | 3.53 | FT @ 300 με |
| | | 4 | 61.0 | 52.3 | 399 | 3091.5 | 3.46 | FST |
| | 2 | 1 | Beam Broke During Fatigue Testing @ 320 με! | | | | | |
| | | 2 | 61.5 | 53.3 | 400 | 3169.3 | 2.62 | FT @ 180 με |
| | | 3 | 64.0 | 53.8 | 399 | 3311.9 | 2.74 | FST |
| | | 4 | 65.0 | 53.0 | 399 | 3353.0 | 2.88 | FT @ 300 με |
| | 3 | 1 | 64.5 | 51.5 | 398 | 3163.7 | 5.64 | FT @ 250 με |
| | | 2 | 63.5 | 51.5 | 397 | 3119.8 | 4.72 | FT @ 200 με |
| | | 3 | 64.0 | 51.0 | 394 | 3092.4 | 4.91 | FT @ 300 με |
| | | 4 | 64.0 | 51.5 | 397 | 3101.1 | 5.61 | FT @ 240 με |

### 4.4.1 Flexural Stiffness Results

The results have been displayed as follows:

- Table 4.15 indicates flexural stiffness results for Type B 40% RA 80/100 AE-2 (SBS) elastomer control mixes and Figure 4.10 illustrates the master curves.
- Table 4.16 indicates flexural stiffness results for Type B 40% RA 80/100 AE-2 (SBS) elastomer Sasoflex mixes and Figure 4.11 illustrates the master curves.
- Figure 4.12 compares the master curves for Type B 40% RA 80/100 AE-2 (SBS) elastomer trial and control mixes.

### Table 4.15 Flexural Stiffness Results for Type B 40% RA 80/100 AE-2 (SBS) Elastomer Control Mixes

| Flexural Stiffness for Type B 40% RA 80/100 AE-2 (SBS) Elastomer Control Mix Beam 3 Slab 1 (MPa) | | | | | |
|---|---|---|---|---|---|
| **Frequency(Hz)** | **5° C** | **10° C** | **15° C** | **20° C** | **25° C** |
| **0.5** | 13842.4 | 10719.1 | 7594.0 | 4660.5 | 2573.3 |
| **1** | 14924.6 | 11565.3 | 8506.4 | 5589.0 | 3261.5 |
| **2** | 15962.8 | 12605.8 | 9627.3 | 6652.7 | 4087.9 |
| **5** | 17234.8 | 14172.3 | 11683.4 | 8550.4 | 5675.8 |
| **10** | 18284.8 | 15249.6 | 13062.4 | 9964.8 | 7116.1 |
| **Flexural Stiffness for Type B 40% RA 80/100 AE-2 (SBS) Elastomer Control Mix Beam 3 Slab 2 (MPa)** | | | | | |
| **Frequency(Hz)** | **5° C** | **10° C** | **15° C** | **20° C** | **25° C** |
| **0.5** | 13624.6 | 9912.4 | 6852.6 | 4318.9 | 2442.5 |
| **1** | 14122.0 | 10839.6 | 7845.4 | 5164.6 | 3005.0 |
| **2** | 15008.1 | 11835.2 | 8851.5 | 6068.4 | 3725.0 |
| **5** | 16455.5 | 13461.4 | 10492.5 | 7704.1 | 5064.5 |
| **10** | 17294.0 | 14622.2 | 12017.0 | 9123.4 | 6357.9 |

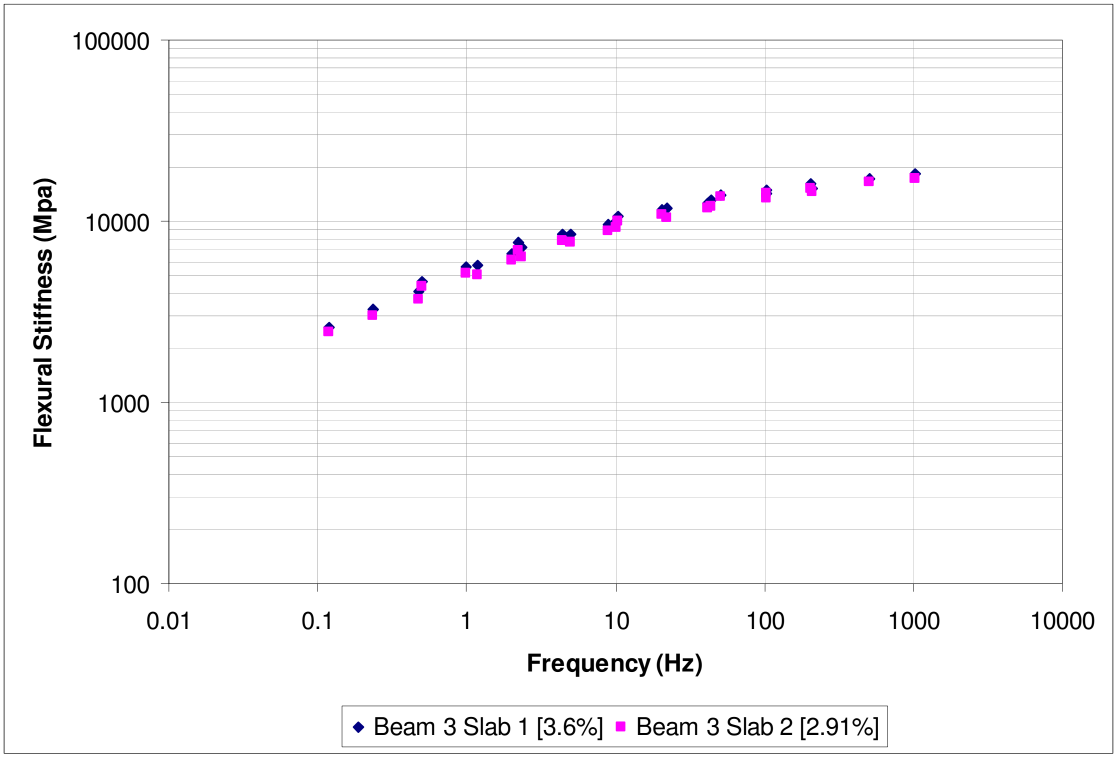


**Figure 4.10 Master Curves at Reference Temperature 20° C for Type B 40% RA 80/100 AE-2 (SBS) Elastomer Control Mixes [Void Content (%)]**

## Table 4.16 Flexural Stiffness Results for Type B 40% RA 80/100 AE-2 (SBS) Elastomer Sasoflex Mixes

| Flexural Stiffness for Type B 40% RA 80/100 AE-2 (SBS) Elastomer Sasoflex Mix Beam 4 Slab 1 (MPa) | | | | | |
|---|---|---|---|---|---|
| **Frequency(Hz)** | **5° C** | **10° C** | **15° C** | **20° C** | **25° C** |
| **0.5** | 14640.6 | 10850.3 | 7436.9 | 4143.4 | 2232.7 |
| **1** | 15363.3 | 11787.0 | 8449.0 | 5237.9 | 2823.3 |
| **2** | 16344.7 | 13116.5 | 9721.5 | 6390.6 | 3757.4 |
| **5** | 17658.8 | 15220.7 | 11889.9 | 8523.7 | 5300.9 |
| **10** | 18084.4 | 16358.9 | 13494.3 | 10239.4 | 6931.5 |
| **Flexural Stiffness for Type B 40% RA 80/100 AE-2 (SBS) Elastomer Sasoflex Mix Beam 3 Slab 2 (MPa)** | | | | | |
| **Frequency(Hz)** | **5° C** | **10° C** | **15° C** | **20° C** | **25° C** |
| **0.5** | 13824.0 | 8833.6 | 5826.5 | 3532.8 | 2039.1 |
| **1** | 14425.7 | 9303.0 | 6469.0 | 4343.0 | 2457.8 |
| **2** | 15316.5 | 10021.0 | 7316.2 | 5099.7 | 3115.0 |
| **5** | 16962.1 | 11317.3 | 8861.0 | 6399.6 | 4208.0 |
| **10** | 16691.5 | 12328.6 | 9735.7 | 7483.3 | 5143.6 |

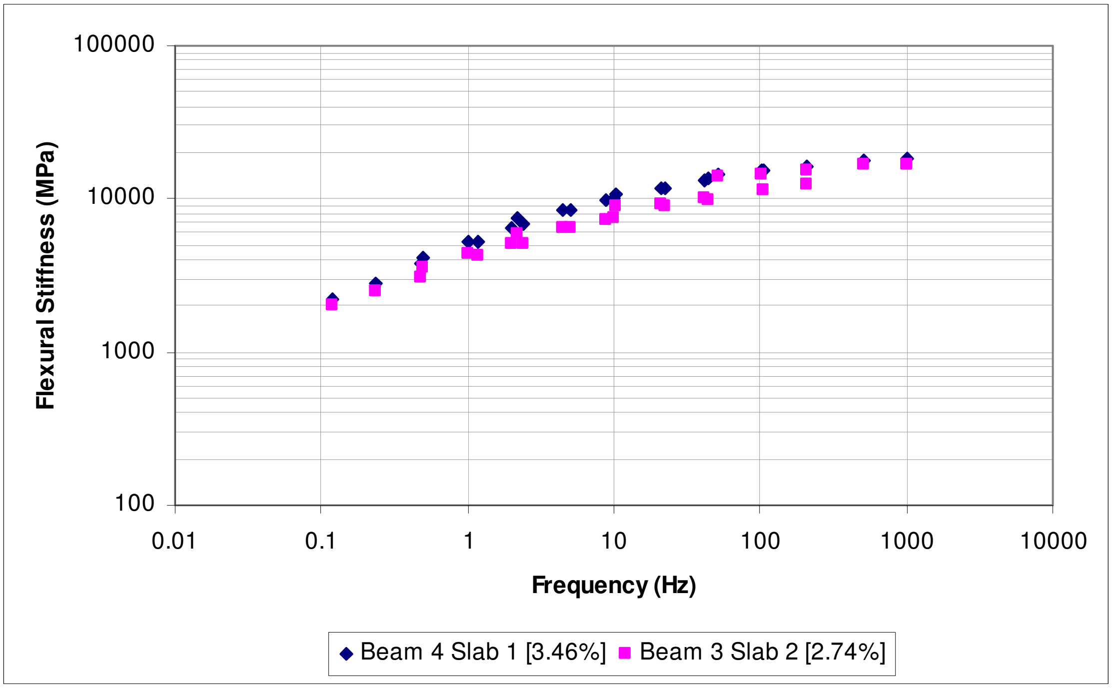


**Figure 4.11 Master Curves at Reference Temperature 20° C for Type B 40% RA 80/100 AE-2 (SBS) Elastomer Sasoflex Mixes [Void Content (%)]**

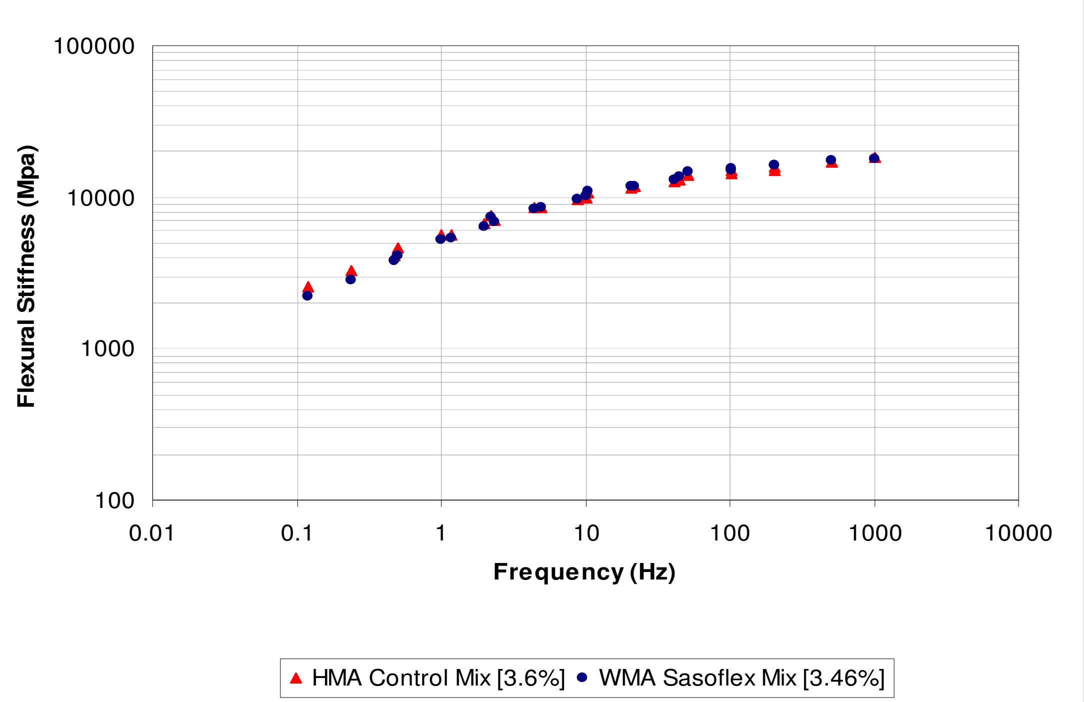


**Figure 4.12 Master Curves at Reference Temperature 20° C for Type B 40% RA 80/100 AE-2 (SBS) Elastomer Trial and Control Mixes [Void Content (%)]**

When looking at Figure 4.10 it can be seen that the two beams yielded similar results for the control (HMA) mix. The first beam (beam 3 slab 1) was selected as the representative result since its void content (3.6%) was closest to the optimum void content.

When considering Figure 4.11 the first beam (beam 4 slab 1) gave a much smoother curve than the second test and also gave better results. Hence, the first beam was selected as the representative result for the Sasoflex (WMA) mix, and is compared with the control (HMA) mix on Figure 4.12. The Sasoflex (WMA) mix performed reasonably equivalent in terms of flexural stiffness to its corresponding control (HMA) mix as can be seen in Figure 4.12. Looking at the flexural stiffness values from Table 4.15 and 4.16 it can be seen that the flexural stiffness of the Sasoflex (WMA) mix is slightly more at higher frequencies which represent the fatigue performance of the mix, and the control (HMA) mix performed slightly better at lower frequencies which represent the rutting resistance of the mix.

Hence, it could be deduced that the control (HMA) mix may have a slightly better rut resistance than the Sasoflex (WMA) mix at a reference temperature of 20° C. This could be attributed to the less aged binder of the WMA mix since the production temperatures were lower than those of the HMA mix. When a mix portrays higher flexural stiffness at the right hand side of the master curve (highest frequency), there is generally a higher risk that the mix will have a shorter fatigue life than the mix with a lower flexural stiffness.

### 4.4.2 Fatigue Results

For Type B 40% RA 80/100 AE-2 (SBS) elastomer mixes the three strain levels at which the fatigue tests were performed included 180 - 200 µε, 230 - 250 µε and 300 µε. Since the fatigue performance of these mixes at strain levels higher than 300 µε were poor and the beams broke, it was decided that lower strain levels would be selected than those recommended by Taute et al (2001) to ensure achievable results.

The results have been displayed as follows:

- Table 4.17 provides the fatigue results and evaluation for Type B 40% RA 80/100 AE-2 (SBS) elastomer mixes and Figure 4.13 and 4.14 illustrate the relative fatigue performance of these mixes with regards to the two approaches considered.
- Table 4.18 provides the model coefficients and $R^2$ values for these mixes.

**Table 4.17 Fatigue Results for Type B 40% RA 80/100 AE-2 (SBS) Elastomer Control and Trial Mixes**

| Type B 40% RA 80/100 AE-2 (SBS) Elastomer Beam Specimens | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Mix Type** | **Slab No.** | **Beam No.** | **Void Content (%)** | **Initial Flexural Stiffness (MPa)** | **Strain Level [Peak to Peak] (µε)** | **Number of Load Repetitions** | **Cumulative Dissipated Energy (MPa)** | **Average Phase Angle (Degrees)** |
| **Control** | 1 | 2 | 3.1 | 18026 | 180 | 1920090 | 61.319 | 2.50 |
| | 2 | 1 | 3.4 | 16757 | 200 | 3827586* | 145.816 | 3.02 |
| | 3 | 4 | 3.4 | 19029 | 200 | 5372881* | 163.459 | 2.66 |
| | 1 | 4 | 4.2 | 17988 | 230 | 649580 | 34.553 | 4.23 |
| | 2 | 4 | 3.3 | 20557 | 230 | 955790 | 67.190 | 4.47 |
| | 3 | 3 | 2.8 | 19527 | 250 | 943730 | 60.315 | 2.81 |
| | 1 | 1 | 4.5 | 17377 | 300 | 331100 | 29.957 | 4.74 |
| | 2 | 2 | 2.7 | 19044 | 300 | 233740 | 21.253 | 1.97 |
| | 3 | 2 | 2.4 | 18845 | 300 | 410660 | 31.125 | 2.17 |
| **Sasoflex** | 1 | 1 | 4.6 | 16581 | 180 | 1475790 | 53.105 | 3.80 |
| | 2 | 2 | 2.6 | 18989 | 180 | 6000000* | 152.739 | 3.07 |
| | 3 | 2 | 4.7 | 15532 | 200 | 950530 | 42.617 | 3.79 |
| | 1 | 2 | 3.2 | 19709 | 230 | 411410 | 25.137 | 1.79 |
| | 3 | 4 | 5.6 | 15373 | 240 | 354140 | 18.703 | 4.92 |
| | 3 | 1 | 5.6 | 14744 | 250 | 275280 | 19.035 | 6.23 |
| | 1 | 3 | 3.5 | 16981 | 300 | 159830 | 15.054 | 5.89 |
| | 2 | 4 | 2.9 | 18791 | 300 | 317830 | 28.079 | 3.51 |
| | 3 | 3 | 4.9 | 16050 | 300 | 180360 | 17.560 | 4.69 |

*Note: Values with * indicate an extrapolated point*

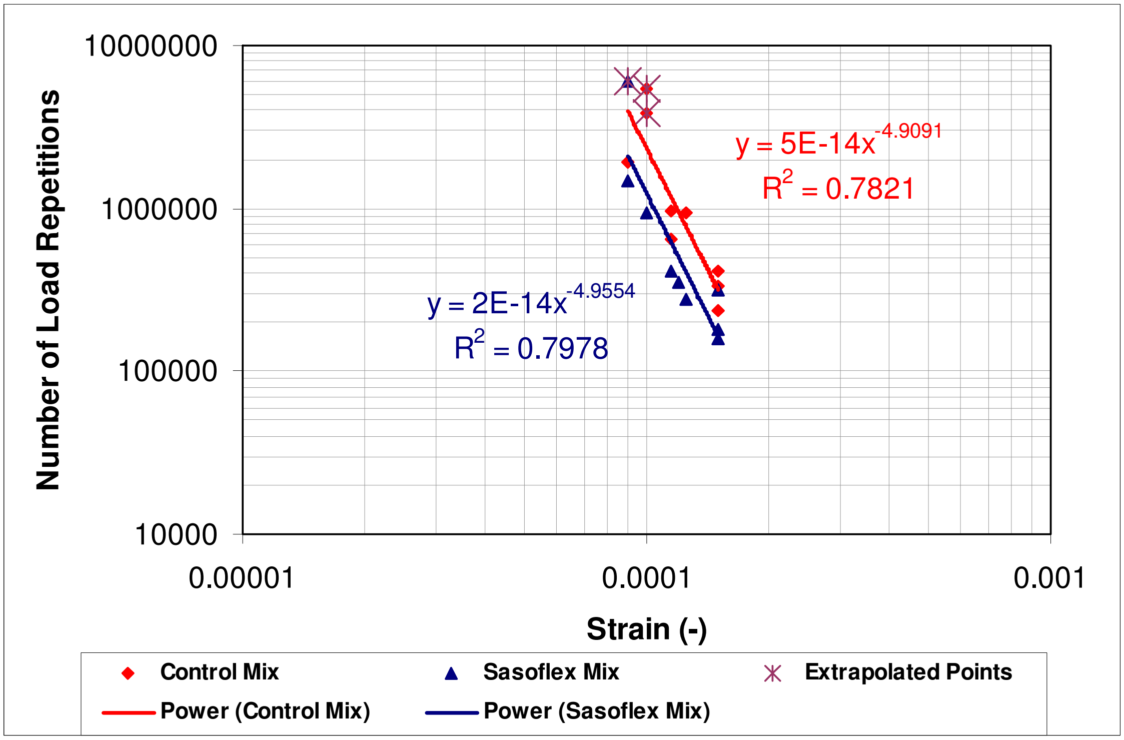


**Figure 4.13 Strain vs. $N_f$ for Type B 40% RA 80/100 AE-2 (SBS) Elastomer Trial and Control Mixes**

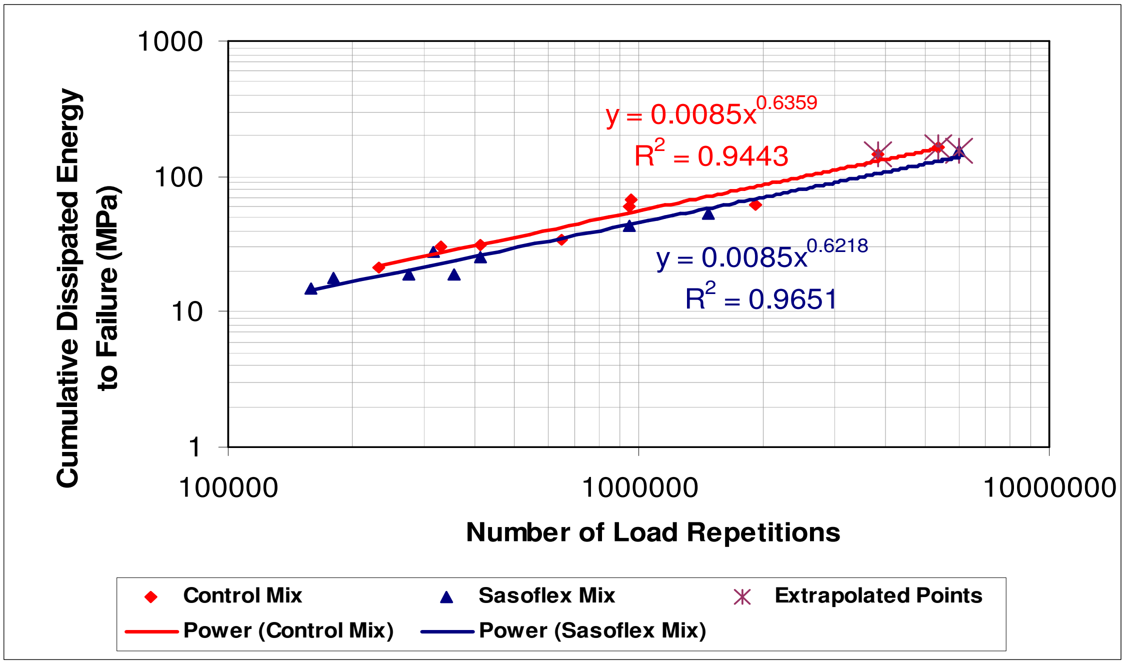


**Figure 4.14 Cumulative Dissipated Energy vs. $N_f$ for Type B 40% RA 80/100 AE-2 (SBS) Elastomer Trial and Control Mixes**

**Table 4.18 Fatigue Approach Comparison for Type B 40% RA 80/100 (AE-2) Elastomer Control and Trial Mixes**

| Type B 40% RA 80/100 AE-2 (SBS) Elastomer Mixes | | | | |
|---|---|---|---|---|
| **Wöhler's Approach** | | | | |
| **Mix Type** | **$k_1$** | **$k_2$** | **$R^2$** | **$N_f = k_1(1/\varepsilon)^{k2}$** |
| **HMA Control** | 5E-14 | -4.9091 | 0.782 | $N_f = 5E\text{-}14(1/\varepsilon)^{4.9091}$ |
| **WMA Sasoflex** | 2E-14 | -4.9554 | 0.798 | $N_f = 2E\text{-}14(1/\varepsilon)^{4.9554}$ |
| **Cumulative Dissipated Energy Approach** | | | | |
| **Mix Type** | **A** | **Z** | **$R^2$** | **$W_n = A(N_f)^Z$** |
| **HMA Control** | 0.0085 | 0.6359 | 0.944 | $W_n = 0.0085(N_f)^{0.6359}$ |
| **WMA Sasoflex** | 0.0085 | 0.6218 | 0.965 | $W_n = 0.0085(N_f)^{0.6218}$ |

When looking at Figure 4.13 it can be seen that the control (HMA) mix performed better than the Sasoflex (WMA) mix in terms of fatigue life. The Sasoflex (WMA) mix showed more sensitivity towards high strain regimes than its corresponding control (HMA) mix.

Figure 4.14 confirms the findings above by illustrating that overall, more dissipated energy was required to fatigue the control (HMA) mix beams than what was required to fatigue the Sasoflex (WMA) mix beams. This means that control (HMA) mix will have a longer fatigue life than the Sasoflex (WMA) mixes.

The cumulative dissipated energy approach to fatigue life gave higher $R^2$ values than the Wöhler approach, as can be seen in Table 4.18. This is attributed to the fact that the Wöhler model does not incorporate other variables within its mathematical relationship.

## 4.5 TYPE B 40% RA 80/100 AP-1 (EVA) PLASTOMER TEST RESULTS

For Type B 40% RA 80/100 AP-1 (EVA) Plastomer mixes three beams were selected for each strain regime with regards to the fatigue testing. Two beams were selected for the flexural stiffness test for the Rediset (WMA) mix but only one beam was tested for the control (HMA) mix since two beams were lost during fatigue testing as indicated in Table 4.19 which gives the beam details for these mixes.

## Table 4.19 Beam Details for Type B 40% RA 80/100 AP-1 (EVA) Plastomer Mixes

| Type B 40% RA 80/100 AP-1 (EVA) Plastomer Beam Specimens | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Mix Type** | **Slab No.** | **Beam No.** | **Width (mm)** | **Height (mm)** | **Length (mm)** | **Mass in Air (g)** | **Void Content (%)** | **Test Conducted** |
| **Control** | 1 | 1 | Beam Broke During Fatigue Testing @ 300 µε! | | | | | |
| | | 2 | 62.0 | 51.8 | 400 | 3069.4 | 2.93 | FT @ 180 µε |
| | | 3 | Beam Broke During Fatigue Testing @ 300 µε! | | | | | |
| | | 4 | 62.0 | 51.0 | 399 | 3057.4 | 3.29 | FT @ 230 µε |
| | 2 | 1 | 61.5 | 52.0 | 398 | 3271.5 | 1.98 | FST |
| | | 2 | 61.3 | 51.3 | 402 | 3324.4 | 1.58 | FT @ 230 µε |
| | | 3 | 61.0 | 52.0 | 398 | 3261.3 | 1.61 | FT @ 200 µε |
| | | 4 | 62.0 | 51.8 | 398 | 3342.8 | 1.59 | FT @ 200 µε |
| | 3 | 1 | 64.0 | 52.0 | 398 | 3311.2 | 2.44 | FT @ 230 µε |
| | | 2 | 62.8 | 54.0 | 398 | 3312.0 | 2.01 | FT @ 280 µε |
| | | 3 | 65.0 | 54.5 | 396 | 3395.8 | 1.97 | FT @ 200 µε |
| | | 4 | 63.5 | 51.5 | 399 | 3324.3 | 2.09 | FT @ 180 µε |
| **Rediset** | 1 | 1 | 62.0 | 51.5 | 398 | 2958.6 | 5.80 | FT @ 230 µε |
| | | 2 | 61.5 | 51.8 | 399 | 3049.0 | 4.85 | FT @ 300 µε |
| | | 3 | 61.3 | 52.0 | 399 | 3050.3 | 4.90 | FT @ 160 µε |
| | | 4 | 62.0 | 52.5 | 400 | 3123.6 | 4.86 | FST |
| | 2 | 1 | 62.5 | 52.5 | 399 | 3145.0 | 5.09 | FT @ 180 µε |
| | | 2 | 63.0 | 52.3 | 397 | 3228.9 | 4.75 | FT @ 230 µε |
| | | 3 | 63.0 | 52.5 | 400 | 3239.7 | 4.79 | FST |
| | | 4 | 63.0 | 51.8 | 398 | 3183.3 | 4.60 | FT @ 300 µε |
| | 3 | 1 | 62.5 | 52.3 | 398 | 3197.5 | 5.14 | FT @ 200 µε |
| | | 2 | 62.5 | 52.5 | 396 | 3162.1 | 4.98 | FT @ 250 µε |
| | | 3 | 61.0 | 54.5 | 398 | 3180.1 | 4.98 | FT @ 320 µε |
| | | 4 | Extra Beam Never Tested! | | | | | |

### 4.5.1 Flexural Stiffness Results

For the Type B 40% RA 80/100 AP-1 (EVA) plastomer control (HMA) mix only one flexural stiffness test could be done due to beams broken in fatigue tests.

