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Warm Mix Asphalt with Sasobit
An Investigation of Performance Improvements

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Declaration

To the best of my knowledge and belief this thesis contains no material previously published by any other person except where due acknowledgement has been made.

This thesis contains no material which has been accepted for the award of any other degree or diploma.

Signature: ……… ……………………………

Date: ……………September 2018………………………………………

Abstract

Roads have different functions which are equally important, and the development of networks should take into account different considerations and always meet the needs of the population, using the best available technology. Australia, with an extensive road network, is no exception to this advancement. In the road construction industry, Hot Mix Asphalt (HMA) has been the main material used for many years. The asphalt industry over the last thirty years, in response to increasing concerns about environmental and economic issues, has constantly developed and made use of processes which reduce the mixing and compaction temperatures of the asphalt mixture without negatively affecting the mechanical properties of the mix.

Temperature plays a vital role during mixing of the asphalt mixture, paving, and compaction, to ensure full coating of the aggregates. These actions must be achieved within a certain temperature range before cooling, as climatic conditions usually prevent further compaction; hence the development of Warm Mix Asphalt (WMA) technologies. These technologies and processes have been developed to allow a significant lowering of the production, paving and compaction temperatures – compared to conventional HMA – without compromising the quality of the mix, thus the pavement performance.

WMA can assist in the achievement of uniform compaction levels across the pavement surface: a desirable property to ensure a high-quality pavement. WMA improved density tends to decrease permeability and binder hardening due to ageing, resulting in an improved performance in terms of moisture sensitivity and cracking resistance. WMA firstly lowers the production temperatures; this is associated with environmental benefits. It has the potential to allow the asphalt paving to extend into cooler weather, which is not the case for HMA. It permits longer transport distances, where the cooling during transportation will still allow compaction to be achieved at high standards, which again is not the case for HMA. This is an extremely important issue in Western Australia where distances are vast and the use of asphalt becomes uneconomic at greater distances from existing plants.

Several studies have been performed overseas and within Australia to evaluate the properties of WMA, and have reported on the potential benefits of the mix in connection to improved performance. However, no detailed study has been carried out in Western Australia using local materials and equipment. This study presents the evaluation of the potential benefits of producing WMA, using the organic additive Sasobit at different percentages, under Western Australia conditions in comparison to the conventional HMA. The objective is to influence the widespread use and implementation of WMA in Western Australia. The thesis examined, in detail, the characteristics of WMA, and its alleged benefits and drawbacks, with the purpose of validating WMA with Sasobit as a viable alternative to HMA.

The study investigated both the HMA and the WMA mixes, focusing on one major factor: the comparison of the performance of both mixes under the same conditions. The study includes a comprehensive literature review of asphalt and WMA technologies, to determine the performance suitability and potential benefits for Western Australia, in relation to energy cost, transportation range and the reduction in emissions, in comparison to HMA. This was achieved through the observation, documentation, production, placement and performance measurement of HMA and WMA in determined local areas. The road pavements were observed for several years to evaluate their performance, and to allow for comparison of the mixes over time.

The study performed extensive testing – laboratory and field – using all approved methods from the regulatory institutions. Testing was performed to determine the postulated benefits in terms of stiffness, rut resistance, tensile strength ratio and fatigue performance, and the effect of Sasobit on the life and costs of Western Australia pavements, with the additional environmental benefits. Sasobit seems a viable additive to reduce mixing and compaction temperatures. All data collected, and the respective results of the mixes, was used to determine the precise percentage of Sasobit to use for different road functions.

Furthermore, the study evaluated the results and verified the suitability of WMA mixes with Sasobit for implementation in Western Australia.

The study focused on the performance of WMA with Sasobit which, used at a rate of 3% to 6%, will produce a mix characterised by high stiffness, high durability, high resistance to permanent deformation, good fatigue resistance and good workability. This enables WMA with Sasobit to be used for roads with high volumes of traffic, airports, race tracks, and container terminals, among others, but with the additional benefits of contributing to the environment through lower emissions, lower temperatures, and better conditions for the asphalt workers.

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List of Abbreviations

AAPA	Australian Association Pavement Association
AASHTO	American Association of State Highway and Transportation Officials
AC	Asphalt Concrete
AMPT	Asphalt Mixture Performance Tester
AS	Australian Standard
AVC	Asphalt Vibratory Compactor
a_1, a_2	Fitting coefficient
BGC	Buckeridge Group of Companies
BIT%	Percentage of bitumen
B,γ	Shape parameter
CH_2	Methylene
CH_4	Methane

CMA	Cold Mix Asphalt
CO	Carbon Monoxide
CO_2	Carbon Dioxide
DAT	Dispersed asphalt technology
DGA	Dense graded asphalt
E	Estimated Resilient Modulus
E*	Dynamic Modulus
EAPA	European Asphalt Pavement Association
EPA	Environmental Protection Agency
ET	Emulsion technology
ε_t	Peak tensile strain
FGGA	Fine gap graded asphalt
FHWA	Federal Highway administration
FI	Film index
f	frequency
fr	Reduced frequency
GHG	Greenhouse gases
Gj	Gas
H	Recovered horizontal deformation after application of load
HMA	Hot Mix Asphalt
Hz	Hertz
h	beam height
h_c	Average height of specimen
ISCA	Infrastructure Sustainability Council of Australia
ITS	Indirect Tensile Strength
kPa	Peak Tensile Stress

kN	Newton Unit of force
L	Beam span
LVDT	Linear variable displacement transducers
MATTA	Materials Testing Apparatus
MRWA	Main Roads Western Australia
M_1	Mass of Buschner flask in water
M_2	Mass of test portion in air
M_3	Mass of flask
m_{EF}	Mass of matter in extraction fluid in grams
m_{FR}	Mass of matter on filter ring in grams
mp	Mass of the material passing the sieve in grams
m_1	Mass of test specimen in grams
m_2	Mass of suspension device immersed in water
m_3	Mass of specimen
m_4	Mass of oven dish and contents
N	Newtons
NAPA	National Asphalt Paving Association
NATA	National Association of Testing Authorities Australia
NCAT	National Center for Asphalt Technology
NCHRP	National Cooperative Highway Research Program
NO_x	Nitrous oxides
N_2O	Nitrous oxide
OGA	Open graded asphalt
P	Peak load
PAH	Polycyclic aromatic hydrocarbons
Pas	Pascal seconds

P_{BIT}	Density of bitumen at 25 ºC in t/m^3
P_{bulk}	Bulk density of test specimen
P_{max}	Maximum density of asphalt
PMB	Polymer Modified Binders
P_p	Percentage mass of material passing each sieve
PSD	Particle Size Distribution
P_w	Density of water at 25 ºC
QA	Quality assurance
QC	Quality Control
Q_{BIT}	Total binder content
Q_{EB}	Effective binder content
RAP	Recycle Asphalt Pavement
RTA	Road and Traffic Authority
RTFO	Rolling Thin Film Oven
SMA	Stone Mastic Asphalt
S_{mix}	Flexural Stiffness
SO_2	Sulfur dioxide
SP	Softening Point
TOC	Total Organic Compounds
TRB	Transportation Research Board of the National Academies
TSR	Tensile Strength Ratio
TTS	Time Temperature Superposition principle
T_R	Reference temperature
VFB	Voids Filled with Bitumen
VMA	Voids in Mineral Aggregates
VOC	Volatile organic compounds

V_{sample}	Volume of test specimen in cm^3
v_{wax}	Volume of paraffin wax
WA	Western Australia
WAM	Warm Asphalt Mix with foam
WMA	Warm Mix Asphalt
w	Beam width

1 Introduction

Society cannot develop without infrastructure, particularly road infrastructure. Its importance has been prevalent throughout history, with an excellent example of this being the roads of the Roman Empire. Suter (2015) stated that Roman roads are a ‘lasting physical monument to what civilization achieved’. Roads and road improvements are therefore an intrinsic part of any society, and thus a long-term infrastructural vision is vital. Innovation, then, is crucial for Australia’s infrastructural road vision; it has the capacity to boost growth in many industries, especially transport which is essential to the Australian economy.

Due to the utmost significance of the road network in the economic development of the country, each year millions are spend on building new roads and maintaining existing roads around Australia. The asphalt industry is continuously involved in developing and improving products and their performance.

Asphalt mixes are produced at high temperatures of around 170 °C, and placed hot at temperatures between 140 °C and 150 °C for conventional mixes, and 180 °C for mixes modified with polymers. This requires a significant amount of energy, and produces emissions which, although not high, still have an environmental impact. Furthermore, the time available for compaction is limited. Nevertheless, hot mixes require elevated temperatures due to the asphalt viscosity characteristics to achieve a homogeneous mix of the aggregates and bitumen. If a reduction in the mix viscosity is attained at normal temperature, then it is possible to reduce the temperature. On the other hand, if it is possible to improve the workability of the mixture, it is also possible to reduce the compaction temperature.

The investigation of Warm Mix Asphalt (WMA) with Sasobit (an organic additive), was performed specifically for Western Australian materials and conditions. The significance of this study was to investigate the effects of different percentages of the additive Sasobit (organic wax) on the binder, using local materials only. Experience in New South Wales mentioned that for better evaluation and trial purposes in Australia, wax additives and the zeolite technologies were more practical (Figueroa et al, 2007). Wax lowers production temperatures and improves the properties of asphalt, thus achieving all relevant specification parameters. On that basis, Sasobit was chosen as the additive for this research.

To reduce the temperatures needed in the processes of elaboration and compaction, many WMA technologies are available today. The three major categories are organic additives, chemical additives and foaming, all of which must meet certain conditions. The most important conditions are that they should not adversely affect the asphalt binder, and that they should allow for the attainment of an asphaltic mixture of similar or superior properties to conventional hot mix asphalt (HMA).

Technical advantages of using lower temperatures include: less compaction effort, fewer gas emissions, longer storage and hauling distances, less oxidative hardening of the binder and hence reduced cracking on the pavement, reduction of thermal segregation phenomena, less asphalt aging, greater workability of the mixture, reduced cooling rate, less wear and tear of the plant parts, lower risks for workers (less fumes and temperatures) and a larger working window, even outside of the good weather season (Austroads, 2014). WMA also permits the reopening of the covered section to traffic sooner than HMA. Undoubtedly, this is an advantage especially in urban areas, not only during paving but also in patching operations. Consequently, the purpose of designing WMA with Sasobit in this study is not only to determine the optimal proportions of Sasobit in the production of asphaltic mixes for WA conditions, but also to make use of all the above-mentioned advantages.

Asphalt requires certain specifications to be met; with the addition of the organic additive Sasobit, one needs to ensure that all the properties of the mix are fit for the purpose so that they are high quality and hardwearing. It has been proven that Sasobit at high dosages improves the stiffness of the mix, which improves deformation resistance and reduces rutting and ravelling of the pavement, which are some of the most common known pavement distress issues (Sasol Performance Chemicals, 2016). Also, Sasobit is one of the technologies accepted for use in Western Australia by the regulatory institution, Main Roads Western Australia (MRWA).

This research aims to develop an understanding of the investigation into new technologies and provide a thorough understanding of the properties and performance of the WMA mixture with Sasobit, leading to successful implementation. WMA was developed in the field of road pavement technologies to improve workability, production and compaction temperatures of asphalt mixtures. The mixtures are produced at lower temperatures than those typically used in the production of HMA, with HMA production temperatures usually ranging from 150 °C to 180 °C. HMA is the primary and preferred mixture for road construction at present. The study also includes the laboratory performance of the mix compaction and the current methods used for the determination of WMA density and functioning, as well as the performance of WMA in the field.

The purpose of using WMA with Sasobit is to determine the suitability for the Western Australian aggregates and conditions, while reducing energy consumption and the corresponding emission of greenhouse gases (GHG). Therefore, the proportions of bitumen, crushed aggregates and Sasobit required in the production of WMA are essential. That is, WMA should meet the set specifications and result in a high-quality, durable and reliable product. A fundamental aspect of the mix design is to ensure that the volumetric properties of the asphalt are fit for the purpose. MRWA and the Australian Asphalt Pavement Association (AAPA) have established standard specifications for volumetric properties in the design and construction of dense grade HMA. Dense grade asphalt mixture was used to produce WMA in this research. Setting standards and specifications ensures quality control (as much as possible) and avoids or minimises the probability of the pavement undergoing distress such as deformation, cracking and moisture-related damage. Any of these issues could alter the service-life of the asphalt.

Despite its presence in WA, there has been little use of Sasobit over the past decade; MRWA has published some specifications (wearing and intermediate courses). Austroads (2012) stated that there are some concerns with the product in relation to the security of Sasobit supply and the use of Sasobit in other than a batch plant. The concerns are mainly in relation to moisture sensitivity where it is considered an issue if the process of drying is rushed, particularly in drum plants (Austroads, 2012). In Australia only some states, such as Queensland, have developed their own specifications. In Western Australia MRWA standard specification sections 504 and 510 establish specifications for WMA with Sasobit.

At present, the standard specifications to measure density for quality control (QC) and quality assurance (QA) are stipulated by MRWA, AAPA and Austroads. Mechanical testing to determine the performance and empirical properties of WMA use the following tests:

- The Indirect Tensile Strength (ITS), through which the resilient modulus of the mix is measured
- Wheel tracking (measures deformation resistance)
- Tensile Strength Ratio (TSR) which measures moisture sensitivity
- Fatigue resistance
- Stability and Flow
- The Dynamic Modulus which measures the stiffness of the mix
- Plus methods used to determine the volumetric properties of asphalt.

The acceptance of the HMA pavement – the same as for WMA – relies on the accuracy of measurements, particularly the volumetric properties. This research used these methods to validate WMA performance.

The aim of producing WMA mixtures is to achieve a product with similar or better durability, strength and performance characteristics as HMA, through substantial reduction in production temperatures. Decrease in temperature would result in environmental and health benefits, including lower fuel consumption, fewer greenhouse gas emissions, and less exposure to fumes and high temperatures for asphalt workers. These benefits, along with pavement performance improvements by reducing binder aging, extra time for mixture compaction and improved compaction during cool weather, make the implementation of WMA a viable option for paving operations.

1.1 Background

HMA is normally produced in either a batch or drum mix plant, in which the bitumen and the aggregates are heated to temperatures fluctuating between 160 °C and 170 °C, guaranteeing an appropriate viscosity to cover all the aggregate particles. Then, the mix is compacted while still hot at temperatures ranging from 140 °C to 150 °C, which contributes to the attainment of good compaction results (Austroads, 2014).

Temperature is an essential element in the production of hot asphalt mixes. However, due to the chemical composition and high temperatures of the mixes, some of the volatile elements are released in gas form (e.g. carbon dioxide, sulphur dioxide), which are quite harmful to the environment. As time progresses, the effects of this damage are being felt around the world. Sutton (2002) states, those emissions can be classified within a general term of fugitive emissions which refers to material transfer between plant components. These emissions are divided into two categories:

- Invisible emissions – primarily consist of non-condensable volatile organic compounds (VOC_S) that are part of the production of ground-level ozone (smog).
- Visible emissions – there are two types. The visible dust emissions generated at conveyors, stockpiles and roadways, and the others that contain heavier hydrocarbons (compounds made of hydrogen and carbon molecules) that readily vaporise at temperatures around 150 °C. They condense in ambient air and are absorbed to dust and water particles. These emissions have a characteristic fuel odour.

Dorchies et al. (2005) at the United Nations conference on the environment and sustainable development in 1992 stated that it ‘was the inception point for the world to be aware of the direct threat’, particularly climate change. To control some of the harm done by greenhouse gas emissions, many countries signed the Kyoto Protocol in 1997 (United Nations Framework Convention on Climate Change), in which they pledged to reduce emissions. The Kyoto Protocol was designed to halt greenhouse gas concentrations that some believe are the cause of global warming. The road construction industry recognised the need to carry out an effort focused on the preservation of the environment.

Throughout the world, concerns regarding the pollution of airways and the effect of carbon dioxide as a greenhouse gas are driving the demand for cleaner, less energy-intensive methods of production. This applies very much to road construction where energy inputs during manufacture are significant. Therefore, new methods and technologies are always developed and sought after with the aim of improving material and pavement performance, increasing construction performance and reducing emissions.

Hence, road infrastructure – which underpins economic progress – has quite an extensive record of trying to keep pace with the growth. The story of asphalt started thousands of years ago; it was in 1824 in Paris that, for the first time, natural asphalt rock was placed on what is known today as the Champs-Elysees. Later, in 1870, Edward J. de Smedt invented modern road asphalt at Columbia University in New York City. He patented it (U.S. Nos. 103,581; -2) and called it ‘sheet asphalt pavement’, later known as ‘French asphalt pavement’ (Asphalt History, n.d).

On 29 July 1870, the first sheet of Edward de Smedt's asphalt pavement was laid on William Street in Newark, New Jersey. He then engineered what is known as ‘well-graded’ maximum-density road asphalt. The first uses of this road asphalt in 1872 were in Battery Park and on Fifth Avenue in New York City United States of America (USA), where 94% of the paved roads are of bituminous surface. Meanwhile, in Australia, the national percentage is 43.5% (The World Bank, 2009). Bituminous surfaces comprise both asphalt and spray seals; the relative proportion of each is unknown.

Australia has an extensive road network with a total over 823,000 kilometres (Australian Bureau of Statistics, 2009), of which 154,000 kilometres are in Western Australia, where 43% is surfaced with bituminous materials or concrete, with concrete being a very small percentage (Bureau of Infrastructure, 2012). Asphalt is the preferred material used for the construction of roads, as well as airport runways, where HMA has been the main mix used for road surfacing in most urban roads for many years. In Australia, 7.6m tonnes of asphalt were laid in 2010, of which 850,000 tonnes were laid in WA.

The concept of lowering temperatures to produce asphalt mixes is not new. It began in 1956 when Dr. Ladis H. Csanyi investigated the potential of introducing moisture into a stream of HMA during the cold production of bituminous mixtures, Cold Mix Asphalt (CMA) (Jenkins, 2000). This resulted in the foaming of the bitumen, which has been successfully used in many countries. Foam allows for a lower production temperature process that involves injecting steam into the hot bitumen. Mobil Oil, Australia, obtained the patent rights to professor Csanyi's invention in 1968 and modified the original process by replacing the steam with cold water, allowing the process to become more practical (Bowering & Martin, 1976).

In the last twenty years, with an increasing concern regarding global warming, rising energy costs and increasing emissions, the road construction industry has searched for new technologies to reduce the temperature – hence the amount of energy – required to produce HMA. Energy savings and environmental benefits saw the concept of WMA further developed in Europe. Since then, countries like Germany have used waxes as binder viscosity modifiers.

Since the 1970s researchers have been trying to reduce the temperature for producing, placement and compaction of asphalt (Zettler, 2006). One product with encouraging results is Warm Mix Asphalt. The first WMA techniques were developed in the late 1990s based on wax or foamed asphalt. In Germany additives were trialled, while in Norway the WAM-Foam process was developed (European Asphalt Pavement Association, 2015). Since then, a few other WMA processes have been developed in Europe and the United States. In 1995, a program was developed to find a product and a process for the manufacturing of asphalt at lower temperatures. Then, in 1999, a new process was introduced, known as half warm foamed bitumen treatment, which explored the possible benefits of heating a wide variety of aggregates to temperatures above ambient but below 100 °C before the application of foam bitumen (Jenkins et al. 1999).

In the same year, the first initial reports on WMA were presented at the Eurasphalt /Eurobitume, in both the German Forum on Bitumen and the Asphalt Conference in South Africa. At the first world conference on Asphalt Pavements in Victoria, Australia in 2000, Harrison and Christodulaki reported on the Warm

Mix Asphalt process while later that same year Koenders et al. presented a paper describing an innovative warm mixture process, that was tested in a laboratory and evaluated in large-scale field trials in different countries, such as Norway, the United Kingdom and the Netherlands; production and laying refers to dense graded wearing courses. Afterwards, the development of WAM-Foam (Warm Asphalt Mix with Foam) came about.

In 2011 in the United States, the National Cooperative Highway Research Program (NCHRP) recorded 22 different processes used in the production of WMA (report number 691, project 09-43, Mix Design Practices of WMA). Nowadays, WMA use is increasing in first world countries.

WMA is mainly divided into three main categories: the organic, chemical and foaming, with the key factor being lowering the production temperature. As mentioned previously, the main difference between the design of HMA and WMA is the temperature. For HMA, the heated aggregates and hot bitumen are mixed at temperatures ranging from 160 ºC to 170 °C for production and compacted between 140 °C and 150 ºC. For WMA production, temperatures range between 130 ºC and 150 °C and compaction occurs between 120 °C and 130 ºC. It needs to be noted that there are many asphalt mixes, each designed for a specific application, with variations in grading, bitumen type and content, and maximum aggregate size.

Initial procedures to produce WMA used waxes as organic additives or foam as a mechanical method. In the case of wax, when added to hot bitumen and heated beyond the melting point, the viscosity of the bitumen reduces without the need to increase the temperature. The fundamental part of this process is that the melting point of the wax is below the bitumen melting point.

At the Eurobitume congress in 2003, Barthel et al. introduced the use of a synthetic zeolite additive to produce warm mix asphalt. The zeolite creates a foaming effect that results in high workability of the mix. Later in 2005, the National Center for Asphalt Technology (NCAT) published two reports on the use of Sasobit, a synthetic wax, and Aspha-min, a synthetic zeolite. Then in 2007, a team of materials experts from the USA visited several European countries to evaluate several WMA technologies. The aim of the trip was to validate WMA as a viable alternative to HMA. They identified several benefits: among them, environmental aspects, sustainable development, compaction improvements and better working conditions for workers. Since then, many municipalities and state agencies in the USA have performed trials and implemented WMA with positive and reassuring results. Due to the encouraging results Warm Mix technologies have increasingly been used in the United States, Europe, South Africa and – to some extent – in Australia in recent years.

Since WMA can be produced and placed at lower temperatures than HMA, asphalt plants could be located in areas that are not permitted at present – a direct result of the lower gas emissions. The restrictions are in relation to environmental contamination. The reduction in temperature using organic additives lowers the bitumen viscosity, improves material workability and handling, and lowers emissions. Asphalt mixed with Sasobit allows the production and placement of the mix to be performed at temperatures well below 170 ºC (the conventional temperature of HMA).

Based on data, WMA can reduce emissions from asphalt plants. This is achieved due to a significant reduction in production and compaction temperatures. Several studies have been conducted to evaluate the properties of WMA; however, most of these studies have been done overseas or under different conditions within Australia. Therefore, WMA needs to be examined in the context of the extensive Western Australian road network which covers a huge area with a low population density.

Furthermore, no investigations have further examined the performance benefits of WMA with Sasobit in terms of life span and cost, and how the improvements in performance could contribute to the road network. The benefits (if any) will be demonstrated through the analysis of the mixes and their performance.

1.2 Objectives

The overall objective of the research is to evaluate the performance of WMA using the organic additive Sasobit, in comparison to the performance of HMA. The investigation examines the effect/s of Sasobit in an asphaltic mix under WA conditions and materials.

Two field trials were done in areas with controlled conventional asphaltic mix (HMA) and WMA, with the aim of performing valid comparisons using the same equipment and workers in every case. Simultaneously, laboratory and field tests were performed before and following the completion of the sections to analyse the design mix properties. Among them the volumetric properties, field density, air voids and performance (permanent deformations, water resistance, dynamic modulus and resilient modulus).

The central research idea is to observe the feasibility of using an asphaltic mix that can be produced and placed at lower temperatures than those normally used, with the aim of obtaining similar – or even better – results. It was necessary to reduce the temperature by at least 20 °C to 25 °C, at production and compaction of the asphalt mix.

The objectives of this research include the following:

1. To conduct a thorough review of WMA literature.

2. To register all data concerning climate, traffic, paving operations and quality control of the trials (laboratory and field).
3. To document WMA with Sasobit at different percentages, including tests on materials, production, compaction and all data that permits the evaluation of the results.
4. To determine the applicability of Sasobit in the manufacture of WMA and the environmental and economic benefits (if any) derived, specific to the Western Australian context.
5. To determine the performance of WMA with respect to HMA in terms of viscosity of binder, mix composition (binder content), volumetric properties (maximum/bulk densities and air voids), Marshall Stability (Marshall compacted samples), Resilient Modulus (Indirect Tensile Strength), moisture sensitivity (Tensile Strength Ratio), Dynamic Modulus, Fatigue Resistance and Wheel Tracking (Rutting performance)
6. To determine the optimum concentration of Sasobit for the mix depending on road use.
7. To evaluate the laboratory mix to determine the optimum temperature/s of compaction of WMA with Sasobit.
8. To evaluate the mix on field performed under the same climate, load, drainage and structural conditions, both with and without Sasobit.
9. To analyse the comparative costs of conventional HMA and WMA with Sasobit.
10. To provide recommendations for future and further investigations in this area.

The findings from this study will be used to develop recommendations for:

- Validating WMA as a viable environmental alternative to HMA and its implementation.
- Contributing to the improvement of current practices (specifications), and contributing to lower greenhouse gas emissions and workers’ welfare.

1.3 Significance

The significance of this work is twofold:

- To determine the overall mix design benefits by using WMA with Sasobit when viewed in a Western Australian context considering the environmental benefits of energy consumption and road lengths.
- To extend the research into areas where the postulated performance improvements offer considerable long-term contribution to Western Australia’s industry, economy and environment.

1.4 Thesis outline

This thesis has six chapters, including an introduction:

Chapter 1

Comprises an introduction into the entire research study and highlights the background, objectives and methodology of the study.

Chapter 2

This chapter includes a thorough review of literary and theoretical background concerning the research of asphalt and WMA, as well as a detailed review of literature pertaining to the current WMA technologies. Plus a review of mix materials and methods used for testing both volumetric properties and performance testing.

Chapter 3

This chapter comprises a sustainability factor section together with the definition and function of WMA with potential benefits and drawbacks. Includes WMA technologies and categories, and a summary of WMA products available, especially mentioning the additive Sasobit: the subject of this research. Also, includes a brief summary of some WMA trials around the world and within Australia.

Chapter 4

This chapter introduces the methodology and experimental design used, as well as testing methods to measure the performance of the mixes.

Chapter 5

This chapter presents data and analysis of the results of all tests conducted throughout the study, including design and analysis for both laboratory and field testing. Also, presents the tested mixes in terms of strength parameters, durability and deformation in controlled and field-environment conditions. Testing was performed using sophisticated testing equipment, trialling different percentages of Sasobit to determine the suitability and evaluation of WMA under Western Australian conditions and materials.

Chapter 6

This chapter presents two trial of field validation of Warm mix in wearing course in comparison to Hot mix and one trial to validate the performance of WMA with 4% Sasobit.

Chapter 7

This chapter presents the conclusion drawn from the study results, together with recommendations for further research.

The objectives and the study approach were carried out using the following methodology as shown on Figure 1.1.

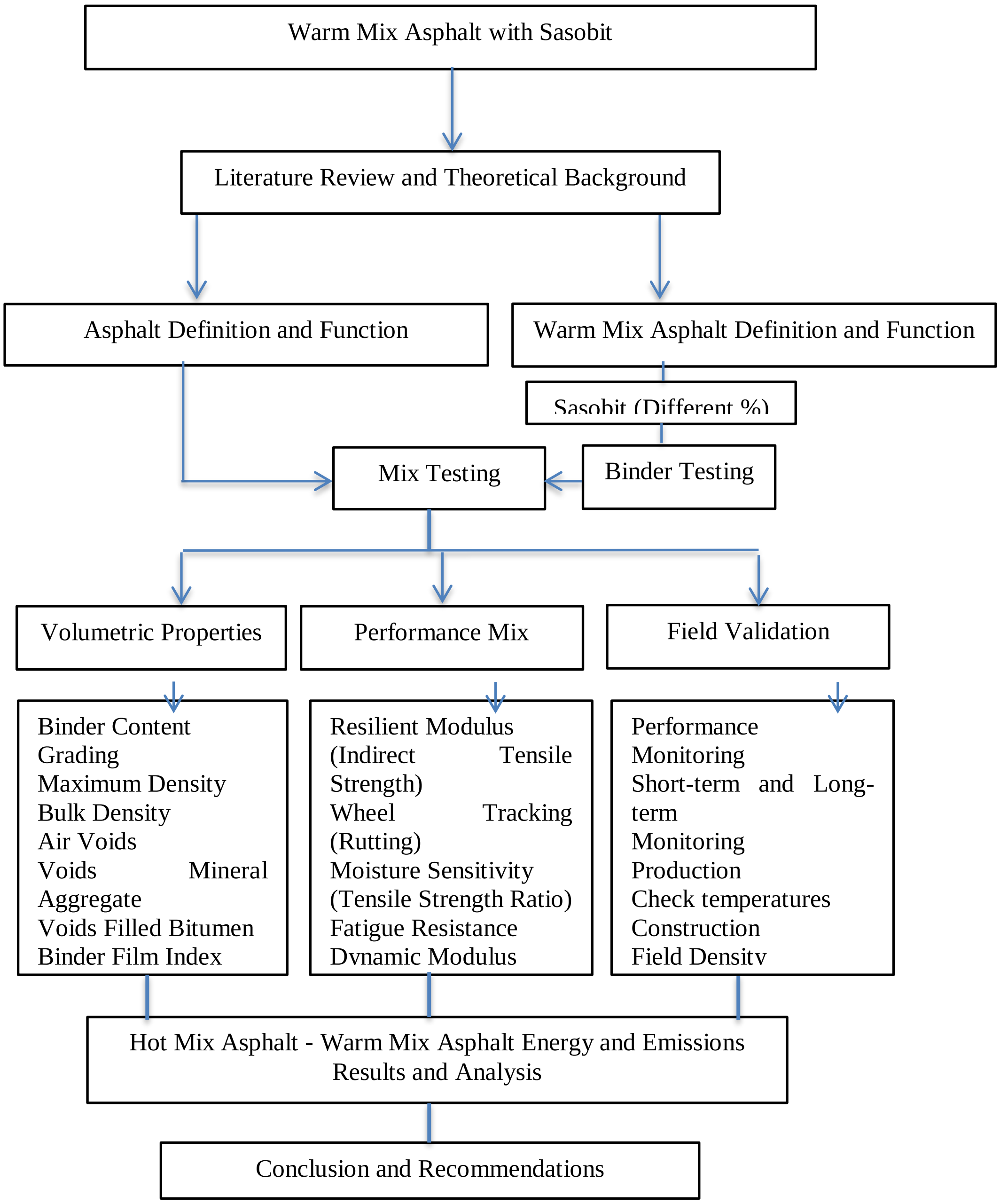


Figure 1.1 Study Methodology

2 Literature Review and Theoretical Background

Overview

This chapter presents a literature review and theoretical background on the significance of roads and the manner in which their performance is paramount and essential to society. Therefore, the asphalt industry is constantly involved in the development of new technologies.

This chapter is divided into twelve main sections. The aim is to develop an understanding through technical and general knowledge of the materials and processes involved in the production, placement and compaction of bituminous mixes - asphalt. The chapter also includes the current methods and the mechanical aspects of quality control used to determine the performance of WMA in comparison to HMA (mixes used in this research).

2.1 Definition and function of asphalt

Asphalt, commonly known as Hot Mix Asphalt (HMA), is the indispensable mixture, primarily used in road construction, which is designed to perform as a specific paving application (European Asphalt Pavement Association, 2015). Generally, an asphalt mixture consists of aggregates (coarse and fine), binder, and filler. HMA is used for constructing, strengthening and maintaining all types of roads including highways, streets, airport runways, driveways and many others. Asphalt is produced at temperatures ranging from 160 °C to 170 °C in a mixing plant, then placed and compacted while hot.

The mixture generally contains approximately 95% of well-graded mineral aggregates, filler, and sometimes additives. Bitumen makes the remaining 5% of the mixture. Consideration is given to the different traffic levels, ranging from light car use and heavily-trafficked roads to pedestrian walkways, including consideration for the range of weather conditions. The appropriate asphalt treatment depends on many factors, such us design, condition of pavement, and surface characteristics among others. The key division among mixes is in terms of particle size distribution hence the diversity of asphalt mixes as they are developed for different purposes. The variances are dependent on the percentage of the aggregates used. Figure 2.1 shows a warm mix paved road.

Figure 2.1 Warm mix asphalt road

Specific percentages of high-quality aggregates are essential to ensure a first-rate product and the durability and quality of the mix. Quality control is crucial for asphalt. Sample testing is required to ensure that a high and consistent standard of asphalt is achieved and maintained, which is obtained by determining the asphalt density.

The manufacture of HMA is usually performed in large fixed plants operating in major cities, with the option of mobile plants outside metropolitan areas. The most common use for asphalt is public roads; hence they are subject to public authority specifications. Work is carried out by contractors under a quality system, which needs to comply with all specifications, including all manufacturing procedures, process control, spreading and compaction procedures, occupational health and safety and an environmental management system (Austroads, 2014). Figure 2.2 shows a WMA paver in operation.

Figure 2.2 WMA paver in operation

The asphalt mixture is laid while it is hot on the surface of the road pavement, either by hand or with an asphalt-paving machine. The usual asphalt layer thickness ranges from 25 mm to 70 mm. Table 2.1 presents the typical mix size for various applications (Austroads, 2014). The mixture is compacted with a vibrating steel drum roller or multi-roller to form a uniform and well-compacted pavement surface (CSR, 2008).

Nominal Mix Size (mm)	Compacted Layer Thickness (mm)
5	15 to 20
7	20 to 30
10	25 to 40
14	35 to 55
20	50 to 80
28	70 to 110

Table 2.1 Asphalt layer thickness (Austroads -2014)

Compaction is the process that follows paving in which the mixture’s air is entrapped in the form of voids between the coated aggregate particles. For a first-rate asphalt surface performance, this entrapped air is of vital importance. It needs to be noted that further densification can occur under normal traffic conditions, and during the expansion of the bitumen in hot weather. All mix designs consist of aggregate grading, filler contents and binder which binds all the materials into a consistent mixture. The result is a cohesive and fluid mix. For testing the method commonly used in Western Australia is the Marshall Method (also used for testing WMA). This method measures the density and permits the calculation of air voids. However, other performance methods are performed to ensure the mix complies with all the specifications.

HMA requires high temperatures to achieve the right balance between low viscosity of the bitumen (to obtain full aggregate coating), good workability during placing and compaction, rapid increase in mechanical strength, and durability during traffic exposure. On the other hand, WMA does not require high temperatures to achieve the same performance.

2.2 Types of Asphalt

Accordingly, as there are different types of roads, there are different types of asphalt. Hence, a diversity of asphalt is used either in the construction of new pavements or for the maintenance of an existing pavement. The aim is to strengthen the road surface, improve the surface irregularities, or to provide a new wearing surface.

During the process of selection of the appropriate asphalt type, a few factors require consideration; among them, the condition of the pavement, reinforcing requirements, asphalt design, and surface characteristics. The mix is selected considering these factors: type of asphalt mix, the layer thickness, the type of binder and aggregate in addition to the nominal size of the mix (Austroads, 2014).

Other elements to consider are: size combination, type and proportions of aggregate, filler, binder, and an additive for warm mix asphalt. These considerations provide the suitable level of structural stiffness, deformation resistance, flexibility, permeability, surface texture and, most importantly, durability (Austroads, 2014).

Types of asphalt are:

- Dense-Graded Asphalt (DGA)
- Open-Graded Asphalt (OGA)
- Stone Mastic Asphalt (SMA)
- Fine Gap Graded (FGGA).

Main asphalt mix types used in Australia are DGA and OGA (Main Roads Western Australia, 2011a).

2.2.1 Dense Graded Asphalt

Dense graded asphalt is a mixture of aggregate particle size, filler and bitumen, which are evenly distributed from coarse to fine. DGA has low air void content, usually ranging between 3% and 7% (Austroads, 2014). DGA is mixed, placed and compacted hot into a dense state which is appropriate for an ample range of uses such as, pavement layering and resurfacing. The in-situ air voids and binder content largely determine the life time of DGA (Austroads, 2014).

DGA requires a uniform grading structure to maximise the intrinsic strength of the aggregate and to keep air voids. It diminishes the possibility of interconnection of void space, consequently not permitting the passage of air and moisture through the surface.

2.2.2 Open Graded Asphalt

Open graded asphalt is a mix characterised by the particle size distribution containing a large proportion of coarse aggregate and a minor amount of fine aggregate and filler, where the aggregates' angular shape is used for texture and a stable surface. OGA has been designed to encourage the passageway of water.

OGA differs from DGA as it has a high air void content generally ranging from 18% to 25%. The mix 'relies largely on mechanical interlock of aggregate particles for stability' (Austroads, 2014). The high air void content can lead to reduction in durability, but this issue can be adapted by using high binder content. In OGA mixes, the aggregate factor is devoid of 'fines' to ensure large void spaces (Aslab, n.d).

Some consequences of using OGA are: reducing tyre noise, glare reflection and water spray, providing a smooth riding surface, and good skid resistance when used as wearing course (Austroads, 2014). Therefore, OGA is used for high-speed multi-lane roads, but it is not recommended for intersections due to its low shear resistance.

OGA are permeable mixes requiring free draining to provide lateral drainage to the edges of the pavement, and to be waterproofed to minimise vertical movement of moisture into the pavement (Austroads, 2014). If water on the surface could become a safety issue, OGA is normally overlayed with DGA, particularly for high-speed roads.

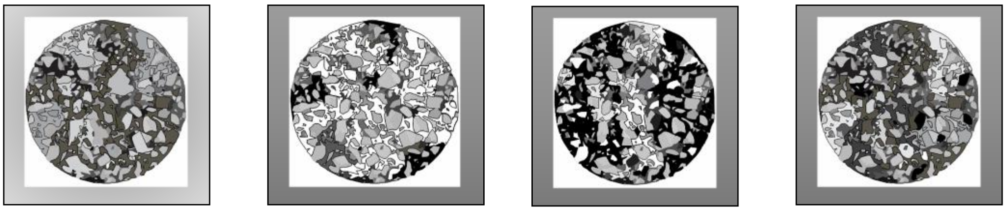
2.2.3 Stone Mastic Asphalt (SMA)

Stone mastic asphalt is a dense wearing course asphalt mix that contains a high proportion of coarse aggregate, resulting in a durable and rut-resistant mixture with a stone-on-stone contact that resists permanent deformation. The mineral aggregate skeleton of SMA is gap-graded and the voids are filled with mastic fine aggregate, filler and binder. It was developed to overcome the issue of rutting due to studded tyres on road surfaces. Among the characteristics of SMA are its suitability for heavily-trafficked roads, high durability, low traffic noise, high deformation resistance, and high resistance to reflection cracking, good skid resistance and low permeability (Austroads, 2014).

SMA is suitable for intersections and other areas of high traffic stress. Following European trends of producing SMA, smaller nominal sizes of 7mm and 10mm are predominantly in use in Australia (Austroads, 2014) as they provide lower surface noise levels, a lesser risk of segregation, and permit a reduced layer thickness, while maintaining a well-textured surface.

2.2.4 Fine Gap Graded Asphalt (FGGA)

Fine gap graded asphalt is a dense mix with a low air void content. The mix contains a large proportion of fine aggregate with a lesser proportion of coarse aggregate. The mix relies on the stiffness of fine aggregate, and filler and binder mixture for stability. It has good fatigue resistance and durability due to its low air voids and high binder content. FGGA is not used as wearing course in heavily trafficked areas due to poor rutting-resistance at high surface temperatures, or in base applications due to reduced stiffness and high production cost (Austroads, 2014). Figure 2.3 shows types of asphalt mixes.



Dense Grade Asphalt

Open Grade Asphalt

Stone Mastic Asphalt

Fine Gap Grade Asphalt

Figure 2.3 Types of asphalt

Similar to the types of asphalt mixes are the WMA technologies, which allow a reduction in temperature in the manufacturing, placing and compacting of the mix, compared to the normal temperatures associated with HMA, thus improving the asphalt workability.

2.3 Compaction factor

A vital part in pavement engineering is compaction: crucial to asphalt performance. It needs to fulfil its purpose of providing an all-weather driving surface that allows for post-compaction densification by traffic. ‘If the asphalt is to perform at its full potential, it needs to be well compacted into a homogeneous layer’ (Read and Whiteoak, 2003). Properly compacted asphalt mix layers are a fundamental parameter concerning the behaviour of the pavement and its durability. The utmost important property of asphalt mix is its density. Compaction is typically conveyed in terms of air void content, which is highly dependent on the efficiency of compaction. Appropriately compacted mixtures have a better rutting and fatigue resistance and longer service life than those which are inadequately compacted. A life service of a poorly compacted pavement could be measured in weeks or months, while a properly compacted mix could be measured in years.

Compaction forces the aggregate particles closer and consequently reduces the amount of air void space within the asphalt layer. ‘Aggregate constitutes about 95% of the mass of asphalt that can have significantly different particle densities depending upon the aggregate’ (Austroads, 2011). Therefore, consideration to the degree of compaction is essential when designing the mixture, as compaction causes the asphalt mix to be compressed and its volume reduced.

Asphalt pavement thickness consists of a few layers where appropriate compaction of each layer is essential before each layer is applied. Compaction increases the resistance to permanent deformation and improves fatigue behaviour, crucial characteristics of an asphalt mix. Compaction can influence the properties of asphalt.

For HMA and/or WMA, density increases and air void content of the mix decreases, thus they are inversely proportional to each other. Therefore, the durability (service life) of the asphalt mixes rest highly on the level of compaction achieved. Figure 2.4 shows a slab with minimum deformation (1.3mm) resulting in a well compacted effort, while Figure 2.5 shows a slab with high deformation resulting in a poor compaction effort.

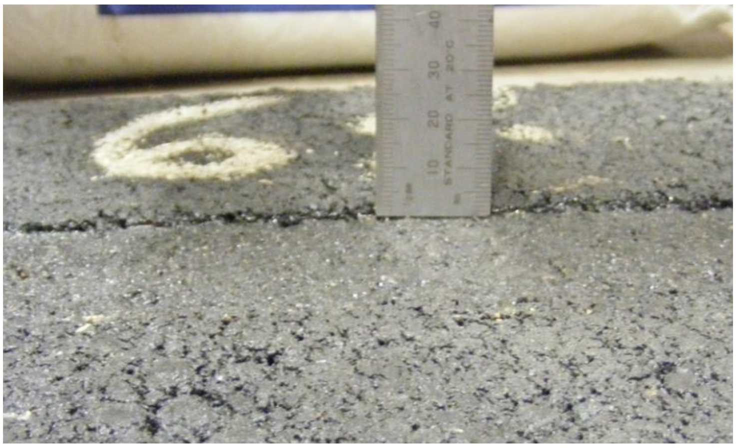


Figure 2.4 Slab with 1.5mm deformation

Figure 2.5 Slab with 12.5mm deformation

The effect of compaction level (air void content), which has been the cause of many studies, concluding that: as the level of compaction augment, positive results are delivered. Some of the benefits include: a reduction in permeability, increased fatigue resistance, increased tensile strength proportion (lower moisture sensitivity), increased mix stiffness, reduced oxidative binder hardening and a reduction in rut propensity. High compaction levels are achieved using WMA, thus the quality of the pavement increases in terms of durability or life extent.

The measurement of compaction varies. Compaction is measured by determining the bulk density of the compacted asphalt which is compared to the maximum density or void less density. Density is defined ‘as the mass per unit volume’ (Austroads, 2011). The volume is quantified as a percentage of air voids by volume which is expressed as ‘percent air voids’. The percent air voids is calculated by comparing a sample’s bulk density with its maximum density (Pavement Engineering, n.d.). It can be determined using different methods. Bulk density is calculated using the following methods:

- Mensuration method

This method measures the spatial dimensions of a sample through the use of a rule or vernier calliper (Austroads, 2011).

- Saturated Surface Dry (SSD)

Performed using water in which displaced water determines the sample's volume.

- Coating method- Waxing

The volume of the sample covered in wax is determined by the volume of displaced water.

- Vacuum sealing method

The sample is vacuum-sealed in a plastic bag and the volume is determined by the volume of displaced water (Austroads, 2011).

Air voids are measured using the Marshall method. Samples are compacted with a Marshall hammer (see Figure 2.6) where pressure and a specific number of blows are applied depending on the pavement and its use. For lightly-trafficked pavements 35 blows are applied; for medium density pavements 50 blows; for heavy duty pavements 75 blows.

Figure 2.6 Marshall hammer in action

Technologies achieving lower temperatures (at production, placing and compaction) than HMA can have a positive impact on the performance of pavements. Technologies like WMA improve the workability of the mix, thus its density (Hurley and Prowell, 2006). Hence, compaction is the key parameter concerning the performance of an asphalt mix.

2.3.1 Laboratory compaction

Several engineering tests are carried out in a laboratory with the purpose of duplicating the compaction attained during the laying of the asphalt on field. The testing of samples is performed to determine if the volumetric properties of asphalt are suitable and comply with the intended purpose. 'The heart of the asphalt mixture design procedures is the laboratory compaction method. It significantly affects the properties of asphalt mixtures by producing its own distinct internal structure. Thus, the selection of the laboratory compaction method has at least as much effect on mix performance as aggregate type, binder type, fines content, or the air void content' (Tashman et al., 2001).

Compaction in a laboratory of an asphalt mix is essentially undertaken as part the mix design process and to produce samples so the volumetric and performance properties can be determined.

Since the most common use for asphalt is public roads, the asphalt mixture has to comply with road agencies' (authorities') specifications. Laboratories use different methods; the main method used is the Marshall method, described in MRWA 731.1- 2016 in which the automated Marshall Compaction hammer is utilised for testing. After the preparation of the test, the sample is placed in the pedestal of the hammer and is compacted. The steel hammer falls freely from a height of 457 mm; afterwards the specimen is inverted, and the same number of blows is applied to the other side of the test specimen. Table 2.2 shows working tolerances for the Marshall compaction hammer.

Apparatus	Value	Working Tolerance
Mass	4.535 kg	±/- 0.02
Drop height	457 mm	±/- 1.0
Foot diameter	98.5 mm	±/- 0.5

Table 2.2 Marshall compaction hammer working tolerances (MRWA 2016)

2.4 Component Materials

Asphalt is a mixture composed of several materials and, as much for HMA and WMA, the quality of materials required to produce high-quality asphalt is essential. Materials include mineral aggregates, filler, adhesion agent and a bituminous binder, plus Sasobit or any other additive to produce WMA. The functions of the aggregate are to provide a surface texture to maintain skid resistance and to avoid disproportionate polish under traffic. The interlocking of the aggregate particles through their frictional resistance to movement provides stability to the mix which forms a hardwearing abrasive resistant material that can resist environmental degradation (Austroads, 2014).

2.5 Aggregate

Aggregates are the major granular solid inert materials used in asphalt production and sealing and are defined as coarse or fine (Australian Asphalt Paving Association, 2003). Classification corresponds to the aggregates passing through a 4.75mm sieve where coarse aggregates are retained and fine aggregates pass, but are retained on a 0.075 mm sieve (Austroads, 2014). The percentage of aggregate for any type of mixture ranges from 93% to 96% (dependant on asphalt mix).

Aggregate functions include:

- To impart stability to the mix (by the interlocking of particles through their resistance to displacement).
- To provide a rough textured surface (maintaining skid-resistance properties).
- To form a durable, abrasion-resistant material (to withstand environmental degradation).
- To spread wheel loads to the lower layers of the pavement (Australian Asphalt Paving Association, 2003).

Aggregates are commonly produced from:

- Crushed and screened quarry products
- Natural sands and gravels
- Manufactured aggregates
- Recycled materials (Austroads, 2014)

The engineering properties of aggregates are influenced by several factors, mainly by the aggregate mineralogy, grain size and texture, aggregate mass structure, and the degree of weathering (Austroads, 2008d).

The aggregate's physical properties determine its suitability for use in asphalt mixes which is determined by its grading, resistance to abrasion, soundness, cleanliness, internal friction and surface properties (Wallace and Martin, 1967). Aggregates are used as base material under foundations, for example roads, and for drainage applications, such a foundation drains, roadside edge drains and retaining wall drains.

The aggregate properties reflect both the process which the material followed and the mineralogy of the source. Properties of the aggregates are: particle size and grading, particle shape, surface texture, resistance to polishing, abrasion resistance, durability and strength, cleanliness, particle density and absorption. Other properties are based on the chemical composition of the aggregate, including the affinity to the bitumen and colour (Austroads, 2014).

Both the aggregate and filler correspond to 85% by volume and 96% by weight of any asphalt pavement (Australian Asphalt Pavement Association, 2007). Aggregates should be resistant to collapse and disintegration from weathering (drying/wetting and thawing/freezing), as breaking apart could cause premature pavement distress. It is possible to assume that the aggregates are directly linked to the durability and strength of the mix. Table 2.3 shows characteristics of aggregates.

Strength	The ability of the aggregate to withstand applied loads in service. This is one of the fundamental performance requirements of all applications, although the absolute strength needed varies with application.
Hardness	The ability of the aggregate to withstand abrasion by other materials that it comes into contact with, mainly relevant to surfacing applications.
Toughness	The ability of the aggregate to withstand impact loadings, mainly relevant to ensuring particle integrity during processing (e.g. mixing) or placement (e.g. during and after sealing).
Soundness	The ability of the aggregate to withstand the effects of fluctuations in moisture content and temperature in service. An essential property in all applications, to ensure that particle strength and integrity is retained.

Table 2.3 Durability characteristics of crushed aggregates (Austroads, 2008d)

The most common known aggregate is the igneous rock which is formed by the cooling and solidification of molten materials. Other aggregates include: basalt, dolerite, granite, andesite, porphyry, diorite and some metamorphic types of rocks that can become altered by the effects of heat and/or pressure. It also includes rocks, such as granulite, gneisses, schists and quartzite. Because aggregates are obtained from different quarries, they fluctuate in specific densities and they differ in size and shape. Aggregates are usually composed of rounded particles, for instance river gravels and some natural sands.

Natural sands and gravels are aggregates that require some form of processing to meet the necessary properties needed for high performance pavements. They can be crushed, screened and washed, or can be obtained as untreated bank run or pit sand (Austroads, 2014). Aggregates are considered essential to the asphalt industry and concrete supply. Products can be specially manufactured for use as aggregates or can be the by-products of an industrial process, such as industrial slag and calcined bauxite (Austroads, 2014).

The properties of aggregates are usually classified into two groups depending on the type of material used (Australian Asphalt Pavement Association, 2007). One group considers toughness, soundness, density, porosity, surface texture, resistance to polishing, and an affinity with bitumen. The other group is reliant on the partially controlled properties, including shape, particle size distribution (grading) and cleanliness (silt, clay and organic matter content). Consideration to the mix design is required in terms of the place/region in which it will be placed, as the properties of the aggregates may differ. A typical delivery tolerance ranges from ±15% for a 26.5 mm sieve to ±5% for a 4.75 mm sieve (Austroads, 2014).

2.5.1 Grading and size of aggregates

Specifications for any asphalt mix design require the aggregate particles to be inside a margin of distribution for the different sizes. Aggregate distribution, usually known as aggregate gradation or mix gradation, is where each particle needs to be present in a specific percentage in a series of sieves. Figure 2.7 and

Figure 2.8 indicate the particle size distribution for 10 mm aggregate and dust gradation.

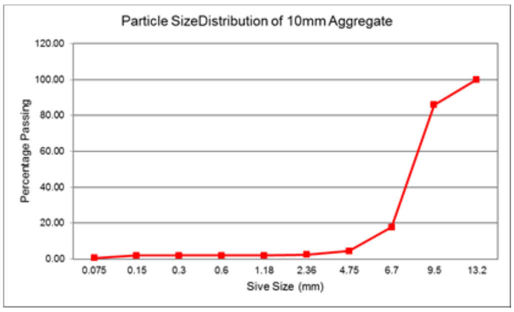


Figure 2.7 10mm aggregate gradation

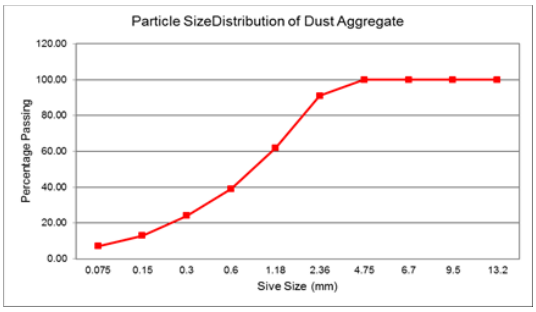


Figure 2.8 Dust gradation

Aggregate gradation affects nearly every important asphalt property including: stiffness, stability, workability, durability, permeability, fatigue resistance and resistance to moisture damage. Specifications determine the type of aggregate most suitable for a specific job as they set a limit to the type and the quantities of undesirable materials, such as vegetation, mudstone, clay lumps and others (Austroads, 2014). These materials could create issues like premature ravelling and stripping.

2.5.2 Cleanliness

Aggregate cleanliness is visually checked, but a wash through a sieve (the weight is compared before and after the wash) provides the precise measurement percentage of the undesirable material finer than 0.075 mm. Generally, crushed material is preferable to natural material because the fractured faces improve bonding and offer better skid resistance. Figure 2.9 shows samples of aggregate.

Figure 2.9 Aggregate samples

The aggregate suitability is evaluated through tests which are stipulated in the Australian Standard AS 1141 Method for sampling and testing aggregates. Tests include:

Flakiness index – Flat or elongated particles tend to break during mixing or when placing: an issue that can significantly change the structure of the asphalt.

Los Angeles abrasion value test: This method gives an indication of the amount of aggregate deterioration that can occur during the mixing and placing processes, indicating the aggregate toughness and abrasion characteristics.

Pendulum friction test (PAFV): The test determines the friction value of the polished aggregate sample (WA 310.1 - 2012 Pavement Skid Resistance: British Pendulum Method).

Water absorption: Determines water absorption of coarse aggregate.

Wet strength: A direct measure of load-carrying ability, it is mainly used for igneous and high-grade metamorphic aggregate.

Wet/Dry strength variation: This method is also known as the 10% fines test. It involves crushing a portion of aggregate and adjusting the applied load to produce 10% of arbitrarily defined fines. The test measures loss of strength due to saturation.

Stripping test value: Determines the stripping value of aggregates.

Degradation factor: It is used as an index of the current stage of decomposition of the source rock used for igneous and metamorphic sources.

Secondary mineral content: The test provides a measure of mineralogical composition and does not involve any failure mechanisms.

Sodium sulphate soundness loss: This test allows for the determination of the aggregate's resistance to disintegration due to weathering action (test measures durability).

Petrographic examination: The rock is examined under a petrographic microscope with the aim of finding the presence and distribution of weaker weathered minerals or minerals that degrade rapidly on exposure to surface environment conditions. Table 2.4 shows test methods and requirements of aggregates.

PROPERTY	REQUIREMENT	TEST METHOD
Los Angeles abrasion value granite and other rock types Basalt	35% Maximum 25% Maximum	WA 220.1-2012
Flakiness index	35% maximum	WA 216.1-2016
Water absorption	2% maximum	AS 1141.6.1
Wet strength	100kN minimum	AS 1141.22
Wet/Dry strength variation	35% maximum	AS 1141.22
Stripping test value	10% maximum	AS 1141.50
Degradation factor	50 minimum	AS1141.25.2
Secondary mineral content	25% maximum	AS 1141.26
Petrographic examination	Statement of suitability for use as an asphalt aggregate	

Table 2.4 Asphalt aggregates specification (MRWA 2016)

2.5.3 Absorption capacity of aggregates

The absorption of water by an aggregate gives an indication of porosity. A good quality aggregate should preferably be dense and of low porosity (Austroads, 2014). The capacity of the aggregate to absorb either water or binder is an important issue. If the aggregate is highly absorbent, it will continue to absorb binder after the mix has come out of the plant, thus leaving less binder on the surface to bind the other aggregate particles. A porous aggregate requires higher quantities of binder than a less porous aggregate.

2.5.4 Aggregate abrasion resistance

This is the resistance of the aggregate particles in withstanding the effects of weathering and abrasion. It is essential to the maintenance of particle interlock and skid resistance under traffic (Austroads, 2014). Aggregates should be able to withstand the crushing and abrasion to which they are subject to in the process of production, paving and compaction, and during its life service (Austroads, 2014). The resistance to abrasion of any aggregate is particularly important in mixes that are used in the upper pavement layers where stress is high.

2.5.5 Aggregate affinity to bitumen

The affinity of the aggregate with bitumen is related to the surface chemistry of the aggregate (Austroads, 2014). The affinity should warranty a force that permits both the aggregate and the bitumen to hold together in diverse environmental conditions to which they are exposed. Bitumen adhesion to the aggregate surface should also resist stripping in the presence of water (Austroads, 2014).

2.5.6 Particle shape

The requirements of the particle form vary slightly depending on the asphalt mix. Ideally particles should have a cuboid form instead of round, elongated or flat as they are susceptible to break under heavily loaded traffic, which can modify the mechanical stability of the asphalt mix (Austroads, 2014).

The shape of particles affects the workability of the asphalt mix during paving, as well as the force necessary for compaction to achieve the required density (Austroads, 2014). The form of the particle also affects the resistance of the pavement structure during its life service.

Additionally, the aggregate particle surface texture (rough or smooth) influences the strength and workability of the asphalt mix as they have their unique qualities. Rough particles produce high internal friction resulting in higher strength than smooth particles; the binder film can easily coat the smooth texture particles.

Figure 2.10 presents particle size distribution for types of asphalt.

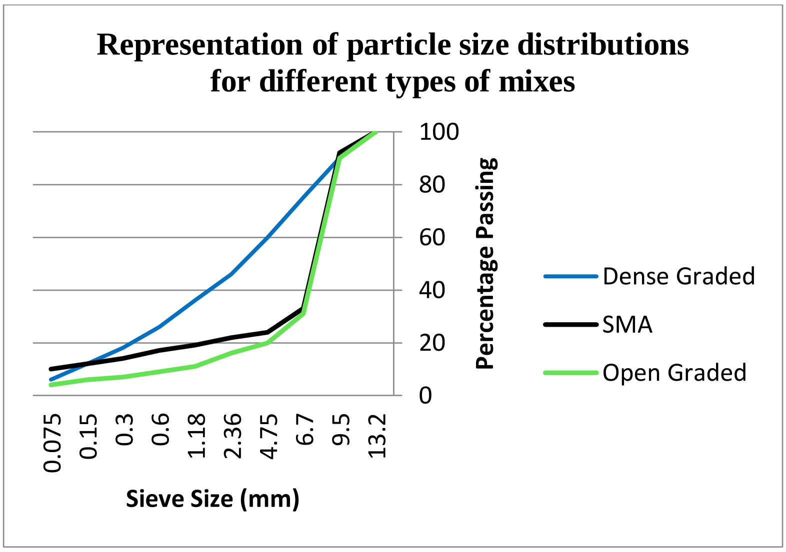


Figure 2.10 Particle size distributions (Austroads 2008d)

2.5.7 Specific weight of aggregates

The specific weight of aggregates is the proportion between the weight of a given aggregate volume and the weight of an equal volume of water (Asphalt Design, 2012). The specific weight is a way to express the weight and volume characteristics of the materials, particularly important in the production of asphalt mixes because aggregates and binder are proportioned to their weight. Knowing the specific weight of the used aggregates helps in calculating the air void percentage of the compacted mixes. Every mix should have a certain percentage of air voids as they play a vital role in the durability of the pavement.

2.6 Fillers

Most fillers are derived from coarse or fine aggregate (mineral matter), that normally pass through a 0.075 mm sieve. The primary function is to increase the resistance of the binder to flow (Austroads, 2014). Fillers are used to fill voids and to stabilise the binder. Filler are the portions extracted from recycled dust that comes from the crushing and screening plant, or from the drums/dryers of asphalt plants. The ratio binder-filler is delineated as the percentage by mass of aggregate passing sieve, to the effective binder content stated as a percentage by mass of the total mix and is mostly in the range of 0.6% to 1.2% (Austroads, 2014).

Common fillers include rock dust derived from coarse and fine aggregate fractions, and other materials such as lime, Portland cement, ground limestone, ground slag, fly ash, and kiln dust. In Western Australia, the most used filler is crushed rock.

In dense-graded mixes the proportion of filler generally ranges from 4% to 6% by mass of the aggregates with a ratio by mass of filler to binder between 0.6 and 1.2 (Austroads, 2007). The function of the filler is to maximise binder properties by filling voids adding stiffness to the binder and stability to the mix. Some filler such as hydrated lime improve the bond between bitumen and aggregate. Relevant filler requirements are available in method AS1141.0 sampling and testing of aggregates.

Fillers properties include: particle size distribution, moisture content, water solubility, loss of ignition, compacted void content, particle shape (depending on the specific surface), plasticity index, and the clay content, as well as particle density and free lime content (Austroads, 2014). Fillers with low particle density result in a greater volume of material. The particle shape is important as it influences the binder film thickness and binder viscosity. The filler binder viscosity is directly related to the specific surface of the filler and its affinity to bitumen.

It is recommended to limit the use of fillers containing high percentages of materials which are soluble in water, such as fly ash and cement flue dust, as the mix could fail. On the other hand, fillers with active lime can alter the surface polarity of aggregates improving the bitumen affinity.

The size, surface area and particle density of the filler determines the appropriate proportion of any asphalt mix. Filler selection is dependent on the cost, hauling and handling of the material (Austroads, 2014). Specification limits have been established to provide a balance between too little or too much filler. In cases where natural filler is insufficient, an introduced material may be used (such as hydrated lime) with the benefit that it can stiffen the bitumen, giving stability to the mix.

2.7 Binders

2.7.1 Bitumen

Figure 2.11 Bitumen sample

Bitumen is one of the oldest engineering materials. Figure 2.11 shows a bitumen sample for testing. Bitumen is a thermoplastic visco-elastic medium that softens when heated and hardens as it cools, holding the asphalt mix (aggregates) together. The main quality of bitumen is to bond the aggregates which provide controlled flexibility to mixtures. It is a non-crystalline high-viscosity fluid (scribd.com), soluble in organic solvents with the characteristic of not affecting the properties of the materials it is mixed with.

The main characteristics are its adhesive and waterproof qualities, as it is insoluble in water. It is temperature susceptible: when heated, it becomes fluid and coats the aggregate particles with a fine film, and as it cools, it becomes more viscous until it forms an elastic solid. Its durability is an essential quality, making bitumen the preferable binder to use in major engineering projects; it strongly binds the aggregate particles and seals and fills all voids between them. In addition, it is relatively economic and easily available. Bitumen classes are presented in Table 2.5 and Table 2.6 shows bitumen properties in low traffic applications. Usually bitumen is supplied in two main viscosity types:

- **170 Class:** used for most general work where heavy traffic or high standing loads are not used (lower traffic applications) and use in cooler climates.
- **320 Class:** used for heavy-duty applications such as major roads or container terminals and in warmer climate zones (Austroads, 2007).

		Viscosity at 60 °C (Pa.s) V	**Viscosity at 60 °C (Pa.s)**
Formal grade designation	**Informal name**	**Pre RTFO treatment**	**Post RFTO treatment**
Class 170	C170	140-200	N/A
Class 240	C240	190-280	N/A
Class 320	C320	260-380	N/A
Class 450	C450	N/A	750-1150
Class 600	C600	500-700	N/A
Multigrade 500	M500	400-600	N/A
Multigrade 1000	M1000	N/A	3500-6500

Table 2.5 Bitumen properties (Austroads, 2014)

Property	Class 170		Class 320		Class 600	
	Min	Max	Min	Max	Min	Max
Viscosity at 60°C, Pa.s	160	230	260	380	550	650
Viscosity at 135°C, Pa.s	0.30	0.50	0.40	0.65	0.60	0.85
Penetration at 25°C, (100g, 5s), pu (1 pu = 0.1 mm)	55	78 (Note)	40	-	20	-
Density at 15°C, kg/m³	1000	-	1000	-	1000	-
Flash Point, °C	250	-	250	-	250	-
Matter insoluble in toluene, percent	-	1.0	-	1.0	-	1.0
Rolling thin film oven test						
Viscosity of residue at 60°C as percentage of original	-	300	-	300	-	300
Ductility at 15°C, mm	400	-	N/A			
Durability value	Refer Clause 511.06.03		N/A			

Table 2.6 Bitumen specifications (Main Roads Western Australia, 2016)

In Australia, asphalt use complies with AS 2008 specification, where bitumen is classified in terms of viscosity at 60°C measured in Pascal seconds (Pa.s) (Austroads, 2014). Due to its high viscosity class, 320 bitumen is principally used and manufactured to perform better in stiffness terms. Bitumen (cool/warm) selection is subject to climate zone as well.

The main characteristics of bitumen are: strong adhesion, water resistance, flexibility and ductility, durability or resistance to weathering, and low toxicity (Austroads, 2014). The quality of the bitumen has considerable relevance to the performance of asphalt pavement; therefore, tests are carried out to determine the quality of the product. It needs to be noted that equally important as the component materials is the proportion of the materials.

A poor or bad design, regardless of the quality of the component materials, will produce poor asphalt. On the other hand, a good design, utilising second-rate materials, has a good chance of producing a functional product. Table 2.7 shows methods used to test bitumen.

METHOD OF TEST	PROPERTY
AS 2341.2 or AS 2341.3	Viscosity at 60°C, Pa.s
AS 2341.2 or AS 2341.3 or AS 2341.4	Viscosity at 135°C, Pa.s
AS 2341.12	Penetration at 25°C, (100g. 5s) Pu (1pu = 0.1 mm)
AS 2341.7	Density at 15°C, kg/m^3
AS 2341.14	Flash Point, °C
AS 2341.8	Matter insoluble in toluene, percent
AS 2341.10	Effect of heat and air on a moving film of bitumen (Rolling thin film oven test)
AS 2341.2 or AS 2341.3	Viscosity of residue at 60°C as percentage of original
AS 2341.11	Ductility at 15°C, mm
AS/NZS 2341.13 or WA 716.1	Durability value

Table 2.7 Bitumen testing methods (Main Roads Western Australia, 2016)

2.8 Additives

Additives are materials added to the binder or to the asphalt mix whose role is to alter the physical characteristics of the binder (Austroads, 2014). They are applied to improve the properties of the asphalt mixture. There is a wide variety of additives, including adhesion agents such as, bitumen flow modifiers, fibres, rejuvenating agents, coloured pigments and natural asphalt modifiers. While some additives' usefulness is apparent during manufacture, transportation and placement, other additives show their utility once the compacted mixture is open to traffic and is exposed to the effect of time. The majority of the additives are added during the mixing process.

2.8.1 Adhesion agents

The purpose of an adhesion agent (anti stripping) is to increase the physio-chemical bond between the asphalt binder and the aggregate (Austroads, 2014).

Some adhesion agents are used to reduce moisture content (water retained in aggregates or filler), hence specific anti-stripping additives are used to increase adhesion of the aggregate crossing point. The function of the additive is to improve mix performance, but not at the expense of other necessary mixture properties.

2.9 Properties of an asphalt mix

Each asphalt mix has intrinsic properties, and so does its field of application. In principle, a mixture cannot fully satisfy all properties because it is dependent on the functionality and structure of the pavement. Each mix is designed, produced and placed to obtain the desired properties. The required properties for high quality asphalt include: stability, durability, flexibility, fatigue resistance, skid resistance, impermeability and workability.

2.9.1 Stability

Stability is the first characteristic considered in any asphalt mix. It has the capacity to withstand displacement and deformation. A stable pavement should maintain its smoothness and shape under heavy loads of traffic. Stability depends on the strength and flexibility of a mix and the degree of compaction. Stability is established after a thorough traffic analysis, and should be adequate to handle traffic (in.gov, 2008).

However, values of stability which are too high could indicate the presence of a pavement which is too rigid, thus less durable than desired. The stability of a mix depends on the internal friction and cohesion of the aggregate particles which is dependent on the characteristics of petrous aggregates, such as shape and surface texture (in.gov, 2008). Table 2.8 presents the causes and effects of pavement instability.

Low Stability	
Causes	Effects
Excess binder in asphalt mixture	Wash boarding, rutting and flushing, or bleeding
Excess medium size sand in asphalt mixture	Tenderness during rolling and for a period after construction, and difficulty in compacting
Rounded aggregate, little or no crushed surfaces	Rutting and channelling

Table 2.8 Causes and effects of pavements instability (in.gov, 2008)

2.9.2 Durability

Durability in an asphalt mix resists the effects of aggregate disintegration, changes in asphalt properties (polymerization and oxidation), separation of the aggregate, and stripping of the binder films from the aggregate. These factors could be the result of climate action, traffic or a combination of the two (in.gov, 2008).

Durability increases with high amounts of binder as thick asphalt films do not age or harden as fast as the thinner asphalt films. In consequence, asphalt can retain its original characteristics longer. In addition, ‘the maximum binder content possible effectively seals a large percentage of interconnected air voids in pavement, making the penetration of air and water difficult’ (in.gov, 2008). Likewise, dense gradation aggregate, which is hard and resistant to separation, contributes to the durability of the pavement. However, the crucial element of durability is compaction. The compacted mix should not have a high air void content which could accelerate the pavement ageing process. Good compaction of a mix equals durability of the pavement. Table 2.9 presents causes and effects of lack of durability in pavement.

Poor durability	
Causes	Effects
Low binder content	Dryness or ravelling
High void content through design or lack of compaction	Early hardening of binder followed by cracking or disintegration
Water susceptible (hydrophilic) aggregate in asphalt mixture	Films of binder strip from aggregate leaving an abraded, ravelled or mushy pavement

Table 2.9 Causes and effects of lack of durability in pavement (in.gov, 2008)

2.9.3 Flexibility

Flexibility is a desirable asphalt characteristic as it enables an asphalt mix to adjust to on-going settlement and movements in the sub-grade layer without cracking. Sub-grade is the portion that has been prepared and trimmed on which the pavement is constructed (Austroads, 2008a). A dense graded mix is more flexible due to a high binder content, while an open graded mix is less flexible because of a low binder content. Flexibility and stability due to each other’s characteristics seem to be in conflict; therefore, a compromise during design in terms of material percentages (binder, aggregates and filler) needs to be performed.

2.9.4 Fatigue Resistance

Fatigue resistance refers to the resistance of the pavement to repeated bending under traffic. Air voids and binder viscosity are key elements in the effect of fatigue resistance (in.gov, 2008). The length of time or life service of a pavement is directly linked to air voids, so if increased, the life service of the pavement is drastically shortened. Similarly, in asphalt containing binder that has aged and hardened considerably, the resistance to fatigue decreases. Table 2.10 presents the causes and effects of poor fatigue resistance.

Poor fatigue resistance	
Causes	Effects
Low asphalt binder content	Fatigue cracking
High design voids	Early aging of binder followed by fatigue cracking
Lack of compaction	Early aging of binder followed by fatigue cracking
Inadequate pavement thickness	Excessive bending followed by fatigue cracking

Table 2.10 Causes and effects of a poor fatigue resistance in pavement (in.gov, 2008)

2.9.5 Skid Resistance

Skid resistance is the capacity of an asphalt surface to minimise skidding of vehicle tyres particularly when the surface is wet. Vehicle tyres should maintain good contact with the aggregate particles. Good skid resistance can be attained with a 10 to 13 mm rough textured aggregate as maximum size. Mixtures that present rutting or bleed, due to too much bitumen on the surface of the road, can present serious skid issues, and ‘inadequate skid resistance can lead to higher incidents of skid related accidents’ (Asphalt Design, 2012).

2.9.6 Impermeability

Impermeability is the resistance of asphalt to the passage of water and air into or through the mixture, and is directly linked to the air void content of the compacted mix. Air voids are an important factor of the mix and their character is vital to determine the degree of impermeability which is subjected to the air voids’ sizes, the interconnection and the relation (access) to the surface. Impermeability plays an important role in the durability of an asphalt mixture so long as the permeability is within the specified limits (in.gov, 2008). Table 2.11 presents causes and effects of permeability.

Mix too permeable	
Causes	Effects
Low binder content	Thin binder films that cause early aging and ravelling
High void content in design asphalt mixture	Water and air may easily enter pavement causing oxidation and disintegration
Inadequate compaction	Results in high voids in pavement leading to water infiltration and low strength

Table 2.11 Causes and effects of a mix too permeable (in.go, 2008)

2.9.7 Workability

Workability is the ability of the asphalt to be worked and handle with ease at placing and compaction. Aggregate shape, grading, filler type and content, binder viscosity and content, mix nominal size, temperature at placing, and compaction are factors to consider in a mix design as they influence the workability of the mix (Austroads, 2014). This is particularly relevant if the mix is to be placed in curvy areas such as kerbs or sharp bends. Table 2.12 presents the causes and effects of problems with workability (in.gov, 2008).

Poor workability	
Causes	Effects
Large maximum size particle	Rough surface, difficult to place
Excessive coarse aggregate	May be hard to compact
Too low an asphalt mixture temperature	Uncoated aggregate, not durable, rough surface, hard to compact
Too much medium sized sand	Asphalt mixture shoves under roller, remains tender
Low fines content	Tender asphalt mixture, highly permeable
High fines content	Asphalt mixture may be dry or gummy, hard to handle, not durable

Table 2.12 Causes and effects of workability problems in pavement

WMA has been proven to maximise workability due to the addition of an additive which keeps the mix hot for longer periods of time.

2.10 Asphalt Mix Design

Asphalt mix design principally entails the selection of a mix type, component materials, and the target binder content. It will optimise the engineering properties in relation to the mix behaviour in service (Austroads, 2014). The selection determines the parameters for the combination of aggregate grading, binder type, volumetric properties and the mix performance (Austroads, 2014). All asphalt mixtures produced must be analysed to determine the performance in the structure of the pavement.

The central factor in the mix design process is pavement thickness which determines the size of aggregates to be used. Frequently, the largest aggregate size possible is used to maximise the pavement stability. The minimum thickness required is 2.5 times the aggregate size. To start the design process, it is important to determine the specific use of the asphalt; consideration needs to be given to the following:

- Asphalt construction
- Course thickness
- Traffic flow
- Asphalt use

It needs to be noted that the designing of mixes has been generally developed around testing hot dense graded mixes (Austroads. 2008b): the mix chosen for this research. Testing is performed to ensure compliance with specifications, such as air void target, and to establish asphalt performance. Specifications define all relevant design parameters. A variety of methods have been developed to test the volumetric and mechanical properties of a mix. The basis of an asphalt mix design is to determine the in-service performance through the measuring of the volumetric properties. Marshall Method (MRWA 731.1- 2016) describes the procedures and tests required for testing.

Volumetric properties measure the:

- Maximum density
- Bulk density
- Archimedes' principle
- VMA (Voids Mineral Aggregate)
- Air voids
- Binder content
- Particle size distribution
- Voids Filled with Binder (VFB)
- Binder film index
- Preparation for volumetric testing

Table 2.13 shows specification 504 of Marshall Properties for dense-graded asphalt for nominal 5mm, 10mm and 14mm mixes 9Main Roads Western Australia, 2016a).

Parameter	Min	Max
Marshall Stability	8.0kN	-
Marshall Flow	2.0mm	4.00mm
Air Voids (WA 733.1):		
Nominal 10mm	3.0%	6.0%
Nominal 10mm – Perth and Southern areas of the state	4.0%	6.0%
Nominal 10mm – Northern and Eastern areas of the state	4.0%	7.0%
Nominal 5mm	3.0%	5.0%
Nominal 14mm (Intersection Mix)	4.0%	7.0%
Voids in Mineral Aggregate:		
Nominal 10mm Laterite	15.0%	-
Nominal 10mm	15.0%	-
Nominal 5mm	16.0%	-
Nominal 14mm (Intersection Mix)	14.0%	-

Table 2.13 Marshall Properties (Main Roads Western Australia, 2016)

Density is one of the fundamental parameters and an important factor affecting the durability of any pavement. It measures the weight per volume of the compacted mix air voids. In simple terms, the density of a material is defined as the weight of the material occupying a certain volume in space. The measurement of air voids ensures the durability and safety; most significantly, the quality of a mix that is properly designed and compacted contains enough air voids to avoid permeability of air and water. The density of any mixture varies according to the type of road, but it cannot be too low or too high. Figure 2.12 presents the constituents of a compacted asphalt mix.

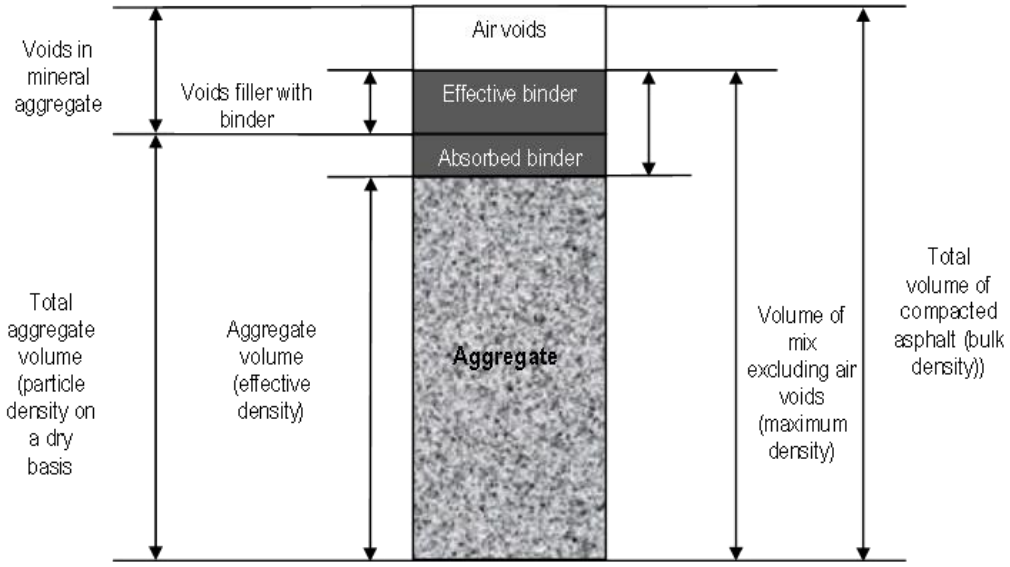


Figure 2.12 Constituents of compacted asphalt mix (Austroads, 2014)

The percentage of air voids in an asphalt mixture is without a doubt the single most important aspect that affects the performance life of an asphalt pavement. The air voids are primarily controlled by asphalt content, followed by the compaction effort during placing, and the additional compaction under traffic. Main Roads Western Australia and Australian Standards (AS) stipulate the methods recommended for use in Australia. These methods are:

- **AS 2891.1** Bitumen content and aggregate grading reflux method.
- **AS 2891.3.2** Bitumen content and aggregate grading: centrifugal extraction method.
- **AS 2891.3.3** Bitumen content and aggregate grading: pressure filler method.
- **AS 2891.7.1** Determination of maximum density of asphalt: water displacement.
- **AS 2891.8** Voids and density relationships for compacted asphalt mixes.
- **AS 2891.9.1** Determination of bulk density of compacted asphalt: waxing procedure.
- **AS 2891.9.2** Determination of bulk density: pre-saturation method.