The results have been displayed as follows:

- Table 4.20 indicates flexural stiffness results for Type B 40% RA 80/100 AP-1 (EVA) control mix.
- Table 4.21 indicates flexural stiffness results for Type B 40% RA 80/100 AP-1 (EVA) Rediset mixes and Figure 4.15 illustrates the master curves.
- In Figure 4.16 there is a comparison of the master curves for all the mix types under Type B 40% RA 80/100 AP-1 (EVA).

## Table 4.20 Flexural Stiffness Results for Type B 40% RA 80/100 AP-1 (EVA) Plastomer Control Mixes

| Flexural Stiffness for Type B 40% RA 80/100 AP-1 (EVA) Plastomer Control Mix Beam 4 Slab 1 (MPa) | | | | | |
|---|---|---|---|---|---|
| **Frequency(Hz)** | **5° C** | **10° C** | **15° C** | **20° C** | **25° C** |
| **0.5** | 15951.5 | 11996.0 | 8094.4 | 4694.9 | 2555.9 |
| **1** | 17370.7 | 13120.6 | 9207.1 | 5772.1 | 3194.9 |
| **2** | 18589.6 | 14630.1 | 10635.8 | 6994.3 | 4113.5 |
| **5** | 20423.4 | 17003.7 | 13171.3 | 9333.4 | 5825.5 |
| **10** | 20355.9 | 18476.9 | 15064.2 | 11154.1 | 7704.6 |

## Table 4.21 Flexural Stiffness Results for Type B 40% RA 80/100 AP-1 (EVA) Plastomer Rediset Mixes

| Flexural Stiffness for Type B 40% RA 80/100 AP-1 (EVA) Plastomer Rediset Mix Beam 1 Slab 1 (MPa) | | | | | |
|---|---|---|---|---|---|
| **Frequency(Hz)** | **5° C** | **10° C** | **15° C** | **20° C** | **25° C** |
| **0.5** | 11244.9 | 7786.9 | 4966.9 | 3230.4 | 1788.8 |
| **1** | 11452.1 | 8172.8 | 5431.4 | 3714.0 | 2071.0 |
| **2** | 12008.2 | 9073.6 | 6271.5 | 4581.1 | 2636.5 |
| **5** | 13043.2 | 10207.2 | 7579.3 | 6073.1 | 3638.0 |
| **10** | 13776.3 | 11167.0 | 8831.7 | 7261.6 | 4658.6 |
| **Flexural Stiffness for Type B 40% RA 80/100 AP-1 (EVA) Plastomer Rediset Mix Beam 3 Slab 2 (MPa)** | | | | | |
| **Frequency(Hz)** | **5° C** | **10° C** | **15° C** | **20° C** | **25° C** |
| **0.5** | 11852.8 | 8904.7 | 6181.8 | 3849.0 | 2165.7 |
| **1** | 12693.1 | 9717.8 | 6953.9 | 4548.2 | 2614.2 |
| **2** | 13793.3 | 10759.9 | 7957.0 | 5501.0 | 3415.4 |
| **5** | 15306.8 | 12532.0 | 9601.6 | 7095.9 | 4593.7 |
| **10** | 16284.5 | 13597.1 | 10976.0 | 8534.7 | 5669.8 |

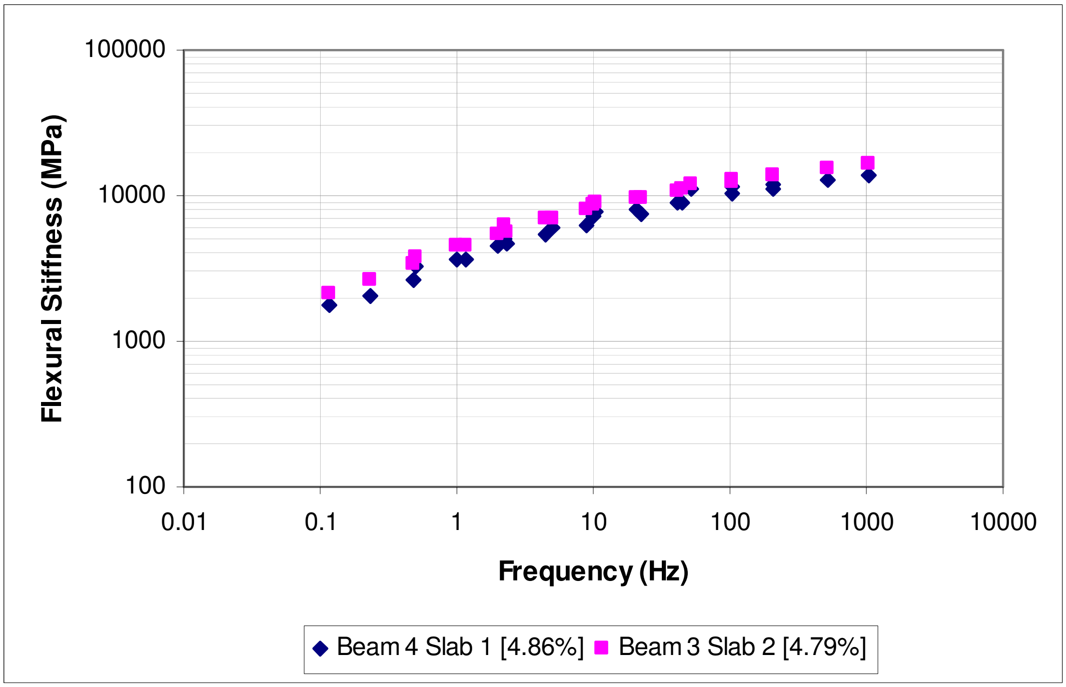


Figure 4.15 Master Curves at Reference Temperature 20° C for Type B 40% RA 80/100 AP-1 (EVA) Plastomer Rediset Mixes [Void Content (%)]

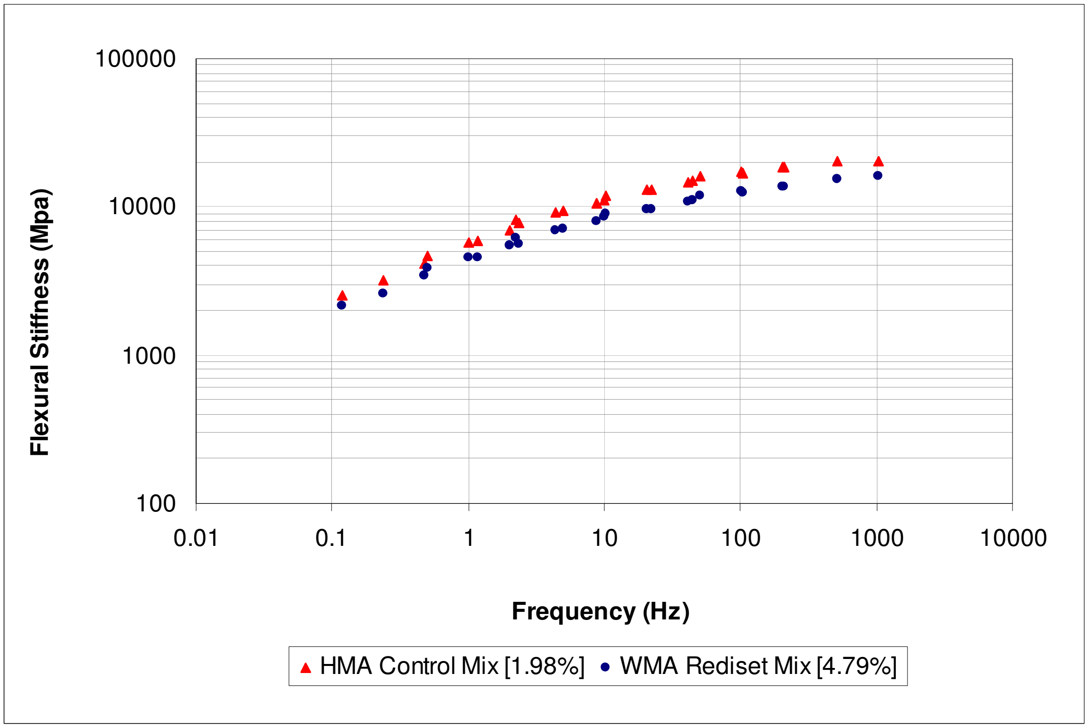


Figure 4.16 Master Curves at Reference Temperature 20° C for Type B 40% RA 80/100 AP-1 (EVA) Plastomer Trial and Control Mixes [Void Content (%)]

As can be seen in Figure 4.15 for the Rediset (WMA) mixes, the second test result (beam 3 from slab 2) was selected as the representative result since its void content (4.79%) was closest to 4%. For the control (HMA) mixes there was only one FST result which was used. The beam tested for the control (HMA) mix had a void content of 1.98% which is very low. These results are compared in Figure 4.16.

As can be seen in Figure 4.16 the control (HMA) mix (1.98% voids) had an overall higher flexural stiffness than the Rediset (WMA) mix (4.79%). This can be attributed to the significant difference in voids (almost a 3% difference) which means the control (HMA) mix was more densely compacted than the Rediset (WMA) mix and hence had a higher relative flexural stiffness.

It could be speculated that if these two mixes had the same relative void content, and given statistical variability, they would perform at relatively the same level, but further testing should be done to validate this assumption.

### 4.5.2 Fatigue Results

The fatigue performance of the control (HMA) mix at strain levels higher than 280 με was poor and the beams broke, therefore it was decided that lower strain levels than those recommended by Taute et al (2001), would be selected to ensure achievable results.

The results have been displayed as follows:

- For Type B 40% RA 80/100 AP-1 (EVA) plastomer control (HMA) mix the three strain levels at which the fatigue tests were performed included 180 - 200 με, 200 - 230 με and 230 - 280 με. Only two sets of fatigue data points could be utilised for the control (HMA) mix, since the third set gave results which could not be extrapolated and due to beams breaking during fatigue testing (no more beams were available to test). The results for the control (HMA) mix displayed on Figure 4.17 are only an indication since only two sets of data points were available and not three as required by Taute et al (2001).
- For Type B 40% RA 80/100 AP-1 (EVA) plastomer Rediset (WMA) mix the three strain levels at which the fatigue tests were performed included 160 - 200 με, 230 - 250 με and 300 - 320 με.
- Table 4.22 provides the fatigue results and evaluation for Type B 40% RA 80/100 AP-1 (EVA) plastomer mixes and Figure 4.17 and 4.18 illustrate the relative fatigue performance of these mixes.
- Table 4.23 provides the model coefficients and $R^2$ values for these mixes.

### Table 4.22 Fatigue Results for Type B 40% RA 80/100 AP-1 (EVA) Plastomer Control and Trial Mixes

| Type B 40% RA 80/100 AP-1 (EVA) Plastomer Beam Specimens | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Mix Type** | **Slab No.** | **Beam No.** | **Void Content (%)** | **Initial Flexural Stiffness (MPa)** | **Strain Level [Peak to Peak] (με)** | **Number of Load Repetitions** | **Cumulative Dissipated Energy (MPa)** | **Average Phase Angle (Degrees)** |
| **Control** | 3 | 4 | 2.09 | 21726 | 180 | 3941177* | 140.492 | 3.89 |
| | 2 | 4 | 1.59 | 20335 | 200 | 2390180 | 128.984 | 2.71 |
| | 3 | 3 | 1.97 | 16343 | 200 | 1703860 | 78.183 | 4.30 |
| | 2 | 3 | 1.61 | 19138 | 200 | 2109800 | 99.424 | 2.72 |
| | 2 | 2 | 1.58 | 20489 | 230 | 3219900 | 228.228 | 3.76 |
| | 3 | 1 | 2.44 | 21665 | 230 | 769370 | 51.331 | 4.30 |
| | 1 | 4 | 3.29 | 18452 | 230 | 146900 | 7.989 | 3.90 |
| | 3 | 2 | 2.01 | 18293 | 280 | 287060 | 22.520 | 2.68 |
| **Rediset** | 1 | 3 | 4.90 | 15669 | 160 | 3772728* | 90.450 | 3.62 |
| | 2 | 1 | 5.09 | 17201 | 180 | 6333333* | 149.347 | 3.28 |
| | 3 | 1 | 5.14 | 18151 | 200 | 1134820 | 58.829 | 3.12 |
| | 1 | 1 | 5.80 | 15906 | 230 | 835890 | 40.964 | 4.53 |
| | 2 | 2 | 4.75 | 17648 | 230 | 1469420 | 87.191 | 4.91 |
| | 3 | 2 | 4.98 | 15862 | 250 | 197790 | 13.985 | 6.22 |
| | 1 | 2 | 4.85 | 17003 | 300 | 118480 | 9.696 | 4.22 |
| | 2 | 4 | 4.60 | 19021 | 300 | 122340 | 11.637 | 5.81 |
| | 3 | 3 | 4.98 | 15174 | 320 | 78730 | 8.082 | 4.22 |

*Note: Values with * indicate an extrapolated point*

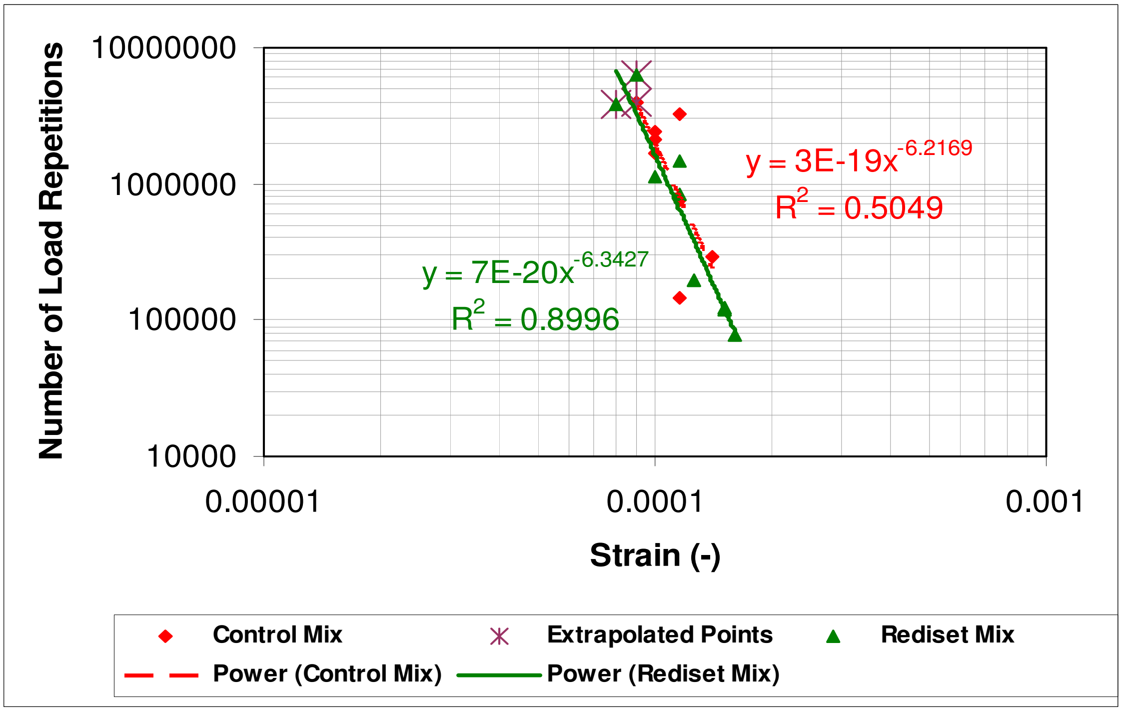


Figure 4.17 Strain vs. $N_f$ for Type B 40% RA 80/100 AP-1 (EVA) Plastomer Trial and Control Mixes

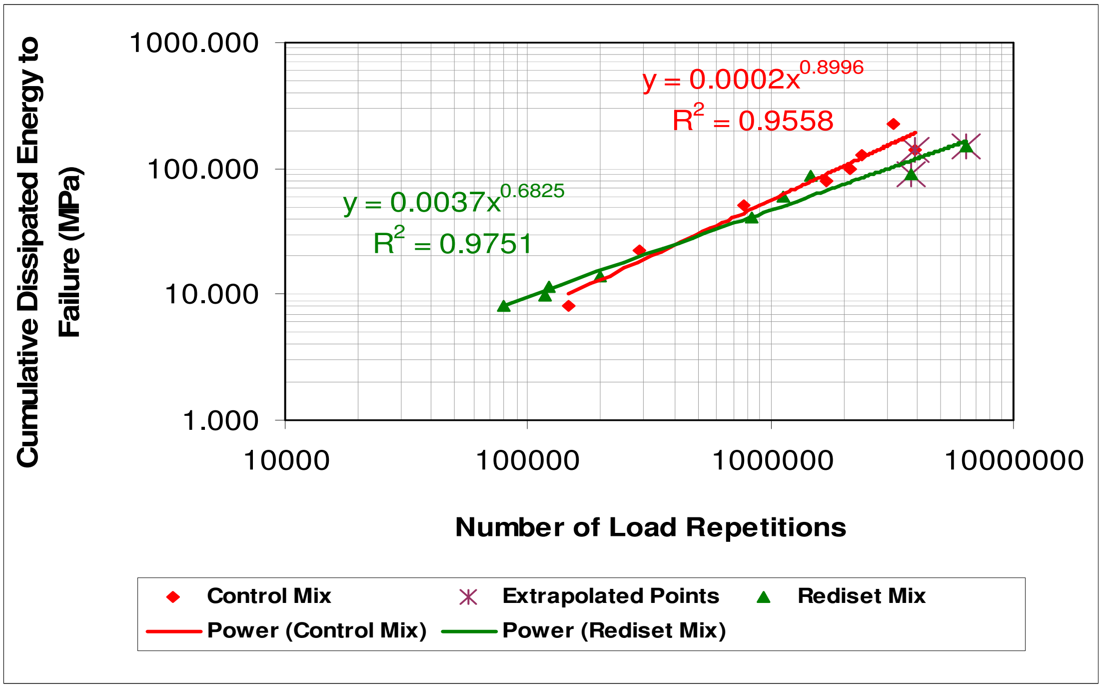


Figure 4.18 Cumulative Dissipated Energy vs. $N_f$ for Type B 40% RA 80/100 AP-1 (EVA) Plastomer Trial and Control Mixes

**Table 4.23 Fatigue Approach Comparison for Type B 40% RA 80/100 (AP-1) Plastomer Control and Trial Mixes**

| Type B 40% RA 80/100 AP-1 (EVA) Plastomer Mixes | | | | |
|---|---|---|---|---|
| **Wöhler's Approach** | | | | |
| **Mix Type** | **$k_1$** | **$k_2$** | **$R^2$** | **$N_f = k_1(1/\varepsilon)^{k2}$** |
| **HMA Control** | 3E-19 | -6.2169 | 0.505 | $N_f$ = 3E-19$(1/\varepsilon)^{6.2169}$ |
| **WMA Rediset** | 7E-20 | -6.3427 | 0.900 | $N_f$ = 7E-20$(1/\varepsilon)^{6.3427}$ |
| **Cumulative Dissipated Energy Approach** | | | | |
| **Mix Type** | **A** | **Z** | **$R^2$** | **$W_n = A(N_f)^Z$** |
| **HMA Control** | 0.0002 | 0.8996 | 0.956 | $W_n = 0.0002(N_f)^{0.8996}$ |
| **WMA Rediset** | 0.0037 | 0.6825 | 0.975 | $W_n = 0.0037(N_f)^{0.6825}$ |

When analysing these results it should firstly be noted that the results for the control (HMA) mix displayed on Figure 4.17, are only an indication since they do not meet all the required data points needed. The $R^2$ value of the control (HMA) mix using the Wöhler approach is extremely low (0.505) and also reaffirm that the control (HMA) result should only be viewed as an indication. Secondly, it should be noted that the control (HMA) mix had a generally lower void content than the Rediset (WMA) mix, as can be seen by the values in Table 4.22 above. In some cases the difference in voids exceeds 4% which is a significant difference and will affect the results.

As can be seen by the slope of the fatigue trend line, control (HMA) is more sensitive to high strain regimes than the Rediset (WMA) mix.
At lower strain levels the control (HMA) performed better than the Rediset (WMA) mix and at higher strain levels Rediset (WMA) performed better than the control (HMA) mix.

## 4.6 TYPE B 10% RA 60/70 AE-2 (SBS) ELASTOMER TEST RESULTS

For Type B 10% RA 60/70 AE-2 (SBS) elastomer mixes three beams were selected for each strain regime with regard to the fatigue testing for the control (HMA) mix but for the Sasoflex (WMA) mix only eight of the nine required data points could be achieved.

Two beams were selected for the flexural stiffness test for the Sasoflex (WMA) mix but only one beam was tested for the control (HMA) mix, since one beam was lost during fatigue testing and one gave bad results, as indicated in Table 4.24 which gives the beam details for these mixes.

**Table 4.24 Beam Details for Type B 10% RA 60/70 AE-2 (SBS) Elastomer Mixes**

| Type B 10% RA 60/70 AE-2 (SBS) Elastomer Beam Specimens | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Mix Type** | **Slab No.** | **Beam No.** | **Width (mm)** | **Height (mm)** | **Length (mm)** | **Mass in Air (g)** | **Void Content (%)** | **Test Conducted** |
| **Control** | 1 | 1 | 62.0 | 50.3 | 399 | 3034.4 | 4.00 | FT @ 180 με |
| | | 2 | 62.5 | 50.0 | 401 | 3124.4 | 2.89 | FT @ 230 με |
| | | 3 | 63.0 | 51.0 | 399 | 3065.7 | 3.05 | FST |
| | | 4 | 63.0 | 52.0 | 400 | 3132.7 | 3.32 | FT @ 300 με |
| | 2 | 1 | 62.0 | 50.3 | 397 | 3180.4 | 3.07 | FT @ 180 με |
| | | 2 | 62.5 | 50.5 | 399 | 3296.1 | 2.66 | FT @ 280 με |
| | | 3 | 62.5 | 51.8 | 399 | 3354.5 | 2.70 | FT @ 230 με |
| | | 4 | Beam Broke During FST Testing! | | | | | |
| | 3 | 1 | 63.8 | 52.0 | 398 | 3334.7 | 4.02 | FT @ 200 με |
| | | 2 | 63.5 | 51.5 | 399 | 3330.9 | 3.28 | FT @ 300 με |
| | | 3 | 62.8 | 51.5 | 399 | 3299.7 | 3.66 | FT @ 250 με |
| | | 4 | 63.5 | 51.8 | 398 | 3287.8 | 3.76 | FT @ 200 με |
| **Sasoflex** | 1 | 1 | 63.0 | 52.0 | 399 | 3146.4 | 4.62 | FT @ 230 με |
| | | 2 | 60.8 | 51.8 | 399 | 3078.6 | 3.37 | FT @ 180 με |
| | | 3 | 62.0 | 52.0 | 398 | 3030.3 | 3.81 | FT @ 300 με |
| | | 4 | 61.8 | 50.0 | 395 | 2949.2 | 3.84 | FST |
| | 2 | 1 | 62.8 | 50.3 | 398 | 3106.6 | 4.68 | FT @ 180 με |
| | | 2 | 62.5 | 52.8 | 398 | 3335.8 | 3.55 | FT @ 300 με |
| | | 3 | 61.0 | 51.0 | 394 | 3133.1 | 3.55 | FT @ 230 με |
| | | 4 | 62.0 | 51.5 | 396 | 3190.3 | 3.76 | FST |
| | 3 | 1 | 65.0 | 52.5 | 397 | 3435.1 | 4.07 | FT @ 180 με |
| | | 2 | 63.3 | 52.3 | 398 | 3406.1 | 3.02 | FT @ 280 με |
| | | 3 | 63.5 | 53.5 | 396 | 3501.2 | 3.09 | FT @ 280 με |
| | | 4 | 63.3 | 53.8 | 399 | 3459.5 | 3.68 | FT @ 230 με |

### 4.6.1 Flexural Stiffness Results

For the Type B 10% RA 60/70 AE-2 (SBS) elastomer control mixes only one flexural stiffness test could be done since one beam broke during a flexural stiffness test and another beam produced inadequate results following a fatigue test at 180 με.

The results have been displayed as follows:

- Table 4.25 indicates flexural stiffness results for Type B 10% RA 60/70 AE-2 (SBS) control mix.
- Table 4.26 indicates flexural stiffness results for Type B 10% RA 60/70 AE-2 (SBS) Sasoflex mixes and Figure 4.19 illustrates the master curves.
- Figure 4.20 is a comparison of the master curves for all the mix types under Type B 10% RA 60/70 AE-2 (SBS) mixes.