- **AS 2891.9.1** Waxing: this procedure eliminates the effect of water permeable voids by sealing the surface with a layer of wax.
- **AS 2891.9.3** Determination of bulk density: Mensuration method refers to the determination of the volume of the specimen by direct measurement of the external dimensions. Usually used for open graded mixes (Austroads, 2014).
- **AS 2891.13.1** Indirect Tensile Strength (ITS) measures the resilient modulus.
- **AS 1141.5** Particle density and water absorption of fine aggregate.
- **AS 1141.6** Particle density and water absorption of coarse aggregate-weighing- in water method.
- **AS 1141.7** Apparent particle density of filler.
- **AS 1141.11.1** Particle size distribution: sieving method.
- **AS 2341.6** Determination of density using a hydrometer.
- **AS 2341.7** Determination of density using a density bottle.

Main Roads Western Australia methods:

- **MRWA 700.1** Sampling procedures for bitumen.
- **MRWA 701.1** Sampling and storage of asphalt.

- **MRWA 705.1 - 2013** Preparation of asphalt for testing.
- **MRWA 732.2 - 2011** Maximum density of asphalt – Rice method.
- **MRWA 733.1 – 2011** Bulk density and void content of asphalt – vacuum sealing method.
- **MRWA 733.2 - 2012** Voids in Mineral Aggregate (VMA).
- **MRWA 733.2 – 2012** Voids Filled with Binder (VFB).
- **MRWA 733.1 – 2012** Air voids bulk density and void content of asphalt.
- **MRWA 730.1 – 2011** Binder content and particle size distribution of asphalt.

Austroads Pavement Testing methods

- **AGPT/T220** Sample preparation: compaction of asphalt slabs.

- **AGPT/T234** Asphalt binder content (ignition oven method).
- **AGPT/T237** Binder film index.
- **AGTT/T231** Wheel tracking.
- **AGPT/T232** Tensile Strength Ratio (TSR)
- **AGPT/T233** Fatigue resistance.
- **AASHTO TP62-07 (AASHTO 2003)** Dynamic Modulus

2.11 Volumetric Properties

The volumetric properties of an asphalt mix design are the basis of asphalt, and largely determine the in-service performance of the mix. Its measurement is crucial to understand and design asphalt, as aggregate grading and binder content are most important in asphalt mix design (Austroads, 2014).

Volumetric properties determine the density of components which measures the mix proportions by mass per unit volume. Measuring the bulk density is the most important parameter of an asphalt mix. Density determination is the basis of volumetric calculations used during field control, paving, and mix design. During the design stage, volumetric properties, the air voids in mineral aggregates (VMA) or the air voids filled with bitumen (VFB), and the percentage of maximum density are used to evaluate the acceptability of the mix. Volumetric properties are invaluable in predicting HMA performance, and therefore WMA.

The initial in-place air voids are determined by comparing the bulk density to the theoretical or maximum density, and the final percentage of in-place air voids is estimated by comparing the bulk density in the laboratory with the compacted field product.

2.11.1 Maximum Density

Maximum density of asphalt mixtures is determined through the Rice method MRWA 732.2- 2011 (Main Roads Western Australia, 2011b) and is one of the main test parameters used for mix design and construction quality control. It is used to calculate the percentage of air voids and stipulate target values of compacted mixes. Maximum density is the mix density excluding air voids. Theoretically, if all the air voids were eliminated from an HMA specimen, the combined density of the remaining aggregate and asphalt is the maximum density. Table 2.14 shows the minimum mass for test portion.

Nominal max size of asphalt (mm)	Minimum test portion size (g)
20, 14	1.500
10, 7, 5	1.000

Table 2.14 Minimum mass for test portion (MRWA 732.2-2011)

Equation to calculate the maximum density of the asphalt:

Equation 2.1

$$\boldsymbol{P_{max}} = \frac{\boldsymbol{M_2}}{\boldsymbol{M_2} - (\boldsymbol{M_3} - \boldsymbol{M_1})}\boldsymbol{P_w}$$

Where:

P_{max} = maximum density of the asphalt in t/m^2

P_w = density of water at 25^o C in t/m^2 (sufficiently correct to use 0.997)

M_1 = mass of Buchner flask in water in grams

M_2 = mass of test portion in air in grams

M_3 = mass of flask + contents in water in grams

2.11.2 Bulk Density

Bulk density is the weight per volume of the compacted mix air voids. Method MRWA 733.1 – 2011 describes the procedure to determine bulk density by water displacement and direct measurement (Main Roads Western Australia, 2011c). It is based on the surface dry saturated method. The bulk density is decisively one of the most important asphalt mix characteristics; it is the base to calculate other parameters, such as air voids, voids in mineral aggregates (VMA), and maximum density. Mix design is based on volume, hence the dependency on bulk density. Density is then indirectly determined using mass and specific gravity. The method basically uses a compacted laboratory or field hot or warm mix asphalt specimen. Figure 2.13 shows specimen measurement for bulk density.

In Western Australia, the vacuum sealing test method is used to determine OGA and SMA bulk density (Austroads, 2014).

Figure 2.13 Measurement of specimen for bulk density

Bulk density uncoated specimen is calculated using the following equations

Equation 2.2

a)

$$V_{sample}\frac{m_{1-}(m_3 - m_2)}{\rho_w}$$

Where:

V_{sample} = volume of test specimen in cm^3

m_1 = mass of test specimen in grams

m_2 = mass of suspension device immersed in water in grams

m_3 = mass of test specimen and suspension device immersed in water

ρ_w = density of water at 25 °C in g/ cm^3 (correct to use 0.997)

b)

Equation 2.3

$$P_{bulk} = \frac{m_1}{V_{sample}}$$

Where:

P_{bulk} = bulk density of test specimen in t/m^3

m_1 = mass of test specimen in grams

V_{sample} = volume of test specimen in cm^3

Bulk density paraffin wax coated method:

a)

Equation 2.4

$$\rho_{bulk} = \frac{m_1}{Vsample - Vwax}$$

Where:

ρ_{bulk} = bulk density of test specimen in t/m^3
m_1 = mass of test specimen in grams
$Vsample$ = volume of paraffin wax coated test specimen cm^3
$Vwax$ = volume of paraffin wax on test specimen in cm^3

2.11.3 Archimedes' Principle

To understand possible causes of potential errors in testing results, it is necessary to comprehend the principle of the water displacement method. The method is based on Archimedes' principle, which states that when an object is completely submerged in a fluid, the level that the fluid rises equals the volume of the object.

The water displacement method uses the following formula to calculate the volume of the specimen, following test method MRWA 733.1 – 2011.

Equation 2.5

$$V_{sample} = \frac{(m_1 - m_2)}{P_w}$$

Where:

V_{sample} = volume of test specimen in cm^3
m_1 = mass of test specimen in air in grams
m_2 = mass of test specimen in water in grams
P_w = density of water at 25^o C in g/cm3 (sufficiently correct to use 0.997)

2.11.4 Voids in Mineral Aggregate (VMA)

VMA is the total volume of intergranular void space within the mass of compacted mixture including air voids and the volume of the binder content –

binder less any binder absorbed into the aggregate (Austroads, 2014) – which is expressed as a percentage of the total volume of the sample. Method MRWA 733.2 -2012 refers to VMA and its equation.

VMA=%AIRVOIDS + BITUMEN BY VOLUME

Equation 2.6

$$VMA = \%\, Air\ Voids + \frac{\rho bulk\ x\ BIT\%}{\rho BIT}$$

Where:

VMA = percentage voids in mineral aggregate

ρ_{bulk} = bulk density of the specimen in t/m^3

$BIT\%$ = percentage of bitumen as determined by WA 730.1.

ρ_{BIT} = density of bitumen at 25°C in t/m^3

VMA affects the performance of the mix in two distinctive ways. If VMA is too low, there is the possibility of over filling the voids with binder, resulting in bleeding or instability, and/or insufficient binder for cohesion and durability. On the other hand, if VMA is too high, it results in the air voids being too high. An increased binder volume to satisfy air void requirements increases the cost of the mix. Figure 2.14 shows VMA air void content in compacted asphalt mix (Austroads, 2014).

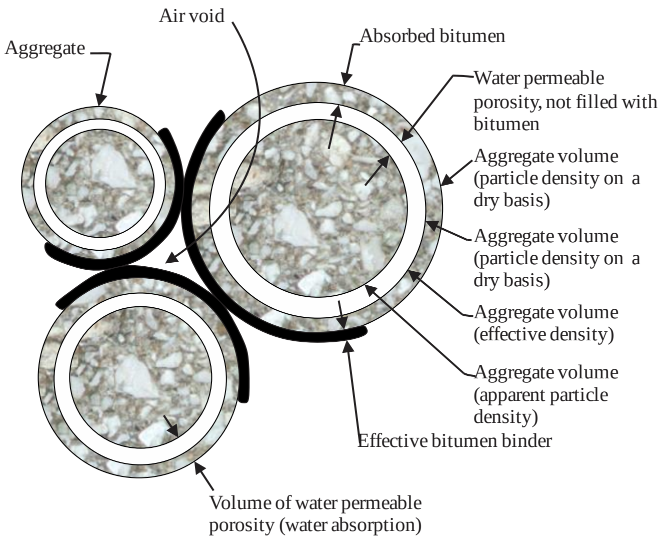


Figure 2.14 VMA, air voids and bitumen content in compacted mixtures

2.11.5 Air Voids

Air void content in asphalt mixes is the total volume of small pockets of air between the coated aggregate particles throughout a compacted paving mixture. It affects the mix stiffness, fatigue resistance and durability (Austroads, 2014) therefore, it is extremely important. The aim when designing a mix is to have the lowest practical air void value within the specifications, decreasing issues like oxidation of the binder (ageing) and water penetration. It needs to be noted that a mix with low air void content (less than 2%) could result in flushing, bleeding, shoving or rutting of the pavement (Austroads, 2014).

The appropriate air void content contributes to the stability of the mix making the pavement more resistant to traffic load and environmental issues. Air voids are expressed as a percentage of the bulk volume of the compacted mixture when compared to the maximum specific gravity.

The equation to determine air voids is provided in method MRWA 733.1 - 2012.

Equation 2.7

$$\%AIR\ VOIDS = \frac{\rho max - \rho bulk}{\rho max}\ x\ 100$$

Where:

ρ_{max} = maximum density of the asphalt determines by WA 732.2. in t/m^3

ρ_{bulk} = bulk of density specimen in t/m^3

2.11.6 Binder Content

Optimal binder content is a balance between being high enough to ensure durability and life of the pavement, but not too high, thus avoiding the mix becoming unstable (Austroads, 2014). Asphalt performance relies on the effectiveness of the binder, excluding the binder absorbed by the aggregates. Binder content design is subject to the aggregate type, the aggregate particle size distribution, the compaction level of the mix, and the air void content to be considered optimal.

Test method MRWA 730.1 – 2011 describes the procedure to determine the bitumen content of hot mixed asphalt and stabilised soil by the centrifuge method. On average, the amount of binder absorbed by aggregate is 0.3 to 0.7 times the water absorption of the aggregate (Austroads, 2014). To calculate the percentage of bitumen, the following formula is used:

Equation 2.8

$$Bit = m_1 - \frac{[(m_5 - m_4) + m_{FR} + m_{EF}]}{m_1} x\ 100$$

Where:

Bit = bitumen content as a percentage
m_1 = mass of test portion in grams
m_4 = mass of oven dish in grams
m_5 = mass of oven dish and contents in grams
m_{FR} = mass of matter on filter ring in grams
m_{EF} = mass of matter in extraction fluid in grams

2.11.7 Particle Size Distribution (PSD)

The PSD test is performed for quality control, and its procedure is described in method MRWA 200.1. Reliable aggregate grading is essential to maintain quality control in the production of asphalt. Most mix specifications state aggregate grading limits to maintain a product within the limits. Production control is based on limits established between the asphalt manufacturer and the aggregate supplier. In simpler terms, aggregates are separated on sieves of different sizes with a delivery tolerance ranging from ±15% for a 26.5 mm sieve to ±5% for a 4.75 mm sieve (Austroads, 2014).

Aggregate PSD calculation procedure:

a) Calculate, by addition, the mass of material passing each of the sieves used for the particle size distribution, commencing with the mass of material passing the smallest aperture sieve.

The total mass of the test portion is recorded after sieving as m_2, to at least the nearest 0.1 g.

If the mass (m_2) of the test portion after sieving varies by more than 1% from the mass of the dried test portion (m_1), then the test portion shall be re-sieved.

b) Calculate the percentage mass of material passing each sieve used in the particle size distribution by dividing the mass passing each sieve by m_2 and expressing the result as a percentage (method WA 201.1-2013 MRWA, 2017).

Equation 2.9

$$Pp = \frac{m_p}{m_2}$$

Where:

Pp = *percentage mass of material passing each sieve.*

m_p = *mass of the material passing the sieve in grams.*

m_2 =*total dry mass in grams*

2.11.8 Voids Filled with Binder (VFB)

Voids filled with binder refer to the volume (proportion) of space (voids) between the aggregate particles of the compacted mix filled with asphalt binder. VFB is expressed as a percentage of the total volume of the sample, ranging from 65 to 80%. Method MRWA 733.2 – 2012 describes the procedure for testing, and the following formula is used:

Equation 2.10

$$VFB = \frac{\%Bitumen\ By\ Volume}{VMA}\ x\ 100$$

$$VFB = \frac{\rho_{bulk}\ x\ BIT\%}{\rho_{BIT}\ x\ VMA}$$

Where:

VFB = percentage voids filled with bitumen

ρ_{bulk} = bulk density of the specimen in t/m^3

$BIT\%$ = percentage bitumen as determine by WA 730.1

ρ_{BIT} = density of bitumen in 25°C in t/m^3

VMA = percentage voids in mineral aggregate

2.11.9 Binder Film Index

Binder film index is calculated as a function of the surface area of the aggregate: filler and binder content are described in method AGPT/T237 *Binder Film Index* (Austroad, 2014). The method is based on standardised surface area features for each particle size.

Equation 2.11

$$FI = \frac{Q_{EB}}{100 - Q_{Bit}} \times \frac{1}{C} \times \frac{10^3}{pBit}$$

Where:

FI = film index (m).

Q_{EB} = effective binder content (% by mass of mix).

Q_{Bit} = total binder content (% by mass of mix).

C = surface area of aggregate blend (m^2/kg).

$pBit$ = density of binder at 25°C (t/m^3).

The surface area of the aggregate is calculated from:

A = (2 + 0.02a + 0.04b + 0.08c + 0.14d + 0.30e + 0.60f + 1.60g) x 0.20482

B = (A x 2.65) / (combined bulk density of components)

C = A when the combined bulk density of the mineral aggregate is in the range of 2.4 to 2.9 t/m^3

D = B when the combined bulk density of the mineral aggregate is < 2.4 or > 2.9 t/m³

Where:

a = percentage passing 4.75 mm sieve

b = percentage passing 2.36 mm sieve

c = percentage passing 1.18 mm sieve

d = percentage passing 0.60 mm sieve

e = percentage passing 0.30 mm sieve

f = percentage passing 0.15 mm sieve

g = percentage passing 0.075 mm sieve.

2.11.10 Preparation for Volumetric Testing

Method MRWA 705.1 – 2013 provides and describes the procedure for the preparation of loose asphalt, or asphalt core or slab samples for testing. It includes:

- Definition of terms
- Apparatus
- Procedures
- Moisture content of core specimens
- Reporting

2.12 Performance/Mechanical Testing

Performance tests are to relate laboratory design to the actual field performance of an asphalt mix. They measure the empirical properties and the performance of asphalt. Performance properties in situ are required for pavement design purposes. Conditions on site vary due to factors such as temperature, loading time, stress conditions, and degree of compaction; these can affect the performance. (Austroads, 2014). Performance testing can be categorised into three groups:

- Performance based on stiffness and fatigue
  - Indirect tensile strength test (resilient modulus)
  - Fatigue resistance (repeated flexural bending)
- Performance related: simulative tests for resistance to deformation and moisture damage
  - Wheel tracking
  - Tensile strength ratio (moisture sensitivity)
- Empirical tests for design of asphalt mixes
  - Marshall test (stability and flow) (Austroads, 2014)

2.12.1 Resilient Modulus by Indirect Tensile Strength (ITS)

Indirect Tensile Strength Australian Standard test method AS 2891.13.1 - 1995 is used to determine the resilient modulus of asphalt, based upon an indirect tensile measurement (Austroads, 2014). Resilient modulus of asphalt is an essential physical property used in the characterisation of pavement design (Minnesota Department of Transportation, 2016). It is dependent on variables such as aggregate gradation, aggregate size, asphalt viscosity, temperature, and frequency of loading. Resilient modulus is the ratio of an applied cyclic to the recoverable horizontal strain of a test sample (Kumlai et al., 2014). The test consists of a repeated vertical compressive force being applied, acting parallel to and along the vertical diametrical plane of the specimen, and the horizontal displacement being measured (Austroads, 2014) as shown in Figure 2.15.

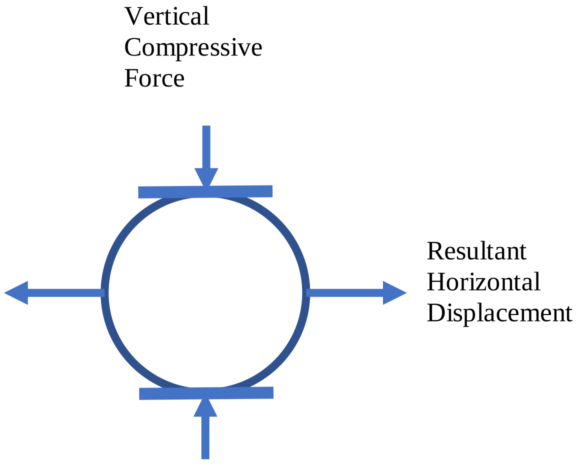


Figure 2.15 Force and displacement test

The modulus is a measure of the material's mean stiffness in specific conditions. The temperature used in this research is 25 °C.

The resilient modulus is calculated using the following equation:

Equation 2.12

$$E = \frac{P(\vartheta + 0.27)}{H \ x \ h_c}$$

Where:

E = estimated resilient modulus (MPa)

P = Peak load (N)

ϑ = Poisson's ratio (0.4, unless more precise information is available)

h_c = average height of specimen (mm)

H = recovered horizontal deformation after application of load (mm)

2.12.2 Wheel Tracking

The wheel tracking test measures the rut depth of a pavement related to deformation under traffic (deformation resistance of asphalt) over 10,000 cycles at 60 °C. Test method AGPT/T231 (Austroads, 2014) describes test procedures which connect well to road performance and distinctive wheel tracking values, permitting testing of both field and laboratory prepared mixes. All samples should be a single layer prismatic with a plan area of 300 x 300 mm, while the depth of the sample usually ranges from 50 to 100 mm. Figure 2.16 shows pavement rutting.

Figure 2.16 Pavement rutting

However, Austroads test method AGPT/T220 describes the procedure for the production of slabs fit for wheel tracking. Cylindrical specimens of at least 200 mm in diameter at a temperature of 60 ± 1°C with a thickness of 50 ± 5mm for 10 and 14 mm nominal size and of 75 ± 5 mm for 20 mm nominal size with a vertical load (N) of 700 ± 20 N are fit for testing.

Wheel tracking specifies air void content ranging from 5% ± 0.5%. The sample's thickness depends on the nominal size of the asphalt mix. To disband any distress due to handling, samples are brought to testing temperature and conditioned for a period of time to the required test temperature.

2.12.3 Moisture Sensitivity by Tensile Strength Ratio (TSR)

TSR measures the stripping potential of asphalt by measuring the strength of an unconditioned specimen and a conditioned specimen. Stripping is the presence of moisture, and refers to the potential for loss of adhesion between the aggregate and binder in the presence of moisture (Austroads, 2014). Hence, stripping, which is not considered a primary distress, only occurs if moisture is present in the pavement. Factors influencing stripping include asphalt mix permeability, type and class of binder, climate and traffic, aggregate affinity for bitumen, poor coating of aggregates and asphalt mix design, including binder content, type of filler and use of other additives (Austroads, 2014).

Causes of unbinding have been classified into three main categories:

Displacement: occurs when the binder adhesion to the aggregate surface is removed by water, caused by a break in the binder coating.
Detachment: separation of the binder from the aggregate surface by a thin film of water with no apparent break in the binder film.
Film rupture: occurs in sharp edges and corners on the aggregate particles where the binder film is thinnest under loads, such as traffic (Austroads, 2014).

Bonding of the binder with the aggregate is quite complex. It is affected by the aggregate surface chemistry where considerable differences can occur between the aggregates, affecting the adhesion.

Tests designed to identify moisture sensitivity and binder stripping potential in asphalt mixes includes method AGPT/T232 Stripping potential of asphalt. Tensile strength ratio is the preferred test for evaluating asphalt moisture sensitivity. The freeze – thaw cycle (optional) test, described under the same method, is recommended for asphalt used in high traffic loadings. This method is based on AASHTO T 238-07 (Austroads, 2014) Figure 2.17 show a sample being prepared for testing.

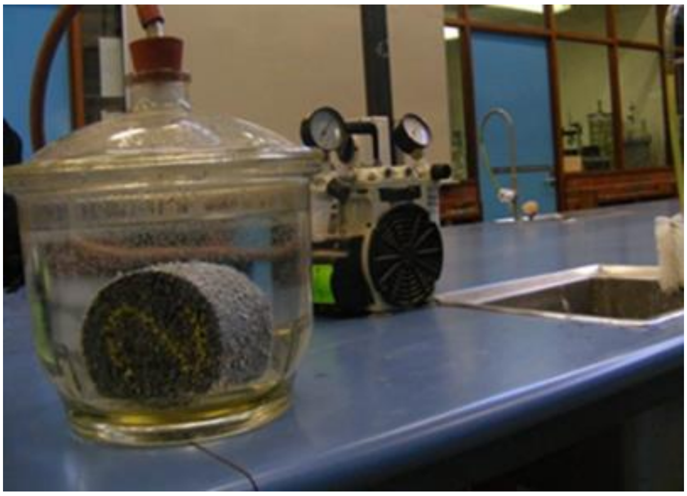


Figure 2.17 Sample preparation

The test requires careful preparation of two sets of three cylindrical specimens to obtain reproducible results. Sample requirements are:

- Height of 65 ± 1 mm for 100 mm ± 2 mm diameter
- Height of 85 ± 1 mm for 150 mm ± 2 mm diameter
- Maximum particle size, greater than 20 mm but less than 40 mm, needs to be nominally 150 mm diameter.
- Maximum particle size less than or equal to 20 mm. Can be either 100 or 150 mm in diameter (preferable diameter 100 mm) (Austroads, 2014).

Samples must be compacted with an air void content between 7% and 9%. A high air void content (up to 12%) allows water to become trapped through the inner connected voids in a layer. With air voids above 12%, the mix becomes permeable resulting in moisture moving freely through the mix. An air void content below 6% results in non-interconnected voids largely impermeable to water (Austroads, 2014).

2.12.4 Fatigue Resistance

Two key issues of deterioration in asphalt pavements are fatigue cracking and rutting. A crucial component of asphalt is its performance, which is measured through mechanical methods, to ensure it is reliable and fit for its purpose mix. Fatigue measurement is crucial as it relates to the ability of the asphalt to withstand cracking under traffic loading (Austroads, 2014). Aspects to consider in fatigue resistance in an asphalt mix are layer thickness, stress/strain level, load repetition period, and pavement temperature. Figure 2.18 shows crocodile cracking, a type of fatigue resistance.

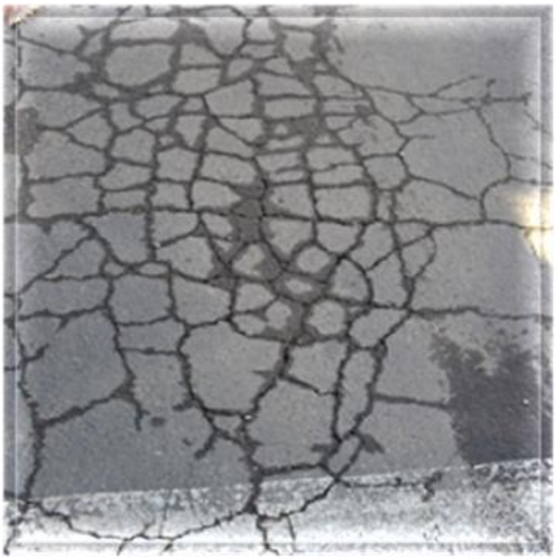


Figure 2.18 Crocodile cracking (failure)

Influences on the resistance of a mix to cracking, entails the following variables: binder volume and type, compaction level, and aggregate grading. It must be noted that factors like thermally-induced stresses can cause cracking. Figure 2.19 shows asphalt beam being placed for testing.

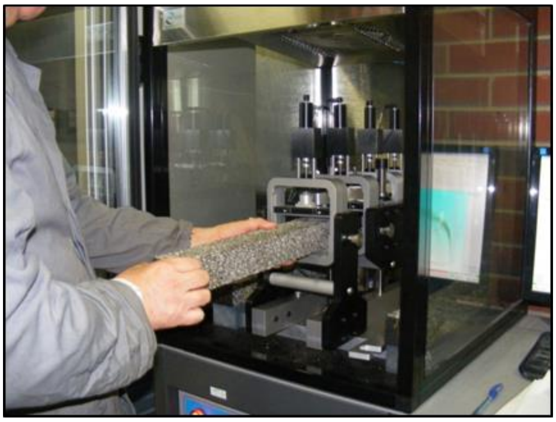


Figure 2.19 Flexural fatigue loading with a warm mix beam

The stresses and strains induced on the tested samples were calculated in accordance with the following equations:

Peak Tensile Stress (kPa)

Equation 2.13

$$\sigma_t = \frac{LP}{wh^2} \times 10^6$$

Where:

σ_t = peak tensile stress (kPa)

L = beam span (mm), typically 356 mm

P = peak force excursion (kN)

w = beam width (mm)

h = beam height (mm)

Peak Tensile Strain (mm)

Equation 2.14

$$\boldsymbol{\varepsilon_t} = \frac{108\delta h}{23L^{2}} \times 10^{6}$$

Where:

ε_t = peak tensile strain (microstrain)

δ = peak displacement (mm)

h = applied beam height (m)

L = beam length between outside clamps

Flexural Stiffness

Equation 2.15

$$S_{mix} = \frac{1000 \times \sigma_t}{\varepsilon_t}$$

Where:

S_{mix} = flexural stiffness (MPa)

σ_t = peak tensile stress

ε_t = peak tensile strain

2.12.5 Dynamic modulus

The dynamic modulus value is the ratio between an induced strain and applied stress. Method AASHTO TP 62-07 (AASHTO 2003) is utilised to test samples. One sample is required to cover a relatively wide range of test conditions subsequently saving time. In the United States of America, dynamic modulus is an input parameter that conveys the intrinsic behaviour of viscoelasticity across a range of temperatures and frequencies or loading time (Transportation Research Board of the National Academies (TRB), 2004).

Dynamic modulus normally decreases with temperature and increases with frequency. If asphalt is treated as a linear viscoelastic material, the dynamic modulus at a given temperature and frequency can also be obtained with other temperature and frequency combinations; taking in consideration the principle of temperature-time superposition. Test results correspond to temperatures and loading frequencies represented in a sigmoid function. Results resemble real pavement conditions which can be applied to the design and structural analysis of the pavement.

The technique permits the creation of a master curve where data attained at various temperatures is transferred to either high or low frequencies. Therefore, the dynamic modulus curve results in a single reference temperature (Kumlai et al., 2014). To achieve a single smooth line the Time Temperature Superposition principle (TTS) is applied (Pellinen et al., 2002) using equation 2.16 and to obtain the function inputs equation 2.17 was utilised. Equation 2.18 was utilised to construct the master curve.

Equation 2.16

$$\log f_r = log f + log\ [a(T)]$$

Equation 2.17

$$log[a(T)] = a_1(T_R - T) + \ a_2\ (T_R - T)^2$$

Where:

f_r = reduced frequency (Hz)

f = frequency (Hz)

a(T) = shift factor

T_R = reference temperature (°C)

T = temperature (°C)

a_1, a_2 = fitting coefficient

Tests indicate the stiffness of an asphalt mix and the absolute value of the peak-to-peak stress divided by the peak-to-peak recoverable strain under sinusoidal loading (Asphalt Design, 2012). A sinusoidal compressive stress is applied along a vertical axis of a cylindrical asphalt sample, and the resulting strain measured is the dynamic modulus value obtained from the following equation:

Equation 2.18

$$log(|E^*|) = \delta + \frac{\alpha}{1 + e^{\beta - \gamma log f_r}}$$

Where:

$|E^*|$ = dynamic modulus (MPa)

δ = minimum log ($|E^*|$)

α = span of log

β, y = shape parameter

2.12.6 Stability and Flow

Testing of Stability and Flow properties is fundamental to the use of the Marshall method. It determines the optimum values for volumetric properties of specimens compacted by the Marshall hammer, by measuring the strength of an asphalt mixture that has been compacted to a standard laboratory compaction effort (Brown et. al, 2001). Test method MRWA 731.1 (Main Roads Western Australia, 2010) provides and describes procedures to perform the testing.

To calculate the Stability for each of the samples tested the following equation was used:

$$Stability = Max.Load \ \times Height\ Correction\ Factor$$

Where:

Max Load = maximum force applied in kN
Height Correction Factor = factor for correcting the stability.

Table 2.15 presents the height correction factors

Height of Specimen (mm)	Height of Correction Factor
57	1.19
58	1.16
59	1.13
60	1.10
61	1.07
62	1.04
63	1.01
64	0.99
65	0.96
66	0.94
67	0.92
68	0.90
69	0.88
70	0.86

Table 2.15 Height correction factor (MRWA731.1 2010)

To calculate the Flow of the specimen the following equation was used:

Equation 2.19

$$Flow = (Final\ Rev.Count - Initia\ Rev.Count)\ \times Rev\ Factor$$

Where :

Flow = vertical deformation (mm)
Rev. Factor = revolution factor (mm/Rev)

3 Warm Mix Asphalt

Overview

Warm Mix Asphalt has become an increasingly viable option to HMA in road construction in many parts of the world and around Australia.

This chapter is divided into sixteen main sections that provide information of several WMA technologies principally focusing on the organic additive Sasobit. The aim of the chapter is to comprehensively understand the potential benefits and the performance of WMA with Sasobit.

3.1 Sustainability factor

‘Sustainability’ and ‘low carbon footprint’ are considered significant terms nowadays; ‘Humanity has the ability to make development sustainable to ensure that it meets the needs of the present without compromising the ability of future generations to meet their own needs’ (World Commission on Environment and Development, 1987). Sustainable advancement infers the need to reduce consumption of raw materials and/or energy, together with reduced emissions. Hence, the need to develop new technologies and guidelines to align decision making with sustainable objectives is essential. In keeping with sustainability, the development and incorporation of sustainable technologies like WMA is vital in road construction, as it can contribute to lowering the carbon footprint and safeguarding natural resources.

The Environment and Sustainable Development conference held in Rio de Janeiro in 1992 marked the beginning of a worldwide awareness of the damage and potential dangers facing the planet. The devastation of natural resources and climate change were the main concerns, and believed to be the principal causes of damage and disruption to ecosystems. One of the main contributors is the industry, for example agriculture and transport.

Greenhouse gases (GHG) are gaseous parts of the atmosphere (natural and man generated) that absorb and emit infrared radiation. They are necessary for maintaining a liveable temperature range on the planet (Austroads, 2010). An excess in GHG leads to trapping additional infrared radiation, therefore raising global temperatures. Life could perish if GHG levels are left too high. Gaseous emissions include: inorganic emissions such as SO_2 (burning process in the dryer), NO_x (mainly from burner in the drying drum), CO (mainly associated with the combustion process in the dryer), and carbon dioxide (CO_2) which is directly related to the type of fuel used and the energy consumption needed for the heating process. Other emissions to consider are: methane (CH_4), TOC (total organic compounds), PAH (polycyclic aromatic hydrocarbons), noise and traffic, odours and water, and effluent ground water pollution (European Asphalt Pavement Association, 2007).

The carbon footprint is a ‘measure of the impact human activity has on the environment in terms of the amount of greenhouse gases produced, measured in units of carbon dioxide’ (Austroads, 2010).

In 1997, the United Nations Framework Convention on Climate Change (Kyoto Protocol) formalised the commitment made by signatory countries to bring GHG emission rates down to 1990’s levels; the agreement was implemented on 13 February 2005.

The asphalt industry worldwide is committed to reducing the extent of GHG from its operations by adhering to many global agreements and national legislative requirements, leading to the improvement in energy efficiency in the asphalt production process. In general terms, emissions come from the heating and drying of aggregates and materials: an issue that can be counteracted with the use of less carbon-intensive products and processes.

The European Union, under the terms of the Kyoto Protocol, made a commitment to reducing GHG. Considering this, the European asphalt industry began using WMA technologies to build asphalt pavements at substantially lower temperatures.

Meanwhile, in Australia, a target was set to reduce GHG emissions by between 5 and 15% by 2020 (Department of Climate Change and Energy Efficiency, 2010) with the long-term aim of reducing the GHG emissions by 60% by 2050. In 2011 the Clean Energy Bill introduced a carbon pricing scheme which inferred that Australia’s largest emitters required permits for each tonne emitted. The scheme was repealed in 2014 and the government set up the Emission Reduction Fund in 2014 instead.

The Environmental Protection Agency (EPA, 2000) estimated that, in a year, a drum mix asphalt plant emitted around thirteen tonnes of CO_2, five tonnes of volatile organic compounds, 0.4 tonnes of sulphur oxides, 2.9 tonnes of nitrogen oxides, and approximately 0.65 tonnes of hazardous air pollutants (average in relation to 200,000 tonnes of production).

In Australia approximately 390,000 tonnes of CO_2 are generated annually from the production of 8,000,000 tonnes of asphalt (Jenny, 2009). Australia could achieve a reduction of 120,000 tonnes of CO_2 per annum if a reduction in temperature at production is achieved. Therefore, WMA technologies can make a significant contribution to the Australian CO_2 balance, considering the reduction in necessary temperature at production and placing of the asphalt mix.

The reduction in temperature during production, placing and compaction (reported in several studies) has potential benefits – economically, environmentally and concerning workability – through improved pavement performance, efficiency and environmental conservation. WMA is viewed as one technology that offers pavement sustainability. The asphalt industry keeps exploring ways to contribute to the reduction in GHG emissions, whilst also adding benefits for asphalt workers and/or by recycling material in the production of asphalt or re-using some materials.

3.2 Emissions associated with asphalt production

HMA is normally produced in a drum mix plant at temperatures ranging from 150 to 170 °C. The high temperatures are utilised to dry the aggregates to attain proper and uniform aggregate coating and the desired mix workability, allowing sufficient time to place and compact the mix. A reduction in production and compaction temperatures has been the researchers' aim for several years, even as early as 1956 (Asphalt History, n.d.).

D'Angelo et al. (2008) stated, 'the reduction in plant emissions from WMA production is very significant': up to a 20-40% reduction in CO_2, a 10-30% reduction in carbon monoxide (CO), a 20-35% reduction in sulphur dioxide (SO_2), up to a 50% reduction of volatile organic compounds (VOC), and a 60-70% reduction in nitrous oxides (NOx). In addition, a '32% reduction in CO_2 is possible when the production temperature is lowered by 20 °C' (Mallick et.al, 2009).

Emission rates vary in the production and transport of asphalt. Research shows that the use of bitumen as a binder for the construction of pavements generates considerably less GHG during production (Ripoll & Farré, 2008). Mixing temperatures had a small – but not insignificant – effect on emissions, as seen on Table 3.1 measured in kg/tonne of asphalt mix production.

Mixing Temperature (C)	CO_2	CH_4	N_2O	CO_2equivalent	Change relative to 155 °C (%)
175	36.3	0.0018	0.0008	36.6	+4.6
155	34.7	0.0018	0.0007	35.0	0
130	32.7	0.0018	0.0007	33.0	-5.7

Table 3.1 Emissions changes due to mixing temperatures

It needs to be noted that adding recycled asphalt pavement (RAP) to WMA mixes has shown a significant effect on emissions, based on remedial work at London's Heathrow airport (Huang et al. 2008).

Another factor to consider is the fuel used in the burner at the asphalt plant, which influences the CO_2 emissions. Study results on emissions in an asphalt plant from the combustion of the heating fuel indicated poor combustion and a rise in CO, VOC and heavy hydrocarbons which are hazardous to workers' health (Paranhos et al. 2008). Another study reviewed emissions (CO_2) resulting from the use of diesel and gas as the heating fuel, and the emission results were higher as it included emissions from the asphalt itself. The CO_2 emissions from HMA were 22 kg/tonne of asphalt and 15 kg/tonne of asphalt for diesel and gas respectively, while CO_2 emissions in the production of WMA were 16 kg/tonne of asphalt and 12 kg/tonne of asphalt using diesel and gas respectively (Harder et al. 2008). Table 3.2 presents emissions from asphalt plant using different fuels (Austroads, 2010).

Fuel Type	CO_2	CO	NO_X	CO_2 equivalent
Gas fuel	1.3	0.5	0.01	4.8
Oil fuel	2.2	0.3	0.09	5.8

Table 3.2 Emissions from asphalt plants (Ripoll & Farré, 2008)

It needs to be taken into account that, in Australia, aggregate stockpiles are commonly exposed to weather. This translates to the stockpiles being damp and the actual moisture content varying upon location and the season of the year. Therefore, more energy might be required to dry the material which means an increase in the CO_2 emissions (Ripoll & Farré, 2008). Table 3.3 shows changes in emissions due to damp aggregates (kg/tonnes of production).

3.3 Fuel – Cost/Savings

As there are different technologies to produce WMA there are differences in the possible energy and/or cost savings which are dependent on the technology used and how much the production temperature was lowered. This is directly linked to the type of fuel used - for this study gas was used - and considering that the price of fuel is constantly rising the possible savings could increase. See section 5.9.3 for gas consumption details.

Aggregate moisture content (%)	CO_2	CH_4	N_2O	CO_2 equivalent	Change relative to 2% (%)
1	32.1	0.0017	0.0007	32.4	-7.4
2	34.7	0.0018	0.0007	35.0	0
5	42.5	0.0020	0.0009	42.8	+22.3

Table 3.3 Emissions change (Ripoll & Farré, 2008)

At present, there are no standard methods for measuring emissions from an asphalt plant. Table 3.4 presents data from various reports showing the reduction in percentage in emissions and energy between various WMA products/processes and conventional HMA (Austroads, 2010). The table utilises data from trials conducted in the USA (Gandhi, 2008).

	CO	CO_2	SO_2	NO_x	Energy
∗FHWA (2008)	10 to 30	15 to 40	18 to 35	18 to 70	20 to 35
Advera	62	●	83	30	●
Aspha-Min	19	3 to 18	18	6 to 23	23 to 30
Double Barrel Green Process	10	11	●	8	24
Evotherm	63	45	81	58	30 to 55
Sasobit	32	18	●	34	20
WAM Foam	8 to 29	31 to 35	25 to 30	62	24 to 35

Table 3.4 Reduction (%) in emissions and energy compared to HMA.

Therefore, technologies produced at lower temperatures than HMA create definite and positive effects on pavement performance, as the mix workability allows a high degree of compaction, resulting in improved density (Hurley and Prowell, 2006). Reducing temperatures can lessen oxidative hardening, decreasing cracking and improving the flexibility and longevity of the pavement. One technology through which the asphalt industry can contribute to sustainability – that is, less carbon-intensive products and processes – is WMA. It is precisely under that context that the development of the warm mix technologies has taken place. Table 3.5 presents reductions in emissions of WMA compared to HMA (European Asphalt Pavement Association, 2010)

Emissions	Reduction in emissions
CO_2	20-40%
SO_2	20-35%
VOC’s	Up to 50%
CO	10-30%
NO_X	Up to 70%

Table 3.5 WMA emissions reductions compared to HMA

3.4 Warm mix asphalt definition and function

WMA is a cluster of technologies that allow a significant temperature reduction in asphalt mixes, at production and placing, in comparison to conventional HMA. These technologies contain additives to reduce binder viscosity and/or increase the workability of the mix, providing a complete coating of aggregates at lower temperatures, with production temperatures between 100 °C and 130 °C.

WMA has been proven to have many constructions and performance benefits (National Asphalt Paving Association, 2009). Numerous methods to produce asphalt at a lower temperature have been developed and are commercially available with over 30 WMA technologies in the USA market (Tutu & Tuffour, 2016)**.** Table 3.6 presents commercially available WMA technologies.

Category	**Product / Process**	**Supplier**	**Web Address**	**Availability of field/ laboratory validation trials**
Sequential aggregate coating and binder foaming	Low energy asphalt (LEA1)	LEA-CO (France)	www.lea-co.com	yes
	Low emission asphalt (LEA2)	Suit-Kote McConnaughay Corporation (USA)	www.lowemissionasphalt.com	yes
	WAM-Foam®	Shell International (UK) / Kolo-Veidekke (Norway)	www.shell.com/bitumen	yes
Water-based binder foaming	AQUABlack®	Maxam Equipment, Inc. (USA)	www.maxamequipment.com	not reported herein
	Double Barrel® Green	Astec Industries (USA)	www.astecindustries.com	yes
	Terex® WMA	Terex® Corporation (USA)	www.Terex®rb.com	not reported herein
	Ultrafoam GX®	Gencor Industries, Inc. (USA)	www.gencorgreenmachine.com	yes
Binder foaming with water-bearing	Advera® WMA	PQ Corporation (USA)	www.Advera®wma.com	yes

additive	Aspha-Min®	Eurovia Services GmbH (Germany)	www.Aspha-Min®.com	yes
Chemical additive(surfactants / emulsions)	CECABASE RT®	Arkema Group (France)	www.cecachemicals.com	yes
	Evotherm® Evotherm® 3G Evotherm® DAT	MeadWestvaco Asphalt Innovations (USA)	www.evotherm.com	yes
	HyperTherm®	Coco Paving Inc. (Canada)	www.cocoasphaltengineering.com	yes
	Rediset® WMX	Akzo Nobel NV (The Netherlands)	www.surfactants.akzonobel.com	yes
Organic additives	Asphaltan B	Romonta GmbH (Germany)	www.romonta.de	yes
	Sasobit®	Sasol Wax (South Africa)	www.sasobit.com	yes
	LEADCAP®	Kumho Petrochemical (Korea)	www.leadcapwma.com	yes
Combined binder modifier/and organic additives	Shell Thiopave®	Shell	www.shell.com	yes
	TLA-X®	Trinidad and Tobago Ltd	www.trinidadlakeasphalt.com	not reported herein

Table 3.6 WMA technologies (Austroads, 2012)

The aim of WMA is to reduce the high temperatures at which HMA mixes are produced and laid, without negatively affecting the properties and, therefore, the performance. Probable added benefits are: a significant reduction in emissions (GHG) and fumes, lower energy consumption (during asphalt manufacture), improved working conditions (workers’ health – less fumes), improved safety benefits due to lower temperatures at production and placing, and improved productivity. The final point is due to the fact that it can be opened to traffic sooner than HMA; WMA allows for layers to be applied earlier.

WMA is produced at temperatures 20 °C to 40 °C lower than the characteristic temperatures of HMA. The technology is the result of many researchers concerned with the concept of reducing temperatures. In Europe, several different technologies have been used with auspicious results (Barthel et al., 2003). Figure

3.1 shows how WMA fits into the range of techniques from cold to hot mix (European Asphalt Pavement Association, 2015).

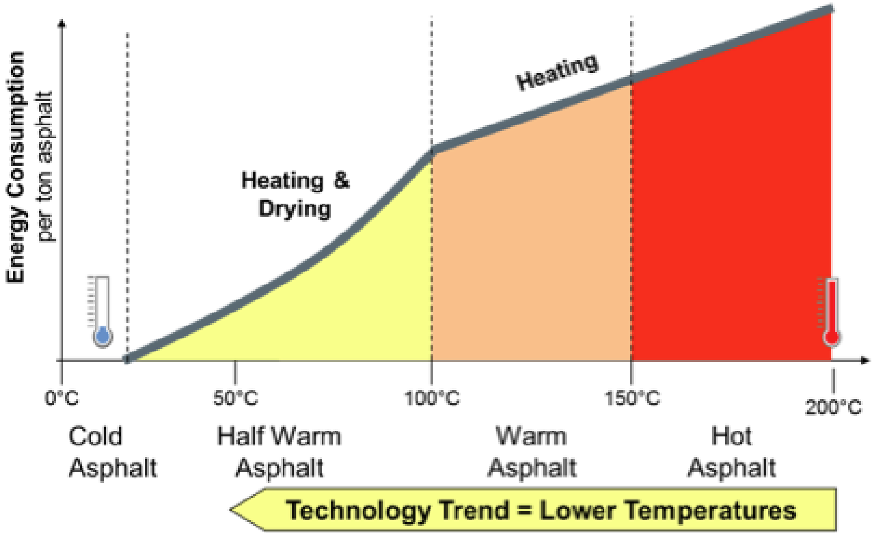


Figure 3.1 Classification by temperature range

But where did the concept of lowering the temperature to produce asphalt initiate? The idea has been a source of discussion for decades. The concept of WMA originated in Europe in the 1990s. Since then several technologies have been developed, particularly in the United States. It is recognised that, as the asphalt temperature decreases, its binder becomes more viscous and resistant to deformation resulting in air void reduction for a given compaction effort. This means that the binder becomes stiff enough to prevent any further reduction in air voids, regardless of the applied compaction effort.

3.5 Potential benefits and drawbacks

WMA technologies reduce the temperature of the asphalt mix at production and placement times, offering sustainability benefits in terms of environment, economy and performance. However, the technology also raises some concerns regarding the mixture. Both of these points are discussed in the thesis.

3.6 Potential benefits

WMA encompasses technologies which set forth benefits. The specific benefits and the degree of these benefits are entirely dependent on the WMA technology utilised (European Asphalt Pavement Association, 2010) and the reduction in temperature obtained. The benefits are in terms of:

3.6.1 Production

- Lower asphalt temperatures, resulting in less hardening of the bitumen/binder during manufacture, consequently improving the longevity of the pavement's service life.
- Lower production temperatures, reducing thermal stress on the asphalt plant components (European Asphalt Pavement Association, 2015).
- Could lead to easier attainment of authorisations for mobile plants in urban and rural zones due to reduced emissions, dust and noise.

3.6.2 Paving

- Reduces compaction effort (process and time) through the reduction in viscosity of the binder.
- Improves workability due to lower bitumen viscosity at paving time.
- Improves operational efficiency: faster construction and faster opening to traffic, due to shorter cooling time.
- Allows for work to be performed during cooler weather/season and/or at night (European Asphalt Pavement Association, 2015) because production and compaction temperatures are lower for WMA than HMA. The temperature drop is less significant (in time); permitting longer time for paving and compaction, yet still obtaining desired densities.

- Allows for longer haul distances, since paving/compaction time is extended due to the lower temperature, without losing workability. Expands market areas to outside metropolitan areas and rural zones.
- Improves working conditions for asphalt workers (Kristjansdottir, 2006) due to lower paving temperature, which translates to enhanced productivity and improved quality.
- Reduces fumes and odour at work sites resulting in less inconvenience for workers and the public in general.

3.6.3 Economic

- Less wear and tear of the asphalt plant due to reduced temperatures.
- Low energy consumption for production and placement, hence lower energy costs and a reduction of the overall costs of WMA production.
- Decreased fuel consumption due to reduced mix production temperatures.
- Increased RAP usage, saving on material cost by reducing the amount of virgin aggregates and binders in new mixes (Tutu & Tuffour, 2016) including material cost associated with transport. Also, savings of landfill space.
- Reduced binder aging, thus longer service life of the pavement.

3.6.4 Environmental

- Reduced emissions of CO_2 and other GHG due to the reduction in temperature needed to produce (asphalt plant), pave and compact WMA. The reduction leads to significant reductions in stack emissions (European Asphalt Pavement Association, 2015).
- Conservation of natural resources.

3.6.5 Safety

- Safer environment due to lower temperatures during production and paving.
- Cleaner working environment. Improved working conditions for asphalt workers (production and paving) due to reduced emissions and odour plus the added benefit of working at lower temperatures. The result of lower mixing and paving temperatures helps minimise fumes, emissions and odour.

3.6.6 Savings

- Due to better compaction, savings can be obtained through fewer roller passes which are needed to achieve density.
- Theoretically better long-term performance of WMA (durability increased through less ageing of bitumen at production and placing). Also, paving in cold weather can provide better compaction than HMA, therefore better durability due to better density.

It is necessary to note that the potential economic benefits in regard to consumption of fuel and gas may differ, because they are subject to the technology used and the reduction in temperature. Also, the fact that some WMA technologies require an initial plant modification while others require a constant cost for the addition of additives affects cost.

3.7 Potential drawbacks

Whilst there are benefits, there are a few concerns regarding the implementation and performance of the different WMA technologies, specifically in relation to specifications and quality control, where more research data is required. The potential drawbacks also depend on the specific technology being used as methods differ. Some of these concerns are as follows:

3.7.1 Water presence

One of the main concerns in the long-term performance of WMA is moisture sensitivity which is the potential for loss of adhesion between the binder and aggregate (Austroads, 2007). Concerns exist that, due to the low production temperatures, the aggregates might not completely dry increasing the potential for moisture issues. An incomplete vaporisation of water – problems such as premature rutting and stripping of the pavement – could occur. Technologies use antistripping additives to improve coating and adhesion to prevent these issues.

3.7.2 Long-term performance

WMA production with water-based technologies may lead to water being retained within the mix. It could also cause less binder absorption into the aggregate due to the lower temperatures. These are issues that could cause problems in relation to moisture susceptibility, cracking and aging in the long term. Also, as some organic additives can increase binder stiffness (at lower temperatures), the potential is consequently increased for thermal cracking.

3.7.3 Insufficient data

Since WMA is a relatively new concept, it is rather early to evaluate the long-term performance of the technology, particularly in Western Australia. In Europe, sections were constructed less than two decades ago and in the USA around ten years ago (Croteau & Tessier, 2008) and negative long-term performance has not been reported; on the contrary, some of the European trialled sections have performed equally to or better than HMA.

3.7.4 Economic

Even considering the benefits of less energy consumption, there are still some concerns with the implementation of WMA due to the added cost of the additives, along with the investment and depreciation of plant modification/s.

3.7.5 Environmental

Refers to concerns about the carbon footprint in the production and transportation of WMA technologies (Tutu & Tuffour, 2016) and the equipment necessary to produce it, as they may offset the environmental benefits.

3.8 WMA technologies

WMA technologies are many and can be grouped into two main classifications: one by the degree of temperature reduction, which includes cold mix (0-30 °C), half warm asphalt (65-100 °C) and warm mix asphalt (100-140 °C), and the other by the technology used to reduce the temperature. Among these technologies there are three main categories: the foaming techniques, chemical additives, and the organic or wax additives (category selected for this research: organic additive Sasobit) (European Asphalt Pavement Association, 2015).

In general terms, the amount of WMA additive depends on the materials used and the size of the mix, but particularly the type of pavement design (traffic volume) and grade of bitumen used.

3.9 WMA categories

There are several commercially available WMA technologies used to reduce the production, placing and compaction temperature. The classification based on table 3.6 section 3.3 is as follows:

- Sequential aggregate coating and binder foaming techniques
- Binder foaming using water-based mechanical systems
- Foaming techniques (water based and water containing)
- Chemical additives
- Organic or wax additives
- Combined chemical-organic additives (Austroads, 2012)

3.10 Sequential aggregate coating and binder foaming technology

This category involves sequential mixing stages of aggregate coating and binder and includes early foaming technologies like, WAM-foam®. The effective coating of the aggregate is considered vital to prevent water from reaching a poor binder-aggregate interface (Austroads, 2012).

3.11 Binder foaming technology using water-based mechanical systems

Foaming technologies use a small amount of cold water that can be injected into the hot binder or directly into the asphalt mixing plant. Water quickly evaporates and is captured in the binder, resulting in a large volume of foam which increases the volume of the binder and lowers the viscosity, thus improving coating and workability. Technologies include: Double Barrel® Green and the AQUABlack® WMA, among others (Perkins, 2009).

For the process to work, enough water must be incorporated to cause foaming, but not too much to cause stripping problems. To avoid the issue, manufacturer advice the use of antistripping additives to ensure moisture susceptibility of the mix is minimised (Austroads, 2012).

Liquid antistripping additives are recommended to produce WMA (the proportion usually used is 0.5% by mass of the binder) which is added to the binder just before mixing with the aggregates (Main Roads Western Australia, 2016).

It needs to be noted that most HMA plants would require modifications to add the water into the system for the foaming process, incurring an extra cost initially.

3.12 Binder foaming technology using water-bearing additives

Two main water-containing products are used in this category: the Alpha-Min and the Advera. Both use finely-powdered zeolite which contains about 20% water of crystallisation (Austroads, 2012). It is introduced at the same time as the binder, and added to the mix. A fine water mist is released, producing foam. It has been reported that a controlled foaming effect could add between six and seven hours of added workability time (Drüschner, 2009).

3.13 Chemical additives (surfactants/emulsions)

Chemical additives are available in many different products with the peculiarity that they do not change the bitumen viscosity. They act as surfactants to regulate and reduce the frictional forces at the microscopic interface of the aggregates and the bitumen at different temperatures. The reduction in temperature depends on the amount of product added, which can be either in the form of an emulsion or added to the bitumen during the production process, and then mixed with the hot aggregates (Chowdhury & Button, 2008). Plant modifications might be required to use some of the additives.

Chemical additives are a combination of emulsification agents, polymers, surfactants and additives, made to improve coating and workability – thus compaction – in addition to antistripping agents for adhesion. Among the most widely used chemical additives are: Evotherm (3 categories), Rediset®, Revix and Cecabase.

3.13.1 Evotherm®

This is a product developed by MeadWestvaco, and under this category there are three types of technologies: Evotherm® ET, Evotherm® DAT (replacing Evotherm ET) and Evotherm® 3G.

3.13.2 Evotherm ET (emulsion technology)

This is a technology used to improve aggregate coating, mixture workability and compaction, through a chemical package of emulsification agents and antistripping agent additives. Evotherm ET decreases the viscosity of the binder at lower temperatures, resulting in full coating of the aggregates at the same temperature. It is delivered as a high-residue emulsion (Evotherm Warm Mix Asphalt Technology, n.d.).

It must be noted that water content in the emulsion flashes off as steam when the emulsion is mixed with the hot aggregates, reducing the temperature by 30% (Jones, 2008).

3.13.3 Evotherm® DAT (dispersed asphalt technology)

This is the same chemical package as previously mentioned, but with a difference. Evotherm DAT is diluted with a small amount of water and is injected into the asphalt line just before the mixing chamber. It decreases the viscosity of the binder when mixing at low temperature, and reduces the production temperature by 30% (Sargand, 2009).

3.13.4 Evotherm® 3G

This is a water-free form of Evotherm®.

3.13.5 Rediset®

Rediset® is a combination of cationic surfactants and organic additives in pellet form that chemically modifies the bitumen by reducing the viscosity and boosting adhesion, thus improving the wetting of the aggregates by the binder. Adding 1.5 to 2% by weight of bitumen permits a reduction in production temperature of between 15 and 30 °C in comparison to HMA (Chowdhury & Button, 2008).

3.13.6 Revix

This technology allows a reduction in mixing temperature of between 15 °C and 27 °C in comparison with similar HMA mixes. Materials used are: waxes, surfactants, polymers, processing aids, and others. This chemical, unlike others, does not depend on foaming or viscosity reduction for reducing mixing and compaction temperatures (Prowell & Hurley, 2007).

3.13.7 Cecabase RT®

Cecabase RT® is a water-free liquid additive developed for warm-coated materials. It contains surface active agents composed of at least 50% renewable raw materials (Austroads, 2012). It can be added to the bitumen and its application allows for a reduction in temperature on the road surface of approximately 40 °C without affecting the mix performance. It is readily soluble in the asphalt binder and does not require premixing with a standard dosage rate between 0.2 and 0.5% based on binder weight (Cecabase RT, 2000).

It should be noted that the combination of both chemical and organic additives to the binder allows for another category of WMA. The addition of a chemical, for example sulphur, can improve the performance of the binder, and the addition of an additive can lower the viscosity of the binder at compacting temperatures, thus increasing workability.

3.14 Organic additives

Organic or wax additives are used to attain a reduction in temperature by reducing the viscosity of the binder, which increases the workability of the mix. The process consists of decreasing the viscosity over the melting point of wax, allowing the production of asphalt mixes at lower temperatures. The organic additives are mostly waxes or fatty acid amides (Austroads, 2012). Once crystallised, the binder stiffness results in resistance to deformation. It is important to choose the right type of wax as the melting point needs to be higher than expected to minimise stiffness of the asphalt at low temperatures (Perkins, 2009).

This category includes technologies such as Sasobit, Asphaltan B, Asphaltan A, Romonta N, Licomont BS 100 and Leadcap®. These are the main organic additives used, and it is also worth mentioning a new product: Sasobit Redux. These can be added either to the mix or the bitumen; nevertheless, they are more effective when added to the binder prior to the manufacturing of the asphalt. Amid all the technologies capable of achieving good results, wax additives are considered to be one. In addition to lowering the temperature at production, wax allows the asphalt to be carted over long distances and to be placed whilst still achieving all the relevant specifications. On this basis, the additive Sasobit was chosen for the investigative trials and is discussed in depth in section 3.5.

3.14.1 Asphaltan B

This additive is a refined Montan wax combined with a fatty acid amide. It acts to enhance asphalt flow at low temperatures, but less than the other Fisher-Tropsch waxes. It offers increased compactability and rutting/moisture resistance. The melting point for Asphaltan B is just below 100 °C (Federal Highway Administration, 2017).

3.14.2 Asphalten A and Romonta N

Montan waxes are obtained through solvent extraction of certain types of lignite or brown coal with a congealing point of 78 °C and 125 °C respectively, where stiffness is increased after cooling as per fatty acid amide. In Germany, Montan waxes have been used with stone mastic asphalt (SMA) due to the ability to modify the binder consistency and improve the adhesion between binder and minerals.

3.14.3 Licomont BS 100

Licomont BS 100, as other additives, is a fatty acid amide which has a melting point of between 140 °C and 145 °C, and solidifies between 135 °C and 145°C. Drüschner (2009) stated that an addition of 3% to the binder increases the softening point by 40 to 45 °C.

3.14.4 Leadcap®

This is a relatively new product from Kumho Petrochemical in Korea, and it has the characteristic of not requiring any plant modification. It has been designed to improve crack resistance and rutting, and to help reduce moisture susceptibility of asphalt. It contains an adhesion promoter for better adhesion of the aggregates and the binder. It also reduces odours and fumes produced during production and paving (Leadcap, 2012).

3.14.5 Sasobit Redux

This additive is designed to reduce viscosity, reduce aging, reduce temperatures and reduce compaction resistance (Sasol Performance Chemicals, 2016).

3.15 Combined chemical and organic additives

These technologies add chemical and organic additives to the binder. The organic lowers the viscosity of the binder while the chemical improves the performance of the binder, thus improving workability. They can be added to the mixture or the bitumen usually in pellet form. Among these technologies are Thiopave® and TLA-X®

3.16 Sasobit

Sasobit is a synthetic, hard, wax, organic additive, free from sulphur and other impurities, manufactured by Sasol Wax International. It is marketed in South Africa, Europe, the Unites States and Asia (Figure 3.2 shows Sasobit pellets). Sasobit-modified asphalts have been successfully used since 1997 in a wide range of applications in road construction. It is safe to both humans and animals, protects resources, and saves costs. One property of the wax is that it can get wet as water does not harm its effectiveness. Sasobit is a versatile additive suited for all asphalt applications, ensuring highly durable asphalt pavements (Sasol Performance Chemicals, 2016).

It offers:

- Enhanced workability
- Improved process reliability
- Temperature reduction (Warm Mix)
- Increased stability and
- Extended service life (Sasol Performance Chemicals, 2016)

Figure 3.2 Sasobit pellets

Sasobit is a fine, crystalline, long-chain, aliphatic hydrocarbon, also known as wax. Its molecular chain length is in the range of 45 to more than 115 carbon atoms, resulting in a higher melting point. In contrast, the molecular chain lengths of paraffin naturally found in bitumen range from 22 to 45 carbon atoms (Sasol Performance Chemicals, 2016). It is available in solid form, either as a prill (about 5mm in diameter or a smaller prill of 1mm in diameter) or in flake form of 3mm chips. It is packaged in 2, 5 or 20 kg bags and 600 kg super sacks. Figure 3.3 shows a Sasobit carbon atom chain.

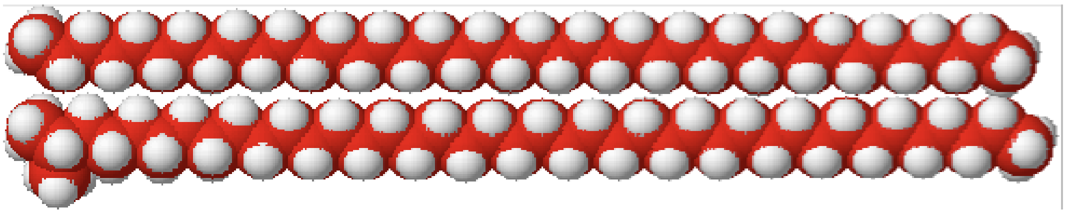


Figure 3.3 Sasobit carbon atom chain

It is produced from coal gasification or the conversion of natural gas using the Fischer-Tropsch (FT) synthetic process of polymerisation (Damm et al., 2002) with a melting point range between 85 °C and 115 °C. It is completely soluble in bitumen at temperatures above 115 °C, significantly reducing viscosity (Sasol Performance Chemicals, 2016).

It is highly crystalline in structure, which results in a hard material in relation to bitumen; therefore, it is easily melted resulting in low bitumen viscosity, and enhancing the workability of the mix. It is precisely the low viscosity that allows the asphalt to be manufactured at lower temperatures and still be uniformly compacted. Figure 3.4 shows viscosity curves of standard bitumen and Sasobit-modified bitumen (Sasol Performance Chemicals, 2016).

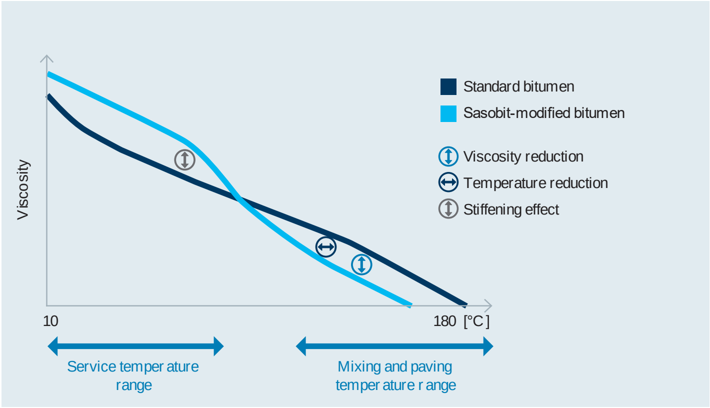


Figure 3.4 Viscosity curves (Bitumen/Sasobit)

Sasobit solidifies in asphalt between 65 °C and 115 °C and is completely soluble in bitumen at temperatures above its melting point. It does not separate in storage.

Sasobit allows an upgrade of softer binder grades to harder grades where resistance to permanent deformation is expected, with improved compaction.

During cooling, Sasobit crystallisation begins at 90 °C forming a lattice structure in the asphalt binder (bitumen), having a stiffening effect which increases the asphalt stability. Figure 3.5 shows Sasobit state mixed with bitumen (Sasol Performance Chemicals, 2016).

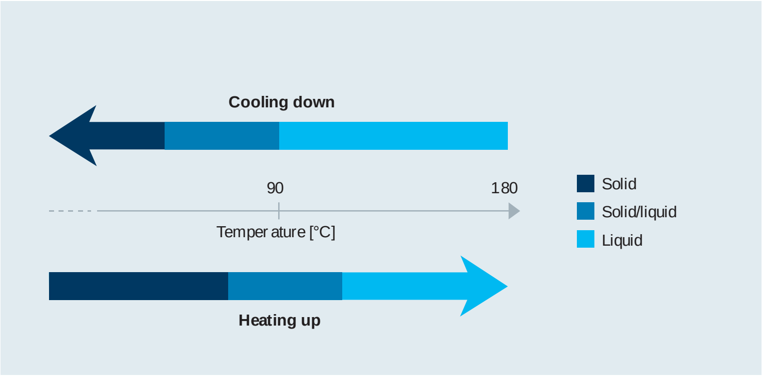
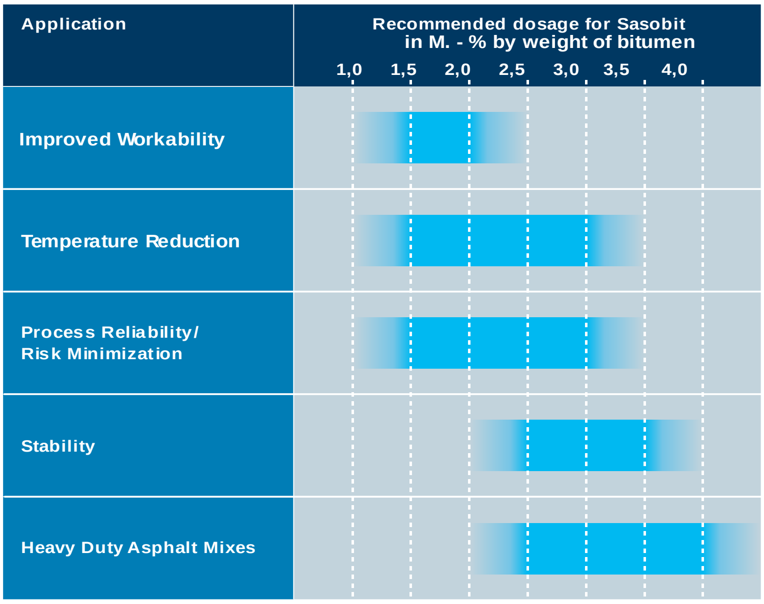


Figure 3.5 Sasobit state at different temperatures

The optimum percentage of Sasobit as stated by the manufacturer is 1.5% by weight of the binder; to produce WMA. However, just by adding 3.5% of Sasobit by weight of bitumen, the softening point is decreased by 20 to 35 °C and the penetration falls by 15 to 25 1/10mm (Drüschner, 2009). This accounts for resistance to rutting obtained with Sasobit modified mixes. The manufacturer recommends blending Sasobit into the hot binder, rather than directly adding the material into the mixing chamber of the asphalt plant, due to issues in relation to the homogeneous distribution of the mix. Table 3.7 shows Sasobit dosages recommended by the manufacturer.



Application	Recommended dosage for Sasobit in M. - % by weight of bitumen 1,0 1,5 2,0 2,5 3,0 3,5 4,0
Improved Workability	
Temperature Reduction	
Process Reliability/ Risk Minimization	
Stability	
Heavy Duty Asphalt Mixes	

Table 3.7 Sasobit recommended dosages

Completely soluble Sasobit forms a homogeneous solution reducing the bitumen's viscosity, thus acting as a flow modifier. It enables mixing and handling temperatures of the asphalt to be reduced by 10 to 30° C in comparison with HMA mixes (Table 3.8 provides fuel and CO_2 savings due to reduced temperatures). Temperature reductions of up to 50 °C can be reached by process optimisation between the mixing plant and paving. The result is a significant reduction of bitumen fume emissions and CO_2 emissions and less energy consumption during operations. Evidence shows that the temperature factor is dominant in influencing CO_2 emissions during asphalt production (Hanson et al., 2012). It has also been indicated that the construction phase and the mixing process represent about 50% of the total energy consumption, while the paving and compaction stages represent around 4% (Zhu et al., 2016).

Savings per Tonne of Asphalt Mix
Temperature reduction = 30 K → Fuel and CO_2 savings of 18– 22%

Table 3.8 Saving fuel and CO_2 (EAPA, 2015)

Sasobit’s liquid state allows the aggregate to move freely in the binder providing good adhesion, without the use of additional chemical additives, which provides increased resistance to stripping (Sasol Performance Chemicals, 2016). Additionally, low-viscosity Sasobit is much harder than bitumen at temperatures below its crystallisation point. Consequently, Sasobit-modified asphalt displays the difference of increased resistance to permanent deformation, with a higher binder softening point depending on the amount of Sasobit added, in the overhaul temperature range. It also promotes workability through lower binder viscosity in the mixing and laying range of temperatures (Sasol Performance Chemicals, 2016).

Improved workability reduces the risk of compaction failure, ensures good compaction during cool or poor weather conditions – which extends the construction season – and guarantees easier manual application of the asphalt mix (Sasol Performance Chemicals, 2016).

Sasobit is unique in respect to other additives as it can be added to both the binder and the mix in several ways. It can be blown into the asphalt stream before the asphalt hits the aggregate, injected into the mix, added in-line with the binder in a molten state, or mixed into the binder with a normal paddle mixer or a simple stirrer. Once blended, Sasobit stays homogeneous and can be kept in storage for several weeks or more as it does not exhibit separation (Sasol Performance Chemicals, 2016).

3.17 WMA performance trials

WMA has been used successfully in many countries for many years. Many technologies have been used, and the results have been similar. The first pavement trials involving WMA were constructed in Germany and Norway between 1995 and 1999.

In Germany, many WMA test sections have been constructed and monitored. Based on data obtained from laboratory and field performance, dense graded mix control sections showed the same or better performance than HMA (European Asphalt Pavement Association, 2015). Tests were followed by the first highway project in 1999 with Alpha-min zeolite-treated mix (Croteau & Tessier, 2008).

In Norway, many projects using WMA began in 2010 where the production temperature was decreased by 30 °C. Additionally, in South Africa in 2011 the WMA Manual was released after the completion of successful trials between 2008 and 2010 where mixing and paving temperatures were recorded 25 °C to 30 °C lower than those of HMA (Naidoo et al., 2011). However, it is in the United Sates where WMA is being focused on as a technology. Since a study trip to Europe in 2002 by National Asphalt Paving Association (NAPA), a growing interest in WMA has begun. The first trials were conducted in 2004, and the Federal Highway Administration (FHWA) identified WMA in its *Every Day Counts Initiative* for accelerated utilisation, with a 533% increase in WMA production since 2009 (National Asphalt Paving Association, 2013).

3.17.1 WMA Australian trials

Some trials have been performed around Australia with the aim of demonstrating the benefits of WMA technology. In Sydney, New South Wales, 1.5% of the additive Sasobit was used for deep heavy patching at Woodville Road. The work comprised a full pavement reconstruction involving milling 410 mm of existing pavement, placing 200 mm of stabilised dense graded road base and 210 mm of asphalt in four layers of 60 mm of AC 20 and two layers of AC 14 with AR450 binder (Figueroa et al., 2007).

The asphalt was mixed at 130 °C and the results of the trial showed low air voids at low temperature and high bulk density, which translates to a pavement highly resistant to deformation and fatigue, low permeability and durable.

In 2006, the Road and Traffic Authority (RTA) and Boral Asphalt New South Wales carried out a series of trials using WMA with Sasobit (Bornmann et al, 2007). Dense graded mixes were used (AC14 and AC20, RTA 2001) with 1.5% of Sasobit of binder by mass used. Temperatures used for production ranged from 130 °C to 140 °C and compaction temperatures of 90 °C to 120 °C, allowing for a satisfactory compaction, and achieving results of on-field air voids of 5% to 6% on average.

4 Methodology and Experimental Design

4.1 Overview

This chapter presents the methodology and the experimental design plan for this research in eight main sections. The objective was to evaluate WMA using local materials under Western Australian conditions. The study evaluates the effectiveness of WMA in properties of both volume and performance. Laboratory testing was divided into four key stages: specimen preparation, binder testing, volumetric property determination, and performance testing. The research addresses specific issues concerning the volumetric and performance properties of DGA mix, with and without Sasobit, using cylindrical specimens. The chapter also includes a brief description of the methods and the respective procedures used to determine the properties and the optimal percentage of additive needed to design and evaluate WMA mixtures.

4.2 Experimental design

The research describes the experimental design developed to assemble evidence to validate WMA for Western Australian conditions. The equipment used for the production, placement, compaction and transportation of WMA was the same as that used for HMA, although modifications were made to the asphalt plant to add the additive (Sasobit). Testing was conducted to determine whether the temperature and the percentage of Sasobit (as part of the process) could be a factor that influences the life service of the asphalt. Figure 4.1 presents the experimental plan used for testing the asphalt mixture.

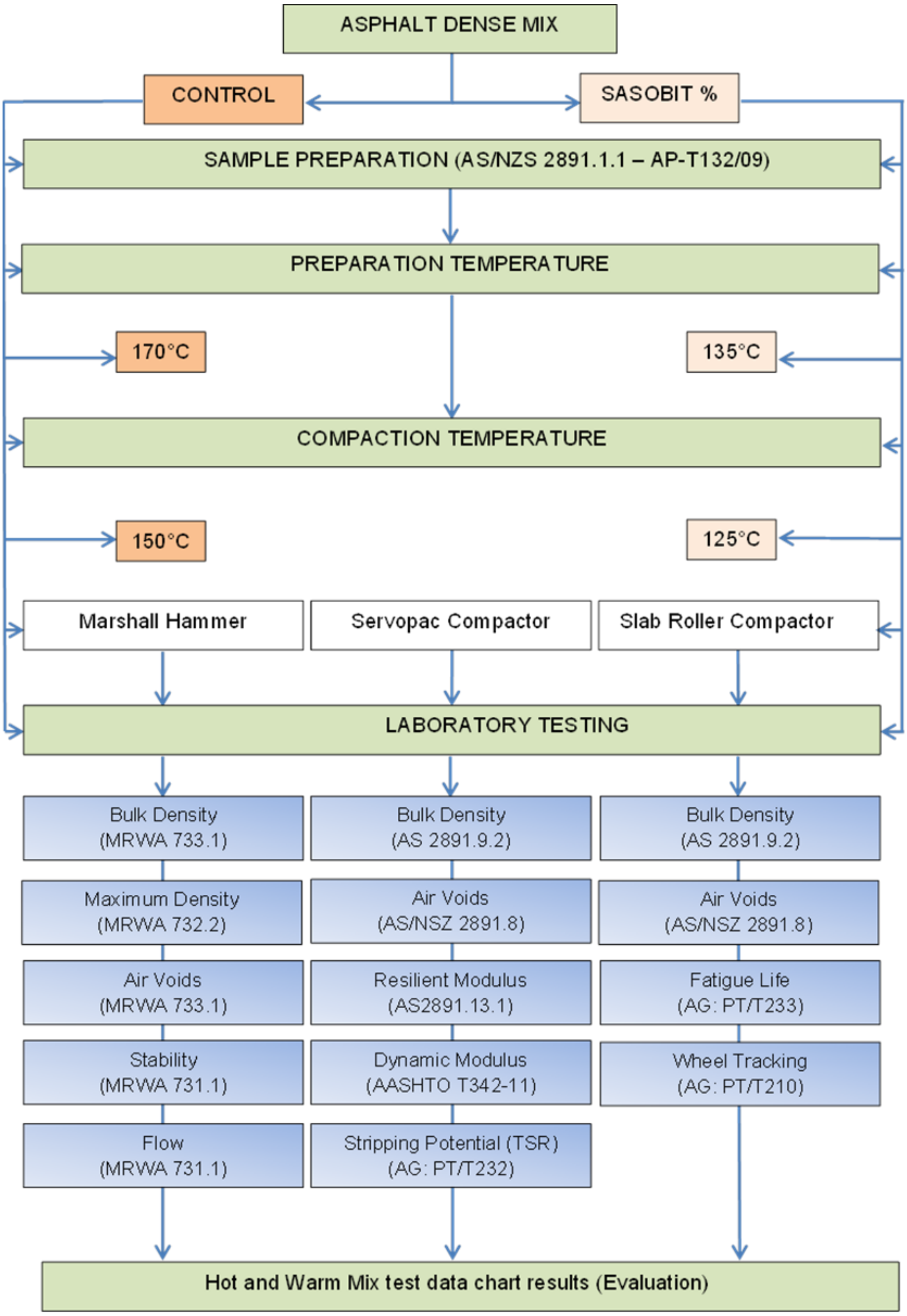


Figure 4.1 Experimental plan for asphalt testing

4.3 WMA production requirements

Asphalt is a mixture of aggregates, binder and filler used for the construction and maintenance of all kinds of roads (European Asphalt Pavement Association, 2015). The process of placing and compacting has been used for a long time, with the basic process of asphalt production starting at a plant which is either fixed or mobile. The latter has the advantage of moving from site to site for major works, and it allows the mixing and placing of asphalt to be a continuous process on the work site.

Plants are divided into two main types: the continuous mixing plants (most commonly a drum mix plant) and the batch plants. In a drum mix plant mixing takes place in the drum, while in a batch mix plant mixing takes place in a special mixer known as a pug-mill. In general, an asphalt plant can be divided into the following main parts:

- hoppers of the cold feed unit
- aggregate drying unit and connected bag filter
- bitumen storage tanks and filler silos
- mixing tower and/or mixing unit (for a batch plant add hot screening and hot aggregate storage bins)
- silos for storing hot asphalt (not always the case) (European Asphalt Pavement Association, 2015)

The asphalt mixing process consists of heating and drying aggregates; combining the aggregates, filler and binder in the appropriate percentages; mixing the binder with aggregates, and finally discharging the mix in optimum conditions for transport, placing and compaction (Austroads, 2014).

The complete plant operation is monitored from the control house of the plant. The degree of automation depends on the plant mobility and age. A modern plant can monitor burner and fuel consumption; process air volumes, drum pressures, exhaust gases, baghouse pressure, flow rates for used materials, and finished mix transfer; discharge and storage selection (European Asphalt Pavement Association, 2015). Small plants are usually monitored through simple control mechanisms.

In Australia, the most common asphalt mixing plants are the batch plants. They have greater flexibility than drum plants as they can change from one size of mix to another without wastage (Austroads, 2014).

Warm mix asphalt can be produced in a continuous or batching plant. A flawless production process requires functioning exhaust stacks to ensure that exhaust temperatures are above the dew point, even during low aggregate temperatures in the dryer drum. The speed of the dryer drum can be adjusted as it can be helpful to reach the right aggregate temperature and match the speed of the burner output and the dryer drum (German Asphalt Pavement Association, 2009). The addition of additives to produce WMA may require some modifications or additions to the plant.

4.3.1 Addition of technology

To produce WMA, additives are an extremely important part; the viscosity of the binder is changed by the addition of different additives, allowing a reduction in production and paving temperatures. Depending on the product used, the manner of introducing the additive to the mix can be through the modification of the bitumen by the producer (ready to be utilised in the asphalt mixing plant), or the addition of technology used at the plant site. The additive is delivered separately from the binder and then mixed together with the rest of the mix. There are two main ways of adding the additives, either dry or wet.