## Table 4.25 Flexural Stiffness Results for Type B 10% RA 60/70 AE-2 (SBS) Elastomer Control Mixes

| **Flexural Stiffness for Type B 10% RA 60/70 AE-2 (SBS) Elastomer Control Mix Beam 3 Slab 1 (MPa)** | | | | | |
|---|---|---|---|---|---|
| **Frequency(Hz)** | **5° C** | **10° C** | **15° C** | **20° C** | **25° C** |
| **0.5** | 12920.5 | 9155.2 | 6237.4 | 3616.0 | 1873.8 |
| **1** | 13835.8 | 10288.3 | 7374.7 | 4534.7 | 2439.2 |
| **2** | 14907.2 | 11519.7 | 8621.9 | 5437.7 | 3120.0 |
| **5** | 16214.8 | 12943.4 | 10392.8 | 7088.5 | 4353.6 |
| **10** | 16786.3 | 14036.6 | 11772.7 | 8640.4 | 5663.3 |

## Table 4.26 Flexural Stiffness Results for Type B 10% RA 60/70 AE-2 (SBS) Elastomer Sasoflex Mixes

| **Flexural Stiffness for Type B 10% RA 60/70 AE-2 (SBS) Elastomer Sasoflex Mix Beam 4 Slab 1 (MPa)** | | | | | |
|---|---|---|---|---|---|
| **Frequency(Hz)** | **5° C** | **10° C** | **15° C** | **20° C** | **25° C** |
| **0.5** | 13332.2 | 9650.3 | 6067.6 | 3476.9 | 1688.4 |
| **1** | 14369.1 | 10991.3 | 7419.2 | 4442.7 | 2245.1 |
| **2** | 15535.4 | 12387.5 | 8713.2 | 5433.9 | 3039.1 |
| **5** | 17151.6 | 14073.8 | 10501.9 | 7258.7 | 4429.7 |
| **10** | 17921.5 | 15342.2 | 12091.2 | 8850.5 | 5770.3 |
| **Flexural Stiffness for Type B 10% RA 60/70 AE-2 (SBS) Elastomer Sasoflex Mix Beam 4 Slab 2 (MPa)** | | | | | |
| **Frequency(Hz)** | **5° C** | **10° C** | **15° C** | **20° C** | **25° C** |
| **0.5** | 13792.2 | 9968.2 | 6418.8 | 3750.5 | 2065.4 |
| **1** | 14786.0 | 11347.7 | 7705.1 | 4711.8 | 2645.9 |
| **2** | 15911.3 | 12578.7 | 8967.8 | 5894.0 | 3457.2 |
| **5** | 17332.1 | 14376.8 | 10971.1 | 7879.2 | 4995.3 |
| **10** | 18172.7 | 15805.0 | 12631.6 | 9319.3 | 6180.9 |

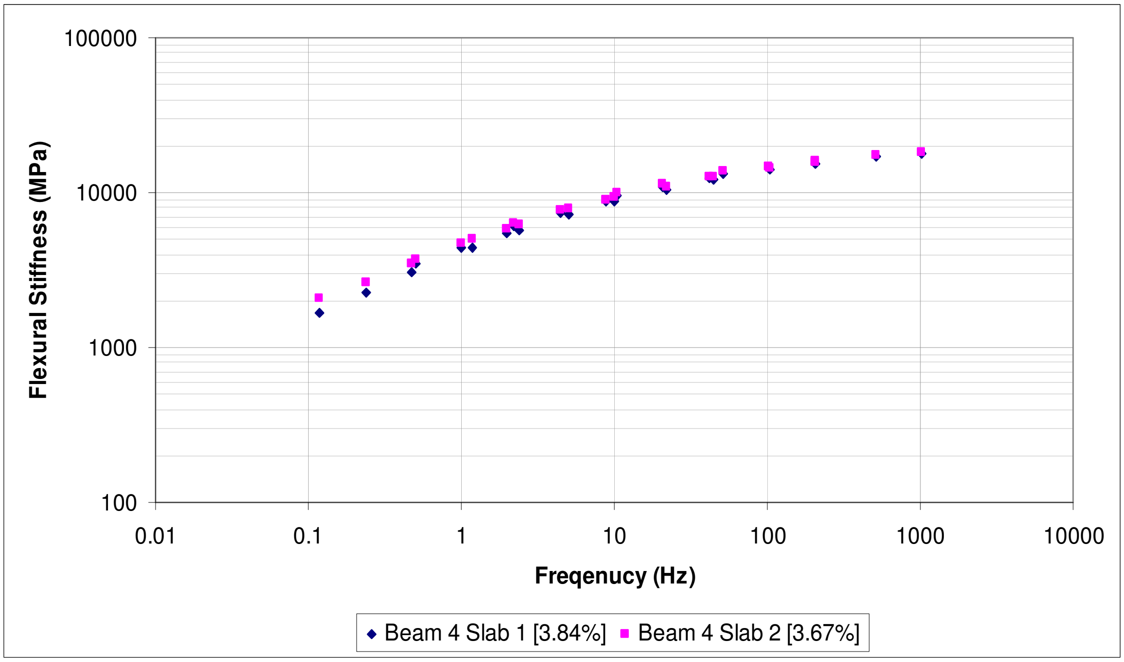


**Figure 4.19 Master Curves at Reference Temperature 20° C for Type B 10% RA 60/70 AE-2 (SBS) Elastomer Sasoflex Mixes [Void Content (%)]**

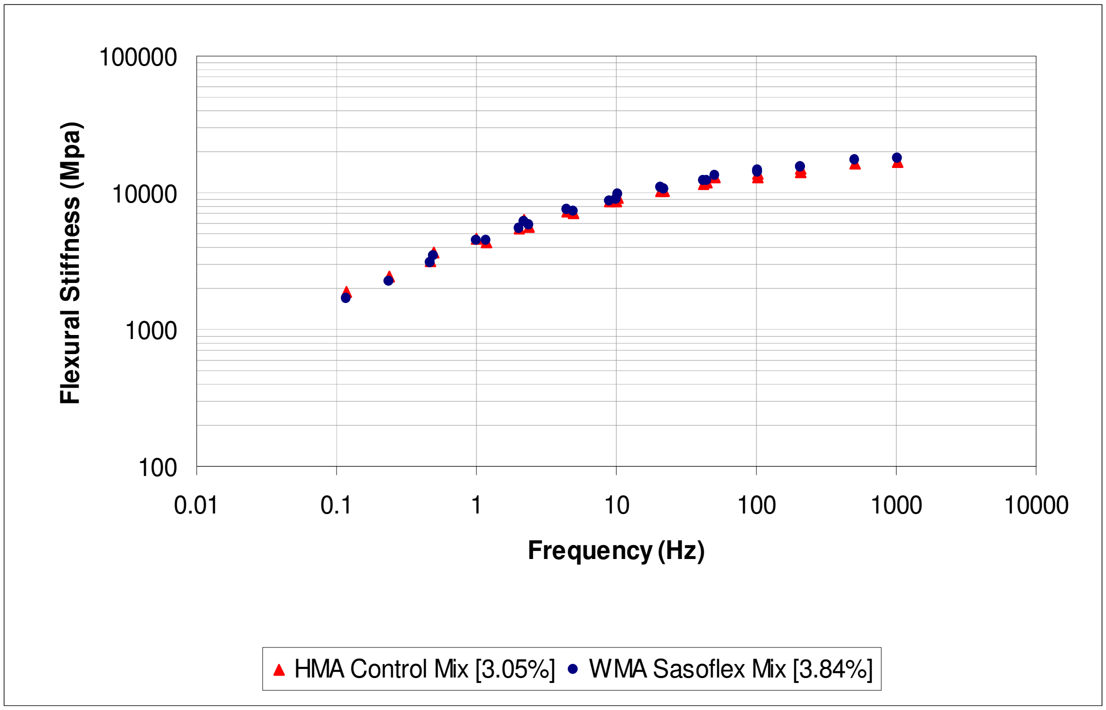


**Figure 4.20 Master Curves at Reference Temperature 20° C for Type B 10% RA 60/70 AE-2 (SBS) Elastomer Trial and Control Mixes [Void Content (%)]**

For the Sasoflex (WMA) mix, the first test result (beam 4 from slab 1) was selected as the representative result since its void content (3.84%) was closest to 4%. For the control (HMA) mix there was only one result and hence these results are compared on Figure 4.20.

It can be noted in Figure 4.20 that the Sasoflex (WMA) mix compared very well with its corresponding control (HMA) mix. The Sasoflex (WMA) mix showed a slightly higher general flexural stiffness than the control (HMA) mix.

A similar flexural stiffness trend was portrayed in Figure 4.12 for the Type B 40% RA 80/100 AE-2 (SBS) Elastomer control and trial mixes and looks almost identical.

### 4.6.2 Fatigue Results

The fatigue performance of the Sasoflex (WMA) mixes at strain levels higher than 280 µε was inadequate and the beams broke, therefore it was decided that lower strain levels than those recommended by Taute et al (2001), would be selected to ensure achievable results.

The results have been displayed as follows:

- For Type B 10% RA 60/70 AE-2 (SBS) elastomer control (HMA) mixes the three strain levels at which the fatigue tests were performed included 180 - 200 µε, 230 - 250 µε and 280 - 300 µε. Only two sets of fatigue data points could be utilised for the control (HMA) mix since the third set had one data point which was poor.
- For Type B 10% RA 60/70 AE-2 (SBS) elastomer Sasoflex (WMA) mixes the three strain levels at which the fatigue tests were performed included 180 µε, 230 µε and 280 µε.
- Table 4.27 provides the fatigue results and evaluation for Type B 10% RA 60/70 AE-2 (SBS) elastomer mixes and Figure 4.21 and 4.22 illustrate the relative fatigue performance of these mixes.
- Table 4.28 provides the model coefficients for the two fatigue models considered for these mixes.

## Table 4.27 Fatigue Results for Type B 10% RA 60/70 AE-2 (SBS) Elastomer Control and Trial Mixes

| Type B 10% RA 60/70 AE-2 (SBS) Elastomer Beam Specimens | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Mix Type** | **Slab No.** | **Beam No.** | **Void Content (%)** | **Initial Flexural Stiffness (MPa)** | **Strain Level [Peak to Peak] (με)** | **Number of Load Repetitions** | **Cumulative Dissipated Energy (MPa)** | **Average Phase Angle (Degrees)** |
| **Control** | 1 | 1 | 4.00 | 17526 | 180 | 1408000 | 52.816 | 3.24 |
| | 3 | 4 | 3.76 | 18031 | 200 | 2180380 | 91.845 | 3.07 |
| | 3 | 1 | 4.02 | 16960 | 200 | 1406940 | 57.269 | 2.62 |
| | 1 | 2 | 2.89 | 21643 | 230 | 1823570 | 126.313 | 3.92 |
| | 2 | 3 | 2.70 | 20409 | 230 | 767890 | 44.834 | 4.39 |
| | 3 | 3 | 3.66 | 18170 | 250 | 243120 | 14.339 | 3.39 |
| | 1 | 4 | 3.32 | 17154 | 300 | 344430 | 27.952 | 3.70 |
| | 2 | 2 | 2.66 | 21477 | 280 | 276990 | 21.014 | 3.43 |
| | 3 | 2 | 3.28 | 17958 | 300 | 91000 | 8.283 | 4.24 |
| **Sasoflex** | 1 | 2 | 3.37 | 18386 | 180 | 5666667* | 150.926 | 3.31 |
| | 2 | 1 | 4.68 | 16441 | 180 | 573600 | 18.166 | 3.96 |
| | 2 | 3 | 3.55 | 18516 | 230 | 711310 | 45.191 | 3.73 |
| | 1 | 1 | 4.62 | 17846 | 230 | 589960 | 38.404 | 3.56 |
| | 3 | 4 | 3.68 | 18711 | 230 | 722810 | 33.816 | 2.82 |
| | 3 | 2 | 3.02 | 19556 | 280 | 260710 | 20.204 | 4.96 |
| | 3 | 1 | 3.81 | 16490 | 300 | 75780 | 5.684 | 4.08 |
| | 3 | 3 | 3.09 | 20321 | 280 | 819020 | 44.399 | 3.38 |

*Note: Values with * indicate an extrapolated point*

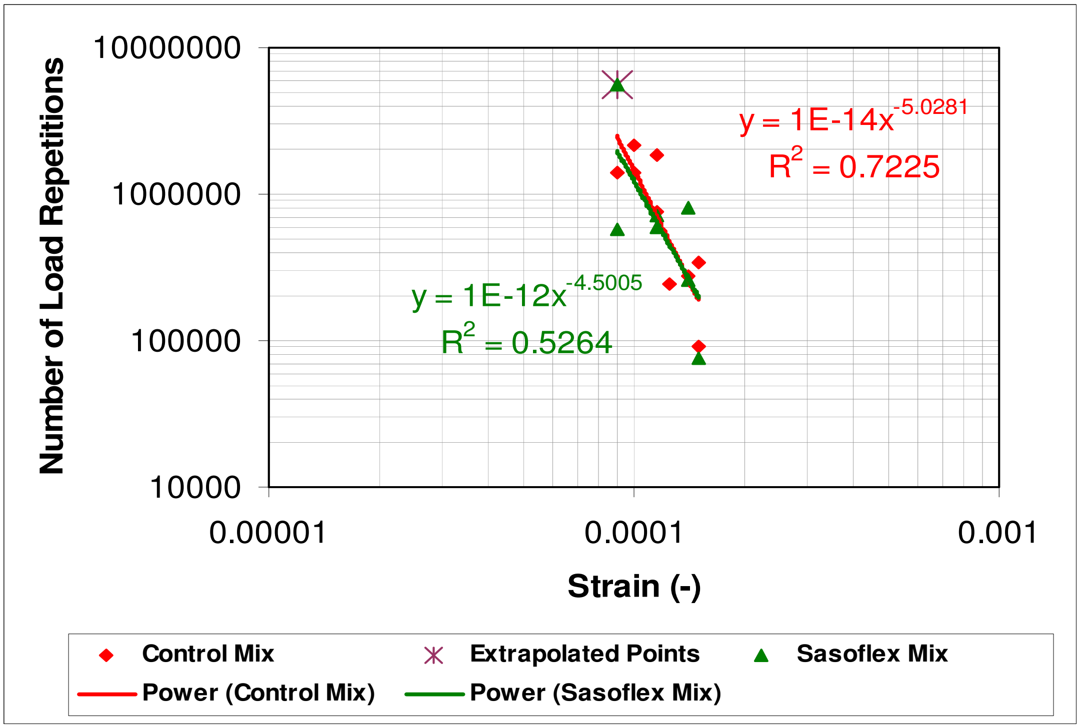


Figure 4.21 Strain vs. $N_f$ for Type B 10% RA 60/70 AE-2 (SBS) Elastomer Trial and Control Mixes

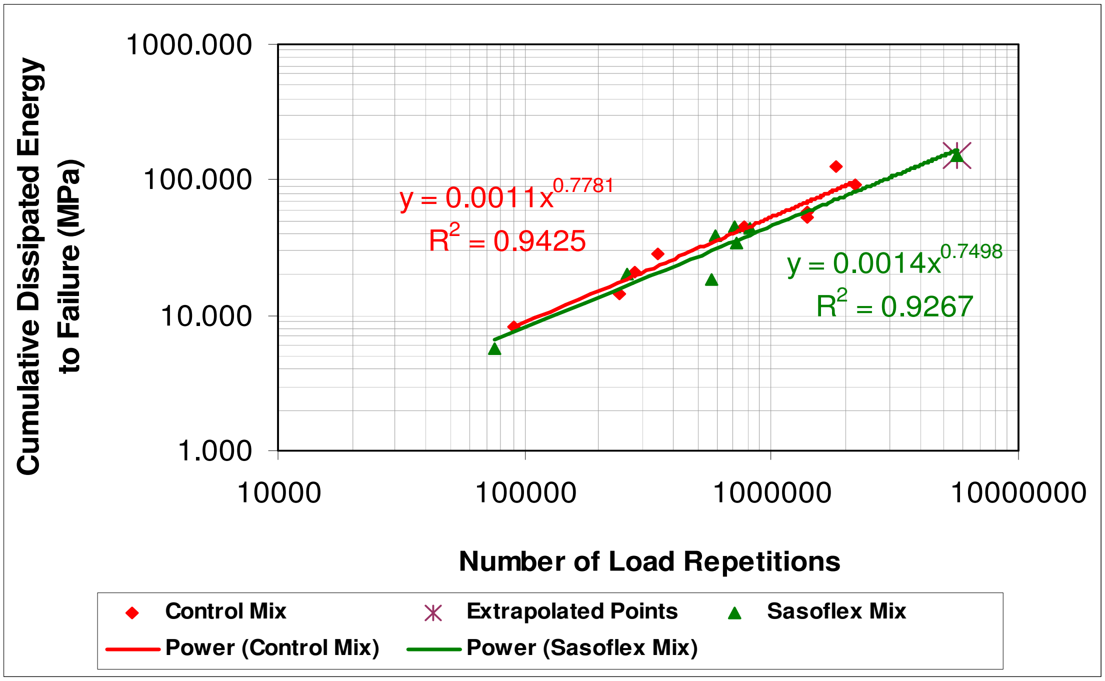


Figure 4.22 Cumulative Dissipated Energy vs. $N_f$ for Type B 10% RA 60/70 AE-2 (SBS) Elastomer Trial and Control Mixes

**Table 4.28 Fatigue Approach Comparison for Type B 10% RA 60/70 (AE-2) Elastomer Control and Trial Mixes**

| Type B 10% RA 60/70 AE-2 (SBS) Elastomer Mixes | | | | |
|---|---|---|---|---|
| **Wöhler's Approach** | | | | |
| **Mix Type** | **$k_1$** | **$k_2$** | **$R^2$** | **$N_f = k_1(1/\varepsilon)^{k2}$** |
| **HMA Control** | 1E-14 | -5.0281 | 0.723 | $N_f = 1E\text{-}14(1/\varepsilon)^{5.0281}$ |
| **WMA Sasoflex** | 1E-12 | -4.5005 | 0.526 | $N_f = 1E\text{-}12(1/\varepsilon)^{4.5005}$ |
| **Cumulative Dissipated Energy Approach** | | | | |
| **Mix Type** | **A** | **Z** | **$R^2$** | **$W_n = A(N_f)^Z$** |
| **HMA Control** | 0.0011 | 0.7781 | 0.943 | $W_n = 0.0011(N_f)^{0.7781}$ |
| **WMA Sasoflex** | 0.0014 | 0.7498 | 0.927 | $W_n = 0.0014(N_f)^{0.7498}$ |

When looking at Figure 4.21 it can be seen that these two mixes compare well in terms of fatigue life. However, the Sasoflex (WMA) mix is slightly more sensitive to high strain regimes than the control (HMA) mix. The $R^2$ values of the mixes in Table 4.28 above show that these trend lines are not very reliable. ($R^2 < 0.8$)

Following the cumulative dissipated energy approach it can be seen that the $R^2$ values have increased to over 0.9 for both mixes, which means that this approach is more viable for this situation. From Figure 4.22 the control (HMA) mix does portray a slightly better fatigue life than the Sasoflex (WMA) mix but are still very comparable.

For all practical reasons these two mixes can be seen as identical, but further testing should be carried out on similar mixes to confirm this finding since the Sasoflex (WMA) mix only had eight of the nine required data points for this evaluation and is therefore only an indication for the Wöhler approach.

## 4.7 TYPE B 10% RA 60/70 AP-1 (EVA) PLASTOMER TEST RESULTS

For Type B 10% RA 60/70 AP-1 (EVA) Plastomer mixes three beams were selected for each strain regime with regard to the fatigue testing for the control (HMA) mix but for the Rediset (WMA) mix only six, and for the Foamtech (WMA) only seven of the nine required data points could be achieved. Two beams were selected for the flexural stiffness test for the control (HMA) and Foamtech (WMA) mixes but only one beam was tested for the Rediset (WMA) mix since too many beams broke during testing, as indicated in Table 4.29 which gives the beam details for these mixes.

## Table 4.29 Beam Details for Type B 10% RA 60/70 AP-1 (EVA) Plastomer Mixes

| Type B 10% RA 60/70 AP-1 (EVA) Beam Specimens | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Mix Type** | **Slab No.** | **Beam No.** | **Width (mm)** | **Height (mm)** | **Length (mm)** | **Mass in Air (g)** | **Void Content (%)** | **Test Conducted** |
| **Control** | 1 | 1 | Beam Broke During Fatigue Testing @ 380 με! | | | | | |
| | | 2 | 61.8 | 51.0 | 400 | 3117.2 | 2.50 | FT @ 230 με |
| | | 3 | 62.0 | 51.8 | 399 | 3125.6 | 2.60 | FT @ 300 με |
| | | 4 | Beam Broke During Fatigue Testing @ 380 με! | | | | | |
| | 2 | 1 | Beam Lost! | | | | | |
| | | 2 | Beam Broke During Fatigue Testing @ 380 με! | | | | | |
| | | 3 | 64.0 | 53.8 | 399 | 3311.7 | 4.13 | FT @ 180 με |
| | | 4 | 63.0 | 51.5 | 399 | 3155.7 | 4.63 | FST |
| | 3 | 1 | 60.5 | 50.0 | 394 | 2974.2 | 5.07 | FT @ 180 με |
| | | 2 | 61.8 | 50.5 | 396 | 3088.3 | 4.67 | FT @ 300 με |
| | | 3 | 61.3 | 50.8 | 397 | 3049.3 | 4.58 | FT @ 230 με |
| | | 4 | 62.0 | 50.5 | 396 | 3096.5 | 5.05 | FST |
| | 4 | 1 | 62.0 | 51.8 | 393 | 3163.8 | 5.03 | FT @ 300 με |
| | | 2 | 62.0 | 51.8 | 398 | 3217.0 | 5.16 | FT @ 230 με |
| | | 3 | 60.0 | 52.0 | 399 | 3144.0 | 5.33 | FT @ 180 με |
| | | 4 | Extra Beam Never Tested! | | | | | |
| **Rediset** | 1 | 1 | 60.5 | 50.8 | 398 | Beam Lost Before BRD Test! | | FT @ 380 με |
| | | 2 | 60.5 | 50.5 | 396 | Beam Lost Before BRD Test! | | FT @ 300 με |
| | | 3 | 61.3 | 51.5 | 395 | 3020.4 | 4.46 | FT @ 230 με |
| | | 4 | Beam Broke During FST Testing! | | | | | |
| | 2 | 1 | 60.0 | 52.0 | 396 | 3012.5 | 3.67 | FST |
| | | 2 | 62.5 | 53.5 | 398 | 3203.0 | 3.19 | FT @ 300 με |
| | | 3 | 64.0 | 52.8 | 398 | 3378.6 | 3.23 | FT @ 230 με |
| | | 4 | Beam Gave Inadequate Results After Fatigue Testing @ 180 με! | | | | | |
| | 3 | 1 | Beam Gave Inadequate Results After Fatigue Testing @ 230 με! | | | | | |
| | | 2 | Beam Broke During Fatigue Testing @ 300 με! | | | | | |
| | | 3 | Beam Broke During FST Testing! | | | | | |
| | | 4 | 62.8 | 50.0 | 398 | 3095.2 | 5.18 | FT @ 200 με |
| **Foamtech** | 1 | 1 | 62.0 | 51.0 | 396 | 2869.2 | 6.62 | FT @ 180 με |
| | | 2 | 61.0 | 51.0 | 399 | 2920.8 | 5.94 | FT @ 230 με |
| | | 3 | 62.0 | 51.0 | 398 | 2963.1 | 6.34 | FT @ 300 με |
| | | 4 | 63.8 | 52.0 | 399 | 3074.1 | 6.64 | FST |
| | 2 | 1 | 61.3 | 51.0 | 399 | 3122.1 | 5.66 | FT @ 180 με |
| | | 2 | 62.3 | 50.5 | 398 | 3116.5 | 5.55 | FT @ 300 με |
| | | 3 | 63.8 | 51.8 | 399 | 3309.2 | 5.32 | FT @ 230 με |
| | | 4 | 61.5 | 51.0 | 399 | 3044.2 | 5.51 | FT @ 230 με |
| | 3 | Beam Broke During Fatigue Testing @ 300 με! | | | | | | |
| | | Beam Broke During Fatigue Testing @ 280 με! | | | | | | |
| | | 3 | 63.0 | 53.5 | 395 | 3300.2 | 5.24 | FST |
| | | 4 | 60.0 | 50.8 | 399 | 3005.3 | 5.82 | FT @ 180 με |

### 4.7.1 Flexural Stiffness Results

For the Type B 10% RA 60/70 AP-1 (EVA) plastomer Rediset (WMA) mix only one flexural stiffness test could be done since two beams broke during flexural stiffness testing and no additional beams were available for flexural stiffness testing.

The results have been displayed as follows:

- Table 4.30 includes flexural stiffness results for Type B 10% RA 60/70 AP-1 (EVA) plastomer control (HMA) mixes and Figure 4.23 illustrates the master curves.
- Table 4.31 includes flexural stiffness results for Type B 10% RA 60/70 AP-1 (EVA) plastomer Rediset (WMA) mix.
- Table 4.32 includes flexural stiffness results for Type B 10% RA 60/70 AP-1 (EVA) plastomer Foamtech (WMA) mixes and Figure 4.24 illustrates the master curves.
- In Figure 4.25 the master curves for all the mix types under Type B 10% RA 60/70 AP-1 (EVA) plastomer mixes are compared.