If introduced dry (as solid prills) the additive is injected into the asphalt line either directly, or just before the mixing chamber. If it is introduced wet (molten liquid selected for this research) the additive is mixed together with the binder until a homogeneous mix is achieved; this is imperative for the quality of the mix, thus its performance. The additive is mixed with the aggregates in the mixing chamber.

4.3.2 Description of specific products

For several products, the producers offer a complete installation package that can be installed in a few days in either a batch or continuous plant. Sasobit can be pre-blended with the binder, blended in-line in a molten state (flakes) or added during the mixing process as a pellet. The safest method for the introduction of Sasobit into the hot binder, according to the manufacturer, is prior to mixing with aggregate (Sasol Performance Chemicals, 2016) which requires an additional blending unit for the plant. It should be noted that when the product is added at the refinery or at the producer's plant, there is an added cost to the production due to the addition of the additive.

4.3.3 Equipment for adding technologies

As there are different technologies, there are different modifications to the equipment required for the introduction of the additive into the mixing plant chamber. Important to consider also is the maintenance of the equipment utilised, as it may require special cleaning or treatment between batches.

The equipment required for liquid additives is a stirring unit where a volumetric pump can be used to introduce the additive into the bitumen tank; a precise metering system is required. To introduce fibre into a mix, the original equipment can be adjusted to incorporate the additive. If no equipment is available, then a pneumatic feeder or weight hopper can be utilised.

For the study, modifications were made to the plant, as small quantities of Sasobit were required to be integrated into the mixing process. Therefore, it was decided to design and build (with the help of a mechanic and electricians) a melting system for the introduction of Sasobit into the bitumen stream, in order to be practical, to obtain a high degree of accuracy and be cost-effective.

A continuous asphalt plant with the capacity of producing 100 tonnes per hour was used, and modifications were made accordingly for the addition of Sasobit to the mix. These modifications allowed the use of the wet method to produce WMA. Figure 4.2 presents a diagram of a melting system and Figure 4.3 through to Figure 4.6 present the melting system with the modifications made to the plant where the additive was introduced in a liquid state to ensure a homogeneous distribution of the mixture. The hot bitumen and liquid Sasobit were blended and then pumped into the drum mix.

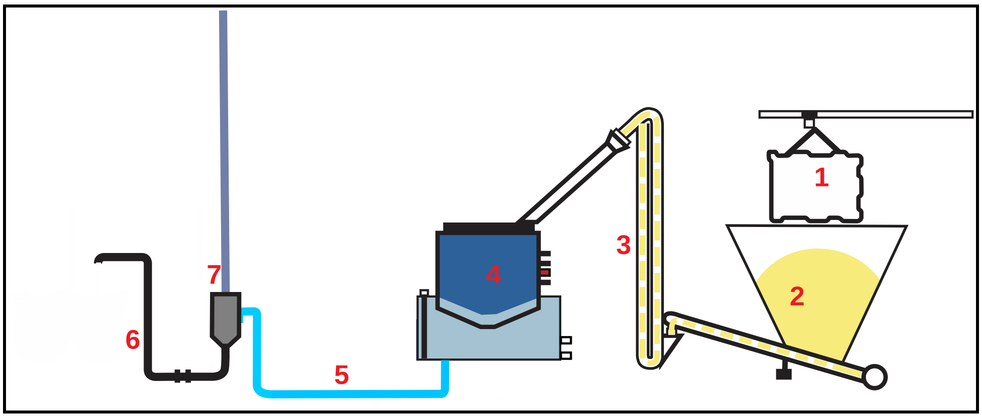


Figure 4.2 Melting system – principle

Legend

1. Sasobit pellets bag (500kg)
2. Sasobit feeder tank
3. Auger
4. Sasobit melting device
5. Sasobit liquid lane feed directly into the bitumen lane

6. Hot bitumen lane
7. Bitumen and liquid Sasobit blended then pumped at the mixing plant

Figure 4.3 Modified plant for warm mix asphalt

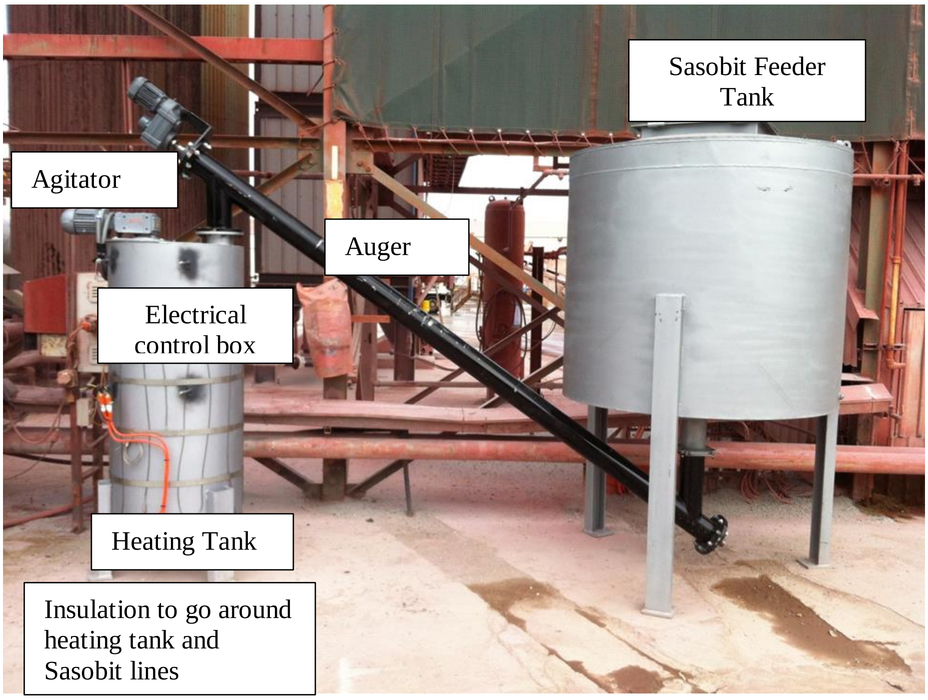


Figure 4.4 Asphalt plant details modifications

Figure 4.5 Insulation Sasobit line

Figure 4.6 Sasobit pumped at the plant

4.4 Main materials

4.4.1 Dense graded asphalt

For the entirety of the study, DGA mix containing Perth aggregates (granite) was selected and used, due to the frequent use of the mix in Western Australia. Specifications from Main Roads Western Australia: Specification 511 (2016), the Australian Asphalt Pavement Association (2012) Western Australian branch, and the Institute of Public Works Engineering Australia (2012) Western Australian branch were followed for the mix design. It is important to notice that the mix was not modified in terms of aggregate and bitumen percentages, only the addition of different percentages of the additive Sasobit.

4.4.2 Inline blending of Sasobit

Additives can be blended with the bitumen stream at the asphalt mixing plant through a melting system or an ejector, to introduce solids into the bitumen stream (German Asphalt Pavement Association, 2009). For the study, and to ensure the passing of small dosages of Sasobit, a weighing device was installed and monitored in the control room. After passing through the melting system, the additive was fed directly into the hot bitumen line. The liquid wax and the hot bitumen were blended and then pumped into the drum mixer at the asphalt mixing plant creating a viscosity modified binder.

It is important to ensure that the passing of a small dosage of the additive (between 1 and 5 percent of Sasobit) is well integrated into the process control during the asphalt mixture production. This ‘leads to a high degree of accuracy and allows a modification of all conventional bitumen grades and types’ (German Asphalt Pavement Association, 2009).

4.5 Bitumen

The main characteristic of bitumen is its viscosity; this is the degree of fluidity of the bitumen at a standard test temperature. Therefore, its properties were tested to obtain an accurate characterisation of the bitumen to identify adequate performance.

Bitumen testing was performed with the aim of:

- Comparing the consistency of pure bitumen with different quantities of additive at different temperatures.
- Determining the optimum percentage of additive for the mixture (depending on pavement purpose).
- Evaluating the suitability of the binder to demonstrate the modified binder properties.
- Determining the mixing and paving temperatures of the modified bitumen.

4.5.1 Experimental plan for bitumen testing

Bitumen testing was performed following the experimental plan presented in Figure 4.7. Tests included in the study were as follows: viscosity, softening point and bitumen aging. The different percentages of Sasobit were used to clearly determine the possible changes in the viscosity of the bitumen, with a minimum, middle and maximum range (1.5%, 3.5% and 6.0%).

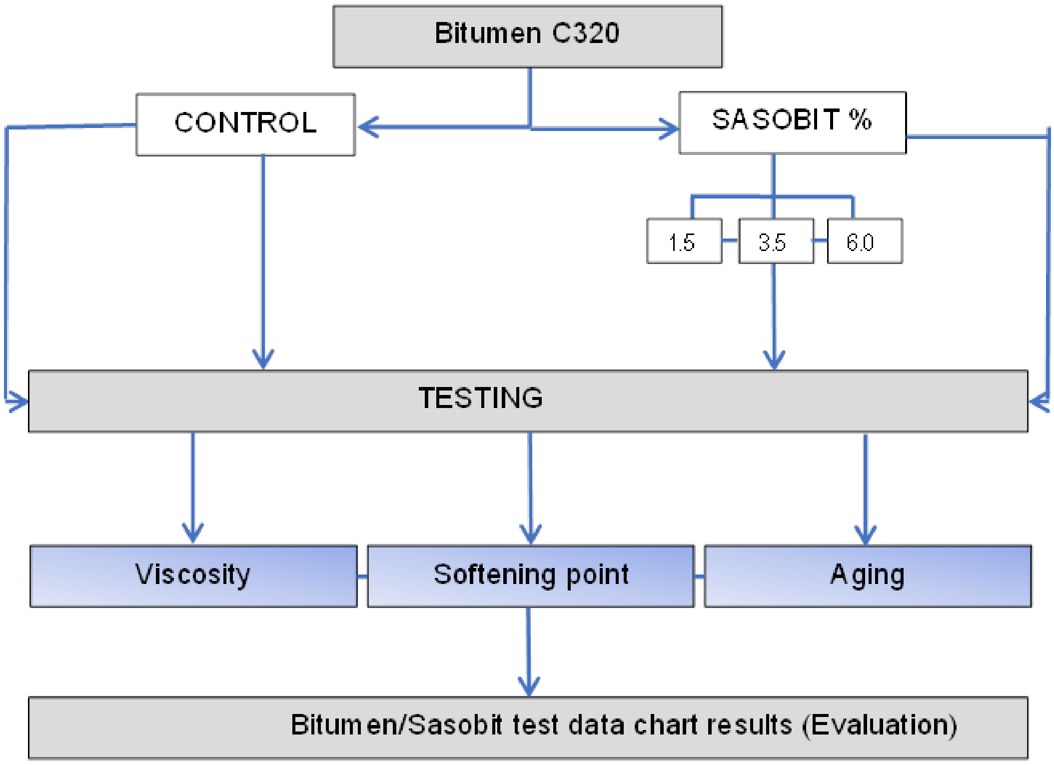


Figure 4.7 Experimental plan for bitumen testing

4.5.2 Bitumen performance testing

Bitumen is a complex visco-elastic material. Its behaviour varies and it is susceptible to temperature and loading time, on which its viscosity and elasticity functions depend (Shell Bitumen, 2003). At very low temperatures or with short loading times, bitumen behaves as elastic solids. At high temperatures or with long loading times, bitumen behaves as a viscous liquid (Asphalt Institute, 2007).

In general terms, it liquefies when heated and solidifies when cooled, with the ability to flow at different temperatures; hence, the importance of classifying the temperatures when testing.

WMA technology’s main function is to change bitumen’s viscous-elastic characteristics by reducing its viscosity during production and paving allowing a reduction in temperature until bitumen remains workable (Shell Bitumen, 2003). The determination of the appropriate temperature for production and paving ensures the long-term service of the asphalt. For the study, standard testing was performed only due to equipment limitations.

4.5.3 Assessment approach to testing bitumen properties

In Australia bitumen testing specifications are based upon traditional empirical methods which have been in practice for many decades with only a few modifications made. These are necessary to evaluate the performance of bitumen, modified or not, as there are several properties required for bitumen to comply with.

Test methods used for testing bitumen are as follows:

- MRWA Specification 511 Materials for Bituminous Treatments
- Bitumen shall be tested in accordance with MRWA 700.1

There are certain aspects of bitumen that are important to consider in road construction, such as purity, consistency at intermediate and high temperatures, consistency at low temperatures, resistance to hardening, and safety. The main properties of bitumen are:

- **Adhesion:** bitumen can adhere to a solid surface in a liquid state, retaining Marshall Stability (Singh & Jain 1997).
- **Resistance to water:** bitumen is water resistant, although some water can be absorbed due to filler content during mixing.
- **Hardness:** bitumen hardness can be measured by the penetration test, which measures depth of penetration in tenths of mm.
- **Viscosity and Flow:** bitumen viscosity and flow properties are important at the low or high temperatures which bitumen is subjected to during service. Flow properties vary considerably with temperature and stress conditions.
- **Softening Point:** bitumen softening point is obtained through a steel ball falling at a known distance through the bitumen when it is heated at a known rate.
- **Ductility:** determines how much bitumen could stretch at temperatures below its softening point: low temperature ductility (Singh & Jain 1997).

There are several tests to assess the bitumen properties. The following Table 4.1 presents tests usually performed:

Test Type	Reference Standard
Viscosity at 60°C (Pa.s)	AS 2341.2
Viscosity at 135°C (Pa.s)	AS 2341.4
Penetration at 25.0°C (p.u)	AS 2341.12
Penetration at 35.0°C (p.u)	AS 2341.12
Penetration Index [1,3]	
Insoluble in Toluene (%)	AS 2341.8
Softening point	AS 2341.18
Mass Change (%)	AS 2341.10
AS2341.2 Dynamic viscosity at 60°C	AS 2341.10
Ratio of viscosity before and after treatment at 60°C (%)	AS 2341.10
Softening Point (°C)	AS 2341.10, AS 2341.18
Increase in softening point after RTFO treatment (°C)	AS 2341.10, AS 2341.18
AS 2341.12 Penetration at 25°C 100g, 5sec. (pu)	AS 2341.10
Retained penetration (%)[1,2]	AS 2341.10, AS 2341.12

Table 4.1 Bitumen test methods

4.5.4 Bitumen viscosity

Test methods used to measure the viscosity of bitumen for the study were:

- Viscosity (Dynamic) test performed at 60 °C (AS 2341.2 or AS 2341.3). Viscosity by flow through a capillary tube (coefficient of shear).
- Viscosity (Kinematic) test performed at 135 °C Pa.s (AS2341.2 or AS 2341.3 or AS 2341.4). Viscosity by flow through a capillary tube.

Viscosity is a vital feature of bitumen as it determines how the material behaves at a given temperature and over a temperature range (Shell Bitumen, 2003). It is measured by a viscometer. The principle behind these methods is to precisely determine the time in seconds required for the bitumen to flow between two timing marks of calibrated, narrow, glass tubes (capillary viscometer) which indicates a particular volume or flow at a closely controlled temperature of 60 °C or 135 °C (Shell Bitumen, 2003). Bitumen can be measured using different types of viscometers, and the basic unit of viscosity is the pascal second (Pa.s).

The dynamic viscosity is the shear stress applied to a sample of bitumen in pascals divided by the shear rate per second; 1Pa.s = 10 P (poise). It can also be measured in units of mm^2/s (1 mm^2/s= 1 centistokes) (Shell Bitumen, 2003). Figure 4.8 shows the viscometer used in this research,

Figure 4.8 Viscometer

There are different types of viscometers in several sizes, which are used to adjust the efflux time required to be greater than 60 seconds. If less time is required, a smaller viscometer needs to be used. During testing, the viscometer and the specimen are mounted in a thermostatically controlled bath. To test at 60 °C, water or oil can be used; to test at 135 °C, oil is used at boiling point above 215 °C which should be allowed to reach equilibrium temperature (Shell Bitumen, 2003). The liquid in the system is released, and a timer is set when it reaches the first period. When it reaches the second timeframe, it is stopped.

The significance to WMA of testing bitumen is that the viscosity of the bitumen changes. It is reduced at high temperatures and, for some additives, increased at low temperatures. It is this fact that allows the production of asphalt at lower temperatures without any adverse effect on the workability of the mix, where sufficient aggregate coating is achieved. It is necessary to consider the relationship between the temperature and viscosity of the bitumen, as it can influence the determination of the appropriate temperature for production and compaction. Thus, there is no linear connection between the viscosity and temperature of the bitumen.

4.5.5 Bitumen Softening Point

The method used for softening point was Australian Standard AS 2341.18 – 1992. The test method consists of a 3.5 g steel ball placed on a sample of bitumen, enclosed in a brass ring that is suspended in a bath of water (for bitumen with a softening point of 80 °C) or glycerine (for bitumen with a softening point greater than 80 °C) (Austroads, 2008c). The temperature of the bath is brought up by 5 °C per minute until the bitumen softens and deforms slowly, with the ball moving through the ring. When the steel ball and the bitumen touch a base plate 25 mm below the ring, the bath temperature is recorded (Shell Bitumen, 2003). It needs to be noted that the test must be performed twice and the mean of the two measured temperatures is reported. Figure 4.9 presents the softening point equipment.

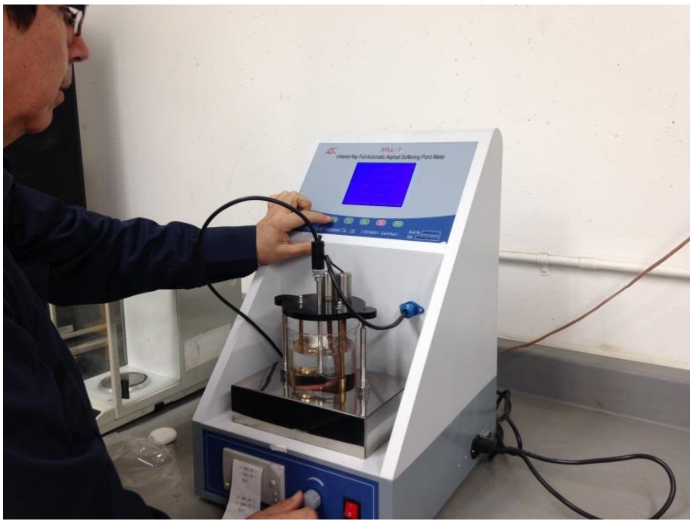


Figure 4.9 Softening point apparatus

4.5.6 Bitumen aging

The Rolling Thin Film Oven (RTFO) test (AS 2341.10) is used to determine the effect of heat and air on the moving thin film of the bitumen (Austroads, 2008c). It evaluates the resistance to hardening of the asphalt. A thin film of bitumen is continuously rotated around the inner surface of a glass jar at 163 °C for 60 minutes (Austroads, 2008c). A jet of air is positioned to blow air, preheated to oven temperature, into the mouth of each jar as it passes through the bottom of each rotation of the carriage that is being rotated, at 15 revs/min. The test provides an indication of the oxidative stability of bitumen as it simulates the aging of bitumen in the manufacture of asphalt (Austroads, 2008c).

Bitumen properties and consistency changes in WMA result in different strength being gained in comparison to HMA. Due to the reduction of the bitumen viscosity at production and compaction, temperatures could result in substantial changes of the mix stiffness in a short period of time. An important factor to consider is how soon the site could be reopened to traffic, so rutting would not become an issue too soon. Short term aging seems to be more critical for WMA than for HMA as it could influence testing results to a large extent (Lee, 2008). Figure 4.10 presents the Rolling Thin Film Oven

Figure 4.10 Rolling thin film Oven (RTFO)

The relevance of WMA is in relation to the physical properties of the bitumen. They were initially the same, and can be influenced by external factors which could lead to different in-service performance known as binder hardening (Asphalt Institute, 2007). The bitumen aging behaviour can be categorised as either long-term or short-term.

Long-term aging of the bitumen occurs as a consequence of a constant supply of air, the influence of high temperatures, and photo oxidation of the binder by ultraviolet radiation. In a laboratory, it is simulated with the Pressure Ageing Vessel method. The main factor that influences bitumen hardening on the road is the air void content of the mix (Shell Bitumen, 2003). This is caused by the constant entry of air, which encourages the oxidation process. Because WMA offers better compaction at low temperatures resulting in low air voids, the oxidation impact on the bitumen hardening is reduced.

Long term aging process requires approximately 200 hours or nine days to be measured by either a shell sliding plate microviscometer (only a handful left in the world) or a DSR rheometer. The laboratory was not equipped to perform this type of testing therefore, for this research the long term aging was not possible to be performed.

Short-term ageing refers to the oxidation and volatilisation occurring during mixing, transportation and placement of the mix. The cause is the loss of volatile fractions in the oxidation happening in the pugmill due to the binder spreading into thin films. Important factors in the degree of hardening are the duration of the mixing (required for homogeneous distribution for some of the additives), temperature and the bitumen film thickness that could result in a reduction in bitumen content (Shell Bitumen, 2003).

The mixing temperature is considered the major factor in the short-term aging of WMA. The higher the mixing temperature, the greater the tendency of the bitumen exposed in thin films on the surface of the aggregate to oxidise (Shell Bitumen, 2003). Therefore, it is possible to conclude that lowering the production and paving temperatures causes considerable changes in the properties of bitumen hardening during the production process.

4.6 Experimental plan for mixture testing

Testing is vital to identify both Hot Mix Asphalt and Warm Mix Asphalt properties and the performance of both on field and in the laboratory. The mixture evaluation methods establish the volumetric properties and the performance of asphalt. In this research, both field and laboratory were combined and visual monitoring of the trial was performed for five to six years. The empirical requirements are based on long-term evaluation and are performance-related. The research was conducted using the same mix composition, and evaluated using the same criteria for both mixes, HMA and WMA.

Some of the tests are designed to simulate some of the field conditions; for example, the wheel tracking test simulates the densification process of the pavement. The comparison with HMA can be beneficial and useful in establishing the performance properties of WMA.

WMA has no restrictions on implementation as it has been used with many different types of asphalt, such as dense graded and stone mastic among others. It has been used with different grades of binder as well, such as polymer modified bitumen, and with different types of aggregate in a variety of layer thicknesses for different traffic levels. However, there are certain factors which need to be taken into consideration regarding WMA design. The traditional mix design for HMA can serve as the basis for WMA, and the additives to be used should be considered for each specific job. The production of WMA with an organic technology is quite simple as it only requires the addition of the right percentage of additive (for this study, Sasobit) and to determine the right temperature for production and compaction.

4.6.1 Temperature effect consideration

The main factor in the workability of WMA is the temperature during the compaction process. The temperature is influenced by placement temperature and the rate of cooling. The asphalt-cooling rate is a combination of heat loss into the pavement base and the atmosphere (Australian Asphalt Pavement Association, 2010). There are a few factors that can affect the temperature, such as the lay-down and pavement temperatures, the layer thickness, and the wind speed among other climate conditions. Temperature is one of the most important factors affecting the test specimen. It is essential that the temperature during testing of the specimen is monitored and controlled to within 150 °C for HMA and 130 °C for WMA.

4.6.2 Specimen sampling

Samples for testing were carefully prepared and were carried out for quality control and/or mix design evaluation. For this study, each specimen was taken from the same batch of dense-graded asphalt warm mix production. The study followed the procedure obtained from Australian Standard AS 2891.1.1-2008. Sampling was performed using materials removed from a truck by hand (Figure 4.11). It needs to be noted that all sampling performed either from the plant, truck or in the laboratory strictly followed all specified procedures.

4.6.3 Sampling procedure

Sampling was performed as follows:

a) At least three sample sites were selected from truck.
b) At least 80 mm thickness of asphalt was removed (300 mm wide / 200 mm deep).
c) A vertical face cut was made through the horizontal bench.
d) A sampling tool was inserted into the vertical face of the exposed bench and the tool was withdrawn without content spilling.
e) The sample increment was placed in a sampler container without loss of asphalt.
f) All the sample increments were combined to form a bulk sample.
g) Each bulk sample was placed in a separate sample container, recorded and identified.

Figure 4.11 Truck asphalt sampling

4.6.4 Preparation of test portions

Each sample required special care at preparation for testing, to avoid segregation and to minimise the loss of temperature which is particularly important regarding moisture loss and volatile oils (AS 2891.1.1 method). Preparation was performed as follows:

a) The bulk sample was broken into small pieces without removing the binder coating on the aggregate or breaking the aggregate particles.
b) It was placed on a quartering tray (Figure 4.12)
c) Then it was thoroughly mixed and formed into a cone by heaping.
d) The cone was flattened and divided into quarters with a quartering tool. Special care was taken to avoid segregation of the mix.
e) Each of the diagonally opposite quarters from the tray were separated to form two sub-samples.
f) Each of the two sub-quarter samples were remixed by taking full scoops alternately from each quarter, and placed on the centre of the plate to form a cone.
g) The above steps were repeated until the combined mass of the two diagonally opposite sub-quarter samples remaining was of a test portion size.

Figure 4.12 Sampling quartering

4.6.5 Binder content

Method MRWA 730.1 -2011 describes the procedure for determining the bitumen content for HMA using the centrifuge method. Each test sample was taken in accordance with test method MRWA 701.1 for asphalt, and each was prepared in accordance with MRWA 705.1.

4.6.6 Particle size distribution

This test method describes the procedure for the determination of the particle size distribution of aggregate. The particle size distribution testing was carried out starting with a test sample taken in accordance with test method MRWA 200.1 – 2012, Sampling Procedures for Aggregates.

4.6.7 Compaction

WMA is considered to achieve better compaction due to reduced viscosity during the production process; less roller passes are needed to achieve the desired density at lower temperatures at paving time, thus the savings in energy. Samples for testing can be prepared in different ways. Similarly to HMA, laboratory compaction for WMA must simulate the density that is achieved on field. Consequently, the compaction temperature should be reduced to replicate the paving temperature. To test WMA, the Servopac machine, the slab roller and a Marshall hammer, were used for compaction. As seen in Figure 4.13, 4.14 and 4.15 respectively.

Figure 4.13 Servopac compactor

Figure 4.14 Slab roller compactor

Figure 4.15 Marshall hammer compactor

The Marshall hammer is usually used for the volumetric properties as it emulates the compaction that takes place on the road. The gyratory and the vibratory compactors are also used. It needs to be noted that in Western Australia for mix design and quality control the Marshall hammer is used only. The equipment necessary for compaction is as follows:

a) Marshall compaction mould assembly (complying with AS 2891.5)
b) Automated Marshall compaction hammer, essential dimensions complying with AS 2891.5
c) Balance of at least 2 kg capacity
d) Digital PT100 thermometer

Compaction was carried out as follows:

a) Prior to compaction the mould (base and extension collar) was placed in the oven for at least one hour. Table 4.2 shows test specimen required temperatures.

Asphalt Type	Dense Graded		Open Graded	
Bitumen Class	Class 170	Class 320	Class 170	Class 320
Temperature C^{o}	140 ± 5	150 ± 5	115 ± 5	125 ± 5

Table 4.2 Test specimen required temperature

b) The mould was removed from the oven and a paper disc was placed into the mould.

c) A single test portion was placed into the mould (normally a mass of between 1200 g and 1250 g is required). A paper disc was then positioned on the surface of the material in the mould, and a thermometer was inserted into the centre of the mould.

d) The temperature of the test portion was recorded. If the temperature had not reached its ideal, according to Table 4.2**,** the mould and test portion were placed back into the oven. Otherwise, the mould and test portion were left to cool down until reaching the desired temperature.

e) The thermometer was removed. The mould and test portion were placed into position on the compaction pedestal. The test portion was 457 mm. The mould was then inverted and the same number of blows was applied to the other end of the test portion. Note that the number of blows varied according to the mix specifications.

f) The mould was given an identification number.

g) The mould and test specimen were left to cool down.

WMA has the potential to achieve excellent compaction due to the decrease in viscosity and less bitumen ageing during the production process. It allows savings in energy and an extended timeframe for compaction due to the lower workable temperature of WMA at paving time.

4.7 Volumetric calculations

Volumetric calculations were performed through:

- The maximum density test (also known as the rice method). Figure 4.16 shows a vacuum apparatus removing bubbles during the maximum density test. This determines the maximum density of the asphalt mix in the loose state, free from occluded air water displacement.

Figure 4.16 Vacuum removing air bubbles

- Bulk density determination was performed using the water displacement method.
- Voids in mineral aggregate (VMA)
- Air voids
- Binder content
- Voids filled with binder
- Binder film index
- Particle size distribution

All of the above test formulas and methods are described in chapter two.

4.8 Performance testing

4.8.1 Indirect Tensile Strength (ITS)

Australian Standard method AS 2891.13.1 was used to measure the resilient modulus which measures the stiffness of the asphalt. For testing, three carefully prepared specimens, with flat surfaces which are dried to a constant mass, are required in order to obtain reproducible results. Right cylinders with a height between 35 and 70 mm for 100 mm (± 2) diameter and a height from 60 to 90 mm for 150 mm (±2) diameter samples are required. Specimens with a maximum particle size greater than 20 mm but less than 40 mm must be of 150 mm diameter, while specimens with a maximum particle size less than or equal to 20 mm can be either 100 or 150 mm in diameter, with a preferred 100 mm diameter (Austroads, 2014). Figure 4.17 shows Resilient Modulus equipment.

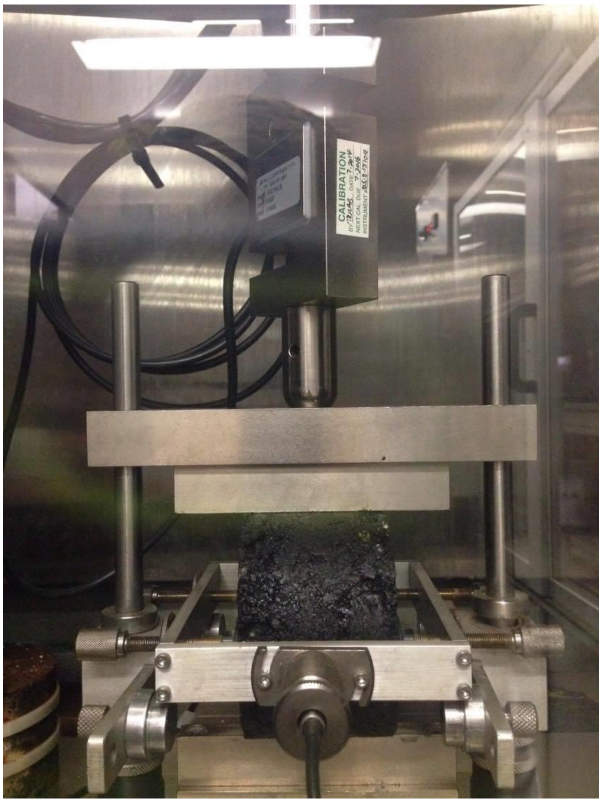


Figure 4.17 Resilient modulus equipment

The test requires the sample to achieve a total horizontal strain of between 30 and 70 microstrain, ensuring that there is enough deformation for the linear variable displacement transducers (LVDTs) to measure accurately, while the response of the sample remains elastic. The sample load is of approximately 4.5 kN and permits samples with 600 to 28 500 MPa of resilient modulus to be tested (Austroads, 2014).

The pneumatic loading response in practice limits the upper resilient modulus to approximately 16,000 to 5,500 MPa for 100 and 150 mm diameter samples, calculated on a sample thickness of between 35 and 90 mm and a rise time of 40 ms (Austroads, 2014). The preferred device for measuring the resilient modulus is the Materials Testing Apparatus (MATTA).

It is necessary to monitor the test temperature during testing as it is one of the most important factors affecting the resilient modulus. Australian Standard AS 2891.13.1 stipulates the temperature of 25 °C for the determination of a standard quality indicator value. It needs to be noted that it is essential for the temperature to be monitored and controlled to within 0.5 °C.

After the resilient modulus testing, the bulk density is determined. In case specimens are partially saturated during cutting or polishing, the bulk density can be determined before the resilient modulus is performed.

4.8.2 Fatigue resistance

Fatigue is a property of asphalt which is the ability of a mix to withstand cracking under traffic. The measurement of fatigue was performed using Austroads method AGPT/233 which measures the flexural stiffness, phase angle, dissipated energy per cycle, cycles to failure, and cumulative dissipated energy, which are subject to four-point beams of asphalt. A sample for fatigue testing consists of a beam of asphalt with a minimum of three test samples required that can be cut from the pavement – requiring a sufficient depth of asphalt – or can be laboratory prepared.

Slabs are prepared using either a footpath-style roller compactor or a laboratory wheel compactor. Samples need to be taken at right angles, and compaction must be performed using the appropriate device to ensure compaction uniformity.

Samples need to be brought to the testing temperature and conditioned for a period, to disperse any stress due to handling. They need to be stored on a flat, rigid surface until they are placed in the test frame. Beams need to be free of notches and the standard dimensions should be 390 ± 5 mm length, 63.5 ± 5 mm horizontal width and 50 ± 5 mm vertical depth. It is advised though that a 2 ± mm of tolerance is attempted if possible. As any other test, fatigue resistance is dependent on the air void content. For testing a 5 ± 0.5 air void target needs to be reached (Austroads, 2014).Figure 4.18 shows the beam ready for testing

Test Procedure:

- Sample needs to dry to a constant mass on a flat rigid surface. The drying process can be accelerated by placing the sample in a fan-forced oven at a temperature not exceeding 40 °C.
- Dummy sample could be 20 °C and placed close to the beam cradle to avoid problems with uneven temperature distribution within the cabinet.
- Sample dimensions are measured and recorded.
- Test conditioned to test temperature for a minimum of two hours resting on a flat surface.
- Air supply and software need to be followed according to manufacturer.
- Sample inserted into beam cradle.
- Set-up parameters entered on computer.
- 100 ms selected for both the pulse width and pulse repetition which gives a continuous loading at 10 Hz. The range for strain level could be set between 100 and 900 $\mu\varepsilon$ if no other information available.
- Sample needs to condition to cradle for at least 10 minutes before test starts.
- Test started and stopped after 50 conditioning pulses. Press enter to accept the nominated termination stiffness.
- Report printed.
- Other samples tested and results reported as per test method.

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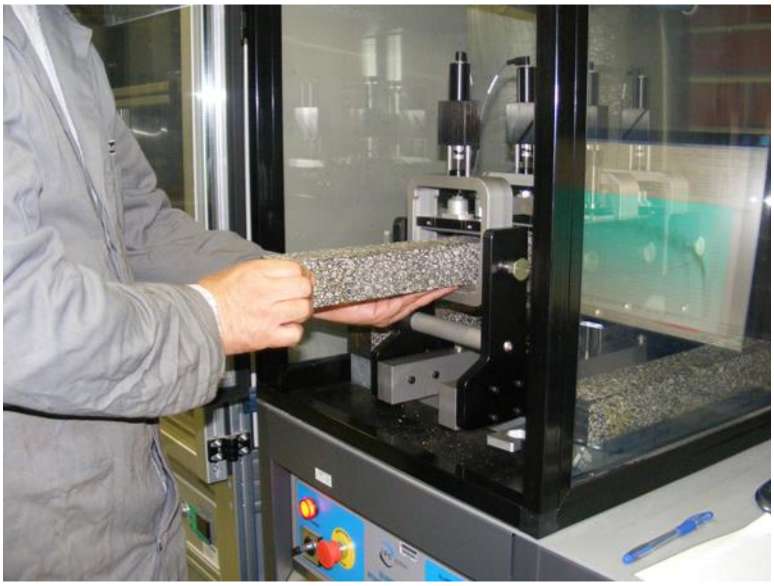


Figure 4.18 Testing fatigue

The tests outputs include:

- Initial strain
- Flexural stiffness
- Fatigue life
- Phase angle
- Dissipated energy per cycle

4.8.3 Wheel Tracking

Austroads test method AGPT/T231 was used to indicate the resistance of the mix to deformation under traffic, and Austroads method AGPT/T220 was used to produce slabs with a plan area of 300 x 300 mm. Cylindrical specimens can also be used, providing they are at least 200 mm in diameter. It is important to note that the monitoring and control of the temperature is essential; it is a significant factor affecting the wheel tracking properties of asphalt and needs to be within 0.5 °C. The monitoring is done using a temperature measuring device fixed in a dummy sample (Austroads, 2014). Figure 4.19 shows the wheel tracking equipment. The test temperature should be 60 ± 1°C. For the sample thickness 10 and 14 mm nominal, size must be 50 ± 5 mm. For 20 mm nominal, size should be 75 ± 5 mm with a vertical load (N) of 700 ± 20 N.

An air void content of 5% ± 0.5% is normally specified, as the wheel-tracking rate is dependent on the air voids. Samples thicknesses vary depending on the nominal size of the asphalt mix. To disband any stresses due to handling, samples need to be brought up to the testing temperature and conditioned for a period at the required test temperature.

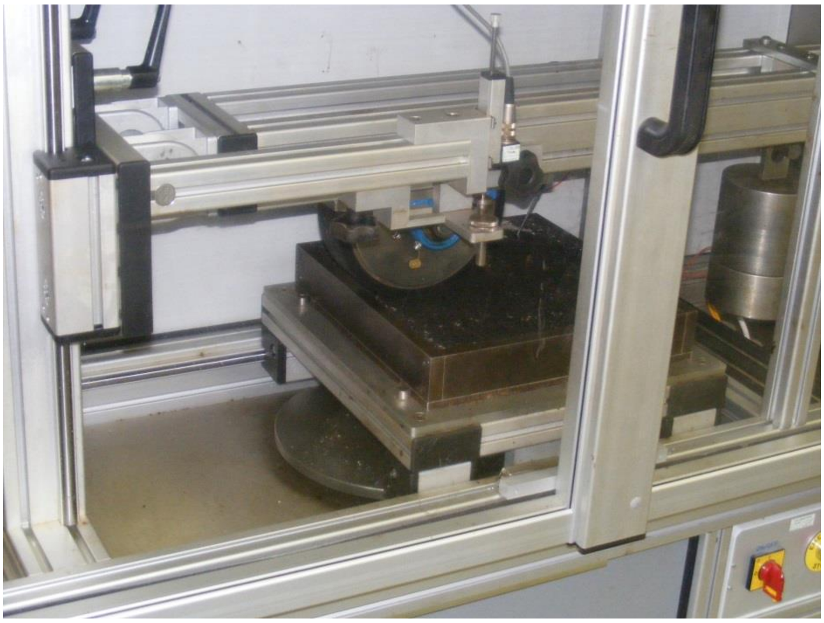


Figure 4.19 Wheel tracking equipment

4.8.4 Tensile Strength Ratio (TSR)

Moisture sensitivity has been a concern for WMA technologies. If the moisture contained in the aggregate does not completely evaporate during mixing due to the low temperatures, water could be retained in the aggregate. This issue could lead to increased susceptibility to moisture damage. It is significant for WMA technologies that involve the use of foaming to reduce the binder viscosity, because of the residual moisture left by the foaming process.

Samples were compacted in accordance with AS 2891.2.2- 2014, and Austroads test method AGPT/T232 was used to determine the ratio of indirect tensile strength between two equal subsets. Moisture damage to asphalt is caused by 'the loss of cohesive strength of the binder or by a loss of adhesion or bond between the binder and the aggregate surface' (Austroads, 2014).

For testing, two sets of triplicate samples are required with the following characteristics:

- Right cylinders with a height of 65 ± 1mm for 100 mm (± 2 mm) diameter and a height of 85 ± 1 mm for 150 mm (± 2 mm) diameter samples.

The equipment required for testing consists of a load frame that enables forces up to 22 kN applied to cylindrical specimens at a rate of travel of 51mm per minute; a Marshall test machine is suitable (see Figure 4.20). The maximum load is measured and the specimen is loaded until failure occurs (Austroads, 2014). The broken faces are inspected after testing to determine the percentage of stripped aggregate (Austroads, 2014).

To obtain the required degree of partial saturation, vacuum pumps and vacuum vessels are required. The vacuum pump is normally used to determine the maximum density of an asphalt mix (Austroads, 2014). The freeze-thaw cycle was designed to utilise a domestic freezer unit; this is optional.

Figure 4.20 Marshall test equipment

Testing was carried out as follows:

- Samples were prepared from the mix design formula with an air void content in the range of 7% to 9% (requires specific compaction).
- Samples were divided into two subsets of approximately equal void content. One subset was saturated with water in the range temperatures of 80% to 85% while the other subset was conditioned in a dry state.
- The tensile strength of each sample was determined. The potential damage by moisture is indicated by the ratio of the tensile strength of the moisture-conditioned subset divided by the dry subset, which is expressed as a percentage (Austroads, 2014).
- Samples are visually assessed to determine if the coarse and fine aggregates show evidence of minimal, moderate or severe stripping as seen in Figure 4.21, 4.22 and 4.23 respectively.

Figure 4.21 Minimal stripping

Figure 4.22 Moderate stripping

Figure 4.23 Severe stripping

4.8.5 Dynamic modulus

The dynamic modulus is a central property of asphalt, and for testing an Asphalt Mixture Performance Tester (AMPT) was used (see Figure 4.24). It is a stand-alone testing machine with an environmental chamber and a measuring system (Industrial Process Control, 2010). Testing was performed in accordance with AASHTO TP62-07 (American Association of State Highway and Transportation Officials, 2003). Three cylinders per temperature were compacted using the Servopac gyratory compactor with a testing range set for three temperatures, 4 °C, 20 °C and 40 °C, along with four loading frequencies of 0.01 Hz, 0.1 Hz, 1 Hz and 10 Hz reaching a 5 ± 0.5 air void target, to attain a series of dynamic modulus values for the production of a master curve.

Figure 4.24 AMPT equipment

4.8.6 Stability and flow

Test samples were prepared and conditioned according to AS 2891.2.1, and MRWA 731.1 – 2010 method was used to determine the stability and flow of the asphalt sample.

The test procedure used was as follows:

- Samples' heights measured to the nearest 1 mm. The height is required to be measured four times at approximately equally spaced distances around each of the samples, and any sample with an average height outside the range of 57 to 70 mm should be discarded.

- The testing head should be maintained at a temperature between 20 °C and 40 °C.
- Test samples are placed in a water bath at a temperature of 60 °C ± 1 °C for 30 to 40 minutes.
- A sample is removed from the water bath and placed centrally, and on its side, in the lower segment of the testing head. Place the upper segment of the testing head on the test sample and then place the complete assembly in position in the testing machine (Figure 4.25).
- Apply force to the test sample so that the rate deformation is 51 ± 3 mm/min ensuring the flow meter starts to register as the load is applied.
- The maximum force and the flow meter reading are recorded.

Figure 4.25 Stability and Flow equipment

5 Results and data analysis

This chapter presents the results of the entire laboratory testing (binder, volumetric and performance), performed on dense-graded mix asphalt with different percentages of the additive Sasobit. The aim of the testing was to determine the volumetric properties and performance of WMA in comparison to HMA, following the methodology and experimental plan established. The results were performed in accordance with all the standard methods for in situ laboratory testing and all the data gathered during testing (volumetric and performance) was analysed and presented in tables and graphs. The study involved the placement of WMA and HMA 10mm and 14 mm dense-graded asphalt approved mixes according to AAPA specifications. Figure 5.1 presents the testing plan used.

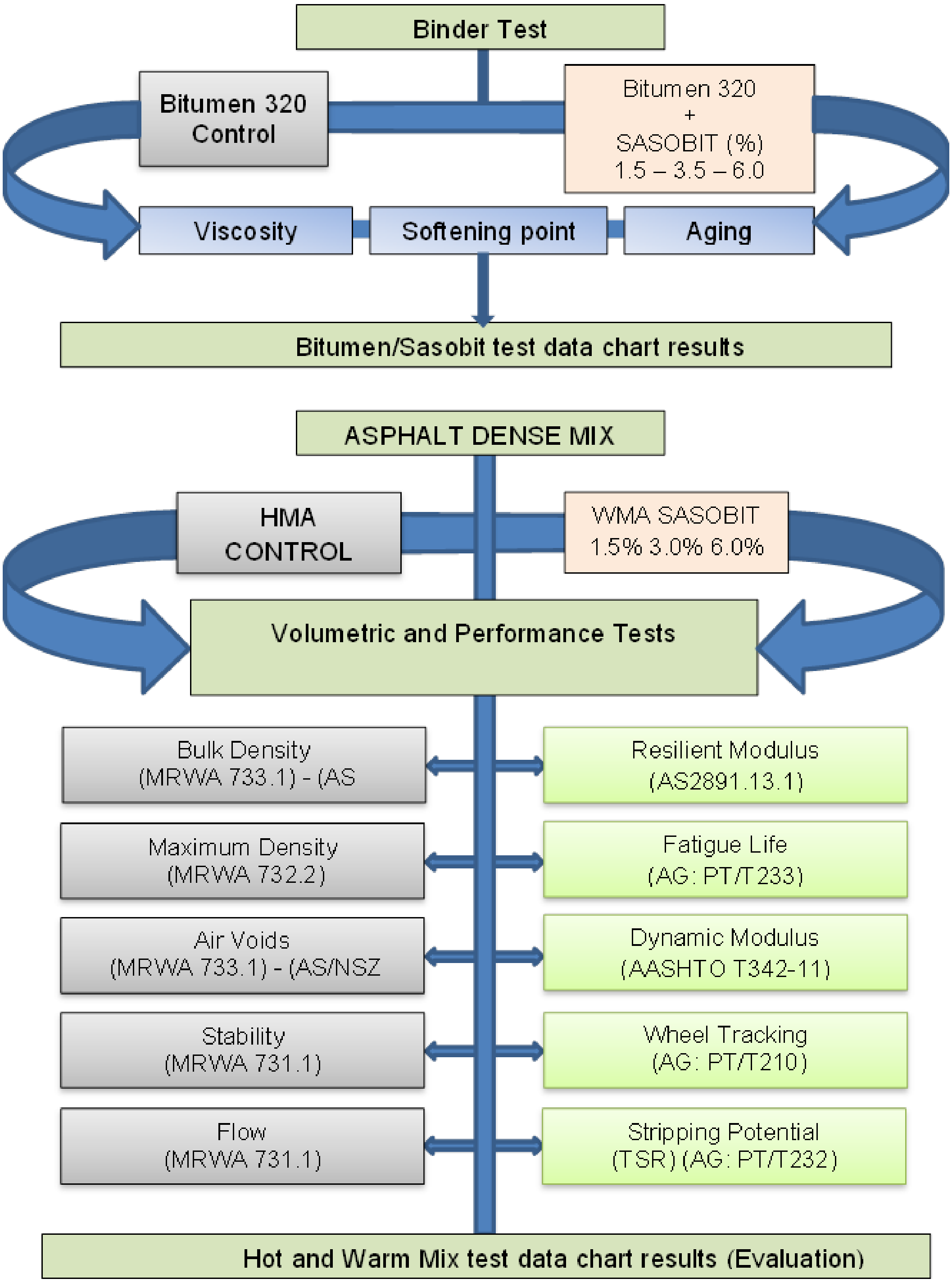


Figure 5.1 Testing plan

5.1 Testing

5.1.1 Binder testing

Binder testing involved the preparation, testing itself and results (all testing reports and the respective results are in Appendix A Testing was performed in order to evaluate the consistency of the bitumen properties, with and without organic additive Sasobit, and to evaluate if the asphalt mixing and compaction temperatures improved. The experimental plan for bitumen testing was performed in three stages:

Stage 1: Preparation of bitumen mixtures for testing

- Straight run bitumen class 320 (C320), and
- Class 320 bitumen mixed with different percentages of Sasobit (1.5%, 3.5% and 6%) at different temperatures.

Stage 2: Bitumen was tested for:

- Dynamic viscosity at 60 °C (AS 2341.2) with a cannon manning capillary viscometer at 60 °C and the result was expressed as the mean of the two measurements.
- Rotational Viscosity at 135 °C (AS 2341.4) with Brookfield viscometer at 135 °C and the result was expressed as the mean of the two measurements.
- Softening point (AS 2341.18) with apparatus in water and in Glycerol (SP above 80 degrees) and the result was expressed as the mean of the two measurements.
- Aging: Rolling Thin Film Oven (RTFO) test (AS 2341.10).

Stage 3: Evaluation of the results in terms of:

- Dosage of Sasobit for mixture design.
- Comparison of the results with and without additive.
- Additive performance.
- The effect of aging on binder with the addition of Sasobit at various percentages.
- The effect on viscosity at various temperatures and percentages of Sasobit compared to straight run bitumen.

5.1.2 Viscosity and aging testing

Testing scope part 1

To assess if Sasobit could have any effect on the aging of the bitumen, for example if Sasobit properties could reduce the effects of heat and air in regard to aging or, on the contrary, if it could have a negative effect on aging.

Testing scope part 2

The initial scope of testing of the Sasobit treated binder was to assess the change in viscosity of the modified material at various temperatures compared to unmodified binder. The aim was to establish the degree of increased or decreased viscosity with various percentages of Sasobit in relation to the mix performance test results.

5.1.3 Preparation of specimens and testing for scope 1

According to the manufacturer, the additive Sasobit can be mixed and is completely soluble in bitumen at production temperatures. Samples were prepared by adding calculated dosages of additive at 1.5%, 3.5% and 6%, by percentage of mass of the binder, to straight run Class 320 bitumen at a temperature of 150 °C.

Upon addition, the sample was mixed thoroughly by hand with a glass stirring rod, at a pace so as not to cause a vortex, for 3 minutes until the sample consistency was homogenous. One sample was left untreated as the base line control sample. All samples where then prepared and poured at 150 °C for viscosity and softening point testing. One set of samples was aged while the other was not. The first set of samples was aged in a Rolling Thin Film Oven in accordance with AS 2341.10 to determine the effect of heat and air on a moving film of bitumen at 163 °C.

5.1.4 Viscosity test of straight run and modified binder unaged for scope 2

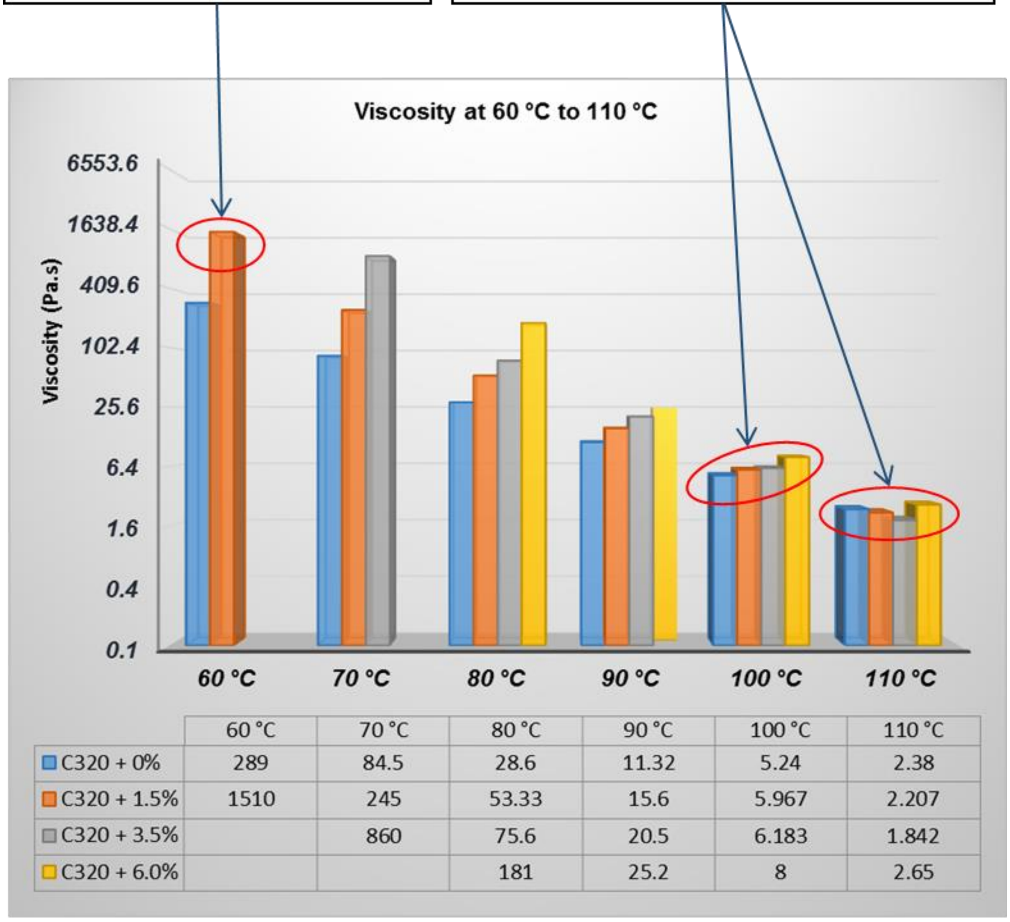
The procedure used was to test the viscosity of all unaged samples, modified and unmodified, at approximately 10 °C intervals starting from 165 °C and decreasing to 60 °C. Figure 5.2 shows bitumen preparation.

Figure 5.2 Bitumen test preparation

It needs to be noted that, at the time of testing WMA modified bitumen, extra care should be given to mixing before testing is performed. Results are presented in Table 5.1 for bitumen with 1.5%, 3.5% and 6% and Figure 5.3 Viscosity results at 60°C to 110°C.

Bitumen type	Dynamic Viscosity at 60 °C	Kinematic Viscosity at 135 °C	Softening Point
Standard method	AS 2341.2	AS2341.2 or AS 2341.4	AS 2341.18 – 1992
Unit	Pa.s	mm^2/s	60 °C
Bitumen C320	289	0.553	56.1
1.5% Sasobit	1510	0.516	65.7
3.5% Sasobit		0.4483	82.15
6% Sasobit		0.575	92.75

Table 5.1 Bitumen testing results



	60 °C	70 °C	80 °C	90 °C	100 °C	110 °C
🟦 C320 + 0%	289	84.5	28.6	11.32	5.24	2.38
🟧 C320 + 1.5%	1510	245	53.33	15.6	5.967	2.207
⬜ C320 + 3.5%		860	75.6	20.5	6.183	1.842
🟨 C320 + 6.0%			181	25.2	8	2.65

At temperatures ranging from 60 °C to 100 °C, Sasobit directly affects the viscosity of the binder by being in its solid state. The rise in viscosity becomes extreme as the temperature drops. The graph below shows the actual figures as opposed to a log graph needed to show the high temperatures of the spectrum.

This is the point where Sasobit reverts from a solid to liquid, approximately 100 °C -105 °C. At this point Sasobit directly impacts the viscosity in the opposite direction making the viscosity of the base binder to decrease. The drop-in viscosity appears to remain linear and consistent, as the temperature rises from 105° to 165°C. As opposed to the temperature below 105 °C, where Sasobit reverts to a solid state mixed with the binder, the increase in viscosity is compounded with every degree.

Figure 5.3 Viscosity results at 60°C to 110°C

The test results for bitumen with 1.5% of Sasobit resulted in an increase in viscosity to 1221 Pa.s. Subsequent percentages of Sasobit, 3.5% and 6% at 60°C were unobtainable as the binder became too stiff and surpassed the limits that the glass capillary viscometer could measure (excess of 3500 Pas). It was possible to begin measuring at these percentages at temperatures of 70°C and 80°C. At this point an extreme drop in viscosity was observed compared to class 320 bitumen with additive. A 10°C drop in temperature had an effect on the viscosity on the straight class 320 bitumen of 204.5 Pa.s. However, in comparison to the 1.5% sample the drop was of 1265 Pas. This was observed to be more pronounced at high percentages of additive for example, at 70°C and 80°C at 1.5% was 191.7 Pas compared to the same temperatures (70°C and 80°C) but at 3.5% falling to 784.4 Pa.s. This means that the compaction window for the Sasobit mixtures is relatively small.

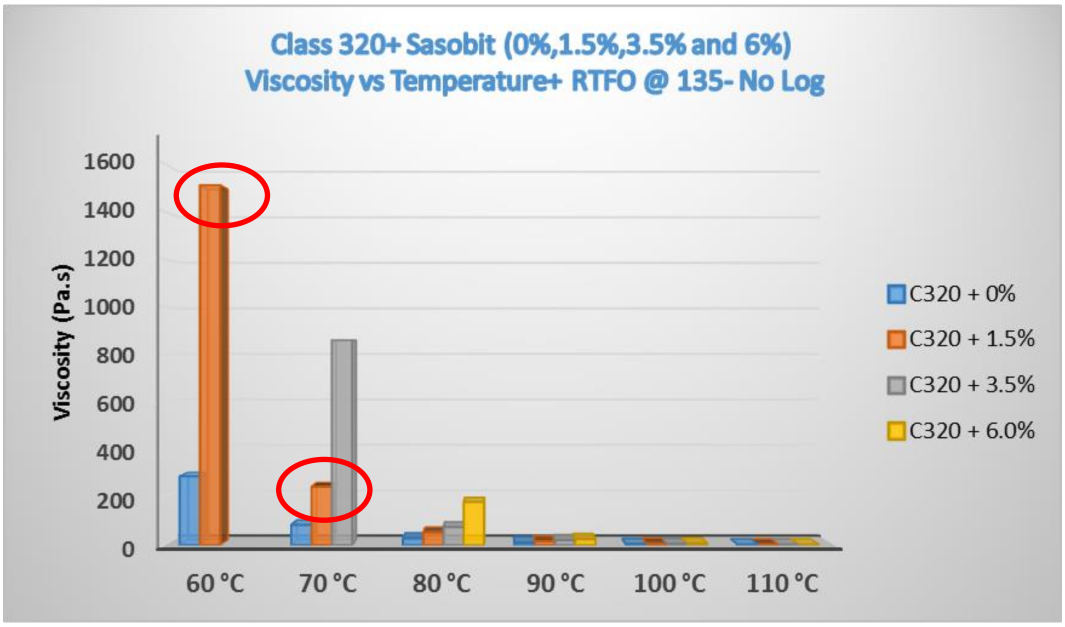


Figure 5.4 Viscosities at different temperatures (not log)

The extreme increase in viscosity, as the temperature falls below the 100-105 °C range where Sasobit solidifies, can be clearly perceived in Figure 5.4. The Brookfield viscometer was unable to read lower temperatures with percentages of Sasobit greater than 1.5% due to the binder stiffness.

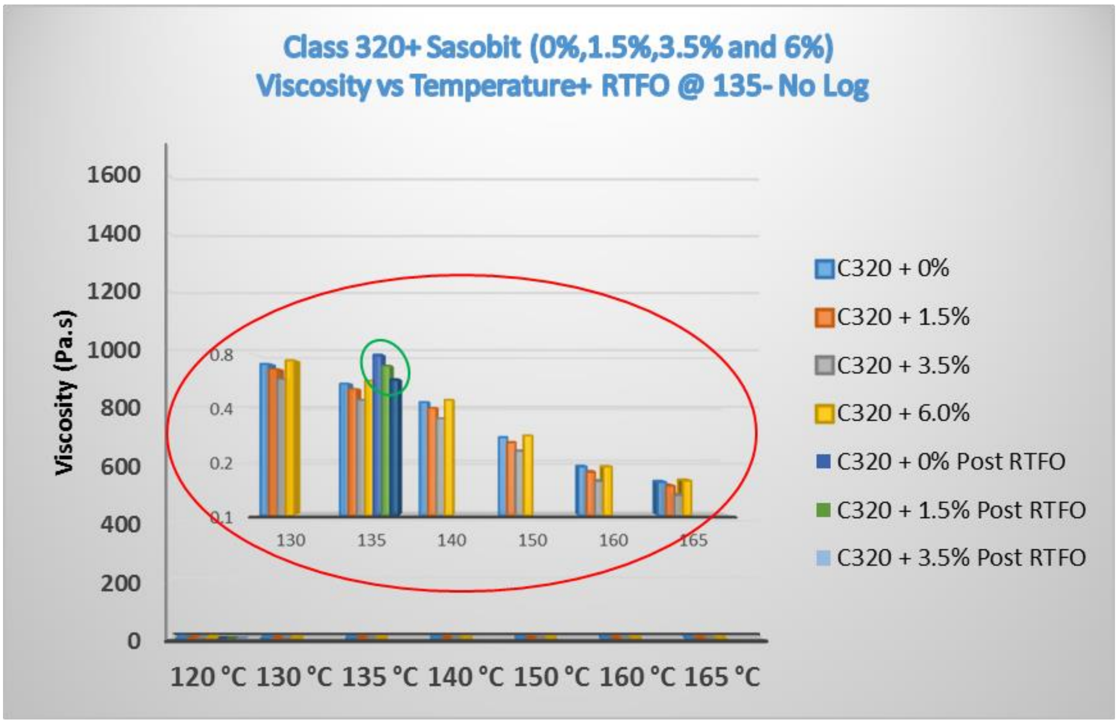


Figure 5.5 Viscosity vs temperature

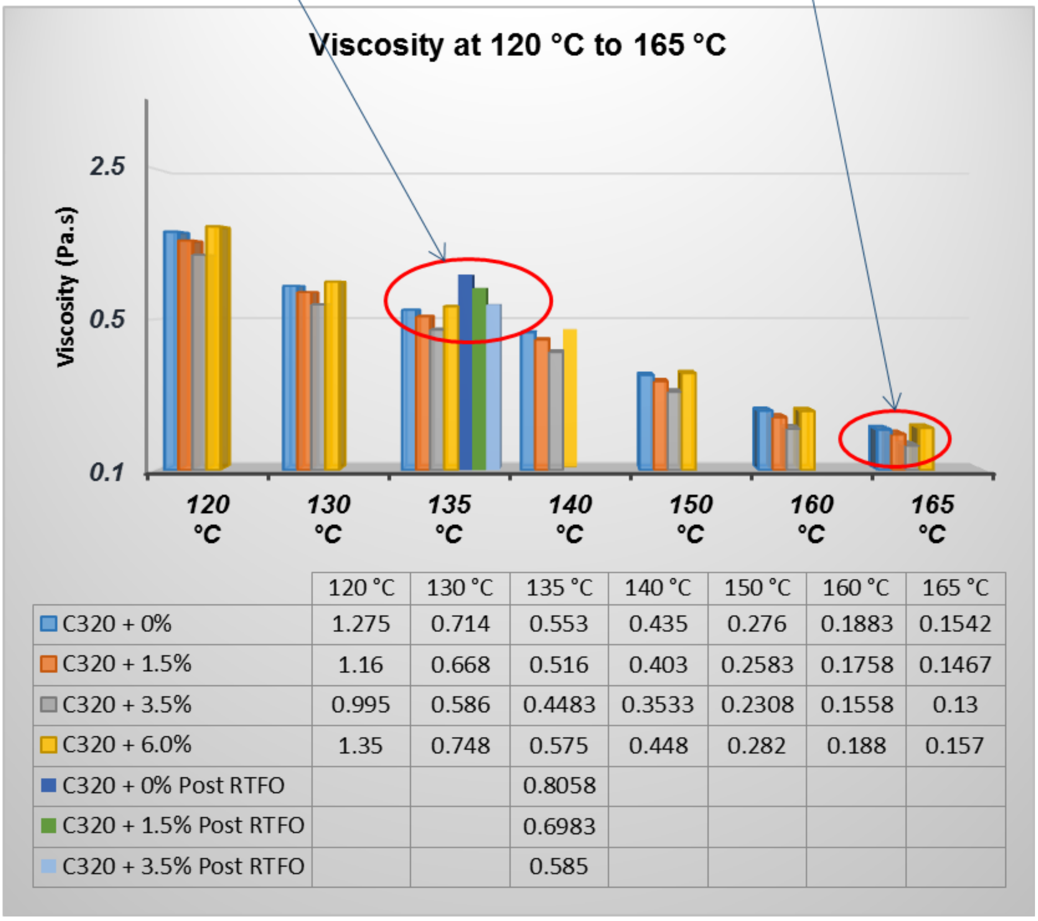
In Figure 5.5 it is possible to observe that the viscosity percentage post RFTO increases at 135 °C and fluctuates from 135.3 to 130.3 °C.

By observing the results of viscosity testing of straight run bitumen, with and without Sasobit, with different percentages, it is possible to conclude that:

- The addition of Sasobit has a significant effect on the consistency of the bitumen as it increases the bitumen viscosity below the crystallisation point of the wax. Translating in high resistance to deformation of the asphalt.
- Changing the dosage of Sasobit from 1.5% to 3.5% indicate that Sasobit lowers the viscosity of bitumen after the melting of the wax.
- The addition of 6% Sasobit indicate a slight increase in the viscosity of the bitumen after the melting of the wax. More testing would be required to validate the increase in the viscosity. Due to the lack of resources it was not possible to do more testing at this percentage.

The viscosity was unmeasurable on the equipment in the laboratory due to the fact that the addition of Sasobit produced an enormous increase in the viscosity at 60 °C from 1.5% upwards. Therefore, in an attempt to quantify the effects aging has on the binder with Sasobit, the base binder was aged and the subsequent samples with Sasobit, viscosity testing was carried out at 135 °C. The purpose was to establish if the Sasobit content had any effect on the aging percentage or additionally if Sasobit protected the binder in any way from aging.

Reading was taken up to 165 °C only. So, performances after the addition of Sasobit could be evaluated alongside various Polymer Modified Binders (PMBs). This can contribute to the preparation of an assessment of the properties of Multigrade 1000/320 and 50/170 to investigate if they can be replicated with the use of Sasobit with differing percentages.



	120 °C	130 °C	135 °C	140 °C	150 °C	160 °C	165 °C
🟦 C320 + 0%	1.275	0.714	0.553	0.435	0.276	0.1883	0.1542
🟧 C320 + 1.5%	1.16	0.668	0.516	0.403	0.2583	0.1758	0.1467
⬜ C320 + 3.5%	0.995	0.586	0.4483	0.3533	0.2308	0.1558	0.13
🟨 C320 + 6.0%	1.35	0.748	0.575	0.448	0.282	0.188	0.157
🟦 C320 + 0% Post RTFO			0.8058				
🟩 C320 + 1.5% Post RTFO			0.6983				
🟦 C320 + 3.5% Post RTFO			0.585				

Figure 5.6 Viscosity at 135°C to 165°C

5.1.5 Softening Point testing

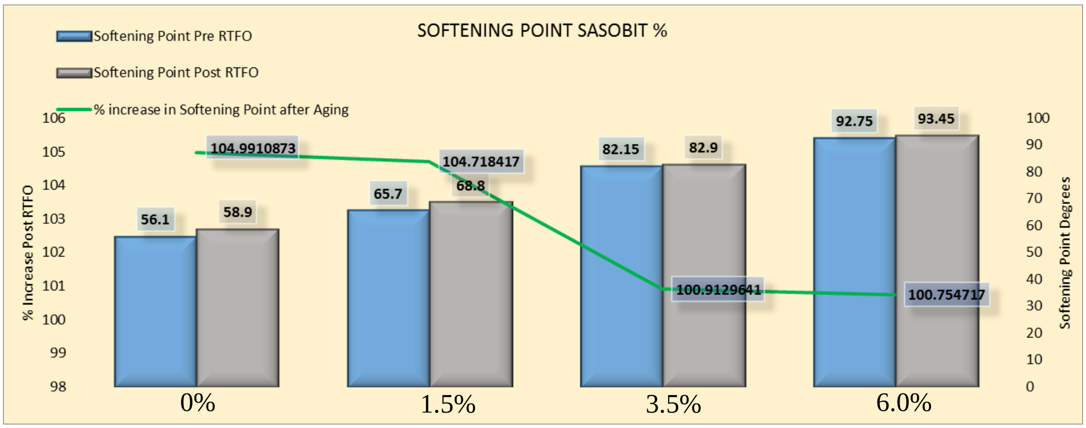


Figure 5.7 Softening point with different percentages of Sasobit

Figure 5.7 shows that, as the percentage of Sasobit rises, there is a significant increase in the softening point value. With a percentage of 3.5% of Sasobit and above, with dipping, the additive appears to have a significant effect on the ageing of the binder, but nearly no effect on exposure to heat and air in regard to softening point. The same trend can be perceived from the viscosity testing, supporting the assumption that Sasobit protects the binder from the effects of heat and air to some degree.

5.1.6 Aging testing

Although the viscosities were not measured above 1.5% before and after aging at 60 °C, the viscosity at 135 °C was measured with the aim of observing if the post RFTO viscosity ratio changes in relation to the percentage of Sasobit added to the binder. At 135 °C the volume of aging appears to have a direct correlation to the percentage of Sasobit in the binder. This suggests that the addition of Sasobit to the binder aids in protecting the bitumen from the effects of heat and air in the ageing process: a trend that appears to be more pronounced as the percentage of Sasobit increases as seen in Figure 5.8.

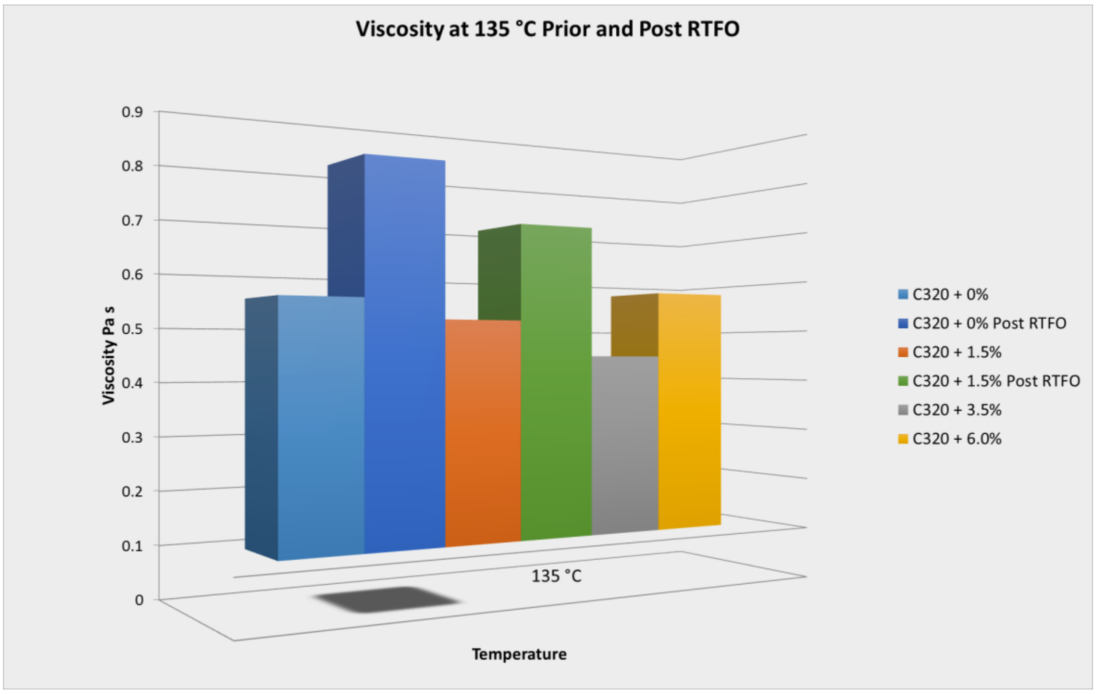


Figure 5.8 Bitumen viscosity at 135°C

5.2 Mix design preparation

The asphalt mix (dense graded asphalt) used for this study was the AC 10/50 and AC 14/75 (AC: asphaltic concrete). The number ten and fourteen indicate the mix maximum aggregate size and the number fifty and seventy five indicate the number of blows for compaction.

5.2.1 Aggregate percentage

In order to produce a suitable homogeneous mix, the aggregate gradation needs to comply with all specifications. For the research, four different sizes of aggregates were used: 10 mm, 7 mm, 5mm and dust acquired from a local quarry (BGC) and 1.4% of the total mix of the adhesion agent lime (Main Road Western Australia requirement). All particles with a size less than 2.36 mm were considered dust. The content percentage and the combine mixed aggregate gradation were obtained to determine the gradation required for the design of dense graded asphalt.

The two mix types' material percentages which were used for laboratory testing are presented in Table 5.2 and Table 5.3, and the combined aggregate grading curve is presented in Figures 5.9 and 5.10 where the green line represents the conformance mix gradation between the upper and lower limit specifications. All calculations for the combined Particle Size Distribution (PSD) are presented in Appendix B**.**

Mix AC 10/50						
Dust %	5mm %	7mm %	10mm %	Lime %	C320 Binder %	Total %
41.2	18.9	14.2	18.7	1.4	5.6	100

Table 5.2 AC 10/50 mix design

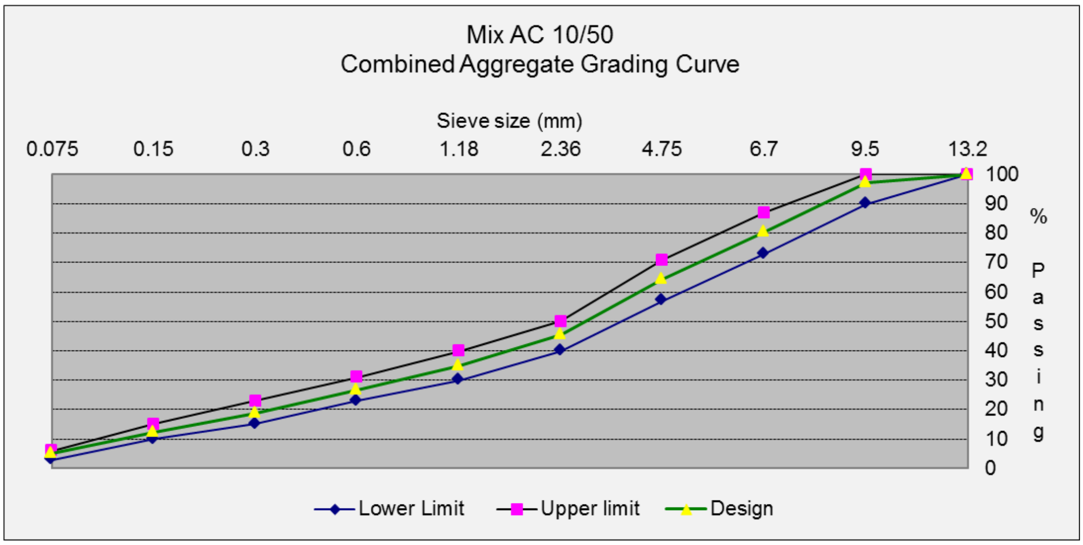


Figure 5.9 AC 10 grading design

Mix AC 14/75						
Dust %	5mm %	7mm %	14mm %	Lime %	C320 Binder %	Total %
36.7	14.3	14.3	28.6	1.4	4.7	100

Table 5.3 AC 14 mix design

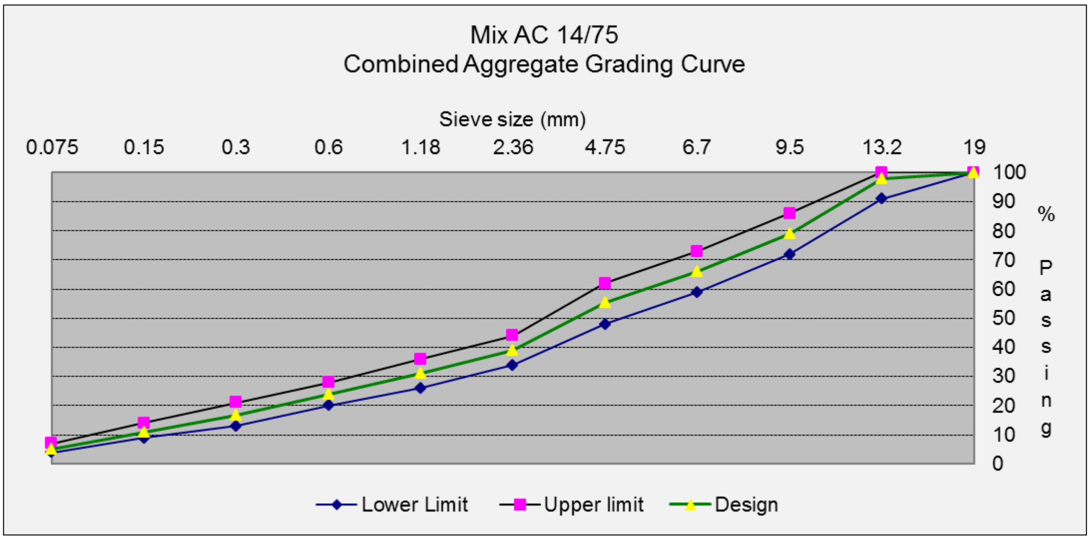


Figure 5.10 AC 14 grading design

5.2.2 Binder percentage

Binder class 320 (bitumen) was used for the research. The selection was based on the predominant usage of this class of bitumen and its suitability for the production of DGA. The asphalt mix design produced for AC 14/75 was 4.7% ± 0.3 % and for AC 10/50 was 5.6 ± 0.3 % of bitumen by weight of batch sample, in order to attain an air void content of 4% to 7% and 4% to 6% respectively (see Table 5.2 and Table 5.3 for percentage design).

5.2.3 Sasobit percentage

The same mix proportions were utilised for both the HMA and WMA designs, except that, for the warm mix, the additive Sasobit was added at rates of 1.5%, 3% and 6% by the weight of the bitumen. The range 1.5% and 6% content was selected as recommended by the manufacturer Sasol Wax, due to the percentage proven optimal performance for different volumes of traffic. The 6% was selected to analyse if that percentage could affect any of the performance properties of the mix.

5.3 Laboratory preparation

In order to evaluate the laboratory performance of the different mixes, loose mix samples were produced in the laboratory according to Preparation of Asphalt Samples for Testing (AP-T132/09). Figure 5.9 shows aggregate temperature check before mixing with binder, and Figure 5.10 shows measurement of the binder for mixture.

Figure 5.9 Aggregate temperature check

Figure 5.10 Measurement of the bitumen

HMA aggregate was placed in the oven for drying at a temperature of 160 ºC, attaining a mixing temperature of 155 ºC. The bitumen was allowed to heat for three hours, simultaneously with the aggregate, until it reached a temperature of 160 ºC, in order to comply with the required mixing temperatures. For WMA, the aggregate was placed in the oven for drying at a temperature of 140 ºC, attaining a mixing temperature of 135 ºC. The bitumen was allowed to heat for three hours, also simultaneously with the aggregate, until it reached a temperature of 160 ºC. Immediately after the temperature required was reached, the bitumen (previously prepared with additive and lime) was added to the aggregates.

To obtain a homogeneous mixture, Sasobit was melted at 120 ºC and then mixed with the hot bitumen to the required measure (Figure 5.11 shows melted Sasobit).

Figure 5.11 Sasobit in liquid state

HMA mix was conditioned to 150 ºC while for WMA mixes were conditioned to 130 ºC for one hour. To assist in the temperature conditioning of the different mixes, two ovens were used to ensure the temperatures were kept to the requirements, thus meaning the final test results are not affected. The final step of the mixing process was to mix all the pre-heated aggregates with the binder and Sasobit. This process was achieved with the use of a Hobart mixer, see Figure 5.12.

Figure 5.12 Mixing process

5.4 Compaction temperature determination

To determine the optimum compaction temperature for the warm mix, five samples of AC 10/50 were compacted using the Marshall Hammer: 50 blows at different temperatures. The test average results are shown in Figure 5.13 All test results are presented in Appendix C. It is possible to conclude that a temperature of 128± 0.3 °C is sufficient to equal the temperature of 150°C required for the hot mix compaction density.