**Table 4.30 Flexural Stiffness Results for Type B 10% RA 60/70 AP-1 (EVA) Plastomer Control Mixes**

<table>
<tr><th colspan="6">Flexural Stiffness for Type B 10% RA 60/70 AP-1 (EVA) Plastomer Control Mix Beam 4 Slab 1 (MPa)</th></tr>
<tr><th>Frequency (Hz)</th><th>5° C</th><th>10° C</th><th>15° C</th><th>20° C</th><th>25° C</th></tr>
<tr><td>**0.5**</td><td>13693.7</td><td>10377.5</td><td>6585.5</td><td>4098.7</td><td>2284.6</td></tr>
<tr><td>**1**</td><td>15158.9</td><td>10877.0</td><td>7367.3</td><td>4846.4</td><td>2902.1</td></tr>
<tr><td>**2**</td><td>16429.2</td><td>11744.2</td><td>8144.0</td><td>5781.5</td><td>3761.0</td></tr>
<tr><td>**5**</td><td>18029.7</td><td>13528.4</td><td>9753.5</td><td>7260.8</td><td>5040.2</td></tr>
<tr><td>**10**</td><td>15836.2</td><td>13990.1</td><td>11179.3</td><td>8629.6</td><td>6562.5</td></tr>
<tr><th colspan="6">Flexural Stiffness for Type B 10% RA 60/70 AP-1 (EVA) Plastomer Control Mix Beam 4 Slab 2 (MPa)</th></tr>
<tr><th>Frequency (Hz)</th><th>5° C</th><th>10° C</th><th>15° C</th><th>20° C</th><th>25° C</th></tr>
<tr><td>**0.5**</td><td>13952.7</td><td>10204.7</td><td>7204.6</td><td>4583.4</td><td>2829.7</td></tr>
<tr><td>**1**</td><td>14740.3</td><td>11224.5</td><td>8297.7</td><td>5486.9</td><td>3468.8</td></tr>
<tr><td>**2**</td><td>15541.4</td><td>12168.0</td><td>9350.9</td><td>6433.4</td><td>4313.9</td></tr>
<tr><td>**5**</td><td>16780.9</td><td>13672.5</td><td>11087.6</td><td>7997.4</td><td>5697.3</td></tr>
<tr><td>**10**</td><td>17505.9</td><td>14940.4</td><td>12364.5</td><td>9359.9</td><td>6944.3</td></tr>
</table>

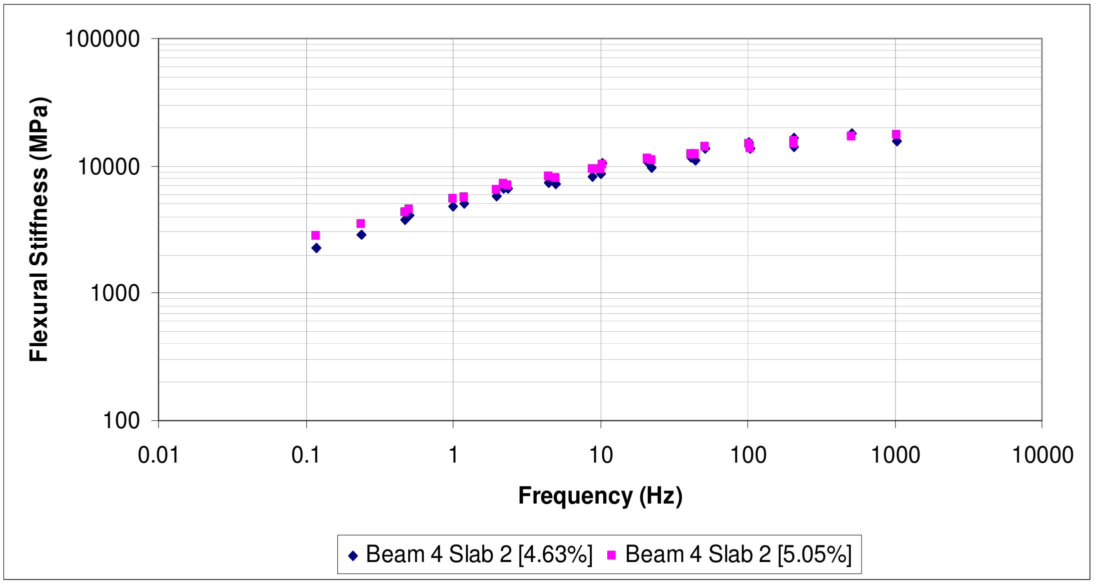


**Figure 4.23 Master Curves at Reference Temperature 20° C for Type B 10% RA 60/70 AP-1 (EVA) Plastomer Control (HMA) Mixes [Void Content (%)]**

**Table 4.31 Flexural Stiffness Results for Type B 10% RA 60/70 AP-1 (EVA) Plastomer Rediset Mixes**

| Flexural Stiffness for Type B 10% RA 60/70 AP-1 (EVA) Plastomer Rediset Mix Beam 1 Slab 2 (MPa) | | | | | |
|---|---|---|---|---|---|
| **Frequency(Hz)** | **5° C** | **10° C** | **15° C** | **20° C** | **25° C** |
| **0.5** | 14818.9 | 11111.5 | 7681.6 | 4699.6 | 2605.7 |
| **1** | 15215.4 | 12154.5 | 8754.7 | 5747.7 | 3259.2 |
| **2** | 16606.2 | 13338.1 | 10092.6 | 6839.3 | 4195.0 |
| **5** | 18093.8 | 15087.8 | 12021.3 | 8837.1 | 5799.7 |
| **10** | 18565.6 | 16287.0 | 13270.9 | 10506.6 | 7391.4 |

**Table 4.32 Flexural Stiffness Results for Type B 10% RA 60/70 AP-1 (EVA) Plastomer Foamtech Mixes**

<table>
<tr><th colspan="6">Flexural Stiffness for Type B 10% RA 60/70 AP-1 (EVA) Plastomer Foamtech Mix Beam 4 Slab 1 (MPa)</th></tr>
<tr><th>Frequency (Hz)</th><th>5° C</th><th>10° C</th><th>15° C</th><th>20° C</th><th>25° C</th></tr>
<tr><td>0.5</td><td>11058.0</td><td>7856.6</td><td>5282.2</td><td>3195.6</td><td>1882.3</td></tr>
<tr><td>1</td><td>11597.4</td><td>8537.5</td><td>5962.7</td><td>3737.9</td><td>2233.6</td></tr>
<tr><td>2</td><td>12219.3</td><td>9389.8</td><td>6878.6</td><td>4493.3</td><td>2797.5</td></tr>
<tr><td>5</td><td>13411.6</td><td>10697.8</td><td>8249.9</td><td>5659.7</td><td>3786.7</td></tr>
<tr><td>10</td><td>13994.1</td><td>11771.6</td><td>9366.8</td><td>6789.0</td><td>4716.4</td></tr>
<tr><th colspan="6">Flexural Stiffness for Type B 10% RA 60/70 AP-1 (EVA) Plastomer Foamtech Mix Beam 3 Slab 3 (MPa)</th></tr>
<tr><th>Frequency (Hz)</th><th>5° C</th><th>10° C</th><th>15° C</th><th>20° C</th><th>25° C</th></tr>
<tr><td>0.5</td><td>13819.4</td><td>10502.4</td><td>7082.3</td><td>4354.8</td><td>2694.3</td></tr>
<tr><td>1</td><td>14605.6</td><td>11207.0</td><td>8084.7</td><td>5151.7</td><td>3329.3</td></tr>
<tr><td>2</td><td>15654.0</td><td>12115.8</td><td>9034.5</td><td>6155.9</td><td>4154.0</td></tr>
<tr><td>5</td><td>17223.5</td><td>13934.2</td><td>10594.9</td><td>7631.0</td><td>5526.8</td></tr>
<tr><td>10</td><td>16984.4</td><td>14756.7</td><td>11865.9</td><td>8930.7</td><td>6645.5</td></tr>
</table>

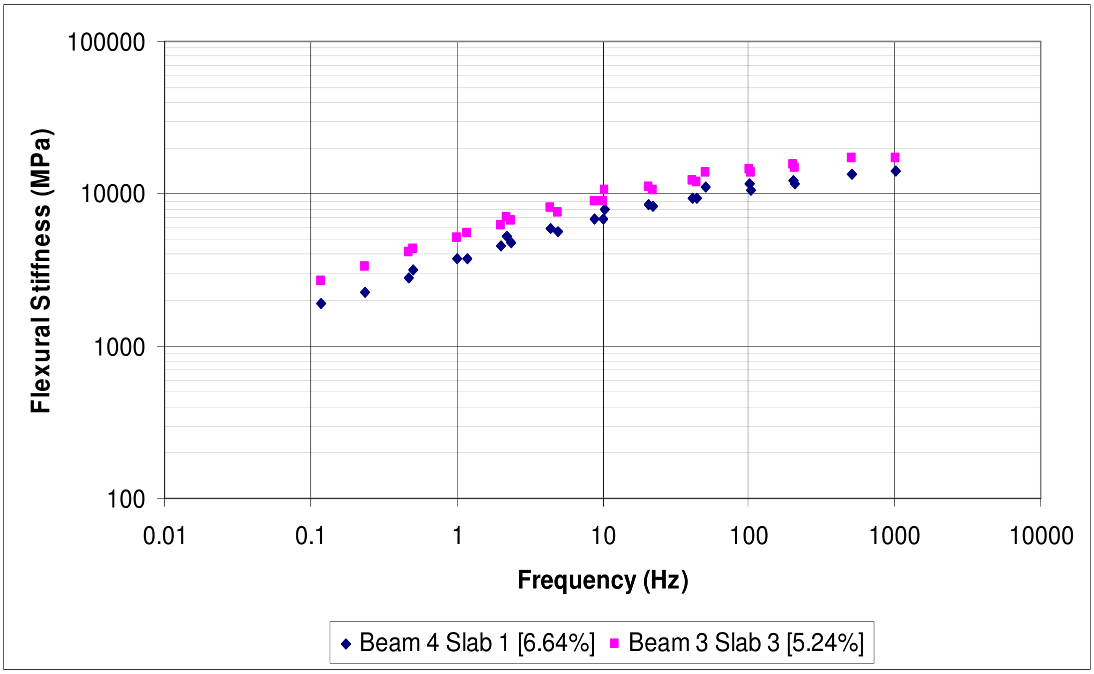


Figure 4.24 Master Curves at Reference Temperature 20° C for Type B 10% RA 60/70 AP-1 (EVA) Plastomer Foamtech Mixes [Void Content (%)]

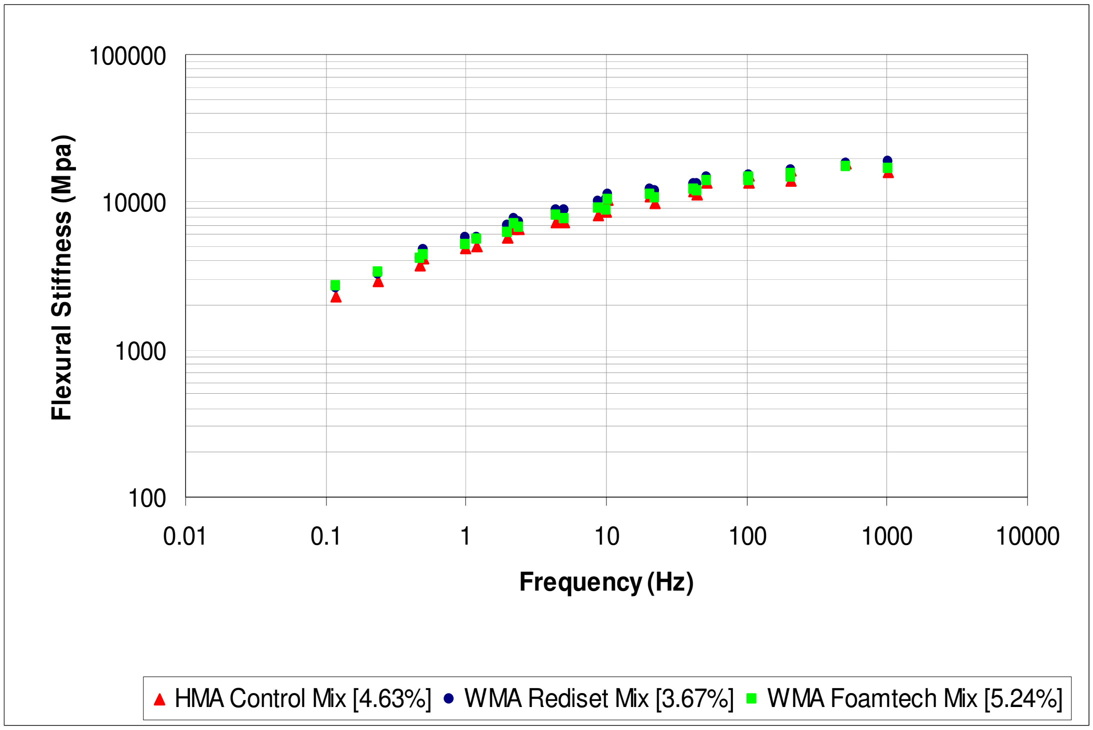


**Figure 4.25 Master Curves at Reference Temperature 20° C for Type B 10% RA 60/70 AP-1 (EVA) Plastomer Trial and Control Mixes [Void Content (%)]**

For the control (HMA) mix the first result was used (beam 4 from slab 2) as the representative result since its void content (4.63%) was closest to 4%. (Refer to Figure 4.23) For the Rediset (WMA) mix there was only one result, with a void content of 3.67%, which could be used. For the Foamtech (WMA) mix the second test results (beam 3 from slab 3) was used as the representative result since its void content (5.24%) was closest to 4%. (Refer to Figure 4.24) These three results are compared on Figure 4.25 above.

From Figure 4.25 above it can be seen that the WMA mixes (Rediset and Foamtech) both gave a generally higher flexural stiffness than their corresponding control (HMA) mix. Although the difference in performance is still very comparable, the control (HMA) mix will be slightly more prone to rutting than the two WMA mixes. Further fatigue analysis will be done under the fatigue results section. The two WMA mixes resulted in practically equivalent flexural stiffness trends and compare very well with each other.

### 4.7.2 Fatigue Results

The fatigue performance of the Rediset and Foamtech (WMA) mixes at strain levels higher than 280 µε was inadequate and the beams broke prematurely, therefore it was decided that lower strain levels than those recommended by Taute et al (2001), would be selected to ensure achievable results. The control mixes were first attempted at 380 µε but the beams failed and lower strain levels were chosen.

The results have been displayed as follows:

- For Type B 10% RA 60/70 AP-1 (EVA) plastomer control mixes the three strain levels at which the fatigue tests were performed included 180 µε, 230 µε and 300 µε.
- For Type B 10% RA 60/70 AP-1 (EVA) plastomer Rediset mixes the three strain levels at which the fatigue tests were performed included 200 - 230 µε, 230 - 300 µε and 300 – 380 µε. Only two sets of fatigue data points could be utilised for the Rediset (WMA) mix since two beams broke during flexural stiffness testing and one during fatigue testing at 300 µε.
- For Type B 10% RA 60/70 AP-1 (EVA) plastomer Foamtech mixes the three strain levels at which the fatigue tests were performed included 180 µε, 230 µε and 300 µε. Only two sets of fatigue data points could be utilised for the Foamtech (WMA) mix since two beams broke during fatigue testing at 280 and 300 µε respectively.
- Table 4.33 provides the fatigue results and evaluation for Type B 10% RA 60/70 AP-1 (EVA) plastomer mixes and Figure 4.26 and 4.27 illustrate the relative fatigue performance of these mixes.
- Table 4.34 gives the $R^2$ values and coefficients for each model in the fatigue analysis.

## Table 4.33 Fatigue Results for Type B 10% RA 60/70 AP-1 (EVA) Plastomer Control and Trial Mixes

| Type B 10% RA 60/70 AP-1 (EVA) Plastomer Beam Specimens | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Mix Type** | **Slab no.** | **Beam No.** | **Void Content (%)** | **Initial Flexural Stiffness (MPa)** | **Strain Level [Peak to Peak] (με)** | **Number of Load Repetitions** | **Cumulative Dissipated Energy (MPa)** | **Average Phase Angle (Degrees)** |
| **Control** | 2 | 3 | 4.13 | 19312 | 180 | 2294070 | 79.772 | 0.920 |
| | 3 | 1 | 5.07 | 16950 | 180 | 880460 | 28.595 | 3.366 |
| | 4 | 3 | 5.33 | 16991 | 180 | 5700000* | 98.030 | 2.186 |
| | 1 | 2 | 2.50 | 21161 | 230 | 1246230 | 75.968 | 3.544 |
| | 3 | 3 | 4.58 | 16865 | 230 | 532650 | 25.762 | 3.962 |
| | 4 | 2 | 5.16 | 19588 | 230 | 920310 | 46.102 | 3.470 |
| | 1 | 3 | 2.60 | 19561 | 300 | 429170 | 35.938 | 3.382 |
| | 3 | 2 | 4.67 | 18552 | 300 | 140010 | 10.808 | 3.716 |
| | 4 | 1 | 5.03 | 17677 | 300 | 802720 | 62.363 | 4.866 |
| **Rediset** | 3 | 4 | 5.18 | 17222 | 200 | 2219340 | 84.619 | 3.510 |
| | 2 | 3 | 3.23 | 20116 | 230 | 1582420 | 110.427 | 5.027 |
| | 1 | 3 | 4.46 | 18471 | 230 | 327380 | 24.279 | 6.102 |
| | 2 | 2 | 3.19 | 17719 | 300 | 574890 | 42.021 | 1.561 |
| | 1 | 2 | No BRD | 18276 | 300 | 146390 | 16.795 | 7.066 |
| | 1 | 1 | No BRD | 17444 | 380 | 118320 | 16.229 | 6.313 |
| **Foamtech** | 1 | 1 | 6.62 | 14369 | 180 | 3951613* | 106.353 | 3.149 |
| | 2 | 1 | 5.66 | 13851 | 180 | 507210 | 14.083 | 4.320 |
| | 3 | 4 | 5.82 | 18557 | 180 | 1224240 | 41.303 | 3.390 |
| | 2 | 4 | 5.51 | 16214 | 230 | 178500 | 9.968 | 3.564 |
| | 2 | 3 | 5.32 | 16604 | 230 | 335000 | 17.474 | 4.639 |
| | 1 | 3 | 6.34 | 14415 | 300 | 70110 | 5.162 | 5.369 |
| | 2 | 2 | 5.55 | 17202 | 300 | 263310 | 24.540 | 4.084 |

*Note: Values with * indicate an extrapolated point*

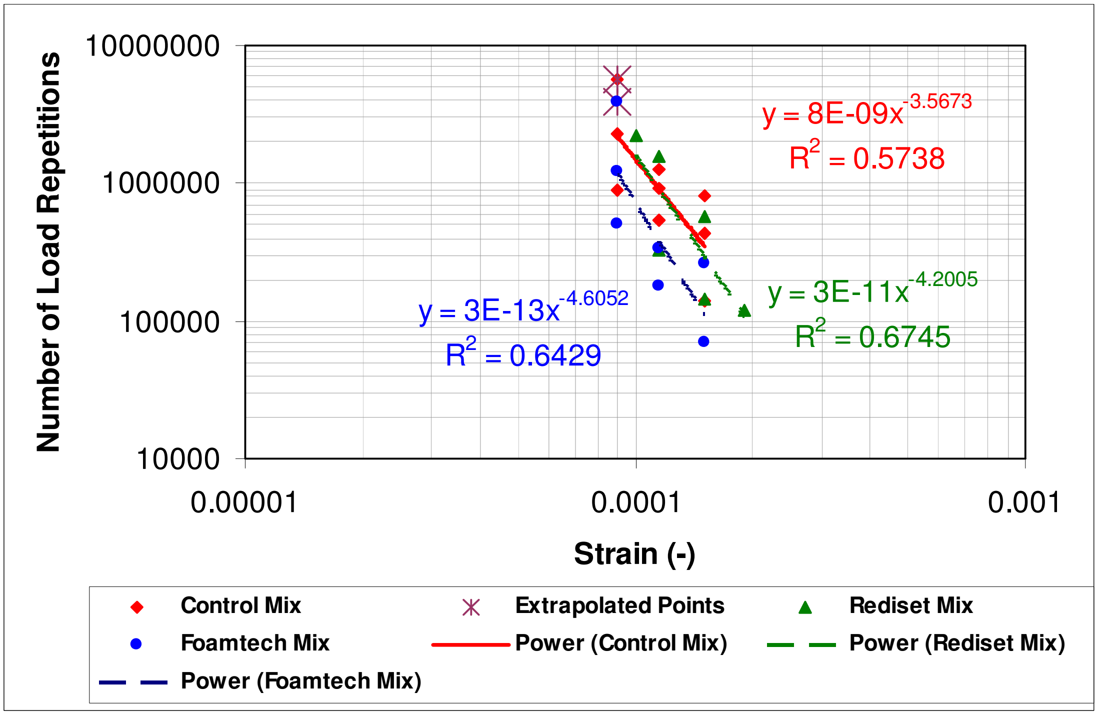


Figure 4.26 Strain vs. $N_f$ for Type B 10% RA 60/70 AP-1 (EVA) Plastomer Trial and Control Mixes

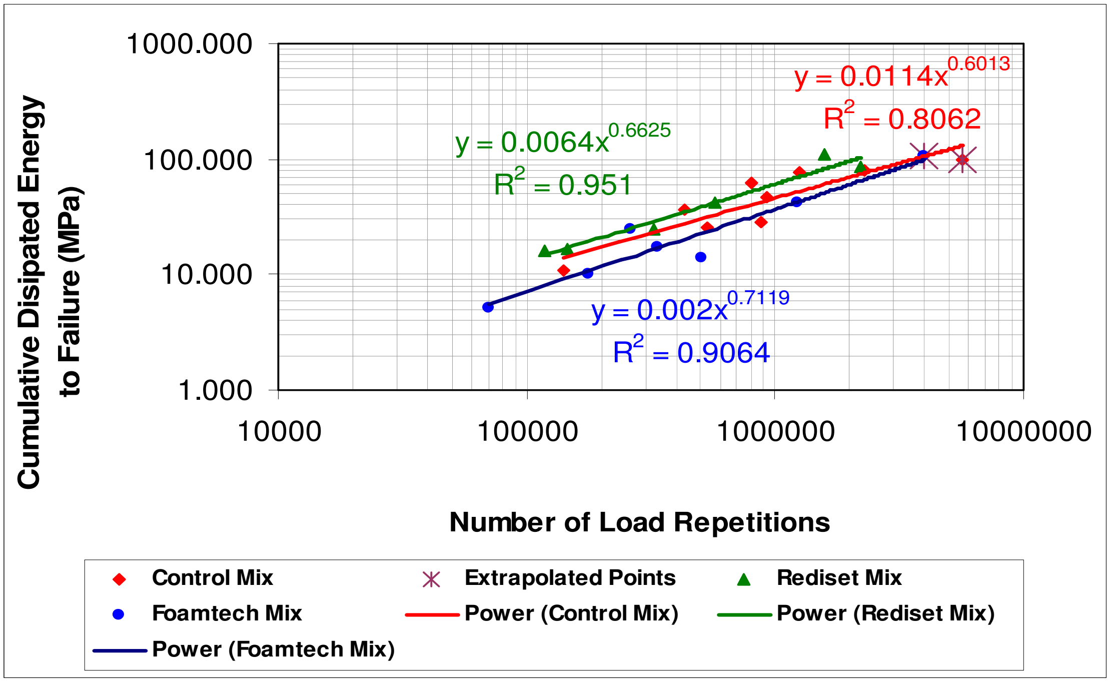


Figure 4.27 Cumulative Dissipated Energy vs. $N_f$ for Type B 10% RA 60/70 AP-1 (EVA) Plastomer Trial and Control Mixes

### Table 4.34 Fatigue Approach Comparison for Type B 10% RA 60/70 (AP-1) Plastomer Control and Trial Mixes

| Type B 10% RA 60/70 AP-1 (EVA) Plastomer Mixes | | | | |
|---|---|---|---|---|
| **Wöhler's Approach** | | | | |
| **Mix Type** | **$k_1$** | **$k_2$** | **$R^2$** | **$N_f = k_1(1/\varepsilon)^{k2}$** |
| **HMA Control** | 8E-09 | -3.5673 | 0.574 | $N_f$ = 8E-09$(1/\varepsilon)^{3.5673}$ |
| **WMA Rediset** | 3E-11 | -4.2005 | 0.675 | $N_f$ = 3E-11$(1/\varepsilon)^{4.2005}$ |
| **WMA Foamtech** | 3E-13 | -4.6052 | 0.643 | $N_f$ = 3E-13$(1/\varepsilon)^{4.6052}$ |
| **Cumulative Dissipated Energy Approach** | | | | |
| **Mix Type** | **A** | **Z** | **$R^2$** | **$W_n = A(N_f)^Z$** |
| **HMA Control** | 0.0114 | 0.6013 | 0.806 | $W_n = 0.0114(N_f)^{0.6013}$ |
| **WMA Rediset** | 0.0064 | 0.6625 | 0.951 | $W_n = 0.0064(N_f)^{0.6625}$ |
| **WMA Foamtech** | 0.002 | 0.7119 | 0.906 | $W_n = 0.002(N_f)^{0.7119}$ |

When comparing Figure 4.26 and 4.27 it is evident that these differences are to be considered significant. The Foamtech (WMA) mix is more sensitive to high strain regimes than the Rediset (WMA) and control (HMA) mixes as shown by Figure 4.26. Overall the Foamtech (WMA) performed more poorly in fatigue than the control (HMA and Rediset (WMA) mixes which in turn compared well with each other in terms of fatigue performance. Keep in mind that the results for the WMA (Foamtech and Rediset) mixes are only an indication since they never met the criteria (9 data points) stipulated by Taute et al (2001). Furthermore, looking at the $R^2$ values in Table 4.34 for the Wöhler approach they are very low (all three are smaller than 0.8) which suggest that those fatigue indications in Figure 4.26 should not be deemed as very realistic.

Further fatigue analysis can be done by looking at the cumulative dissipated energy to failure approach, as shown in Figure 4.27. The Foamtech (WMA) mix required less cumulative dissipated energy to failure in general than the other two mixes which mean that the Foamtech (WMA) mix did not compare well with its corresponding control (HMA) mix. This can be attributed to the high void content of the Foamtech (WMA) mixes which was in the area of 5 - 6 % voids.

The Rediset (WMA) mix compared very well with the control (HMA) mix, performing better or equally in terms of fatigue life. When looking at Figure 4.27 the Rediset (WMA) mix required generally more cumulative dissipated energy to failure than the control (HMA) mix, which suggests that the Rediset (WMA) mix will have a longer fatigue life than the control (HMA) under these loading and temperature conditions.

## 4.8 Summary

The findings of the flexural stiffness testing and fatigue testing of the different mix types was discussed in Chapter 2 and will be summarized here:

- Type D 10% RA 60/70 (unmodified) test results:
    - The flexural stiffness test results compared well with each other showing a similar master curve for all three mixes.
    - The fatigue test results compared well with each other and the fatigue curves display a similar fatigue trend for all three mixes.

- Type B 40% RA 80/100 AE-2 (SBS) elastomer test results:
    - The flexural stiffness test results showed that the control (HMA) mix may have a slightly better rut resistance than the Sasoflex (WMA) mix at a reference temperature of 20° C.
    - The fatigue test results showed that the control (HMA) mix will have a better fatigue life than the Sasoflex (WMA) mix.

- Type B 40% RA 80/100 AP-1 (EVA) plastomer test results:
    - The flexural stiffness test results revealed that the control (HMA) mix had an overall higher flexural stiffness than the Rediset (WMA) mix attributed to the significant void content difference between the two mixes.
    - The fatigue test results showed that at lower strain levels the control (HMA) mix performed better than the Rediset (WMA) mix and at higher strain levels the Rediset (WMA) mix performed better than the control (HMA) mix.

- Type B 10% RA 60/70 AE-2 (SBS) elastomer test results:
    - The flexural stiffness test results compared very well with each other and the Sasoflex (WMA) mix showed only a slight higher flexural stiffness than the control (HMA) mix.
    - The fatigue test results revealed that for all practical reasons the two mixes compared very well with each other.

- Type B 10% RA 60/70 AP-1 (EVA) plastomer test results:
    - The flexural stiffness test results displayed that the two WMA mixes (Rediset and Foamtech) both have a higher flexural stiffness than their corresponding control (HMA) mix.
    - The fatigue test results showed that the Rediset (WMA) and Control (HMA) mixes have a better fatigue life than the Foamtech (WMA) mix.

# CHAPTER FIVE

# COMPARISON OF MIXES

## 5.1 MIX VARIABLES

By now it should be apparent that there are a few variables that change with the mixes. For example the type of binder grade, binder modification (whether elastomer or plastomer), percentage RA content and type of WMA technology are all variables considered. In this section an attempt to compare mixes by keeping most variables constant while changing one or two variable(s) to see the effect of that variable(s) is described. By doing so the effect of the percentage RA content, binder type and WMA technology on the performance of these mixes in terms of flexural stiffness and fatigue life can be determined. The WMA technologies considered are:

- Sasobit (organic or wax additive technology)
- Sasoflex (Sasobit and SBS)
- Rediset (chemical or surfactant additive technology)
- Rediset and EVA
- Foamtech (Free water systems foaming technology

The percentage RA contents considered are 10% and 40%.

The binder types considered are:
- 60/70 unmodified
- 60/70 AE-2 (SBS) Elastomer
- 60/70 AP-1 (EVA) Plastomer
- 80/100 AE-2 (SBS) Elastomer
- 80/100 AP-1 (EVA) Plastomer

### 5.1.1 Effect of Binder

The effect of the binder type will be investigated in this section. It is generally accepted that when it comes to binder modification a plastomer modified binder tends to increase the binder viscosity, rut resistance, stiffness and improves workability at lower temperatures. (Refer to Chapter 2) An elastomer modified binder tends to improve the strength and elastic properties, softening point, cohesive strength, elasticity, low temperature flexibility and resistance to permanent deformation and fatigue cracking. Elastomer modified binders usually have a better fatigue life than plastomers. (Refer to Chapter 2)

Keeping this in mind the different binders will now be compared by keeping the other variables constant. Firstly, the Type B 40% RA 80/100 modified control (HMA) mixes will be compared and secondly the Type B 10% RA 60/70 modified control (HMA) mixes and the Type D 10% RA 60/70 unmodified control (HMA) mix will be compared.