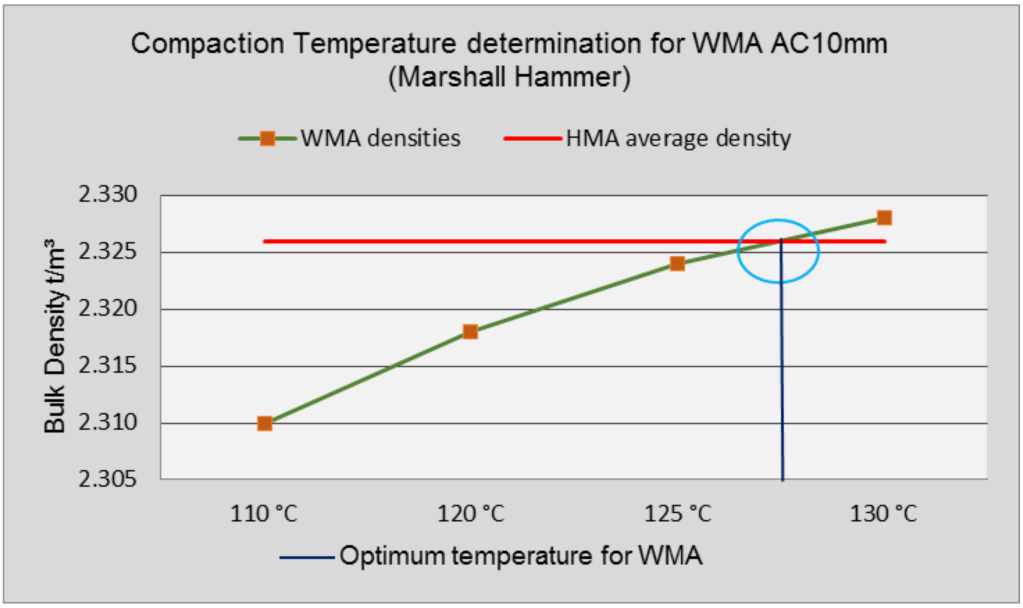


Figure 5.13 WMA compaction temperature determination

Table 5.4 shows the mixing and compaction temperatures for both the laboratory and field trials.

	Temperature (°C)			
	Aggregates	C 320 Binder	Mixing	Compaction
Control Hot Mix	160	170	165	150
Warm Mix Sasobit (1.5%)	140	160	135	128
Warm Mix Sasobit (3.0%)	140	160	135	128
Warm Mix Sasobit (6.0%)	140	160	135	128

Table 5.4 Mixing and compaction temperature

5.5 Particle Size Distribution

Table 5.5 and Table 5.6 present the average of the grading of 10 mm and 14 mm mixes. The results indicate the consistency of the materials. The percentage of aggregates, dust and filler added to the mix is reflected in the PSD results. All the PSD met the target of the design with a minimum variation from the original design. See Appendix D for all PSD, binder content and volumetric properties test results.

Method	AC 10/50 Particle Size distribution average				
MRWA 210.1		HMA	WMA	WMA	WMA
AS Sieve (mm)	Specifications	Control Average	1.5% Sasobit Average	3.0% Sasobit Average	6.0% Sasobit Average
26.5					
19					
13.20	**100**	100.0	100.0	100.0	100.0
9.5	**90 - 100**	96.6	96.8	96.6	96.6
6.7	**70 - 90**	80.6	80.9	80.9	80.1
4.75	**58 - 76**	65.7	65.8	66.0	65.1
2.36	**40 - 58**	45.5	45.6	45.9	44.9
1.18	**27 - 44**	34.91	34.61	34.73	33.74
0.600	**17 - 35**	26.28	26.01	26.22	25.61
0.300	**11 - 24**	18.60	18.15	18.43	18.01
0.150	**7 - 16**	11.45	11.01	11.39	11.06
0.075	**4 - 7**	5.29	4.95	5.26	5.14

Table 5.5 AC 10mm average grading results

Method	AC 14/75 Particle Size distribution average				
MRWA 210.1		HMA	WMA	WMA	WMA
AS Sieve (mm)	Specifications	Control Average	1.5% Sasobit Average	3.0% Sasobit Average	6.0% Sasobit Average
26.5					
19	**100**	**100.0**	**100.0**	**100**	**100**
13.20	**91 - 100**	**97.8**	**97.7**	**97.3**	**97.3**
9.5	**72 - 86**	**79.5**	**80.1**	**79.3**	**78.9**
6.7	**59 - 73**	**66.5**	**67.0**	**66.1**	**65.0**
4.75	**48 - 62**	**55.8**	**56.3**	**55.7**	**54.5**
2.36	**34 - 44**	**39.5**	**39.7**	**39.4**	**38.4**
1.18	**26 -36**	**31.00**	**31.1**	**30.58**	**29.91**
0.600	**20 - 28**	**23.01**	**23.27**	**22.78**	**22.23**
0.300	**13 - 24**	**16.32**	**16.51**	**16.05**	**15.57**
0.150	**9 - 14**	**10.28**	**10.28**	**10.14**	**9.94**
0.075	**4 - 7**	**5.36**	**5.10**	**5.06**	**5.04**

Table 5.6 AC 14mm average grading results

5.6 Bitumen content testing results

The binder content testing implicated testing HMA and WMA with three different percentages of Sasobit. Results of the binder content are presented in Figure 5.14 and Figure 5.15 and indicate that the bitumen for the AC 10/50 and for the AC 14/75 mixes achieved the design target for the HMA and for the WMA respectively. It also indicates that the Sasobit percentages did not have a significant effect on the binder content.

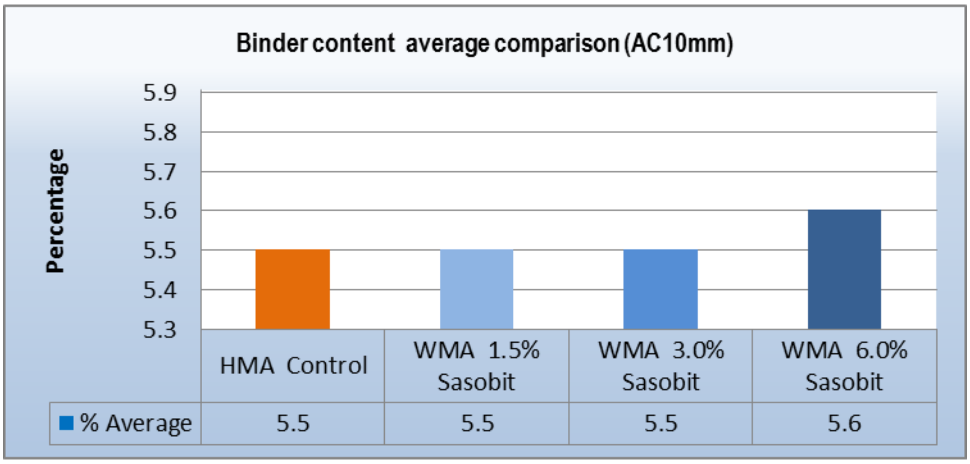


Figure 5.14 AC 10mm binder content results

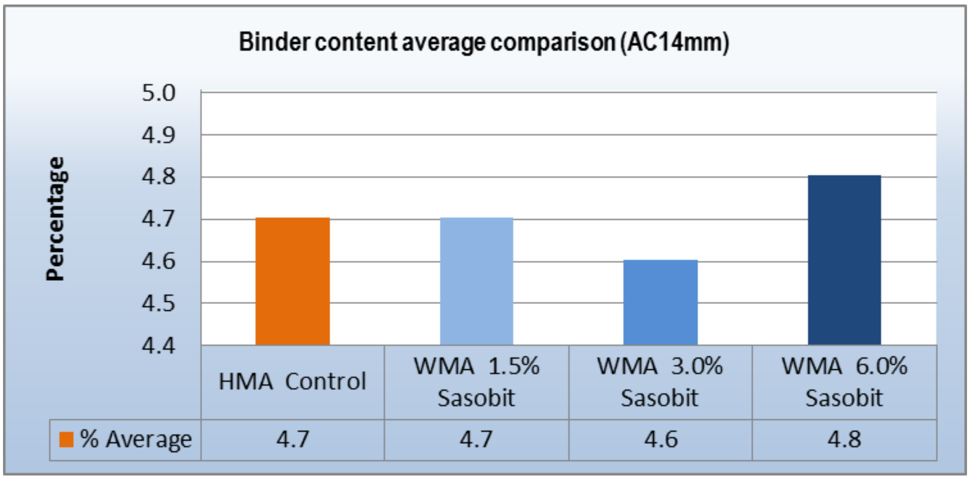


Figure 5.15 AC 14mm binder content results

5.7 Volumetric testing

Volumetric tests were conducted for both WMA with Sasobit at different percentages, and for HMA mix control. All data collected was used for comparison purposes. All the results were tabulated and graphed.

5.7.1 Maximum density

The maximum density of the mixes, produced at different mixing temperatures with different percentages of additive, was measured and is presented in Figure 5.16 and Figure 5.17 for 10mm and 14mm respectively. The aim was to observe whether the maximum density would be affected by the different percentages and/or the mixing temperatures. These results do not indicate a substantial trend between the additions of Sasobit at different percentages and prepared at lower temperatures, as it did not show a significant difference in average values of the maximum density between the mixes.

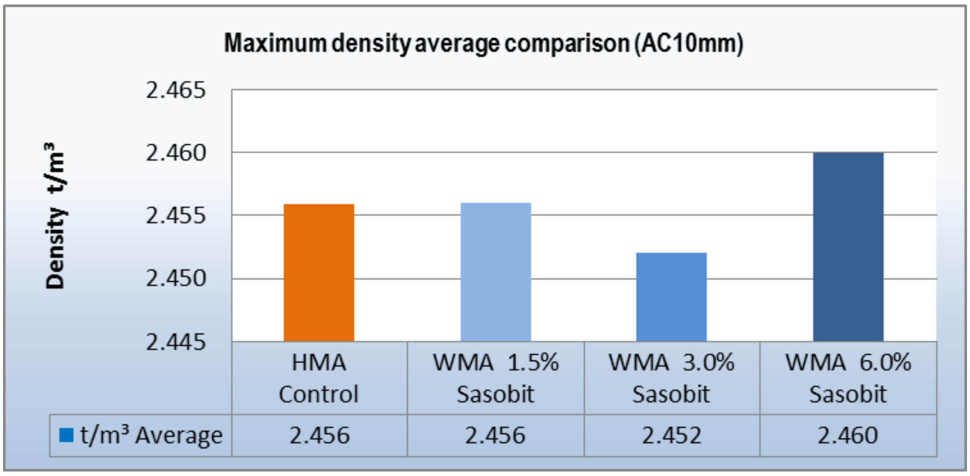


Figure 5.16 AC 10mm MD results

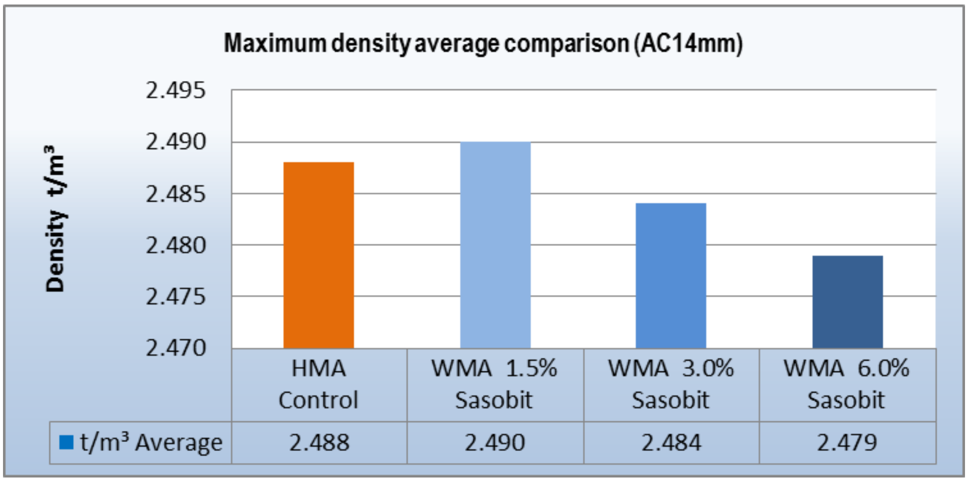


Figure 5.17 AC 14mm MD results

5.7.2 Bulk density

The results of the bulk density show that there is no variation between HMA and WMA at the rate of 1.5% of added Sasobit. However, the density results point out that, at 3.5% and 6%, the addition of the additive Sasobit to the mix significantly assists in lowering the volume of air voids, therefore increasing the density. It is possible to conclude that the reduction rate of air voids is directly related to the additive percentage added. Figure 5.18 and Figure 5.19 present the average bulk densities for both AC 10/50 and AC 14/75.

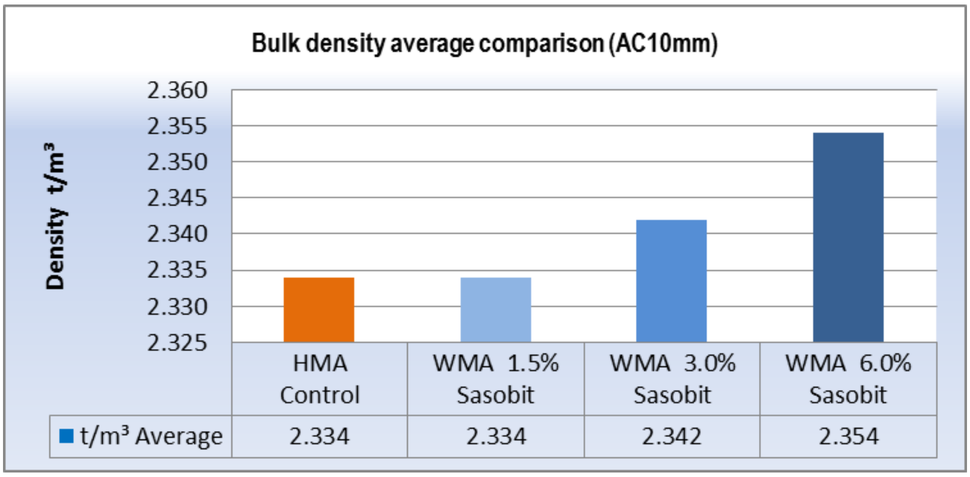


Figure 5.18 AC 10mm bulk density results

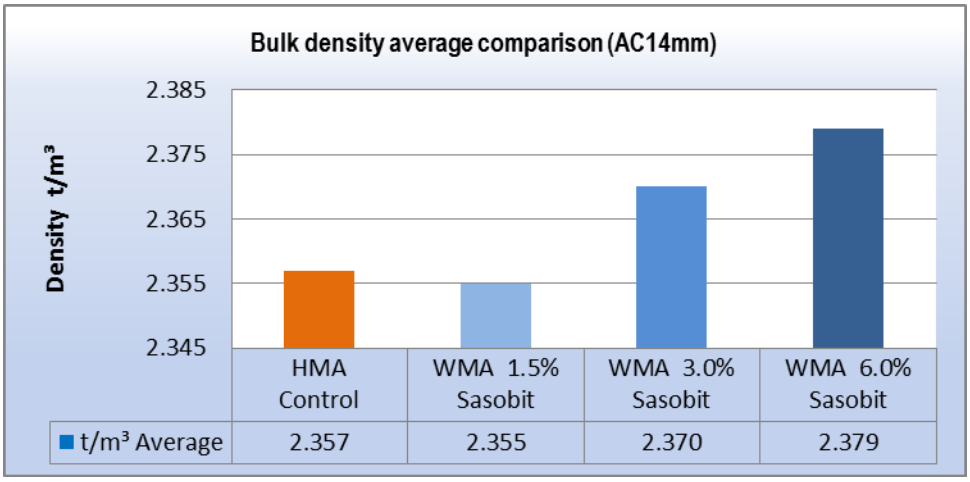


Figure 5.19 AC 14mm bulk density results

5.7.3 Air voids

It can be inferred from the air voids of the compacted mixes in total, presented in Figure 5.20 and Figure 5.21, that the addition of Sasobit largely lowers the air voids of WMA. The bulk density and the air voids of the HMA and WMA with 1.5% of Sasobit are almost equal. However, with 3% and 6% of Sasobit, the difference in air voids is significant. This is indicative that the workability of HMA and WMA with 1.5% of Sasobit is reduced, thus more effort needed to compact.

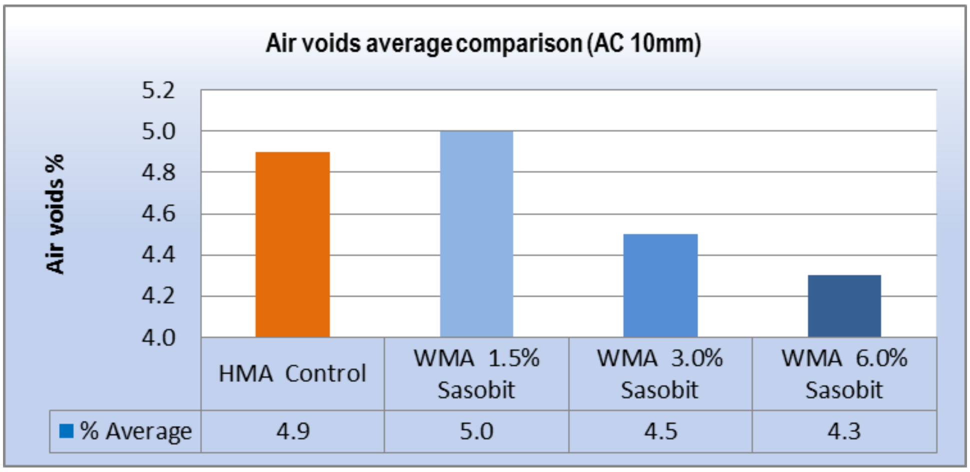


Figure 5.20 AC 10mm air voids results

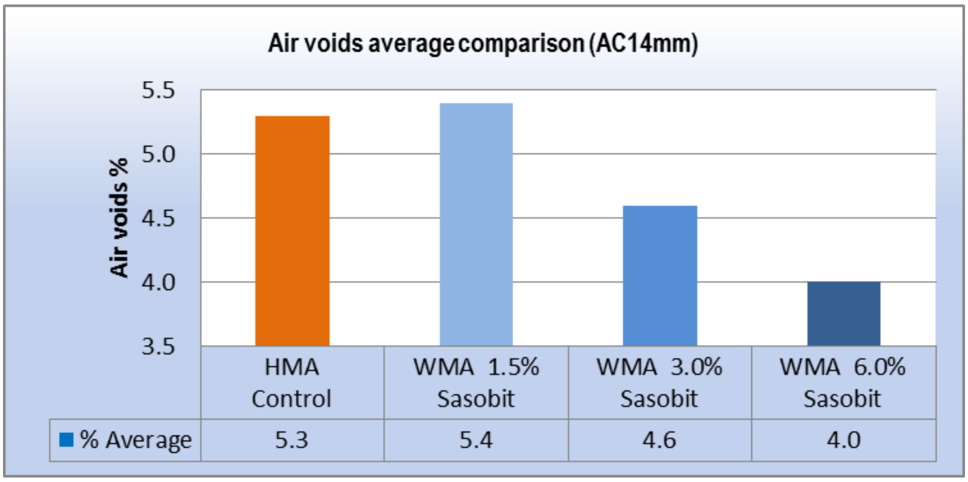


Figure 5.21 AC 14mm air voids results

5.7.4 Marshall Stability and Flow

The results clearly show, in terms of stability and flow, that for both mixes HMA and WMA (1.5% Sasobit) the values are noticeably similar, while for WMA with Sasobit at 3% and 6%, the stability and flow of the mix were higher than for HMA as seen in Figure 5.22 and Figure 5.23 This indicates that the addition of Sasobit clearly influences the stability and flow values which can be attributed to the mixture of bitumen with an additive percentage higher than 1.5%. It is possible to conclude from the results that the addition of Sasobit potentially improves the mix compactibility due to the lower air voids, thus increasing the stability and flow values.

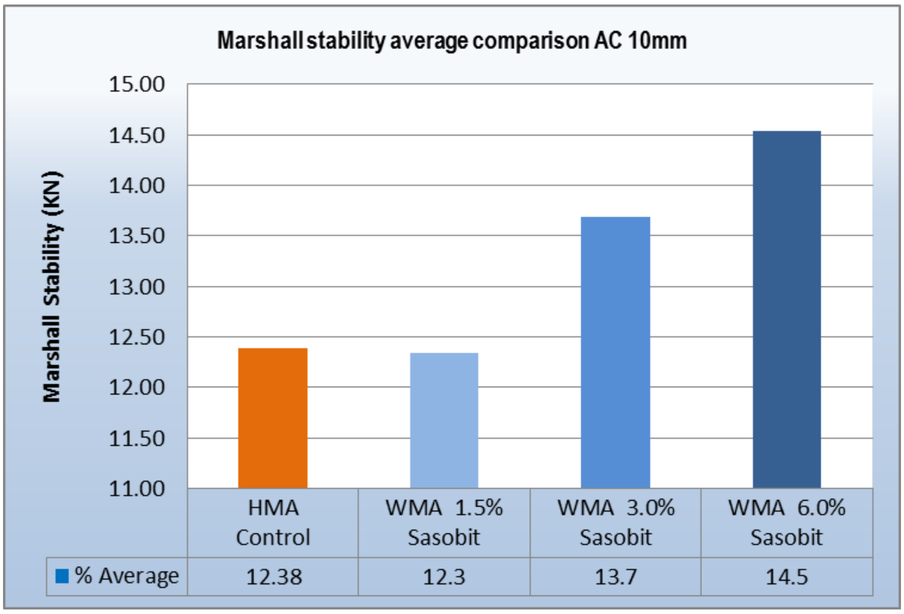


Figure 5.22 AC 10mm Marshall Stability results

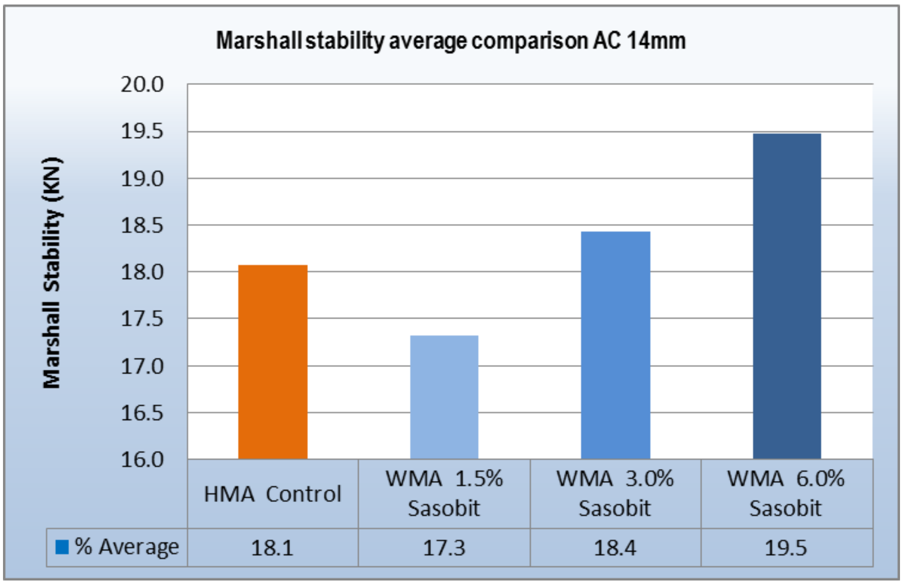


Figure 5.23 AC 14mm Marshall Stability results

5.7.5 Volumetric Mineral Aggregate (VMA)

The volumetric properties are shown in Table 5.7 and Table 5.8 including the VMA results. Both HMA and WMA performed similarly and consistently in all the volumetric testing. However, it needs to be noted that the results are slightly different when there is a 3% or greater addition of Sasobit.

Test Method MRWA 731.1	HMA AC 14/75 Control Average	WMA AC 14/75 1.5% Sasobit Average	WMA AC 14/75 3.0% Sasobit Average	WMA AC 14/75 6.0% Sasobit Average
Marshall Flow (mm)	**3.00**	**3.00**	**3.00**	**3.25**
Nº of Tests (n)	3	3	3	3
Standard Deviation	0.14	0.12	0.00	0.14
Marshall Stability (kN)	**18.1**	**17.3**	**18.4**	**19.48**
Nº of Tests (n)	3	3	3	3
Standard Deviation	0.50	0.04	0.30	0.22
V.M.A. (%)	**16.0**	**16**	**15.2**	**15.07**
Nº of Tests (n)	3	3	3	3
Standard Deviation	0.16	0.19	0.09	0.08
V.F.B. (%)	**67.2**	**66.4**	**69.7**	**73.1**
Nº of Tests (n)	3	3	3	3
Standard Deviation	0.29	0.43	1.03	0.64

Table 5.7 AC 14mm volumetric testing results

Test Method MRWA 731.1	HMA AC 10/50 Control Average	WMA AC 10/50 1.5% Sasobit Average	WMA AC 10/50 3.0% Sasobit Average	WMA AC 10/50 6.0% Sasobit Average
Marshall Flow (mm)	**3.00**	**3.00**	**3.50**	**3.20**
Nº of Tests (n)	3	3	3	3
Standard Deviation	0.01	0.02	0.12	0.24
Marshall Stability (kN)	**12.38**	**12.3**	**13.7**	**14.5**
Nº of Tests (n)	3	3	3	3
Standard Deviation	0.28	0.01	0.19	0.17
V.M.A. (%)	**17.4**	**17.5**	**16.9**	**17.1**
Nº of Tests (n)	3	3	3	3
Standard Deviation	0.03	0.16	0.13	0.12
V.F.B. (%)	**72.5**	**71.5**	**73.4**	**75**
Nº of Tests (n)	3	3	3	3
Standard Deviation	0.38	0.41	0.44	0.40

Table 5.8 AC 10mm volumetric testing results

5.7.6 Voids Fill with Binder (VFB)

The results of the VFB indicate that there is a slight increase in the WMA mix with Sasobit in comparison to HMA, particularly with 6% Sasobit.

5.8 Performance testing

The dense-graded asphalt mix used for the performance testing in this study was the AC 10/50. This mix was chosen because it is the most used mix in Western Australia. The asphalt mix performance tests were conducted on laboratory and plant-produced samples in order to compare the rutting, moisture sensitivity, fatigue and stiffness of HMA and WMA with Sasobit.

All testing results from the samples prepared in the laboratory are presented in Appendix E**.**

5.8.1 Resilient Modulus

The Indirect Tensile Strength measures the horizontal recovery of HMA, and the resilient modulus is the outcome of the testing which is the material's mean stiffness under specific conditions.

5.8.1.1 Testing/specimen preparation

For this investigation, the resilient modulus testing was performed according to AS 2891.13.1-1995 on the specimens produced using the gyratory compactor (Servopac). Several specimens were manufactured, for control (HMA) and WMA with different percentages of Sasobit (1.5%, 3.0% and 6.0%). Asphalt mixes were recorded and three replicate specimens were produced for testing.

Specimens were prepared by pouring the asphalt mix into moulds and a gyratory compactor (Servopac) was used with an air void target of 5 % ± 0.5 for each specimen. Figure 5.24 show mould set up for gyratory compaction. See Table 5.4 in section 5.4 for working temperatures.

Figure 5.24 Setting the mould

The air voids of the compacted specimens were measured using method AS 2891.9.2- 1993.

5.8.1.2 Resilient Modulus testing

The resilient modulus tests were conducted in accordance with AS 2891.13.1 – 1995 (Australian Standard, 1995). A repeated load of indirect tensile techniques were applied to determine the resilient modulus of a test sample. For this study, a Universal Testing machine with a 25 kN load capacity was used with a conditioned sample placed in the cabinet at a single temperature of 25 ± 5 ºC for two hours. Figure 5.25 shows the specimen being tested.

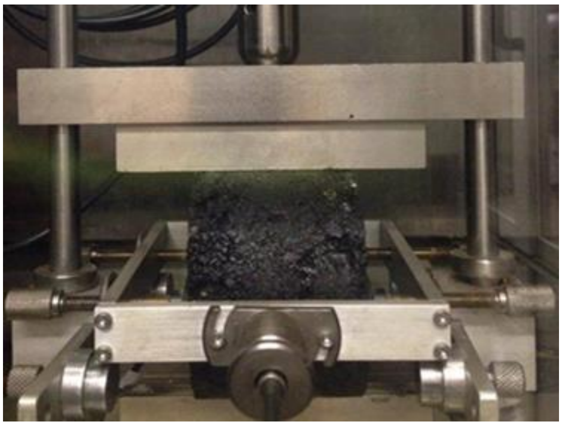


Figure 5.25 Specimen being tested

After the temperature conditioning stage, the resilient modulus was performed by applying haversine load pulses to generate the recoverable horizontal strain of 50 ± 20 $\mu\varepsilon$ with a rise time of 0.04 ± 0.005s and a pulse repetition period of 3.0 ± 0.005s.

5.8.1.3 Monitoring test temperature

Temperature is one of the most important factors affecting the resilient modulus; it is essential to monitor the temperature during testing according to method which specifies the temperature to be used as 25 ± 5 ºC. The temperature was monitored through the use of a dummy specimen with a thermometer.

Figure 5.26 shows a typical five pulses of ITS where each pulse is spread three seconds apart. Colours are representative as follows:

- The red line shows the force used to deform the specimen in Newtons (N)
- The blue line shows the deformations in the horizontal direction when the vertical load is applied

It needs to be noted that the resilient modulus is dependent on strain, force and time.

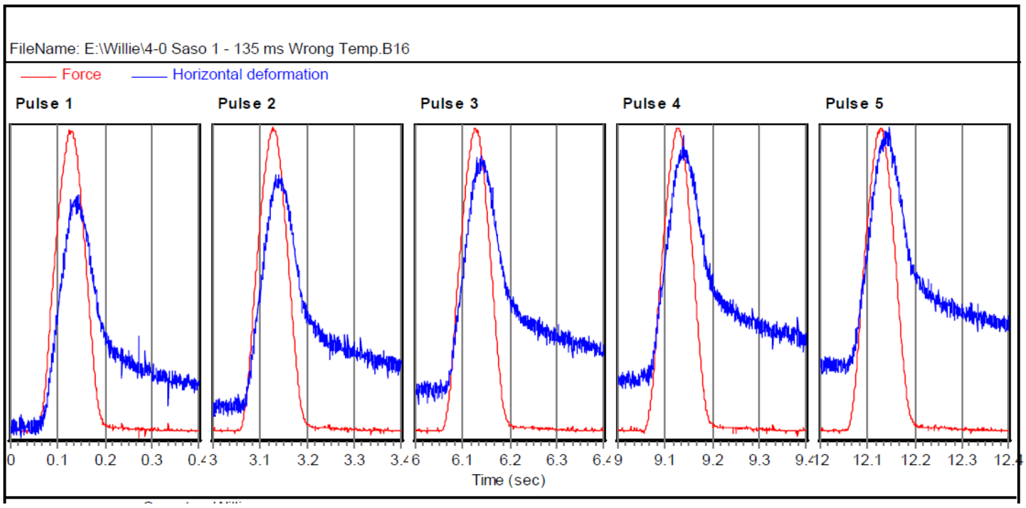


Figure 5.26 Typical five pulses of ITS

5.8.1.4 Results analysis

The results presented in Table 5.9 are a summary of the average of the resilient modulus. The results clearly show that all WMA controlled specimens are within the range of the typical values of resilient modulus for dense graded asphalt as shown in Table 5.10 (Austroads, 2012a). The data presented indicate that preparation and compaction at a low temperature does not significantly affect the stiffness of the mix. On the contrary, if the percentage of Sasobit is increased from 3% to 6%, the resilient modulus also increases which is equivalent to C600 modulus, given that the air voids are kept to 5 %. Also, it was observed that the modulus slightly decreases at 1.5 % of Sasobit compared to control mix. Figure 5.27 presents the resilient modulus average.

Mix Type	Specimen Nº	Average rise time (ms)	Average force (N)	Average of five pulses (MPa)	Standard deviation	Average Resilient Modulus (MPa)
HMA Control	1	24	1822	4397	388.91	**4652**
	2	37	2068	4814	103	
	3	36	2238	5190	155.69	
	4	39	1784	4206	110.94	
WMA 1.5% Sasobit	1	18	1984	4061	165.46	**4490**
	2	31	2102	4919	495.63	
WMA 3.0% Sasobit	1	37	2436	5370	131.27	**5286**
	2	43	2467	5286	65.28	
	3	42	2425	5201	114.57	
WMA 6.0% Sasobit	1	37	3364	6611	127.39	**6835**
	2	41	3231	6812	109.93	
	3	36	3408	7081	117.34	

Table 5.9 Average Resilient modulus results

Binder Type	**Mix size (maximum particle size) (mm)**					
	10 mm		**14 mm**		**20 mm**	
	Range	**Typical**	**Range**	**Typical**	**Range**	**Typical**
Class 170	2 000–6 000	3 500	2 500–4 000	3 700	2 000–4 500	3 300
Class 320	300–6 000	4 500	2 000–7 000	5 000	3 000–7 500	5 200
Class 600	3 300–5 000	6 000	4000–9 000	6 500	4 000–9 500	7 000
Multigrade	1 500–5 000	4 500	3 000–7 000	5 000	4 000–7 000	5 500
SBS	1 500–4 000	2 200	2 000–4 500	2 500	3 000–7 000	3 000
EVA			3 000–6 500	5 600		

Table 5.10 Typical laboratory resilient values (Austroads, 2012a).

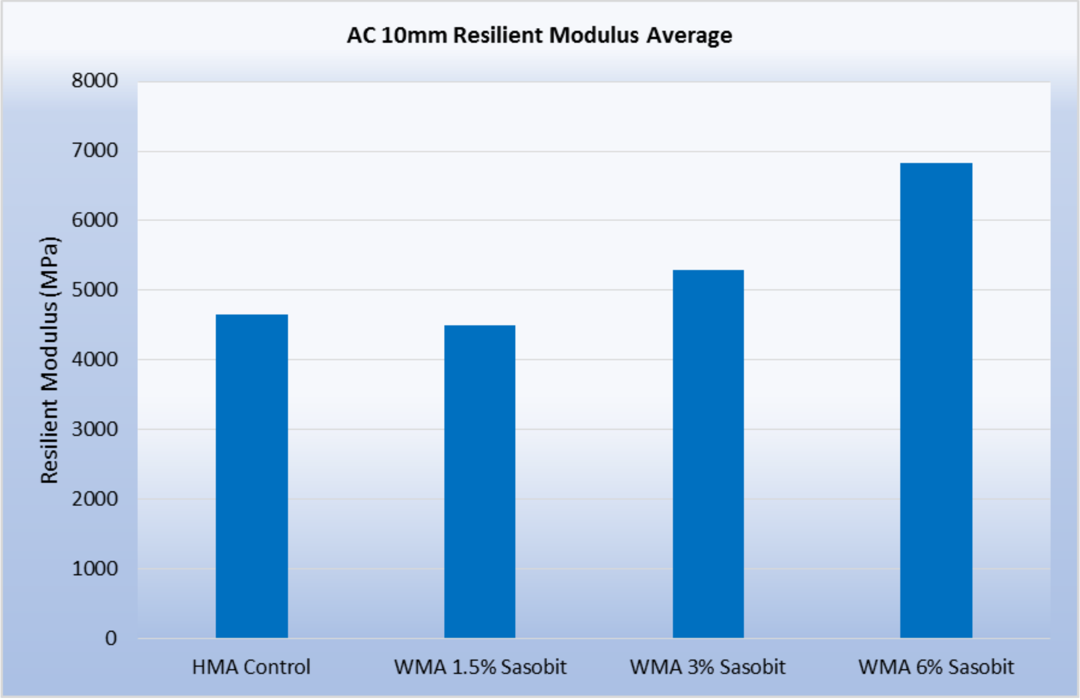


Figure 5.27 Resilient modulus average values

5.8.2 Tensile Strength Ratio (TSR)

TSR measures the stripping potential of an asphalt mix by measuring the strength of an unconditioned and of a conditioned specimen. For the investigation, testing was performed according to method AGPT/T232, and MRWA specification 510 specifies limits for TSR testing of 850 kPa for an unconditioned specimen and of 750 kPa for a conditioned specimen (Main Roads Western Australia, 2016).

5.8.2.1 Testing/specimen preparation

Three specimens were moisture conditioned and processed through an accelerated moisture conditioning, single freeze-and-thaw cycle, and normal moisture conditioning, while three specimens were kept until the strength testing was performed for control with different percentages of Sasobit asphalt mixes.

The specimens for the accelerated moisture conditioning permit water penetration into the air voids of the sample by vacuum pressure. The specimen was placed in a desiccator filled with water at 50 °C ± 5 °C. The level of the water in the desiccator needed to be at least 25 mm above the upper level of the sample. Figure 5.28 shows the accelerated moisture conditioning. The specimen degree of saturation was between 55% and 80%. At less than 55%, the specimen needed to be re-saturated for an additional 30 minutes.

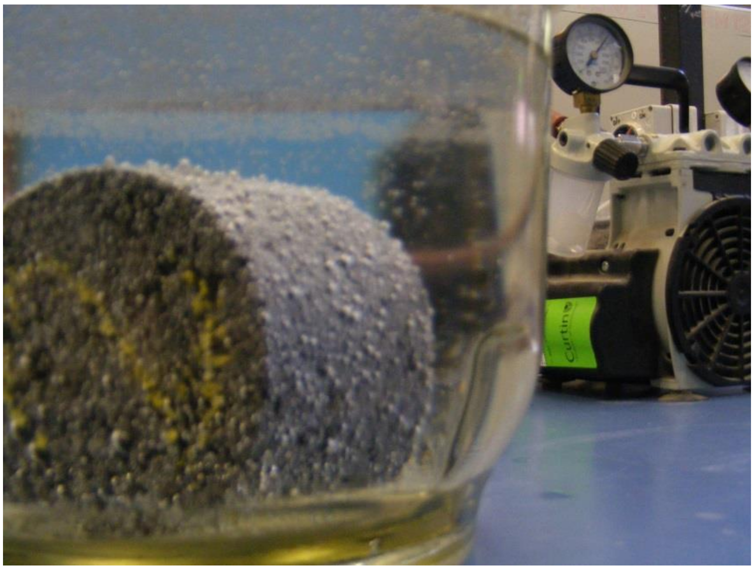


Figure 5.28 Accelerated moisture conditioning

In the freeze-and-thaw cycles (test required by Main Roads Western Australia), after the accelerated moisture conditioning, the specimens were placed in separate sealable plastic zip bags containing 10 ml of water, and sealed. The bags were placed in the freezer at a temperature of – 18 °C ± 3 °C for 18 ± 1 hour. This process accelerates potential problems and assists in the generation of internal stress, by detecting a lack of bitumen/aggregate adhesion in the presence of water.

After the freeze-and-thaw cycle, moisture conditioning was performed on the specimens without the plastic bags. They were placed in a water bath which was maintained at 60 °C ± 1°C and they remained in the bath for 24 hours ± 1 hour, at the specified temperature.

At completion of the conditioning the specimens, were moved to another water bath and maintained at 25 °C ± 1°C for a further 2 hours ± 5 minutes. It needs to be noted that an allowance of 10 minutes for the specimen transfer and handling was included to ensure equal conditioning, uniformity, and that the surfaces of the specimens were not in contact with each other.