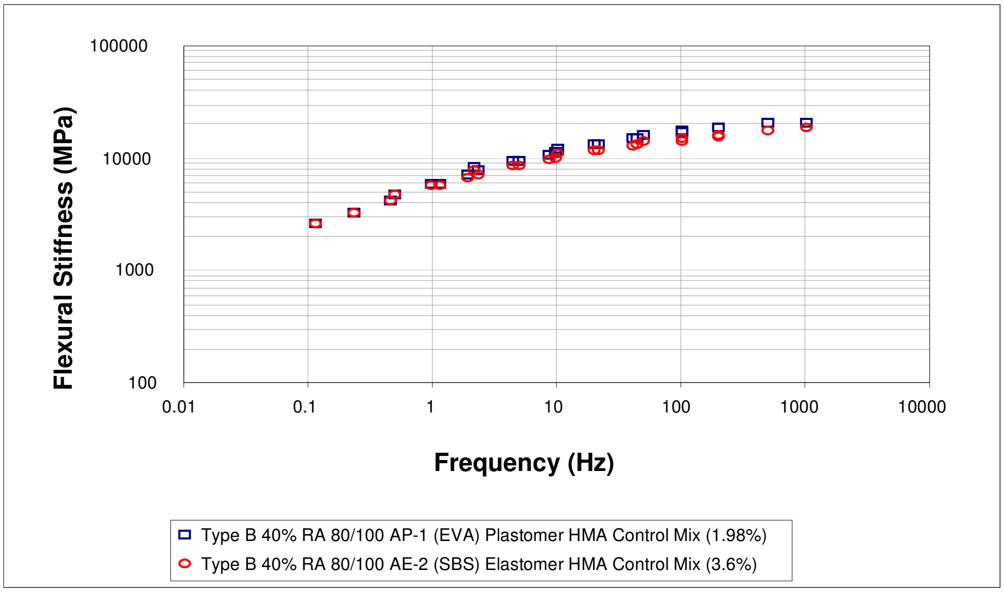


**Figure 4.28 Master Curves at Reference Temperature 20° C for Type B 40% RA 80/100 Modified Control (HMA) Mixes [Void Content (%)]**

Figure 4.28 indicates that the plastomer and elastomer mixes compare well with each other in terms of flexural stiffness. The 40% RA plastomer mix had only a slightly higher stiffness than the 40% RA elastomer mix which can be attributed to the difference in void content between these two mixes. (3.6% vs. 1.98%) Further fatigue analysis will be done by looking at the fatigue comparisons below.

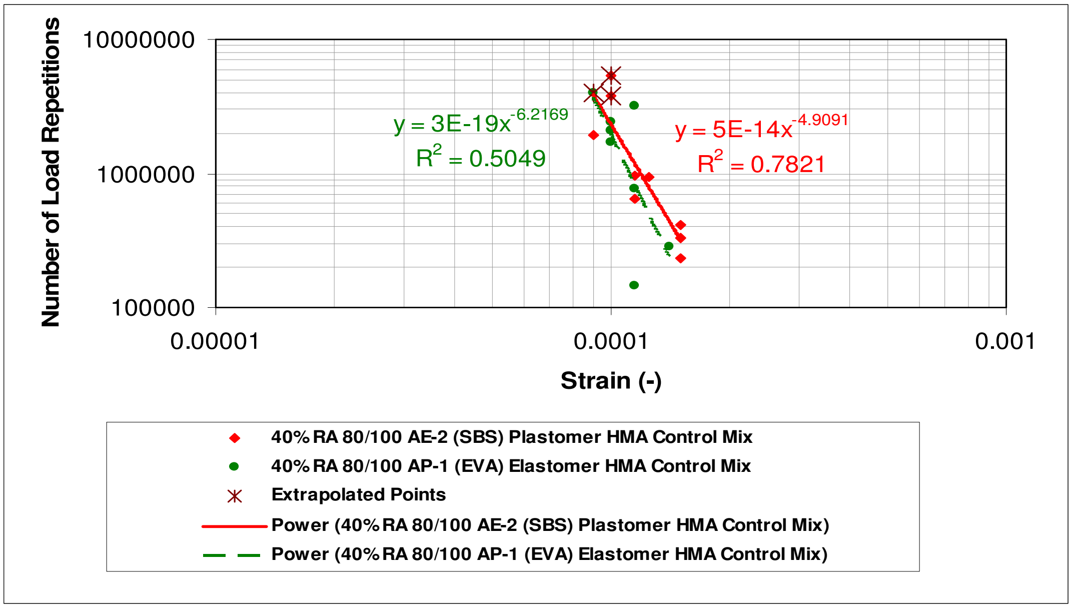


**Figure 4.29 Strain vs. $N_f$ for Type B 40% RA 80/100 Modified Control (HMA) Mixes**

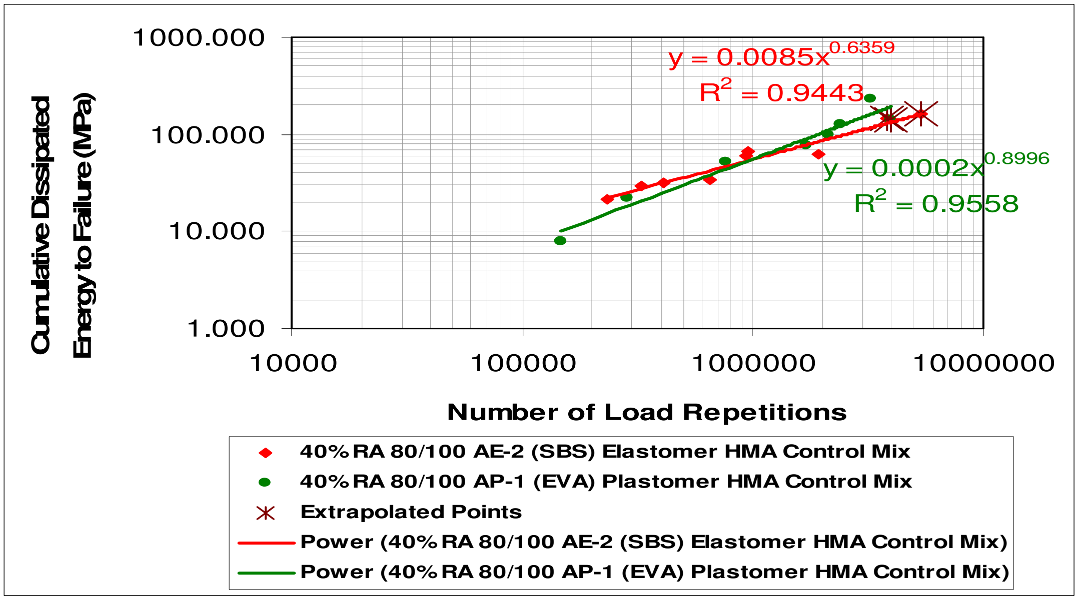


**Figure 4.30 Cumulative Dissipated Energy vs. $N_f$ for Type B 40% RA 80/100 Modified Control (HMA) Mixes**

Figure 4.29 and 4.30 show that the 40% RA elastomer mix has a higher fatigue life than the 40% RA plastomer. The plastomer mix will be more sensitive to higher strain regimes since it has a higher slope than the elastomer mix. This can be confirmed by the fact that the plastomer beams broke when they were tested at strain levels higher than 280 με. At low strain regimes the two mixes compared well with each other in terms of fatigue life.

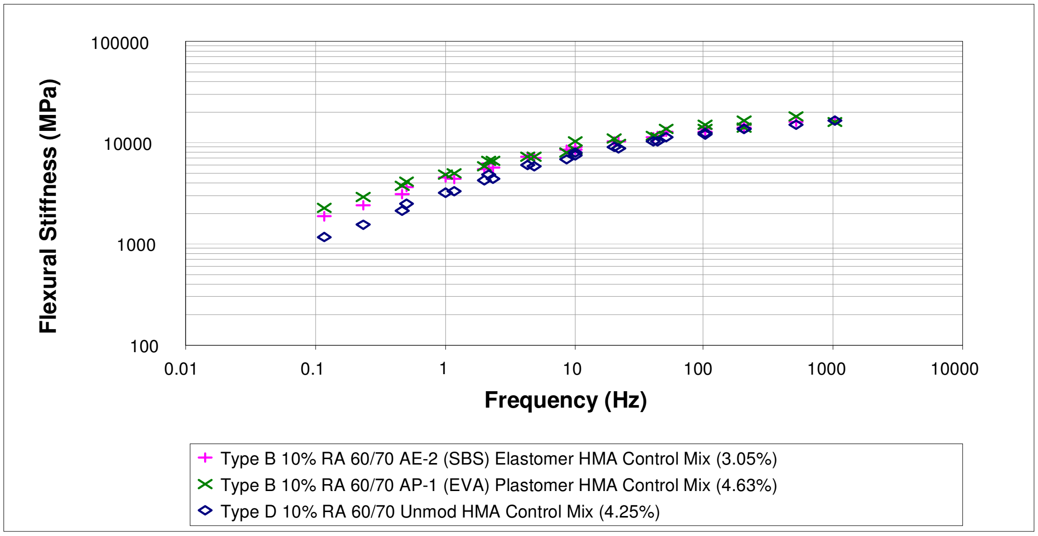


**Figure 4.31 Master Curves at Reference Temperature 20° C for Type B and D 10% RA 60/70 Control (HMA) Mixes [Void Content (%)]**

As portrayed by Figure 4.31, the 10% RA 60/70 AE-2 (SBS) elastomer and 10% RA 60/70 AP-1 (EVA) plastomer control (HMA) mixes displayed a similar flexural stiffness trend and overlapping of data points. The plastomer mix did however show a slightly higher resistance to rutting than the elastomer which was expected, since a plastomer modified binder will have improved rut resistance. (Refer to Chapter 2) The 10% RA 60/70 unmodified mix displayed a different trend than the other two mixes since it is a different type of mix (surface mix) and the binder is unmodified. The modified binders portrayed a higher flexural stiffness trend than the unmodified binder.

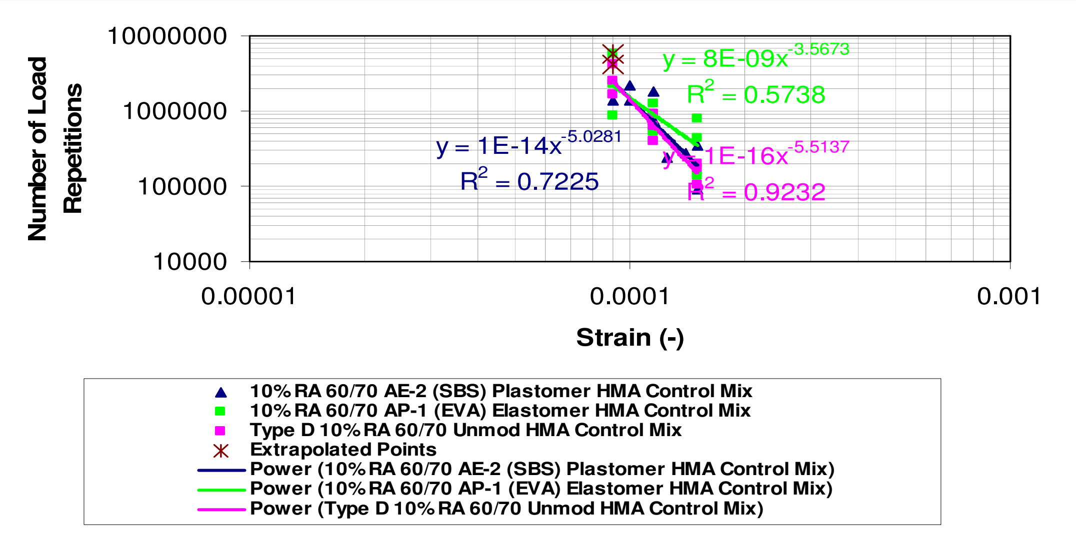


**Figure 4.32 Strain vs. $N_f$ for Type B and D 10% RA 60/70 Control (HMA) Mixes**

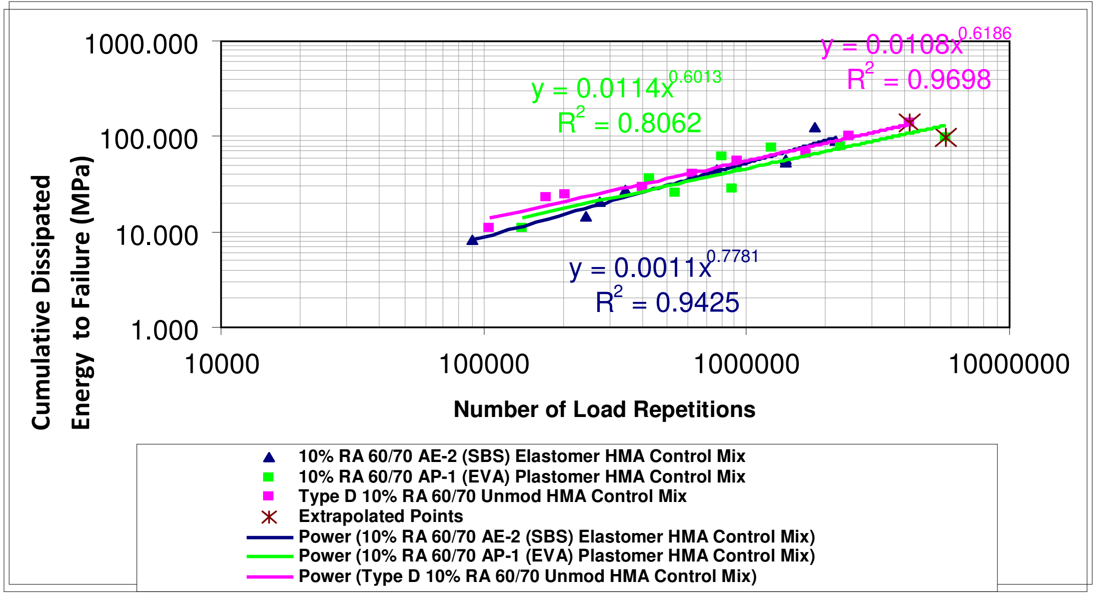


**Figure 4.33 Cumulative Dissipated Energy vs. $N_f$ for Type B and D 10% RA 60/70 Control (HMA) Mixes**

As can be seen in Figure 4.32, these three mixes performed relatively comparably in terms of fatigue life. The 10% elastomer mix will be slightly more sensitive to higher strain regimes as shown by the slope values. Figure 4.33 shows that the type D 10% unmodified mix will have a better fatigue life than the rest since it generally took more dissipated energy to fatigue it than it took with the other two mixes. The other two modified mixes are very comparable in terms of fatigue life.

### 5.1.2 Effect of WMA Technology

In this section the same comparisons made in the previous section about the effect of binder will be made, but with the trial (WMA) mixes instead of the control (HMA) mixes in order to investigate the effect of the WMA technologies. The Type D 10% RA 60/70 unmodified mixes have already been discussed in section 4.3. The Type B 40% RA 80/100 modified trial (WMA) mixes comparison will follow and the Type B 10% RA 60/70 modified trial (WMA) mixes comparison.

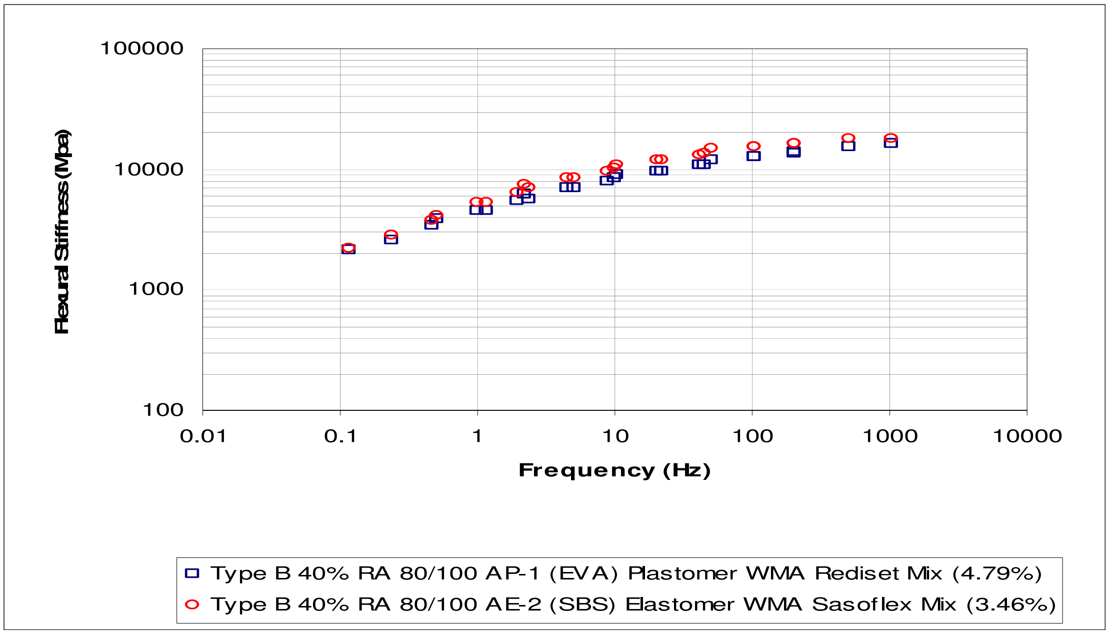


**Figure 4.34 Master Curves at Reference Temperature 20° C for Type B 40% RA 80/100 Modified WMA Trial Mixes [Void Content (%)]**

Figure 4.34 shows that these two mixes compared very well with each other in terms of flexural stiffness. The Sasoflex (WMA) elastomer mix did show a slight higher flexural stiffness than the Rediset (WMA) plastomer mix, which can be attributed to the void content difference between the two mixes. (1.3% difference)

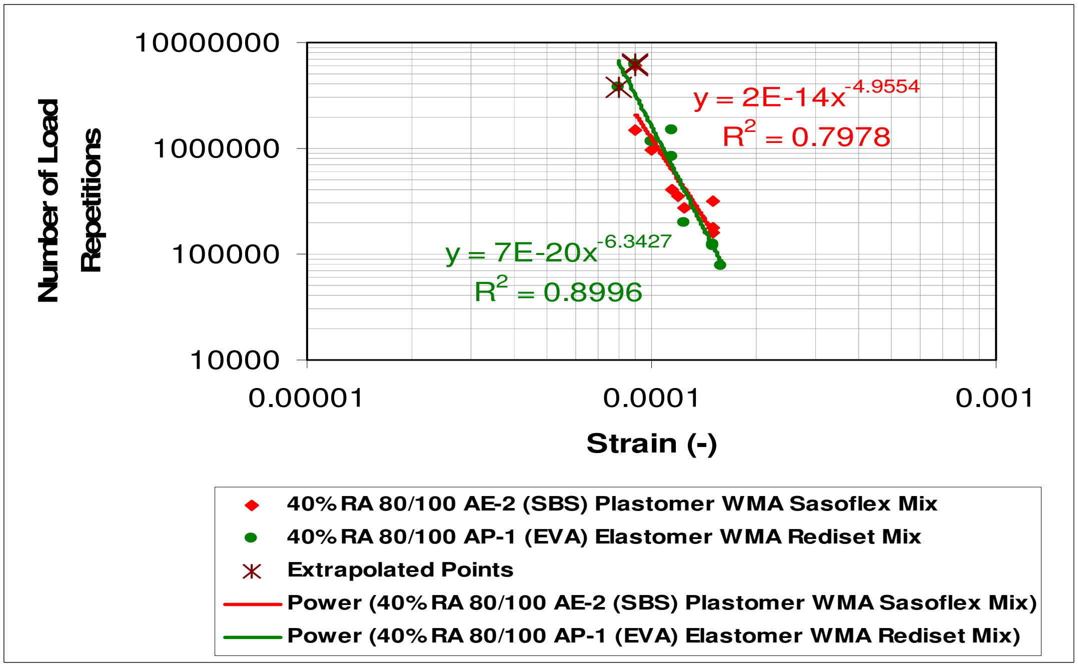


**Figure 4.35 Strain vs. $N_f$ for Type B 40% RA 80/100 Modified WMA Trial Mixes**

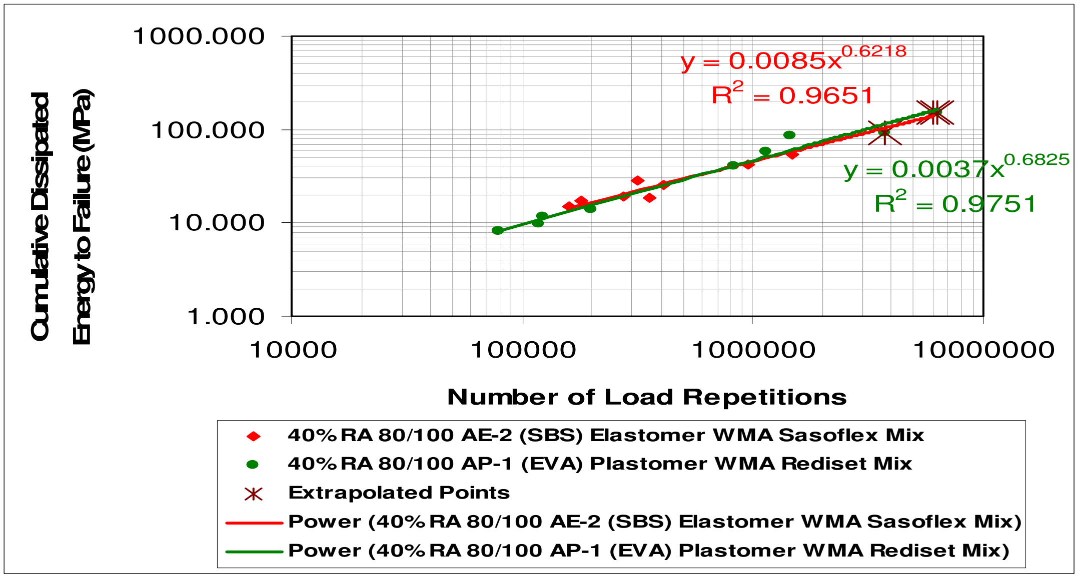


**Figure 4.36 Cumulative Dissipated Energy vs. $N_f$ for Type B 40% RA 80/100 Modified WMA Trial Mixes**

The Rediset (WMA) plastomer mix showed more sensitivity towards high strain regimes than the Sasoflex (WMA) elastomer mix. Figure 4.35 and 4.36 displays that these two mixes performed comparably in terms of fatigue life and can be considered equivalent in terms of fatigue life performance.

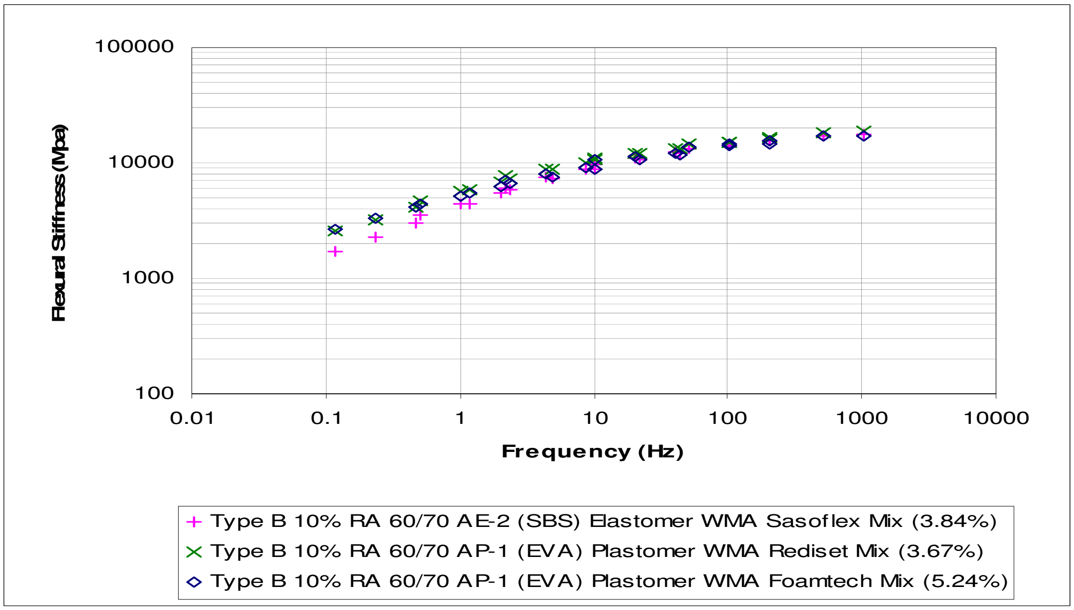


**Figure 4.37 Master Curves at Reference Temperature 20° C for Type B 10% RA 60/70 Modified WMA Trial Mixes [Void Content (%)]**

Figure 4.37 shows that the Rediset and Foamtech (WMA) plastomer mixes performed similarly in terms of flexural stiffness. The Sasoflex (WMA) elastomer mix shows a different trend since it has a much lower stiffness at lower frequencies which means that the elastomer mix will be more prone to rutting than the two plastomer mixes, which is to be expected. (Refer to Chapter 2)

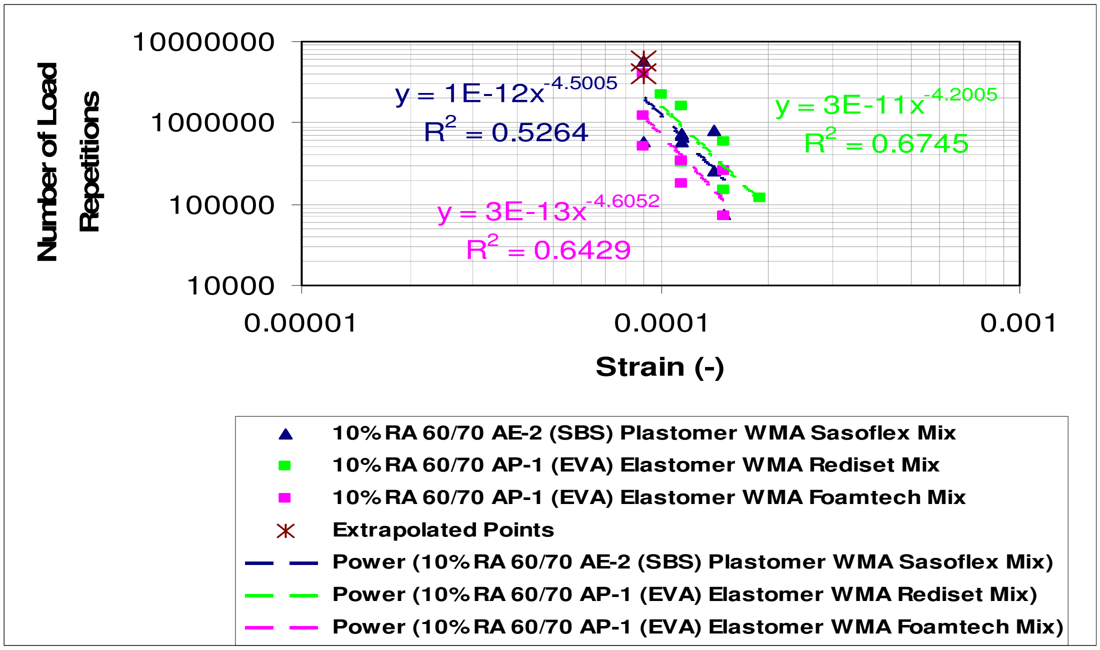


**Figure 4.38 Strain vs. $N_f$ for Type B 10% RA 60/70 Modified WMA Trial Mixes**

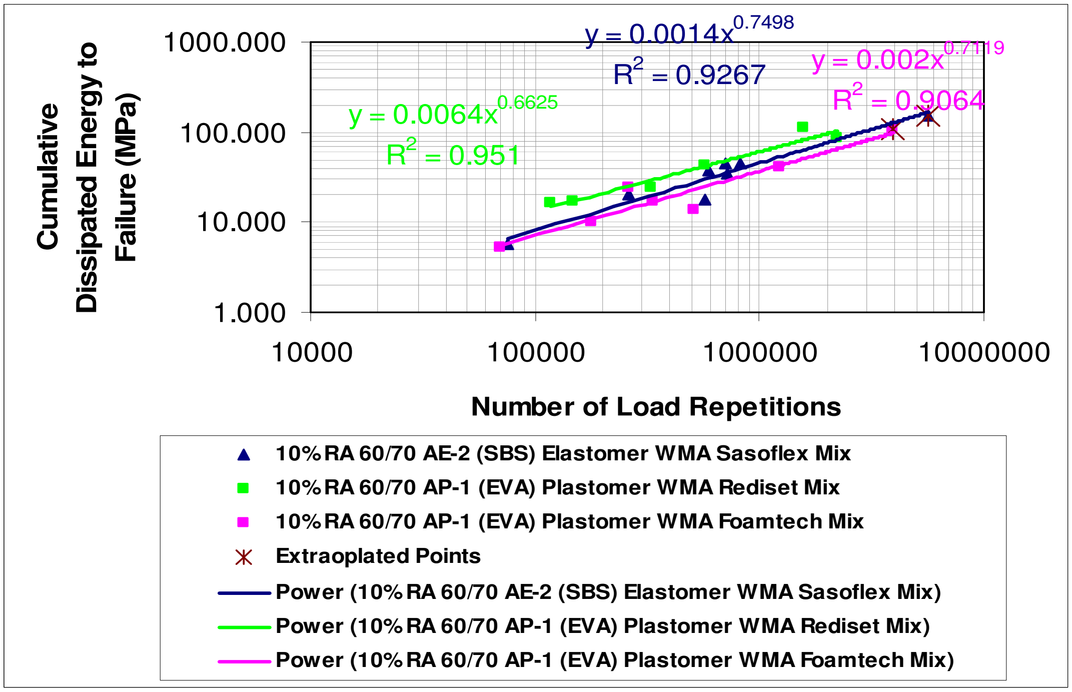


**Figure 4.39 Cumulative Dissipated Energy vs. $N_f$ for Type B 10% RA 60/70 Modified WMA Trial Mixes**

It should be noted that for the Wöhler approach (Figure 4.38), none of the three mixes met the required nine data points stipulated by Taute et al (2001) and hence these trend lines are only an indication, and are thus shown as a dashed line.

An improved fatigue analysis can be achieved by considering the cumulative dissipated energy approach (Figure 4.39). This approach shows that the Rediset (WMA) plastomer mix requires more dissipated energy to fatigue than the other two mixes resulting in the Rediset (WMA) plastomer mix with the better fatigue life. Secondly, the Sasoflex (WMA) elastomer mix has a longer fatigue life than the Foamtech (WMA) plastomer mix.

### 5.1.3 Effect of % RA Content

The effect which the percentage RA content has on the fatigue and rutting performance of these mixes will be shown in this section by means of bar graphs. To show and compare the effect of the percentage RA content on the rutting performance of the mix, the flexural stiffness results were shown on a bar chart for the different frequencies. To show and compare the effect of the percentage RA content on the fatigue performance of the mix, the number of load repetitions from the fatigue tests was shown on a bar chart at a selected fixed strain level.

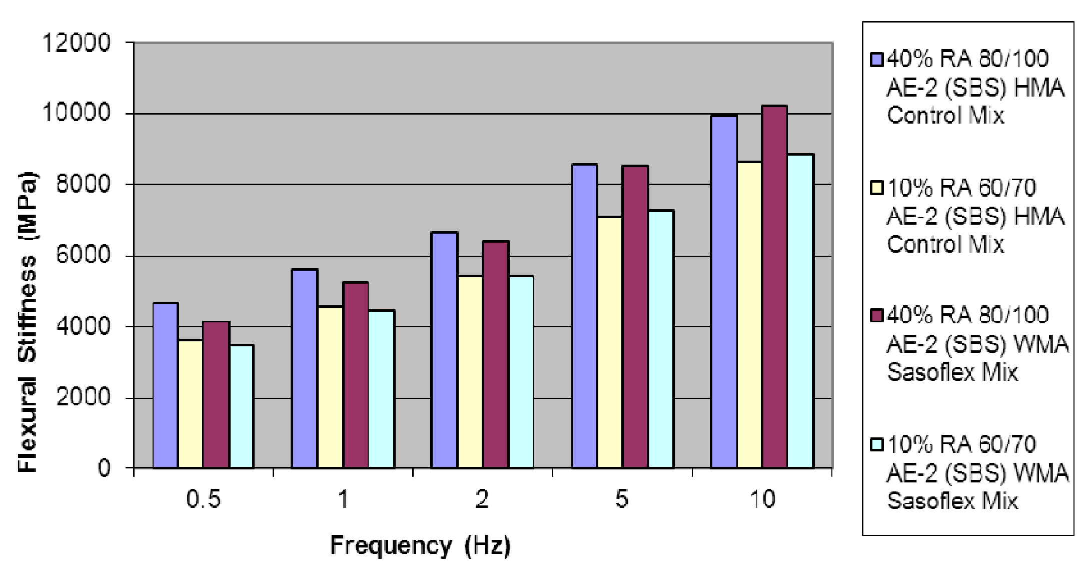


**Figure 4.40 Effect of % RA content on rutting performance for Type B 40% vs. 10% AE-2 (SBS) elastomer mixes**

In general the left hand side of the flexural stiffness graph displays the flexural stiffness results at low frequencies which depict the rutting resistance of the mix. This means that at low a low frequency the higher the flexural stiffness generally the higher the rutting resistance will be. Looking at Figure 4.40 it can be seen that for the HMA mixes at lower frequencies (0.5 and 1 Hz) the mix with 40% RA had a higher flexural stiffness than its corresponding mix with 10% RA content. The expected rutting resistance will be slightly better for the 40% RA content mix than the 10% RA mix. Similar findings were shown for the WMA Sasoflex mixes. This could also be attributed to the different binder type in each mix being compared. (80/100 vs. 60/70)

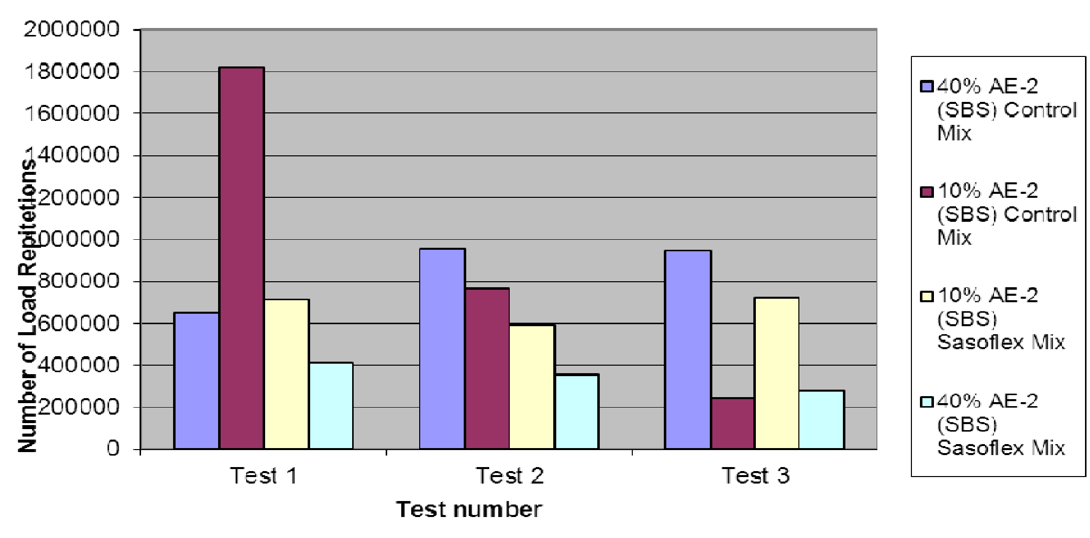


**Figure 4.41 Effect of % RA content on fatigue performance of Type B 40% vs. 10% RA AE-2 (SBS) elastomer Mixes at a fixed Strain of 230-250 με**

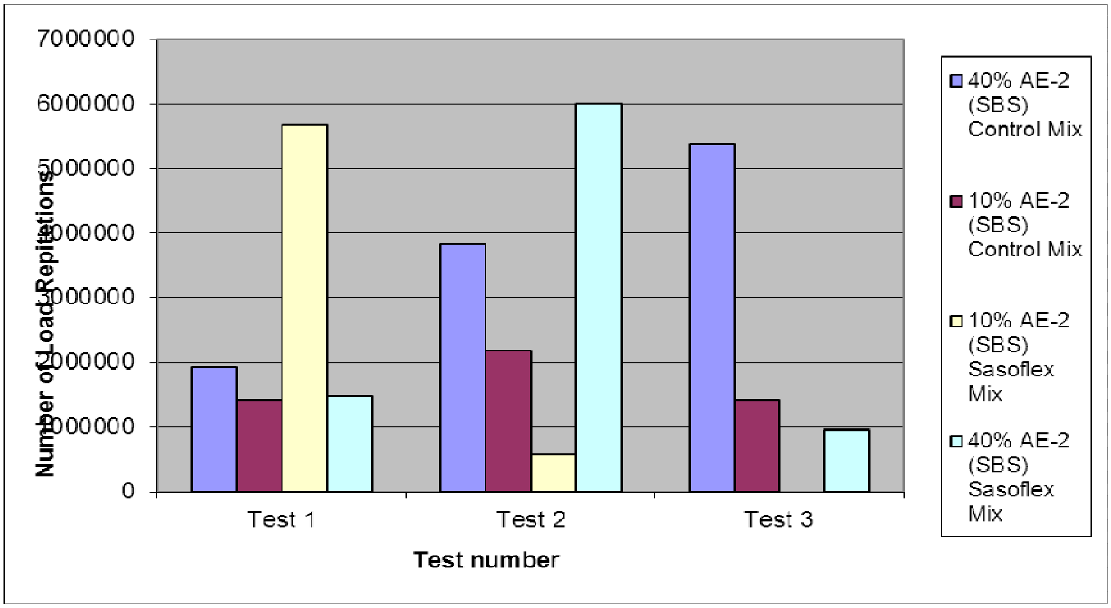


**Figure 4.42 Effect of % RA content on Fatigue Performance of Type B 40% vs. 10% RA AE-2 (SBS) elastomer Mixes at a fixed Strain of 180-200 με**

Looking at Figure 4.41 it is shown that at medium strain level (230 -250 με) the 40% RA Control mix had a higher fatigue life in general when compared to the 10% RA Control mix. (With the exception of Test 1 result for 10% Control mix which seems like an outlier) This is also evident in Figure 4.42 for these two mixes showing the 40% RA Control mix having a higher fatigue life than the 10% RA Control mix. Looking at the WMA Sasoflex mix results it can be seen that the 10% RA Sasoflex mix had a higher fatigue life than the 40% RA Sasoflex mix. The variability in the results for test 1 to test 3 can be attributed to the difference in void contents for the different mixes and beams.

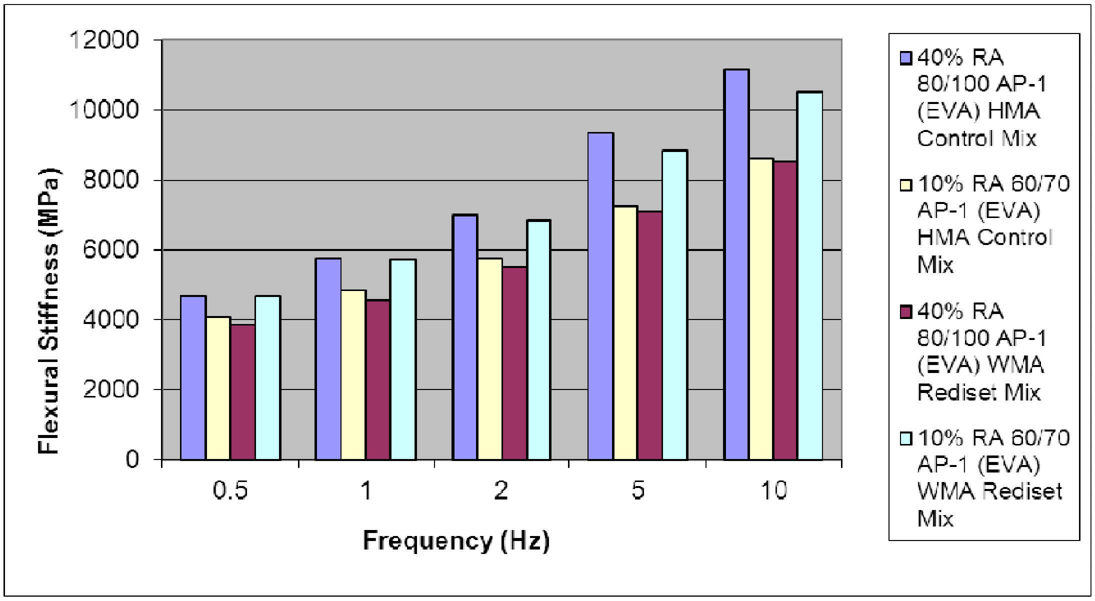


**Figure 4.43 Effect of % RA content on rutting performance for Type B 40% vs. 10% AP-1 (EVA) plastomer mixes**

Looking at Figure 4.43 it can be seen that the 40% RA Control mix displayed a slight better flexural stiffness at lower frequencies depicting a better rut resistance than the corresponding 10% RA Control mix. For the WMA mixes it can be seen that the 10% RA Rediset mix has a better rut resistance than its corresponding 40% RA Rediset mix.

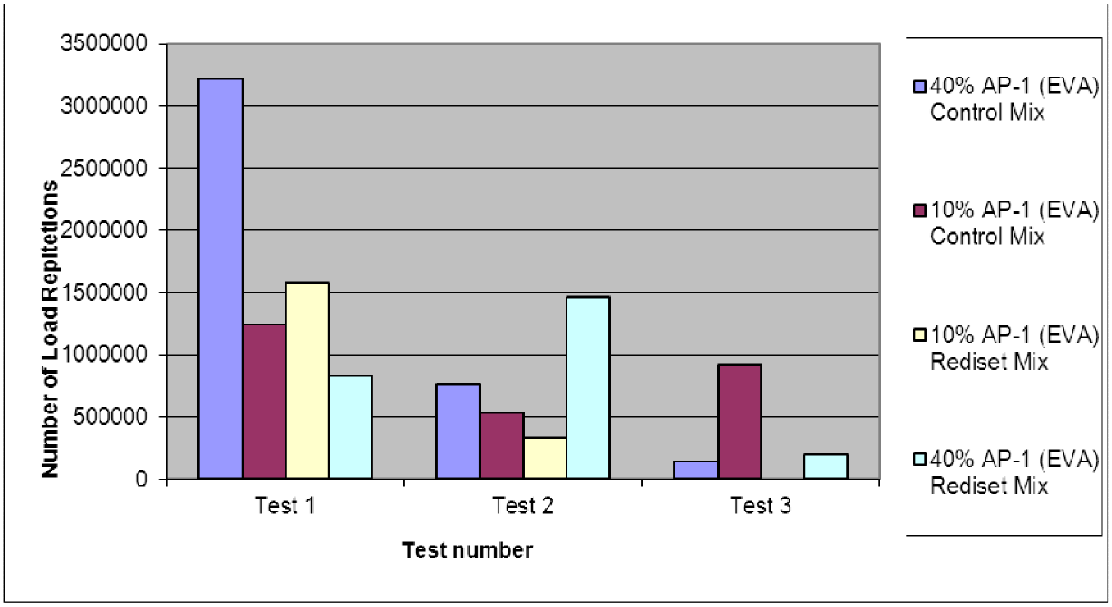


**Figure 4.44 Effect of RA content on Fatigue Performance of Type B 40% vs. 10% RA AP-1 (EVA) plastomer Mixes at a fixed Strain of 230-250 με**

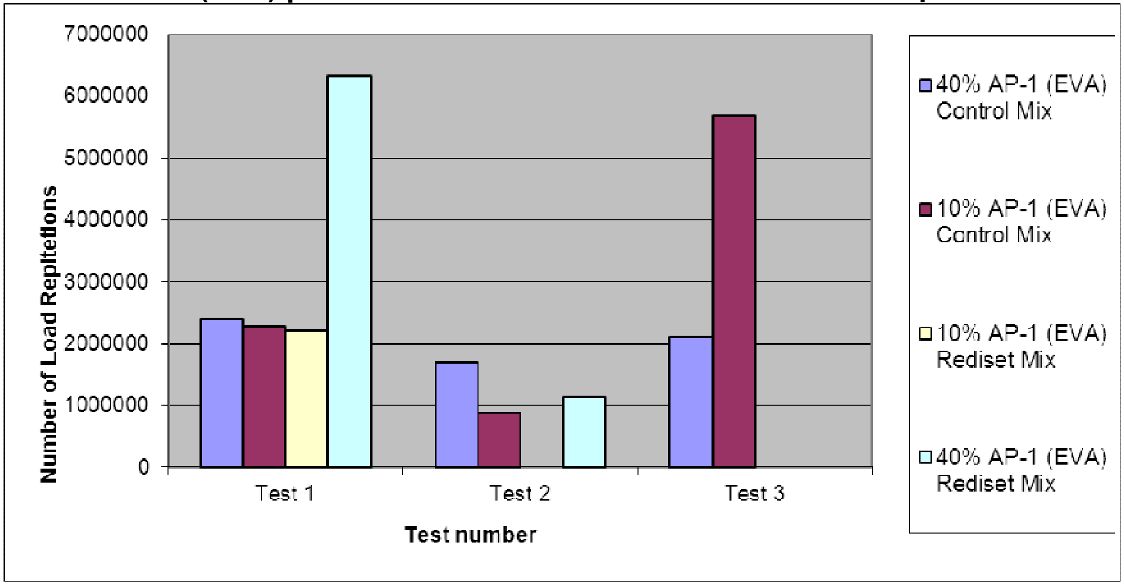


**Figure 4.45 Effect of RA content on Fatigue Performance of Type B 40% vs. 10% RA AP-1 (EVA) plastomer Mixes at a fixed Strain of 180-200 με**

Looking at Figure 4.44 and 4.45 it can be seen that the results for each test varied for each mix type which could be attributed to the different void contents of these beams tested.

## 5.2 PHASE ANGLE RESULTS

The phase angle is used to predict the visco-elastic behaviour of the mix. Testing a mix with the IPC Four-Point Bending Beam Fatigue apparatus gives you the phase angle which can be used to analyse the visco-elastic behaviour of the mix. In this section there will be a discussion of the phase angle data obtained while performing the flexural stiffness test on the mixes.

When analysing the phase angle of a mix, the higher the phase angle the less elastic and more viscous the mix will be, thus it will be more prone to rutting and have a higher resistance to fatigue cracking. The lower the phase angle the more elastic and less viscous the mix will be, thus having a higher resistance towards rutting and be more susceptibility to fatigue cracking.

The flexural stiffness testing was done at 5 different temperatures from 5 to 25 °C. In this discussion only the two extreme temperatures namely 5 and 25 °C are considered and then the phase angle over the 5 temperatures for a fixed frequency of 10 Hz is displayed.

### 5.2.1 Type D 10% RA 60/70 (Unmodified) Mix Phase Angle Results

The phase angle results for the surfacing mixes (Type D) are presented in Table 4.35 below and displayed in Figure 4.46 to 4.47. As one can see from Table 4.35 below, the relationship between the phase angle and flexural stiffness is related to the frequency and temperature of the test. At constant temperature with an increase in frequency the phase angle decreases but the flexural stiffness increases. With an increase in temperature the phase angle will increase but the flexural stiffness will decrease. This implies that the factors that affect flexural stiffness influence the phase angle.

### Table 4.35 Phase Angle Results for Type D 10% RA 60/70 Unmodified Control and Trial Mixes (Data from Flexural Stiffness Testing at 5 °C and 25°C)

| Type D 10% RA 60/70 (Unmodified) Beam Specimens | | | | |
|---|---|---|---|---|
| **Mix Type** | **Temperature (℃)** | **Frequency (Hz)** | **Flexural Stiffness (MPa)** | **Phase Angle δ (Degrees)** |
| **Control (Beam 2 Slab 1) [4.25 % Voids]** | 5 | 0.5 | 11431 | 11.27 |
| | | 1.0 | 12532 | 12.23 |
| | | 2.0 | 13734 | 9.90 |
| | | 5.0 | 15173 | 7.95 |
| | | 10.0 | 16473 | 6.07 |
| | 25 | 0.5 | 1176 | 49.25 |
| | | 1.0 | 1578 | 46.97 |
| | | 2.0 | 2162 | 38.76 |
| | | 5.0 | 3302 | 36.77 |
| | | 10.0 | 4400 | 34.77 |
| **Rediset (Beam 1 Slab 2) [3.39% Voids]** | 5 | 0.5 | 10988 | 12.58 |
| | | 1.0 | 12131 | 11.62 |
| | | 2.0 | 13393 | 9.24 |
| | | 5.0 | 15029 | 7.01 |
| | | 10.0 | 16061 | 5.78 |
| | 25 | 0.5 | 1053 | 50.73 |
| | | 1.0 | 1350 | 51.47 |
| | | 2.0 | 1941 | 46.42 |
| | | 5.0 | 2856 | 39.75 |
| | | 10.0 | 3990 | 35.12 |
| **Sasobit (Beam 1 Slab 1) [4.05% Voids]** | 5 | 0.5 | 10539 | 13.77 |
| | | 1.0 | 11495 | 12.72 |
| | | 2.0 | 12654 | 10.72 |
| | | 5.0 | 14309 | 7.86 |
| | | 10.0 | 15525 | 5.86 |
| | 25 | 0.5 | 1138 | 48.70 |
| | | 1.0 | 1380 | 48.99 |
| | | 2.0 | 1930 | 41.70 |
| | | 5.0 | 2932 | 38.46 |
| | | 10.0 | 4007 | 35.38 |

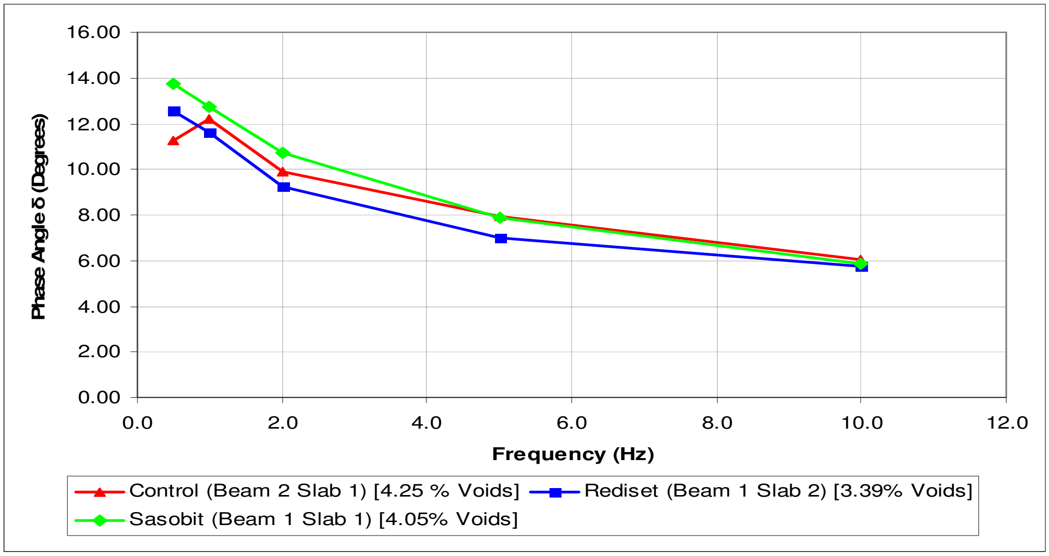


**Figure 4.46 Phase Angle for Type D 10% RA 60/70 Unmodified Mixes at 5 °C [Void Content (%)]**

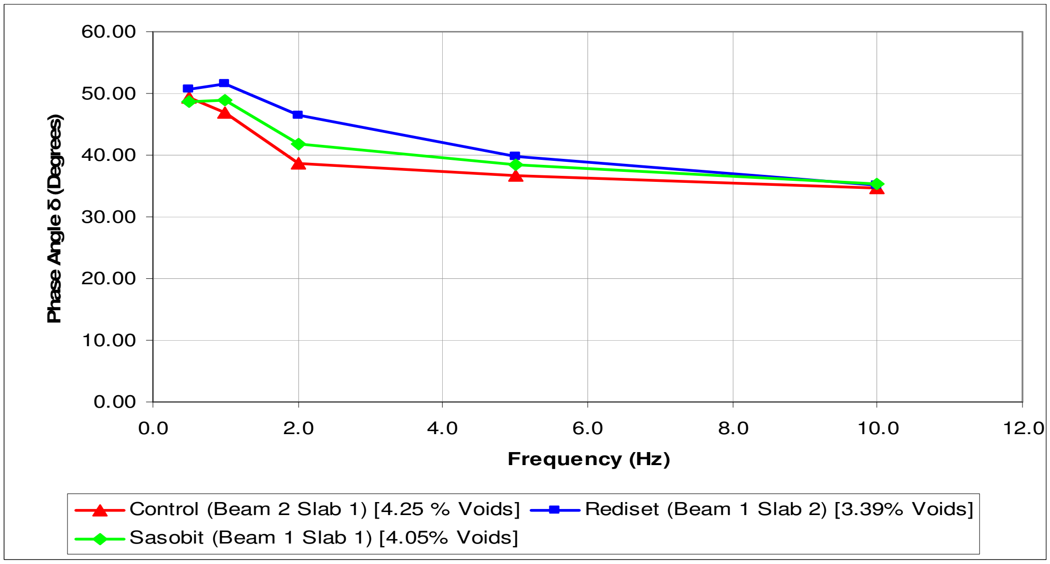


**Figure 4.47 Phase Angle for Type D 10% RA 60/70 Unmodified Mixes at 25 °C [Void Content (%)]**

From Figure 4.46 it can be seen that at low temperatures (5 °C) the control (HMA) and Sasobit (WMA) mixes have similar phase angle values for frequencies 5 – 10 Hz. For lower frequencies the Sasobit mix has a higher phase angle than the Control mix. Thus for low temperatures (5 °C), at lower frequencies the Sasobit mix will behave less elastic and more viscous than the control (HMA) mix. The Rediset (WMA) mix displayed a lower phase angle than the Sasobit (WMA) and control (HMA) mixes which means the Rediset (WMA) mix will be more elastic, less viscous and be more resistant to rutting than the Sasobit (WMA) and control (HMA) mixes at low temperatures (5 °C).

Figure 4.47 displays the phase angle for these three mixes for high temperatures (25 ℃). The control (HMA) mix has the lowest phase angle, followed by the Sasobit (WMA) mix. The Rediset (WMA) mix showed the highest phase angle for 25 ℃. From these observations it is evident that at high temperatures (25 ℃) the Rediset (WMA) mix will be the least elastic and most viscous and will be more resistant to fatigue than the Sasobit (WMA) and control (HMA) mixes. The control (HMA) mix having the smallest phase angle will be the most elastic and least viscous and be more resistant to rutting than the Rediset and Sasobit (WMA) mixes.

**Table 4.36 Phase Angle Results for Type D 10% RA 60/70 Unmodified Control and Trial Mixes (Data from Flexural Stiffness Testing at 10 Hz only)**

| Type D 10% RA 60/70 (Unmodified) Beam Specimens | | | | | |
|---|---|---|---|---|---|
| **Mix Type** | **5 ℃** | **10 ℃** | **15 ℃** | **20 ℃** | **25 ℃** |
| Control (Beam 2 Slab 1) [4.25% Voids] | 6.07 | 10.47 | 15.62 | 23.98 | 34.77 |
| Rediset (Beam 1 Slab 2) [3.39% Voids] | 5.78 | 10.59 | 16.96 | 25.41 | 35.12 |
| Sasobit (Beam 1 Slab 1) [4.05% Voids] | 5.86 | 12.22 | 18.17 | 25.51 | 35.38 |

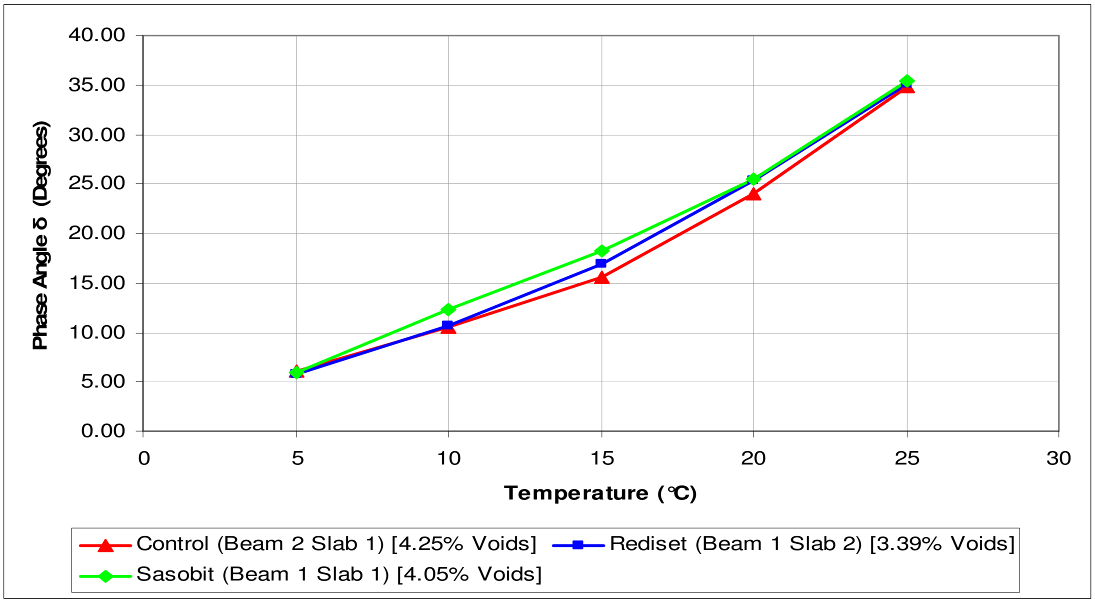


**Figure 4.48 Phase Angle for Type D 10% RA 60/70 Unmodified Mixes at Frequency of 10 Hz [Void Content (%)]**

Table 4.36 present the phase angle results for increasing temperatures of the Type D 10% RA 60/70 unmodified mixes and Figure 4.48 displays these results at a fixed frequency of 10 Hz. At high frequencies the three mixes compared very well with each other in terms of phase angle results.

### 5.2.2 Type B 40% RA 80/100 Phase Angle Results

The use of modified binders affects the phase angle since the phase angle is sensitive to the chemical nature of materials and the chemical used to modify the binder affects the mixture properties. In this section two combinations of modified binder and WMA technology are assessed, namely EVA with Rediset WMX and SBS with Sasobit (Sasoflex). Table 4.37 below display the phase angle results for Type B 40% RA 80/100 AE-2 (SBS) elastomer control (HMA) and Sasoflex (WMA) mixes. Figure 4.49 and 4.50 show these results graphically.

**Table 4.37 Phase Angle Results for Type B 40% RA 80/100 AE-2 (SBS) Elastomer Control and Trial Mixes (Data from Flexural Stiffness Testing at 5°C and 25°C)**

| Type B 40% RA (AE-2) 80/100 Beam Specimens | | | | |
|---|---|---|---|---|
| **Mix Type** | **Temperature (°C)** | **Frequency (Hz)** | **Flexural Stiffness (MPa)** | **Phase Angle δ (Degrees)** |
| **AE-2 Control (Beam 3 Slab 1) [3.6% Voids]** | 5 | 0.5 | 13842 | 7.84 |
| | | 1.0 | 14925 | 6.78 |
| | | 2.0 | 15963 | 5.68 |
| | | 5.0 | 17235 | 4.49 |
| | | 10.0 | 18285 | 3.97 |
| | 25 | 0.5 | 2573 | 37.76 |
| | | 1.0 | 3261 | 33.28 |
| | | 2.0 | 4088 | 29.61 |
| | | 5.0 | 5676 | 26.03 |
| | | 10.0 | 7116 | 24.72 |
| **AE-2 Sasoflex (Beam 4 Slab 1) [3.46% Voids]** | 5 | 0.5 | 14641 | 7.66 |
| | | 1.0 | 15363 | 7.44 |
| | | 2.0 | 16345 | 6.35 |
| | | 5.0 | 17659 | 4.81 |
| | | 10.0 | 18084 | 3.65 |
| | 25 | 0.5 | 2233 | 44.81 |
| | | 1.0 | 2823 | 37.21 |
| | | 2.0 | 3757 | 32.95 |
| | | 5.0 | 5301 | 30.04 |
| | | 10.0 | 6932 | 28.73 |

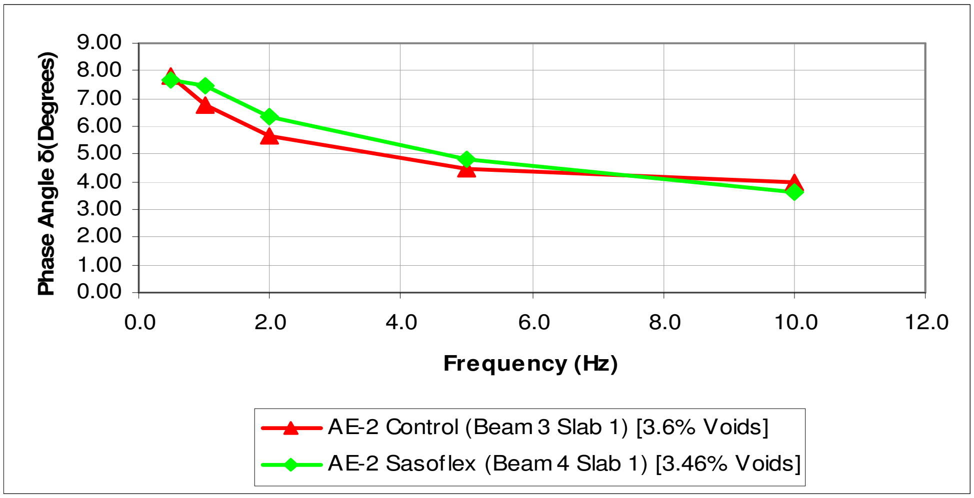


**Figure 4.49 Phase Angle for Type B 40% RA 80/100 AE-2 (SBS) Elastomer Mixes at 5 °C [Void Content (%)]**

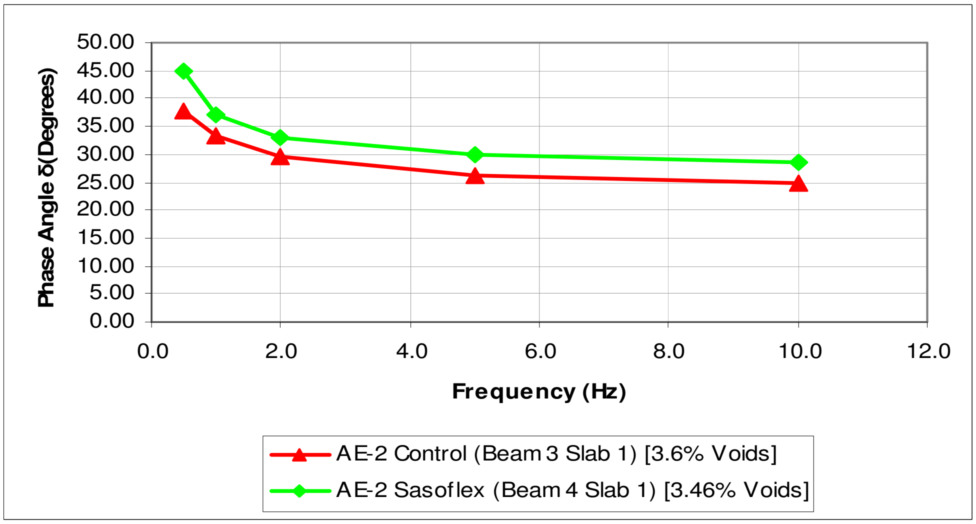


**Figure 4.10 Phase Angle for Type B 40% RA 80/100 AE-2 (SBS) Elastomer Mixes at 25 °C [Void Content (%)]**

Figure 4.49 indicates that the control (HMA) and Sasoflex (WMA) mixes have very comparable phase angle values at low temperatures (5 ℃) as can be confirmed by Figure 4.51 below. The control (HMA) mix has a smaller phase angle than the Sasoflex (WMA) mix for all frequencies at higher temperatures (25 ℃).

The control mix will thus be more elastic, less viscous and will be more resistant to rutting than the Sasoflex mix which will be more resistant to fatigue cracking than the control mix at a test temperature of 25 ℃. At lower temperatures it is expected that these mixes will behave similarly according to their phase angle results.

**Table 4.38 Phase Angle Results for Type B 40% RA 80/100 AE-2 (SBS) Elastomer Control and Sasoflex Mixes (Data from Flexural Stiffness Testing at 10 Hz only)**

| Type B 40% RA (AE-2) 80/100 Elastomer Beam Specimens (Data From Flexural Stiffness Testing at 10 Hz only) | | | | | |
|---|---|---|---|---|---|
| **Mix Type** | **5 ℃** | **10 ℃** | **15 ℃** | **20 ℃** | **25 ℃** |
| AE-2 Control (Beam 3 Slab 1) [3.6% Voids] | 3.97 | 6.15 | 10.46 | 17.32 | 24.72 |
| AE-2 Sasoflex (Beam 4 Slab 1) [3.46% Voids] | 3.65 | 6.31 | 12.57 | 19.14 | 28.73 |

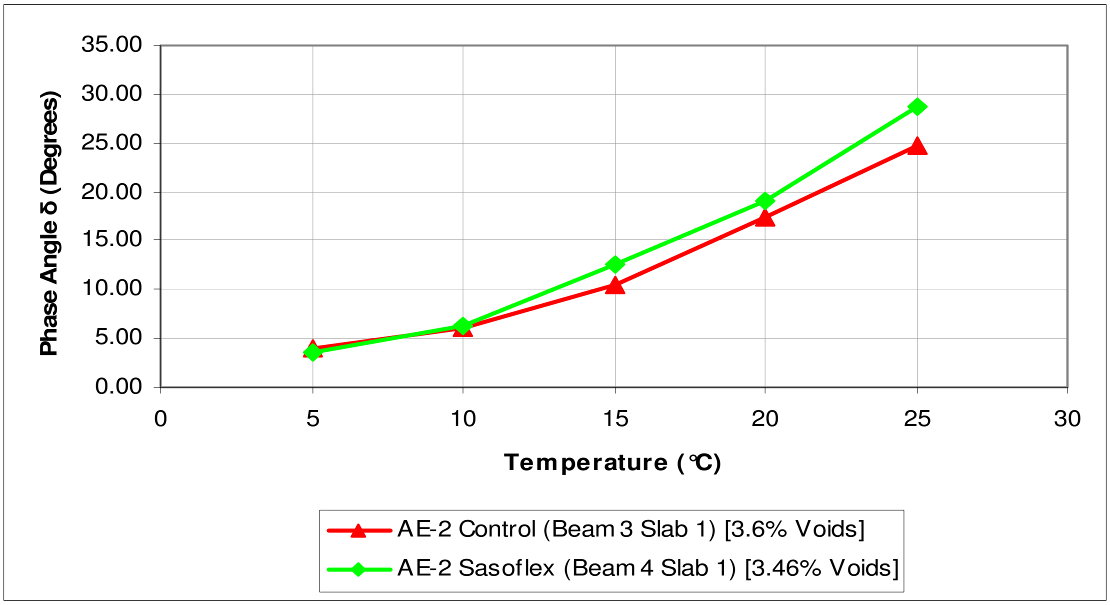


**Figure 4.51 Phase Angle for Type B 40% RA 80/100 AE-2 (SBS) Elastomer Mixes at Frequency of 10 Hz [Void Content (%)]**

Table 4.38 and Figure 4.51 indicate that for a fixed frequency of 10 Hz the control (HMA) and Sasoflex (WMA) mixes compared very well in terms of phase angle results at low temperatures of 5 and 10 ℃. For higher temperatures the control (HMA) mix had a lower phase angle than the Sasoflex (WMA) mix. Therefore, it is to be expected that at low temperatures of 5 and 10 ℃ these two mixes will behave similarly but for temperatures above 10℃ the Sasoflex (WMA) mix will be less elastic, more viscous and be more resistant to fatigue than the control (HMA) mix.

Table 4.39 below indicates the phase angle results for the Type B 40% RA 80/100 AP-1 (EVA) plastomer control (HMA) and Rediset (WMA) mixes. Figures 4.52 and 4.53 display the results graphically.

**Table 4.39 Phase Angle Results for Type B 40% RA 80/100 AP-1 (EVA) Plastomer Mixes (Data from Flexural Stiffness Testing at 5 °C and 25°C)**

| Type B 40% RA (AP-1) 80/100 Plastomer Beam Specimens | | | | |
|---|---|---|---|---|
| **Mix Type** | **Temperature (℃)** | **Frequency (Hz)** | **Flexural Stiffness (MPa)** | **Phase Angle δ (Degrees)** |
| **AP-1 Control (Beam 4 Slab 2) [1.98% Voids]** | 5 | 0.5 | 15961 | 7.05 |
| | | 1.0 | 17371 | 6.69 |
| | | 2.0 | 18590 | 5.17 |
| | | 5.0 | 20423 | 2.95 |
| | | 10.0 | 20356 | -7.66 |
| | 25 | 0.5 | 2556 | 40.56 |
| | | 1.0 | 3195 | 35.87 |
| | | 2.0 | 4113 | 32.79 |
| | | 5.0 | 5826 | 29.15 |
| | | 10.0 | 7705 | 26.27 |
| **AP-1 Rediset (Beam 3 Slab 2) [4.79% Voids]** | 5 | 0.5 | 11853 | 10.77 |
| | | 1.0 | 12693 | 10.31 |
| | | 2.0 | 13793 | 8.77 |
| | | 5.0 | 15307 | 6.59 |
| | | 10.0 | 16285 | 4.91 |
| | 25 | 0.5 | 2166 | 38.19 |
| | | 1.0 | 2614 | 35.10 |
| | | 2.0 | 3415 | 31.62 |
| | | 5.0 | 4594 | 28.65 |
| | | 10.0 | 5670 | 27.22 |

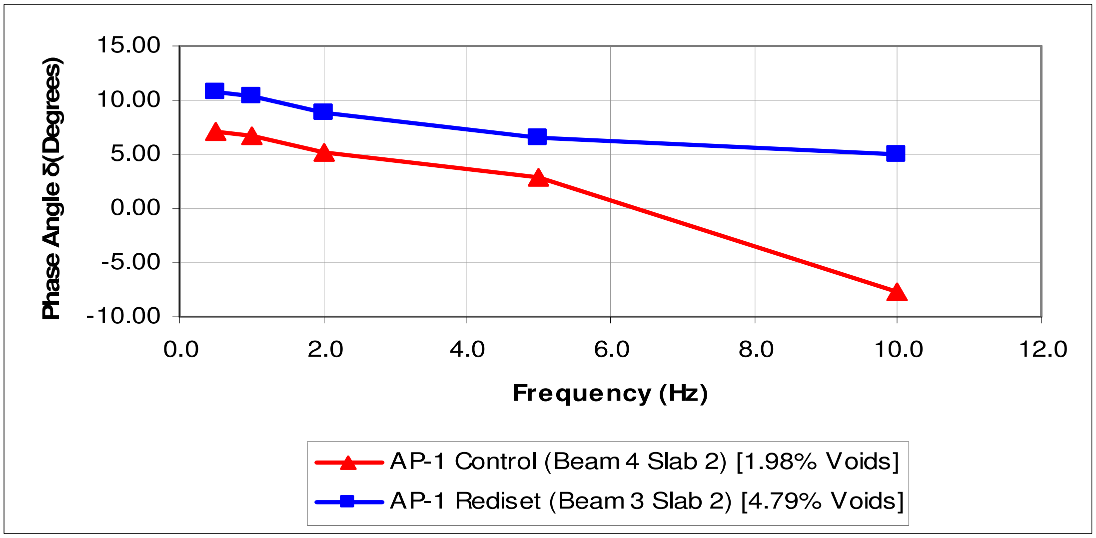


**Figure 4.52 Phase Angle for Type B 40% RA 80/100 AP-1 (EVA) Plastomer Mixes at 5 °C [Void Content (%)]**

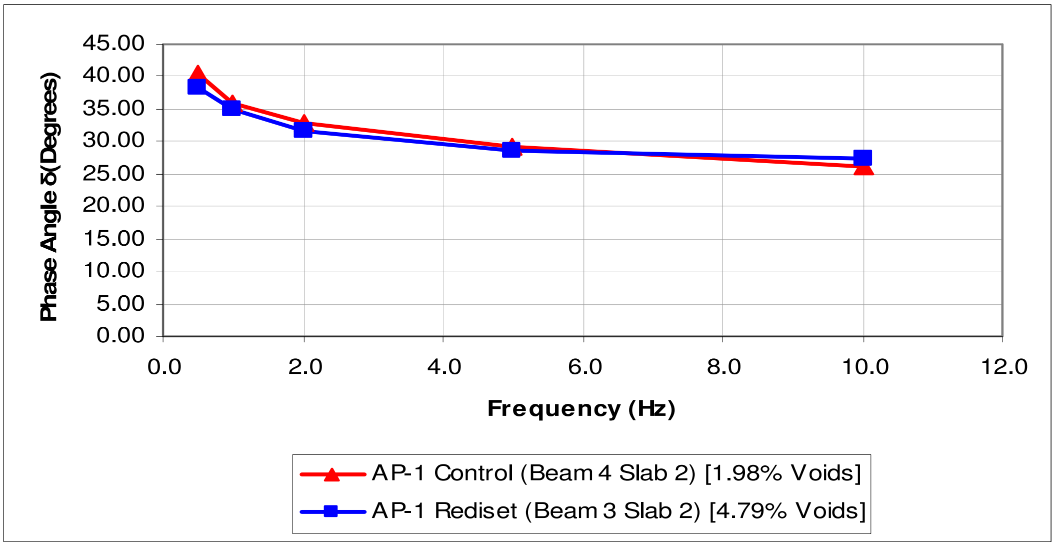


**Figure 4.53 Phase Angle for Type B 40% RA 80/100 AP-1 (EVA) Plastomer Mixes at 25 °C [Void Content (%)]**

Figure 4.52 above shows that the control (HMA) plastomer mix has a much lower phase angle for all frequencies than the Rediset (WMA) mix, which means that the control (HMA) mix will be more elastic, less viscous and be more resistant to rutting but more susceptible to fatigue than the Rediset (WMA) mix at temperatures of 5 °C. Looking back at the fatigue results for these mixes it can be seen that the Rediset (WMA) mix has a better fatigue life than the control (HMA) mix, which confirms the finding above since all fatigue testing was done at 5 °C. At 25 °C (Figure 4.53) these two mixes performed comparably in terms of phase angle results.

**Table 4.40 Phase Angle Results for Type B 40% RA 80/100 AP-1 (EVA) Plastomer Mixes (Data from Flexural Stiffness Testing at 10 Hz only)**

| Type B 40% RA (AP-1) 80/100 Plastomer Beam Specimens (Data From Flexural Stiffness Testing at 10 Hz only) | | | | | |
|---|---|---|---|---|---|
| **Mix Type** | **5 °C** | **10 °C** | **15 °C** | **20 °C** | **25 °C** |
| AP-1 Control (Beam 4 Slab 2) [1.98% Voids] | -7.66 | 5.61 | 10.95 | 18.18 | 26.27 |
| AP-1 Rediset (Beam 3 Slab 2) [4.79% Voids] | 4.91 | 8.82 | 13.93 | 19.67 | 27.22 |

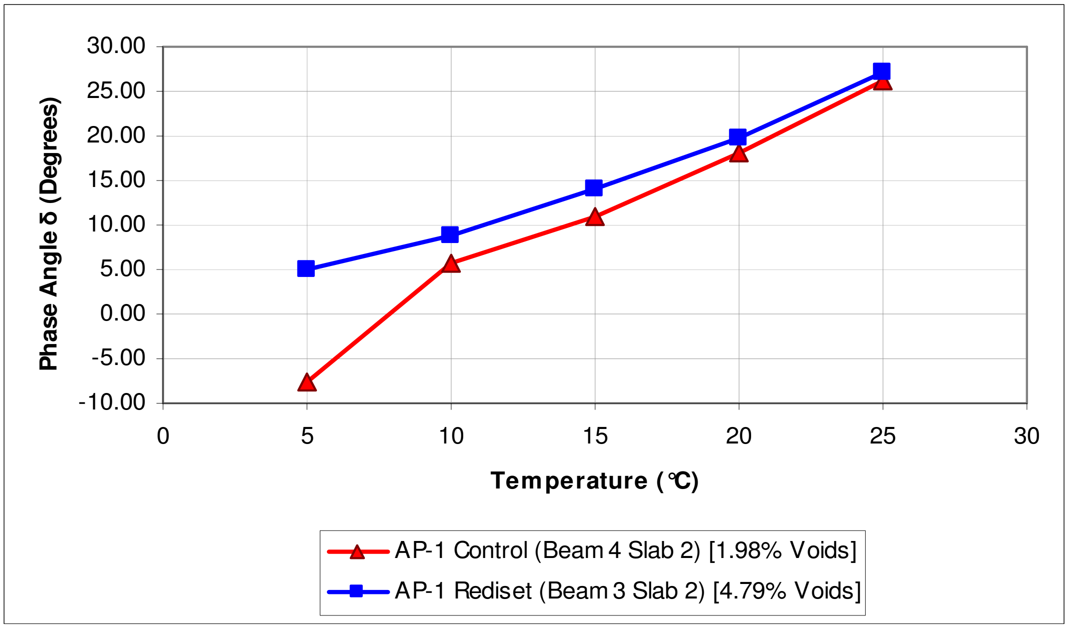


**Figure 4.54 Phase Angle for Type B 40% RA 80/100 AP-1 (EVA) Plastomer Mixes at Frequency of 10 Hz [Void Content (%)]**

Looking at Table 4.40 and Figure 4.54 it is evident that in general the control (HMA) mix showed a lower phase angle than the Rediset (WMA) mix. This could be attributed to the aged binder in the control (HMA) mix (resulting from the increased production temperature) as well as the void content difference between the two mixes. (1.98% vs. 4.79%)

### 5.2.3 Type B 10% RA 60/70 Phase Angle Results

In this section the phase angle results for the Type B 10% RA 60/70 mixes are dealt with. Three combinations of modified binder and WMA Technologies are investigated here, namely SBS with Sasobit (Sasoflex), EVA with Foamtech and EVA with Rediset WMX.

Table 4.41 below gives the phase angle results for the elastomer mixes and Figures 4.55 and 4.56 displays these results graphically.

## Table 4.41 Phase Angle Results for Type B 10% RA 60/70 AE-2 (SBS) Elastomer Mixes (Data from Flexural Stiffness Testing at 5 °C and 25°C)

| Type B 10% RA 60/70 AE-2 (SBS) Elastomer Beam Specimens | | | | |
|---|---|---|---|---|
| **Mix Type** | **Temperature (℃)** | **Frequency (Hz)** | **Flexural Stiffness (MPa)** | **Phase Angle δ (Degrees)** |
| AE-2 Control (Beam 3 Slab 1) [3.05% Voids] | 5 | 0.5 | 12921 | 8.99 |
| | | 1.0 | 13836 | 8.54 |
| | | 2.0 | 14907 | 6.74 |
| | | 5.0 | 16215 | 4.65 |
| | | 10.0 | 16786 | 3.47 |
| | 25 | 0.5 | 1874 | 44.10 |
| | | 1.0 | 2439 | 38.98 |
| | | 2.0 | 3120 | 32.52 |
| | | 5.0 | 4354 | 30.28 |
| | | 10.0 | 5663 | 28.96 |
| AE-2 Sasoflex (Beam 4 Slab 1) [3.84% Voids] | 5 | 0.5 | 13332 | 10.16 |
| | | 1.0 | 14369 | 8.88 |
| | | 2.0 | 15535 | 7.31 |
| | | 5.0 | 17152 | 4.36 |
| | | 10.0 | 17922 | 2.93 |
| | 25 | 0.5 | 1688 | 48.38 |
| | | 1.0 | 2245 | 42.78 |
| | | 2.0 | 3039 | 36.21 |
| | | 5.0 | 4430 | 31.96 |
| | | 10.0 | 5770 | 30.19 |

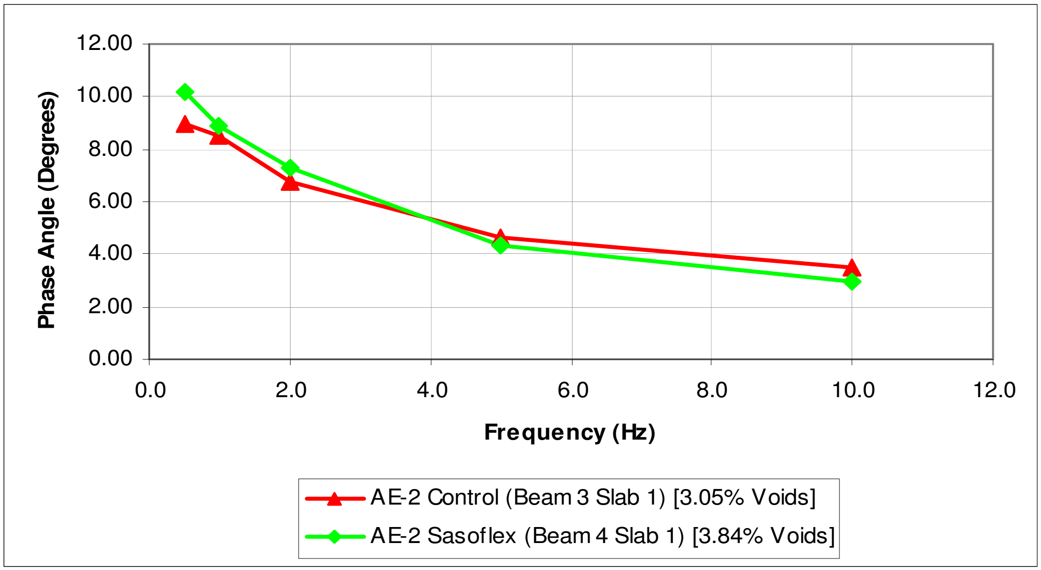


Figure 4.55 Phase Angle for Type B 10% RA 60/70 AE-2 (SBS) Elastomer Mixes at 5 °C [Void Content (%)]

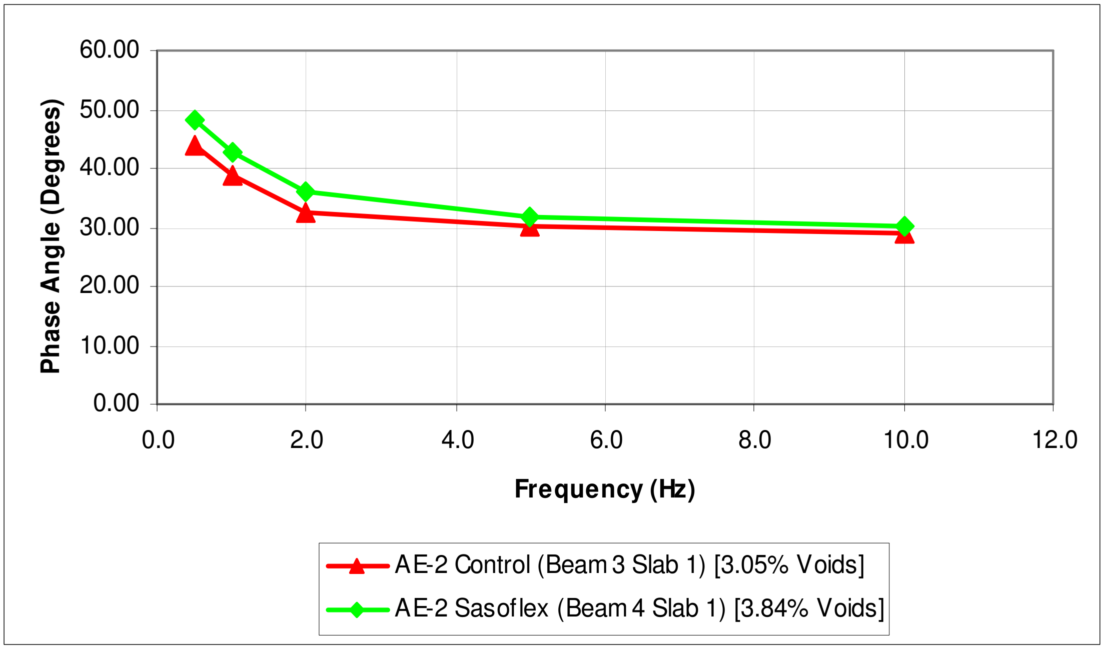


**Figure 4.56 Phase Angle for Type B 10% RA 60/70 AE-2 (SBS) Elastomer Mixes at 25 °C [Void Content (%)]**

The control (HMA) and Sasoflex (WMA) elastomer mixes performed comparably in terms of phase angle results as indicated by Figures 4.55 and 4.56. It can be assumed that these two mixes will behave similarly and by looking back at the fatigue and flexural stiffness results for these mixes this is confirmed, since they performed relatively comparably.

Table 4.42 and Figure 4.57 below display the phase angle results over the temperature ranges (at 10 Hz frequency) and once again confirm that these two mixes performed very similarly.

**Table 4.42 Phase Angle Results for Type B 10% RA 60/70 AE-2 (SBS) Elastomer Mixes (Data from Flexural Stiffness Testing at 10 Hz only)**

| Type B 10% RA (AE-2) 60/70 Elastomer Beam Specimens (Data From Flexural Stiffness Testing at 10 Hz only) | | | | | |
|---|---|---|---|---|---|
| **Mix Type** | **5 °C** | **10 °C** | **15 °C** | **20 °C** | **25 °C** |
| AE-2 Control (Beam 3 Slab 1) [3.05% Voids] | 3.47 | 7.36 | 12.86 | 19.56 | 28.96 |
| AE-2 Sasoflex (Beam 4 Slab 1) [3.84% Voids] | 2.93 | 7.44 | 13.33 | 20.43 | 30.19 |

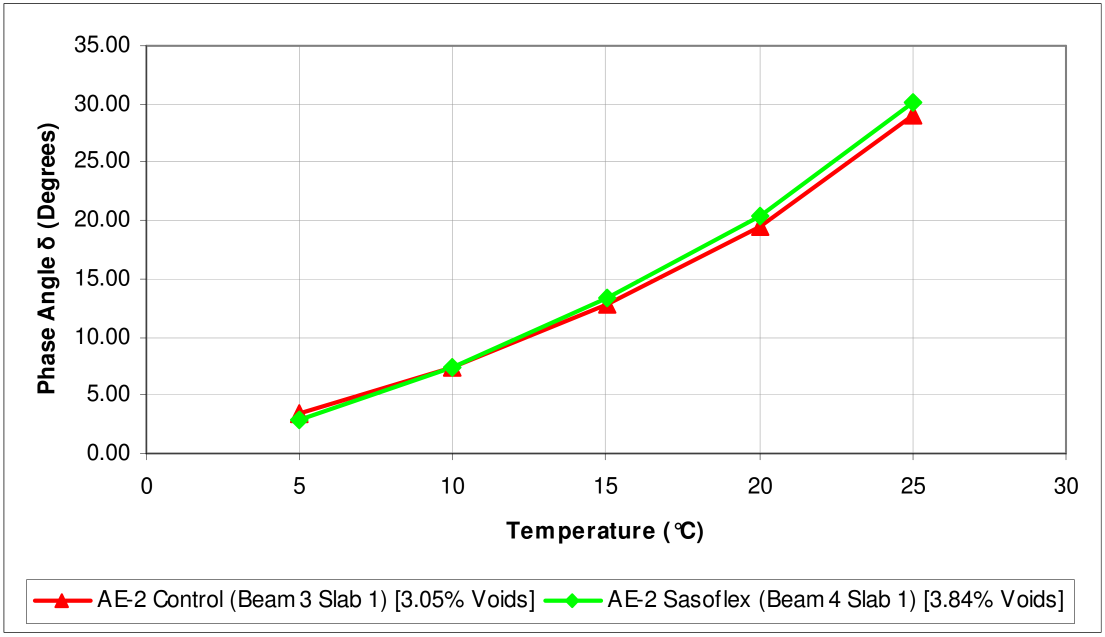


**Figure 4.57 Phase Angle for Type B 10% RA 60/70 AE-2 (SBS) Elastomer Mixes at Frequency of 10 Hz [Void Content (%)]**

Table 4.43 below gives the phase angle results for the Type B 10% RA 60/70 plastomer mixes and Figures 4.58 and 4.59 displays these results graphically.

## Table 4.43 Phase Angle Results for Type B 10% RA 60/70 AP-1 (EVA) Plastomer Mixes (Data from Flexural Stiffness Testing at 5 °C and 25°C)

| Type B 10% RA (AP-1) 60/70 Plastomer Beam Specimens | | | | |
|---|---|---|---|---|
| **Mix Type** | **Temperature (℃)** | **Frequency (Hz)** | **Flexural Stiffness (MPa)** | **Phase Angle δ (Degrees)** |
| **AP-1 Control (Beam 4 Slab 2) [4.63% Voids]** | 5 | 0.5 | 13694 | 8.93 |
| | | 1.0 | 15159 | 7.61 |
| | | 2.0 | 16429 | 5.98 |
| | | 5.0 | 18030 | 4.23 |
| | | 10.0 | 15836 | -1.77 |
| | 25 | 0.5 | 2285 | 41.04 |
| | | 1.0 | 2902 | 38.10 |
| | | 2.0 | 3761 | 31.47 |
| | | 5.0 | 5040 | 28.57 |
| | | 10.0 | 6563 | 27.38 |
| **AP-1 Rediset (Beam 1 Slab 2) [3.67% Voids]** | 5 | 0.5 | 14819 | 6.57 |
| | | 1.0 | 15215 | 7.56 |
| | | 2.0 | 16606 | 4.16 |
| | | 5.0 | 18094 | 2.54 |
| | | 10.0 | 18566 | -4.57 |
| | 25 | 0.5 | 2606 | 37.06 |
| | | 1.0 | 3259 | 33.90 |
| | | 2.0 | 4195 | 29.12 |
| | | 5.0 | 5800 | 26.40 |
| | | 10.0 | 7391 | 24.16 |
| **AP-1 Foamtech (Beam 3 Slab 3) [5.24% Voids]** | 5 | 0.5 | 13819 | 9.36 |
| | | 1.0 | 14606 | 7.87 |
| | | 2.0 | 15654 | 5.96 |
| | | 5.0 | 17223 | 3.50 |
| | | 10.0 | 16984 | 2.48 |
| | 25 | 0.5 | 2694 | 34.63 |
| | | 1.0 | 3329 | 28.67 |
| | | 2.0 | 4154 | 27.01 |
| | | 5.0 | 5527 | 23.76 |
| | | 10.0 | 6645 | 23.13 |

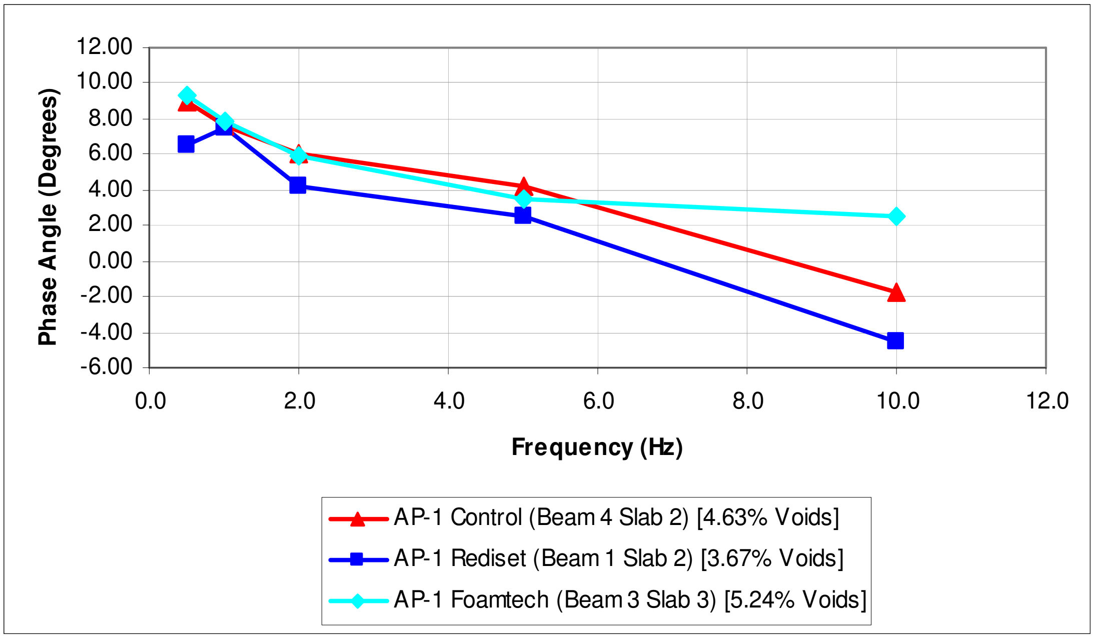


**Figure 4.58 Phase Angle for Type B 10% RA 60/70 AP-1 (EVA) Plastomer Mixes at 5 °C [Void Content (%)]**

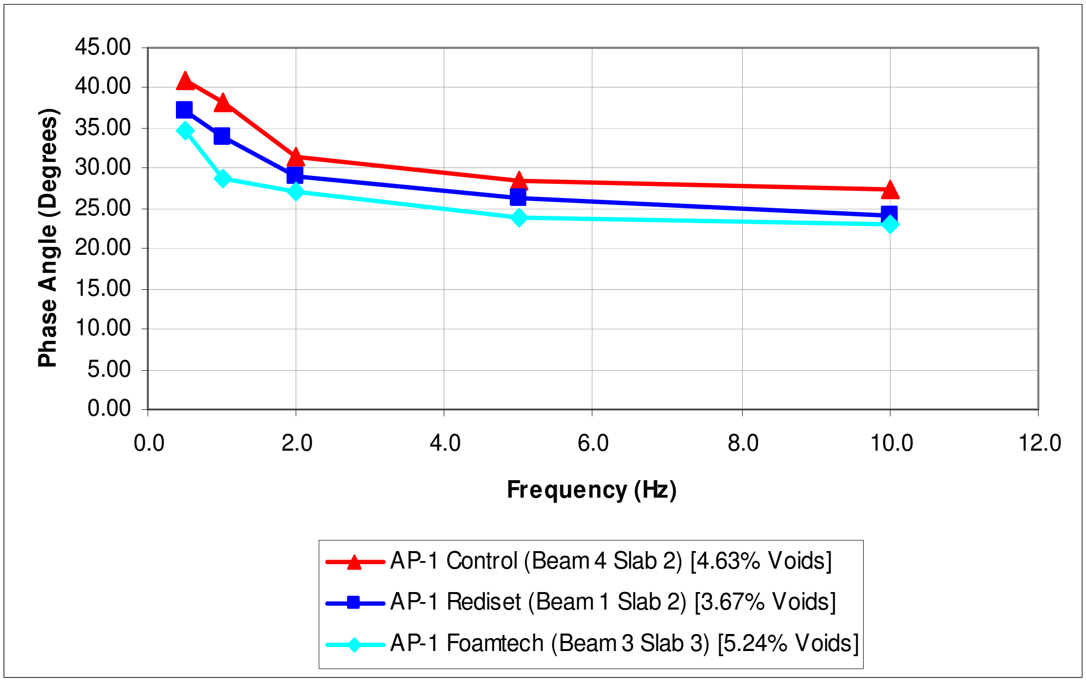


**Figure 4.59 Phase Angle for Type B 10% RA 60/70 AP-1 (EVA) Plastomer Mixes at 25 °C [Void Content (%)]**

There is a notable difference in phase angle value between the Foamtech and Rediset (WMA) mixes at 10 Hz for 5 °C as indicated by Figure 4.58 which can be attributed to the void content difference (5.24% vs. 3.67%). Figure 4.59 indicates that at 25 °C the control (HMA) mix has the highest phase angle, followed by the

Rediset (WMA) mix and then the Foamtech (WMA) mix. Table 4.44 and Figure 4.60 display the phase angle results for these three mixes for increasing temperatures at a fixed frequency of 10 Hz.

**Table 4.44 Phase Angle Results for Type B 10% RA 60/70 AP-1 (EVA) Plastomer Mixes (Data from Flexural Stiffness Testing at 10 Hz only)**

| Type B 10% RA (AP-1) 60/70 Plastomer Beam Specimens (Data From Flexural Stiffness Testing at 10 Hz only) | | | | | |
|---|---|---|---|---|---|
| **Mix Type** | **5 ℃** | **10 ℃** | **15 ℃** | **20 ℃** | **25 ℃** |
| AP-1 Control (Beam 4 Slab 2) [4.63% Voids] | -1.77 | 6.49 | 11.16 | 18.62 | 27.38 |
| AP-1 Rediset (Beam 1 Slab 2) [3.67% Voids] | -4.57 | 4.40 | 10.29 | 15.39 | 24.16 |
| AP-1 Foamtech (Beam 3 Slab 3) [5.24% Voids] | 2.48 | 10.98 | 11.41 | 17.38 | 23.13 |

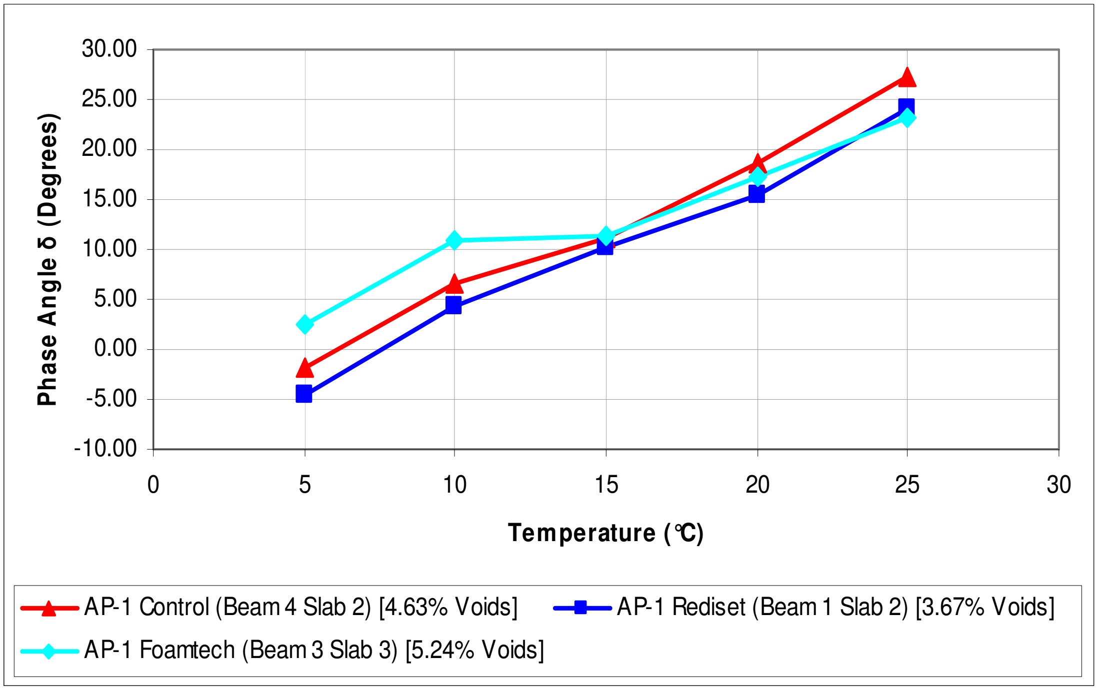


**Figure 4.60 Phase Angle for Type B 10% RA 60/70 AP-1 (EVA) Plastomer Mixes at Frequency of 10 Hz [Void Content (%)]**

# CHAPTER SIX

# CONCLUSIONS & RECOMMENDATIONS

## 6.1 INTRODUCTION

Conclusions are drawn and recommendations are made in this chapter from the laboratory analysis and evaluation of the test results as described in Chapters 4 and 5. The conclusions focus on the evaluation of the WMA trial mixes against their equivalent HMA control mixes (as the benchmark) in terms of flexural stiffness and fatigue life performance. Conclusions based on the behaviour of the mixes by means of phase angle results are also made.

The flexural stiffness of these mixes are evaluated by means of master curves which illustrate the flexural stiffness trend over the varying test frequencies for each mix at a reference temperature of 20° C. (Refer to chapter 2 of this thesis for a detailed description)

The fatigue life performance of these mixes is evaluated by means of two different fatigue damage approaches namely the Wöhler and the cumulative dissipated energy approach. (Refer to chapter 2 for a detailed description) The Wöhler approach relates the number of load repetitions to failure to the tensile strain of the mixes. The cumulative dissipated energy approach correlates the cumulative dissipated energy to the number of load repetitions to failure.

The phase angle results are also evaluated with reference to the visco-elastic behaviour of the mixes under consideration. (See section 5.2 of Chapter 5)

Conclusions are also drawn from the comparisons made in Chapter 5 to demonstrate the effect the varying binder types and WMA technologies, incorporated in the different mixes, has on the performance of these mixes.

Lastly, recommendations are made regarding future research and further validation of the results and conclusions made in this study.

## 6.2 CONCLUSIONS

In this study surface (Type D) and base (Type B) WMA trial mixes containing varying binder types (60/70 or 80/100), modifiers (AE-2 (SBS) or AP-1 (EVA)), WMA technologies (Rediset, Sasobit, Sasoflex or Foamtech) and percentage reclaimed asphalt content (10% or 40% RA) are evaluated against their equivalent HMA control mixes. From the laboratory test data analysed in chapter 4 the following conclusions and recommendations are made:

- For all intents and purposes the surface (Type D) 10% RA 60/70 unmodified trial WMA (Rediset and Sasobit) mixes performed equivalent to their corresponding control (HMA) mix in terms of flexural stiffness and fatigue life. This means that the WMA technologies incorporated in the WMA mixes successfully reduced production and paving temperatures without compromising the performance of the mixes.

- In terms of phase angle results (visco-elastic behaviour of mixes) for the surface (Type D) mixes, the Rediset (WMA) mix yields a more elastic, less viscous binder and be more resistant to rutting than the Sasobit (WMA) and control (HMA) mixes at low temperatures (5° C). The Sasobit (WMA) mix shows a more viscous, less elastic binder and is more resistant to fatigue than the control (HMA) and Rediset (WMA) mixes at low temperatures (5° C). For higher temperatures (25° C), the WMA (Rediset and Sasobit) mixes are more resistant to fatigue than the control (HMA) mix at 25° C.

- The base (Type B) 40% RA 80/100 AE-2 (SBS) and 10% RA 60/70 AE-2 (SBS) elastomer mixes both displayed similar trends in their performance. In both cases the Sasoflex (WMA) mixes performed equivalent in terms of flexural stiffness to its corresponding control (HMA) mixes. For the 40% RA 80/100 mixes the control (HMA) mix depict a better fatigue life than their equivalent Sasoflex (WMA) mix but are still very comparable. For the 10% RA 60/70 mixes the Sasoflex (WMA) mix display equivalent fatigue performance as their control (HMA) mix. Further testing and research should be done to validate the findings.

- The phase angle results for both cases shows that the Sasoflex (WMA) mixes compared very well with their corresponding control (HMA) mixes at low temperatures (5° C). For higher temperatures (25° C), the 40% RA 80/100 Sasoflex (WMA) mix is more resistant to fatigue cracking than its control (HMA) mix and the 10% RA 60/70 mixes show equivalent visco-elastic behaviour.

- The base (Type B) 40% RA 80/100 AP-1 (EVA) plastomer Rediset (WMA) mix shows an overall lower flexural stiffness than the equivalent control (HMA) mix. This could be attributed to the low void content of the control (HMA) mix and the less aged binder of the Rediset (WMA) mix due to lower production temperatures. The Rediset (WMA) mix displays a slightly better fatigue life than the control (HMA) mix. Further research concerning the less aged binder in WMA mixes relative to HMA mixes is recommended.

- The phase angle results for Type B 40% RA 80/100 AP-1 (EVA) plastomer Rediset (WMA) mix depict a less elastic, more viscous and more resistant to fatigue cracking than the equivalent control (HMA) mix at lower temperatures (5° C). For higher temperatures (25° C) the phase angle values become more comparable and these two mixes are similar in terms of visco-elastic behaviour.

- For the base (Type B) 10% RA 60/70 AP-1 (EVA) plastomer mixes, both WMA (Rediset and Foamtech) mixes have an overall higher flexural stiffness and is more resistant to rutting than their equivalent control (HMA) mix. Overall the Foamtech (WMA) performed weaker in terms of fatigue performance than the control (HMA) and Rediset (WMA) mixes, which in turn compared well with each other. This is attributed to the high void content of the Foamtech (WMA) mixes.

- The phase angle results for the base (Type B) 10% RA AP-1 (EVA) plastomer mixes show that the Rediset (WMA) mix is more resistant to rutting than its corresponding control (HMA) mix for low and high temperatures. The Foamtech (WMA) mix display higher resistance to fatigue at low temperatures (5° C) than the two other mixes but for higher temperatures it is more comparable with the two other plastomer mixes.

- Comparing the AE-2 (SBS) elastomer control (HMA) mix with the AP-1 (EVA) plastomer control (HMA) mix for the base (Type B) 40% RA 80/100 and 10% RA 60/70 mixes, shows the influence of the modified binder type on mix performance. The plastomer mixes display a slight higher flexural stiffness and hence better resistance to rutting than the elastomer mixes which is to be expected from a plastomer modified mix. The elastomer mixes has a longer fatigue life than the plastomer mix which is expected from an elastomer modified mix.

- Comparing the AE-2 (SBS) elastomer Sasoflex trial (WMA) mix with the AP-1 (EVA) plastomer Rediset trial (WMA) mix for the base (Type B) 40% RA 80/100 mixes, shows the influence of the WMA technology and modified binder type on mix performance. These two mixes performed relatively equivalent in terms of flexural stiffness and fatigue performance. This means the Rediset WMA technology added to the plastomer modified (EVA) binder improved the fatigue performance and the Sasoflex WMA technology added to the elastomer modified (SBS) binder improved the flexural stiffness and rut resistance.

- Comparing the AE-2 (SBS) elastomer Sasoflex trial (WMA) mix with the AP-1 (EVA) plastomer Rediset and Foamtech trial (WMA) mixes for the base (Type B) 10% RA 60/70 mixes, shows the influence of the WMA technology and modified binder type on mix performance. The two plastomer mixes has a generally higher flexural stiffness and is more resitant to rutting than the elastomer mix, which is to be expected from a plastomer mix. The Rediset mix has a better fatigue life than the other two mixes and the Sasoflex mix has a better fatigue life than the Foamtech mix. This means that the Rediset WMA technology improved the fatigue performance of the plastomer mix.

- By comparing the flexural stiffness of the elastomer and plastomer mixes at fixed frequencies, the effect of the % RA content was investigated. Firstly, it was noted that the 40% RA mixes showed a slight better rutting resistance when compared to its corresponding similar 10% RA content mixes. This does not mean that adding more RA content to the mix will always increase the rutting resistance of the mix. Other variables like void content and bitumen type (60/70 vs. 80/100) also played a role in the results.

- By comparing the fatigue results at fixed strain levels for the elastomer and plastomer mixes on bar charts, the effect of the % RA Content was investigated. It was found that the comparisons of the results did not give sensible conclusions which could mean that the effect of the % RA content was not significant enough to display consistent and significant differences. Other factors also contributed to the varied results such as void content and different binder grades (60/70 vs. 80/100). These added variables make it difficult to compare the results and effectively note the effect the % RA content will have.

## 6.3 RECOMMENDATIONS

- It is recommended that additional testing and evaluating of WMA mixes with different WMA technologies, modified binders and RA contents should be conducted to validate these findings and to calculate the mix recipes needed for a desired performance.

- Increased monitoring and control should be carried out when compacting mixes since several of the mixes tested in this study did not reach the required optimum void content of 4% (some mixes differed by 2-3%) which has a reckonable influence on the performance results.

- When comparing different mixes one should try keep as many variables as possible constant and only vary one or maximum two variables so to effectively investigate the effect of the varied variable. (Without any other variables contributing to the results) This will increase the effectiveness of comparing mix results.

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