Conditioning of the dry specimens was performed in a temperature-controlled environment maintained at 25 °C ± 1°C, simultaneously to the wet specimens being transferred to the bath at 25 °C.

5.8.2.2 TSR testing

Figure 5.29 Specimen being tested

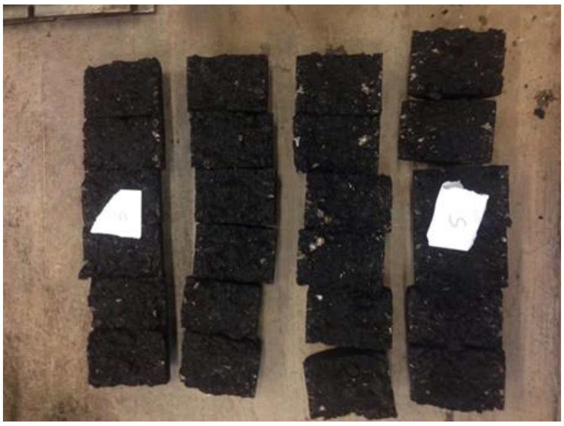


Figure 5.30 Specimen completely split

All specimens were loaded to the Marshall loading frame to complete the testing: failure and the maximum load sustained by the specimens were recorded to the nearest 0.001 kN until the specimen completely split (see Figure 5.29 and Figure 5.30).

5.8.2.3 Results analysis

The TSR results of HMA and WMA (with different percentages) presented in Table 5.11, TSR average results for HMA and WMA, indicate that the mixes had acceptable moisture sensitivity as they met the value of 80 % minimum required for TSR (according to Austroads). Also, they met the 850 kPa for unconditioned specimens and 750 kPa for conditioned specimens according to MRWA specifications 510. The results are indicative that the specimens prepared at 140°C and compacted at 125° C do not affect the moisture sensitivity as believed to be a potential cause of stripping. Lime, an antistripping agent was added to all the mixes in order to achieve the specifications. It needs to be noted that lower temperature properties were not further investigated in this study.

Test method used AGPT/T232	HMA Control	WMA 1.5% Sasobit	WMA 3.0% Sasobit	WMA 6.0% Sasobit	Specification
Dry set air voids (%) (Average of 3)	8.1	8	7.9	8.1	
Dry tensile strength at 25 °C (kPa) (average of 3)	1058.3	1008.2	1049.3	1046.5	850
Wet set air voids (%) (average of 3)	7.9	8.2	8	8.1	
Wet tensile strength at 25 °C (kPa) (triplicates)	956.8	876.2	937.6	932.4	750
Tensile Strength ratio (%)	90.4	86.9	89.4	89.1	80.0

Table 5.11 TSR average results for HMA and WMA

An increase in the Sasobit percentage showed no improvement in the TSR values, indicating that the adhesion agent is a key factor in the TSR values.

5.8.3 Wheel tracking

The wheel tracking test measures the rutting depth of asphalt, and testing was performed according to test method AGPT/T231 where a loaded wheel is placed on a pressurised linear rubber hose which rests on the test samples.

5.8.3.1 Testing/specimen preparation

Figure 5.31 Specimen being compacted

The specimens were produced using a slab compactor shown in Figure 5.31 Specimen being compacted, and all samples were compacted to the required 5 ± 1.0 % air voids. The samples were conditioned for a minimum of 6 hours at 58 °C before testing was carried out. Rut testing was completed at 60 °C. All rut depths were measured at 10,000 cycles.

5.8.3.2 Wheel tracking testing

Figure 5.32 Wheel tracking apparatus

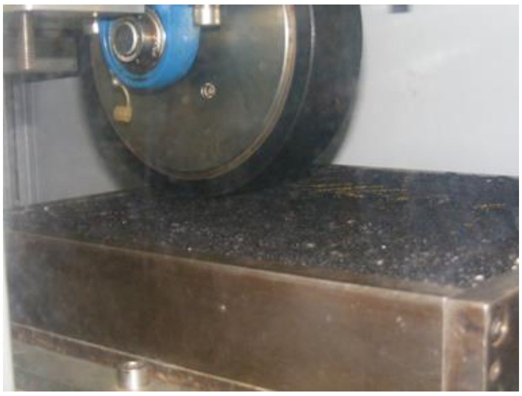


Figure 5.33 Wheel tracking test

The wheel depression or rut is monitored using a linear variable displacement transducer (LVDT), which is like an electronic dial gauge. The wheel moves backwards and forwards over the test sample, and the test was completed at 10,000 cycles at 60 °C, as seen in Figure 5.32 and Figure 5.33 while Figure 5.34 shows wheel tracking slabs after 10,000 cycles.

Figure 5.34 Slabs after 10,000 cycles

5.8.3.3 Results analysis

Both mixes indicated a less than 3 mm rut depth at 10,000 wheel-load cycles which is considered a superior performance according to the typical tracking depth for laboratory specimens stipulated in Austroads, 2014. Different percentages of Sasobit were added to the mix to observe if any changes occur in the mixture properties.

Controlled HMA and WMA 1.5% samples show less than 3 mm rutting, indicating no significant difference between them. Therefore, WMA performed slightly better than HMA. However, the 3.0% and 6.0% of Sasobit showed a significant reduction in rutting, validating that an increase in the Sasobit percentage improves rutting resistance. Figure 5.35 presents the control and WMA samples' average rutting depth.

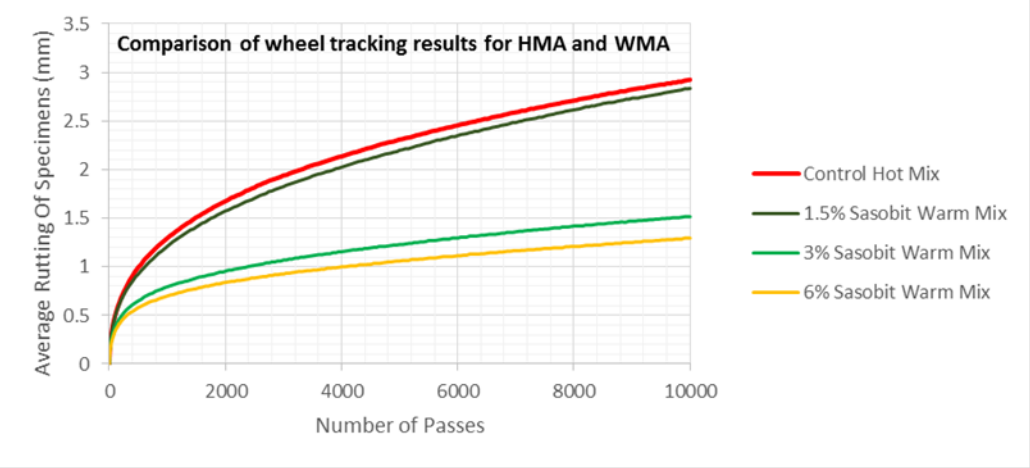


Figure 5.35 Comparison of wheel tracking average results

5.8.4 Fatigue resistance

Fatigue resistance properties were measured using the four-point bending test according to test method AGPT/T233. This method utilise one strain level at

400 ± 10 microstrain and three replicate specimens. The test measures the ability of asphalt to resist cracking due to flexural loading from the moving wheel loads.

5.8.4.1 Testing/specimen preparation

Figure 5.36 Slabs cutting to produce beams

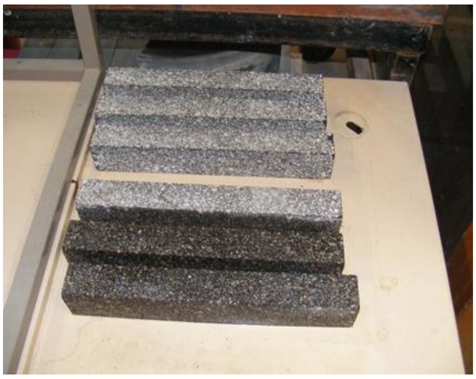


Figure 5.37 Beams ready for testing

All samples were compacted using an Asphalt Vibratory Compactor (AVC) and were kept within the target air voids of 5.0 ± 0.5%. The compacted samples were cut into beams and allowed to dry to constant mass (no moisture) and three replicated specimens were produced for testing. Figure 5.36 and Figure 5.37 present the preparation of the fatigue beams**.**

5.8.4.2 Fatigue testing

Samples were cycled through continuous haversine displacement loads applied at a frequency of 10 Hz and a horizontal strain of 400 microstrain, required to reduce the initial flexural modulus to 50% stiffness reduction at a temperature of 20 °C. Testing was performed until the mix stiffness was reduced to half its initial value and it was noted as the fatigue life of the mix. Figure 5.38 and Figure 5.39 show the testing process.

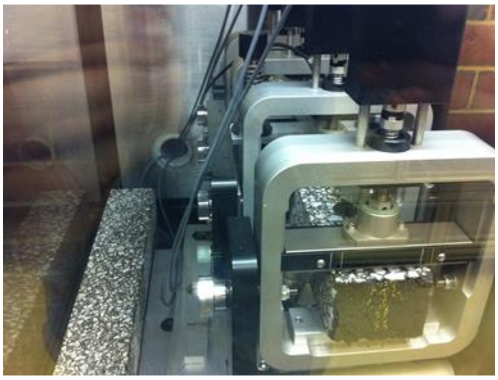


Figure 5.38 Initial phase testing

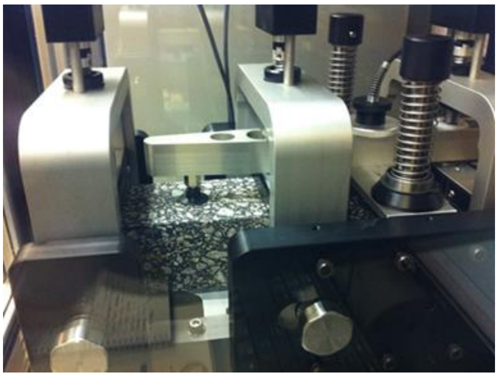


Figure 5.39 Beam testing

5.8.4.3 Results analysis

Beam testing results for fatigue resistance and the initial flexural stiffness for both mixes WMA and HMA samples, are shown in Table 5.12. It needs to be noted that only three specimens were tested at 400 µ at 20 °C (standard temperature for standard conditions). It was not possible to validate the fatigue resistance performance in comparison to HMA as other tests with different temperatures are required. More beams at different strain levels are required to make an accurate analysis. A full characterisation requires extensive and time consuming testing; it is considered the only feasible way to obtain reliable results.

In this study, as seen in Table 5.12 HMA control and WMA with 1.5% Sasobit performed best with regard to fatigue resistance. WMA with 6% of Sasobit required a significantly lower number of cycles to reach fatigue failure in comparison to HMA. As can be seen in Figure 5.43 an increase in the percentage of Sasobit in the WMA enhances the flexural stiffness but reduced the number of cycles to fatigue failure. Also, the 3% and 6% of Sasobit show higher initial flexural fatigue properties and lower fatigue life than the HMA and WMA with 1.5 % of Sasobit. See Appendix E for all testing results.

Mix	Beam Nº	Air voids (%)	Initial Flexural Stiffness (MPa)	Termination Stiffness (50% of the initial Stiffness (MPa)	Cycle count of 1000000
HMA Control	1	5.2	5296	2648	220990
HMA Control	2	5.3	5115	2557	473310
HMA Control	3	4.9	5617	2809	457630
Average		5	**5343**	2671	**383977**
WMA Sasobit (1.5%)	1	5.0	6474	3237	192270
WMA Sasobit (1.5%)	2	4.8	6220	3110	151940
WMA Sasobit (1.5%)	3	4.9	6138	3069	196700
Average		5	**6277**	3139	**180303**
WMA Sasobit (3.0%)	1	5.1	6228	3114	182210
WMA Sasobit (3.0%)	2	5.2	6369	3185	130870
WMA Sasobit (3.0%)	3	5.1	6411	3205	180400
Average		5	**6336**	3168	**164493**
WMA Sasobit (6.0%)	1	5.0	7825	3913	145340
WMA Sasobit (6.0%)	2	4.9	7565	3783	106080
WMA Sasobit (6.0%)	3	4.9	6834	3813	77000
Average		5	**7408**	3836	**109473**

Table 5.12 Beam testing results

Figure 5.40 through to Figure 5.43 present the fatigue property results of the three specimens for each mix, and Figure 5.44 presents the average fatigue properties of WMA in comparison to HMA.

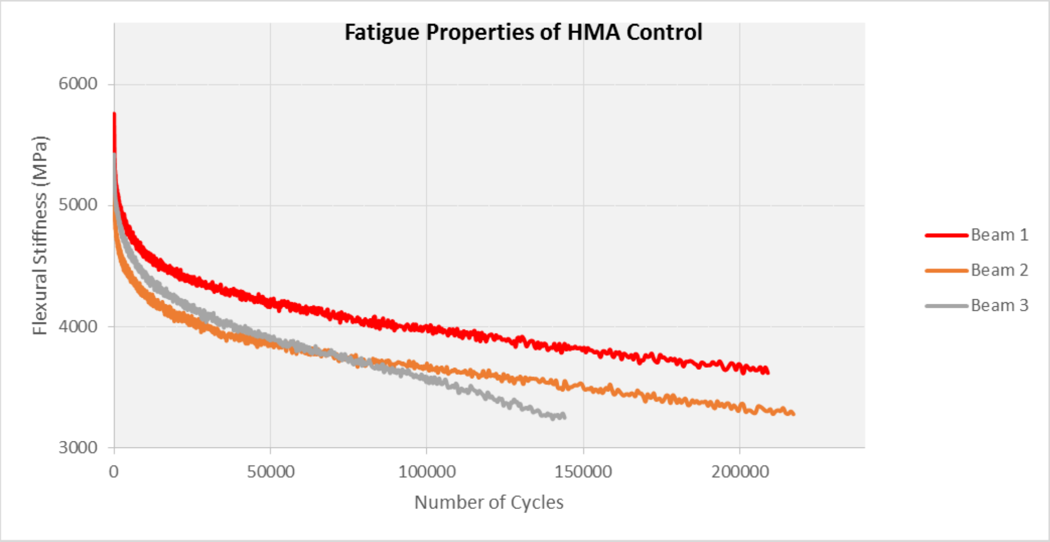


Figure 5.40 Stiffness and fatigue life results (control)

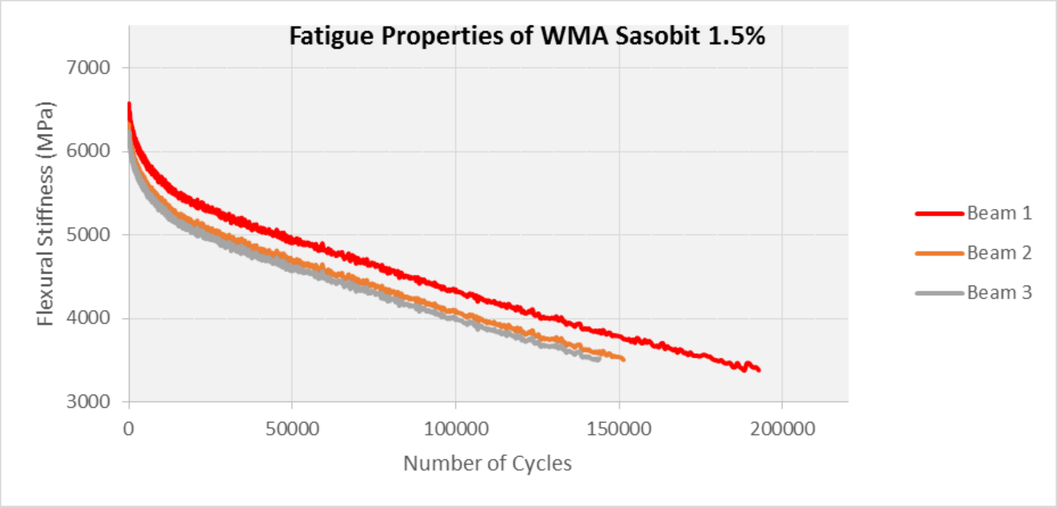


Figure 5.41 Stiffness and fatigue life results (1.5% Sasobit)

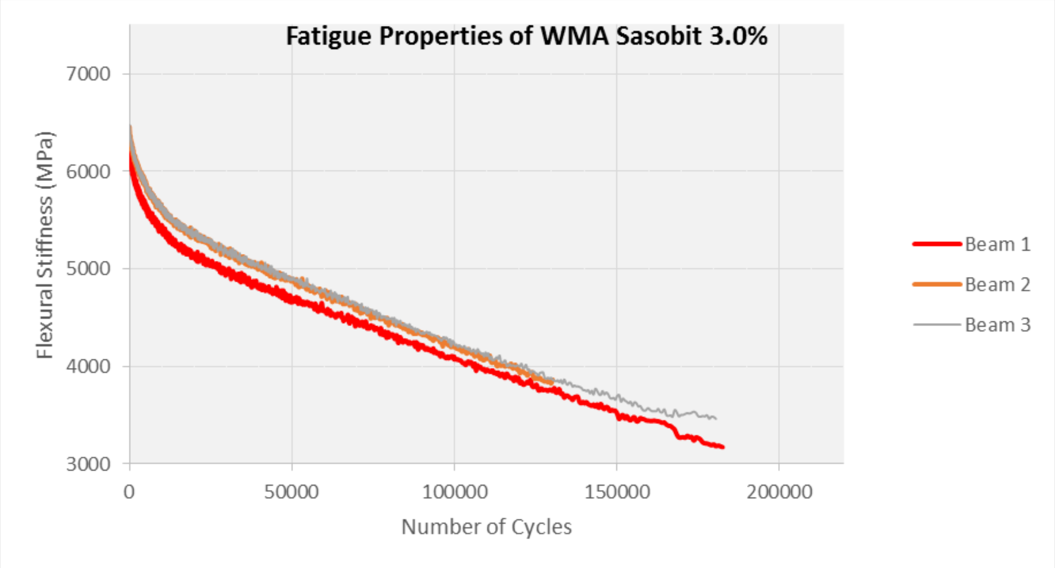


Figure 5.42 Stiffness and fatigue life results (3.0% Sasobit)

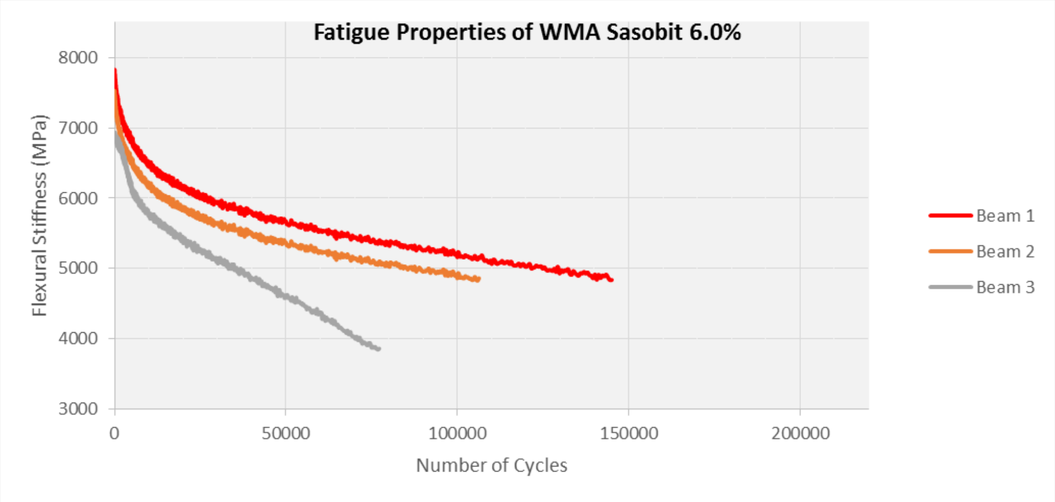


Figure 5.43 Stiffness and fatigue life results (6.0% Sasobit)

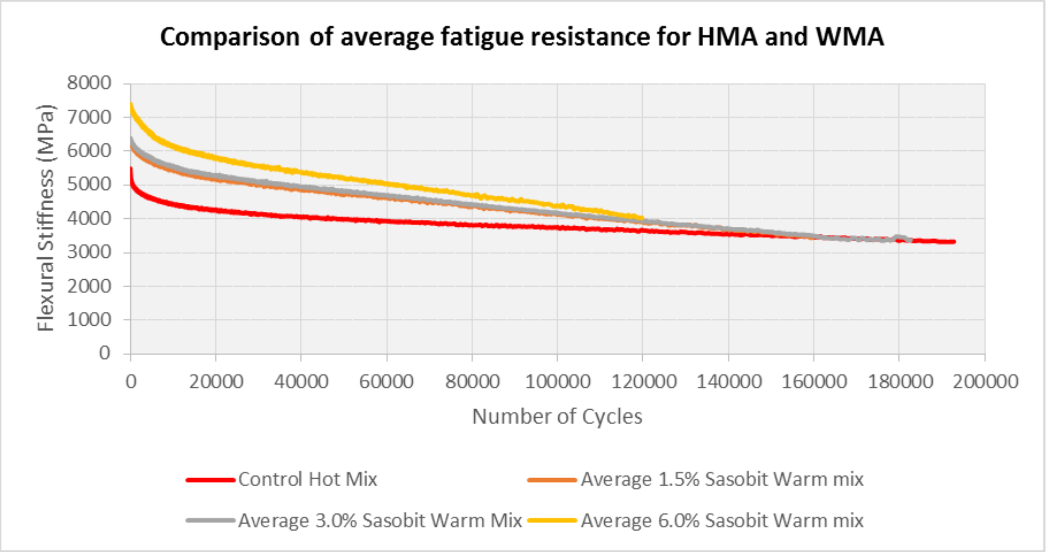


Figure 5.44 Stiffness and fatigue life average results

It needs to be noted that testing for fatigue life was for ranking purposes only. Fatigue testing requires different strain levels at different temperatures and more beams for pavement design.

5.8.5 Dynamic Modulus

Dynamic modulus indicates the stiffness of a mix, which is a fundamental property of asphalt. It is the utter value of the peak-to-peak stress divided by the peak-to-peak recoverable strain under sinusoidal loading. In the test, a sinusoidal compressive stress is applied along a vertical axis of a cylindrical asphalt sample, and the resulting strain is measured.

The principal of time temperature superposition permits the mix to be treated as a linear viscoelastic material, and a master curve can be developed from the data obtained of the effects of temperature and loading frequency, from which the dynamic modulus can be determined at different temperatures.

5.8.5.1 Testing/specimen preparation

Figure 5.45 Cylinder preparation

Dynamic modulus testing was carried out using method AASHTO TP62-07 (AASHTO, 2003). Three laboratory samples (cylinders) were produced for each temperature (Figure 5.46 shows cylinder preparation for testing) and a Servopac gyratory compactor was used for compaction to the required target air void of 5 ± 0.5 % at a specific temperature. Table 5.4 presents compaction temperatures. Samples were top and bottom cut to obtain the standard test dimensions of 100 mm in diameter, and 150 mm in height, according to test method.

5.8.5.2 Dynamic modulus testing

An asphalt mixture performance tester (AMPT) machine was used for testing which includes an environmental chamber and a measuring system presented in Figure 5.46. For this study, three temperatures were set (4 C°, 20 °C and 40 °C) along with four loading frequencies of 0.01 Hz, 0.1 Hz, 1 Hz and 10 Hz, with the aim of obtaining a series of dynamic modulus values to generate a master curve. Strain gauges were fixed to the specimens and used to measure strain under sinusoidal conditions in order to calculate the dynamic modulus and phase angle data.

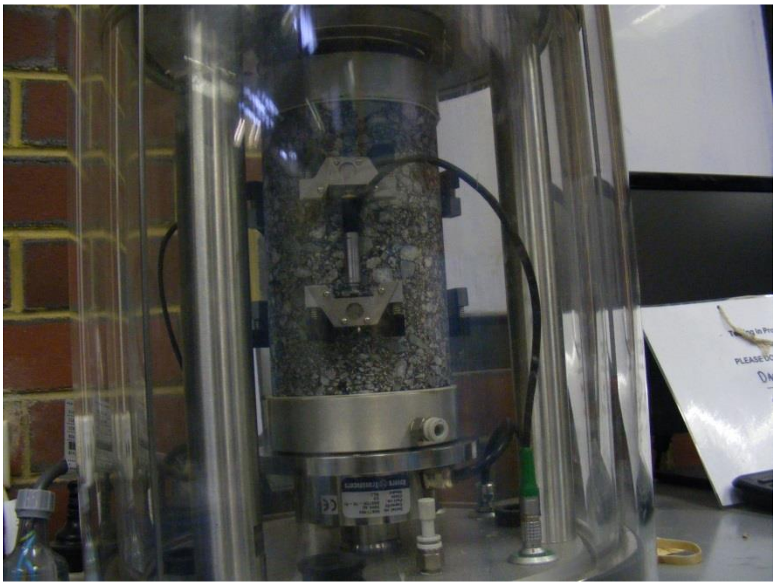


Figure 5.46 Cylinder being testing

The dynamic modulus test usually produces two main outputs: the dynamic modulus and the phase angle. For this study, a series of dynamic modulus and phase angle values were obtained, but only the dynamic modulus values were used to construct the master curve. The second-order polynomial and sigmoidal functions were applied for fitting shift factors to construct the master curve concurrently with the non-linear least square method.

To determine the value of fitting coefficients, the optimisation technique was utilised. Both the Solver function in MS EXCEL and the computer program SPSS were used as optimisation tools. A master curve was created with all the coefficients by applying shift factor to produce reduced frequencies as seen in Figure 5.47 through to Figure 5.50**.**

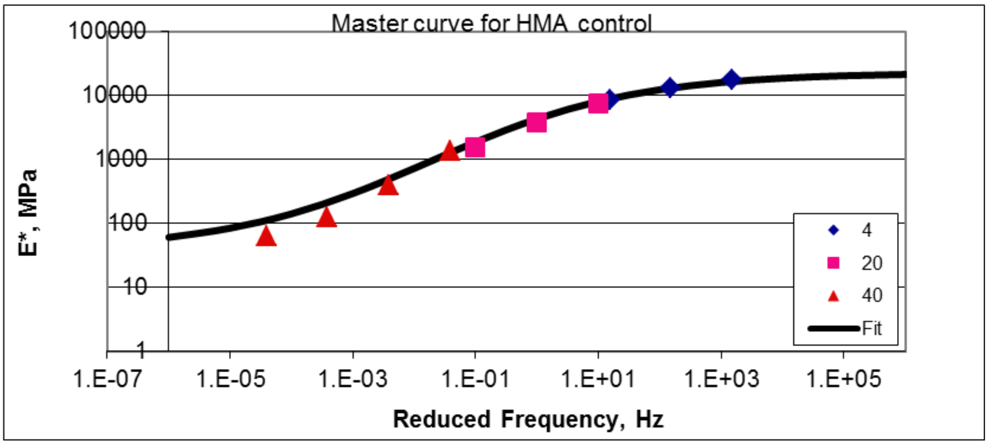


Figure 5.47 Master curve results (control)

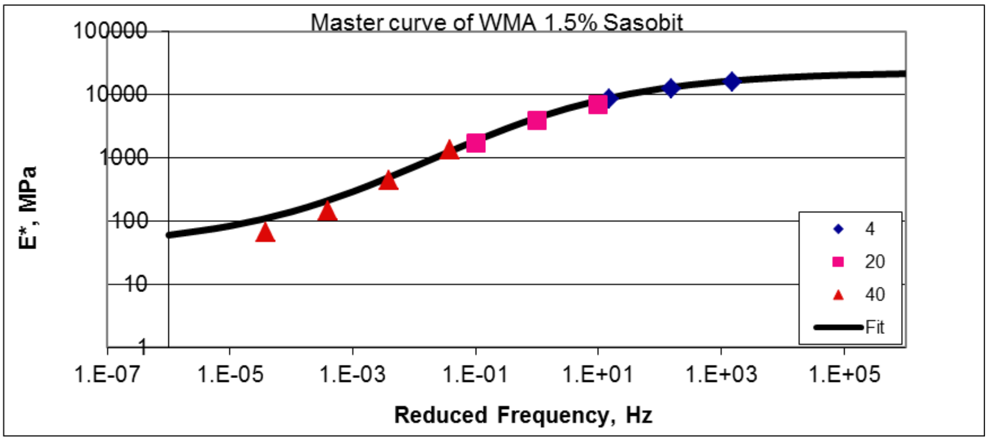


Figure 5.48 Master curve results (1.5% Sasobit)

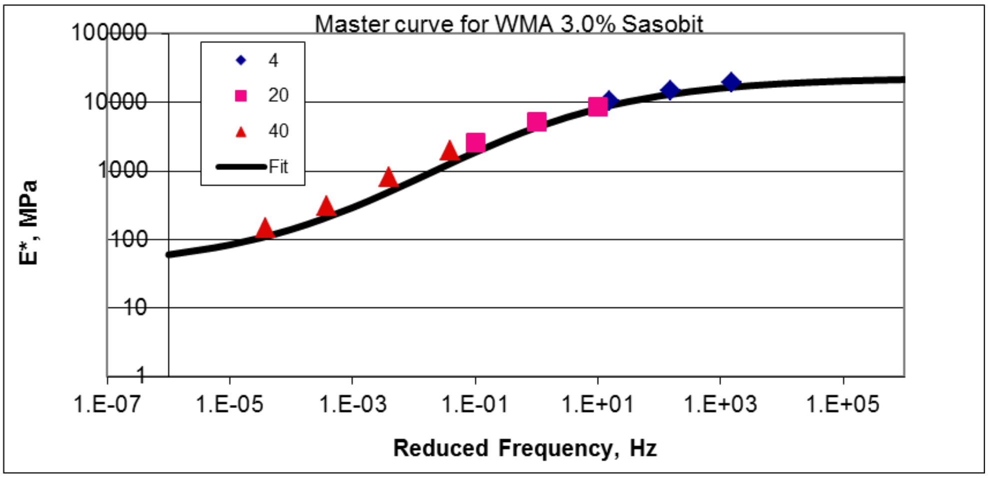


Figure 5.49 Master curve results (3.0% Sasobit)

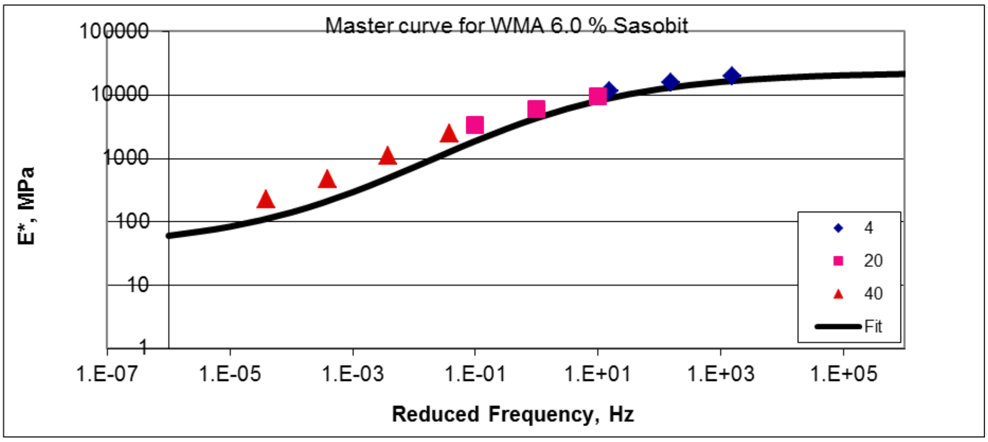


Figure 5.50 Master curve results (6.0% Sasobit)

5.8.5.3 Results analysis

Based on the results, it is possible to conclude that the mix response to cyclic loading conditions is dependent on temperature and frequency. Sasobit at 3% and 6% could have affected the dynamic modulus values of the asphalt at low temperatures, or at low and high frequencies. The likely cause is due to the chemical properties of Sasobit which, at a dry stage, result in a stiff binder. Dynamic modulus average values are presented in Figure 5.51 through to Figure 5.53.

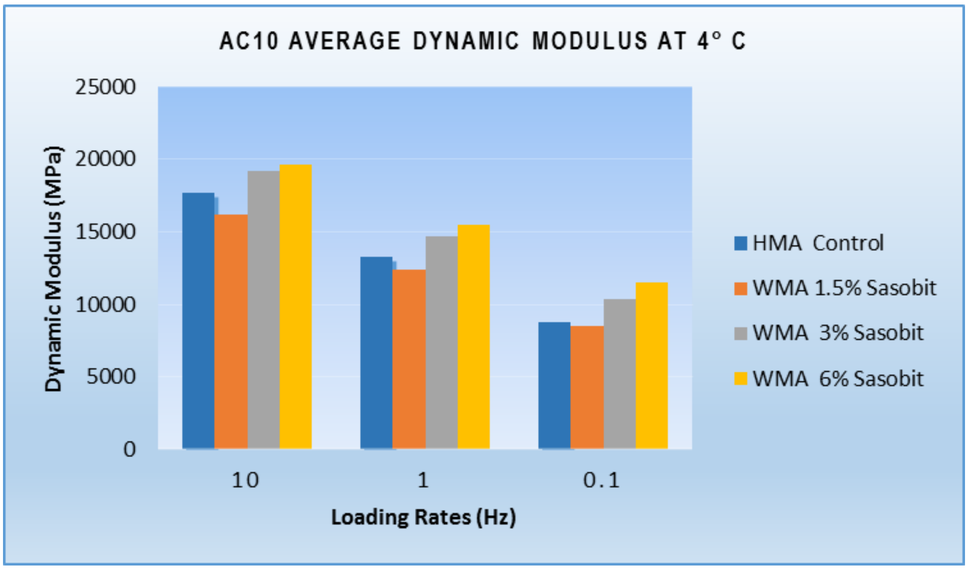


Figure 5.51 Average results at 4°C

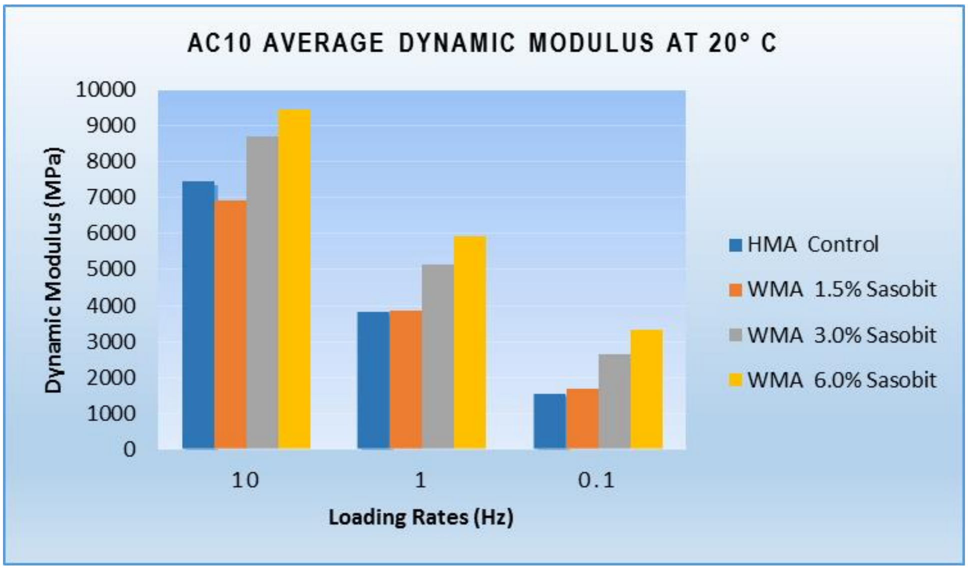


Figure 5.52 Average results at 20°C

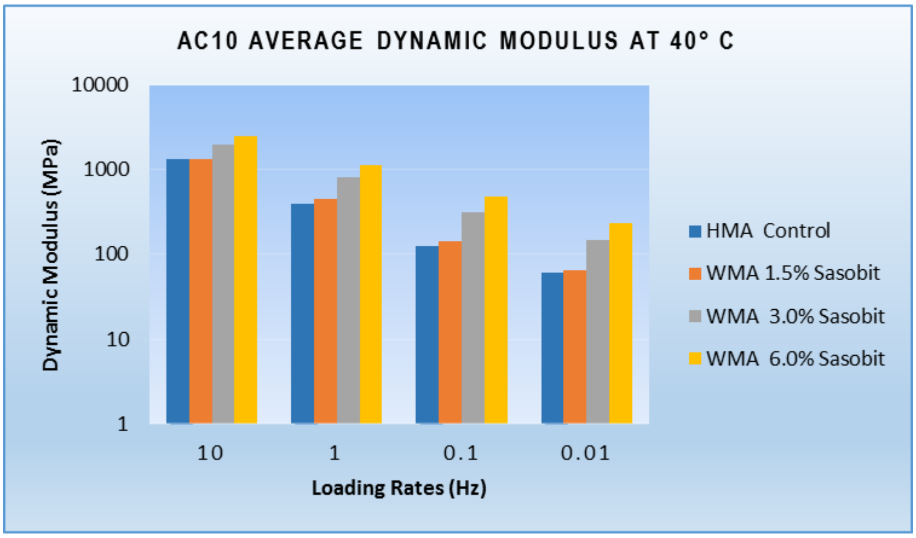


Figure 5.53 Average results at 40°C

The results of the resilient modulus, initial flexural stiffness and dynamic modulus show that all moduli of the representative mixes, increased in modulus values. The increase is particularly visible within the range of 3% and 6% of Sasobit as seen in Figure 5.54. The comparison of the resilient modulus, flexural stiffness and dynamic modulus can be made at the point where the test conditions, in terms of temperature and frequency, are the same.

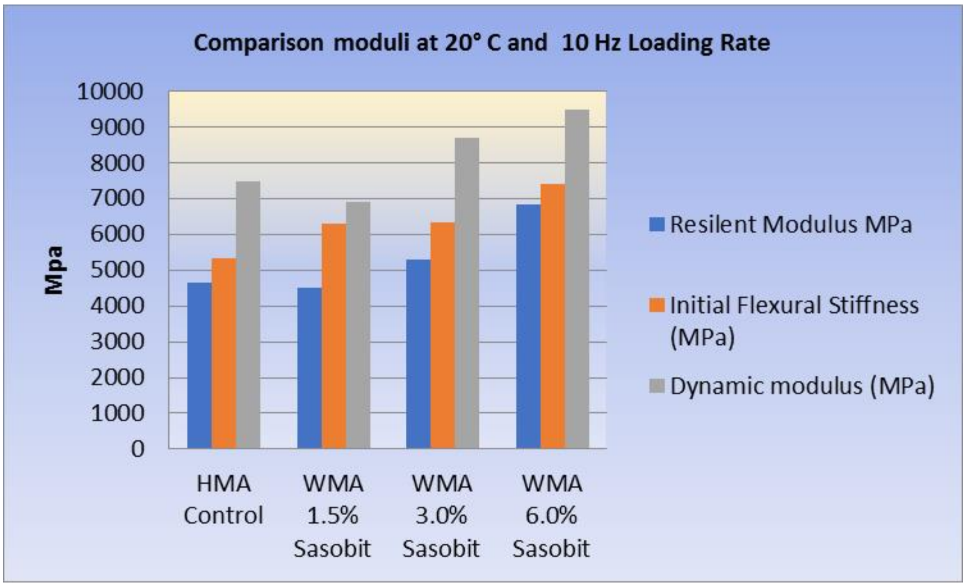


Figure 5.54 Comparison moduli

6 Warm Mix Validation Site

This section presents a record of the production of HMA and WMA for the City of Gosnells Council project which took place during the day at three trial sections at three different sites on different dates with the third site only placed with WMA.

- Trial 1: Reservoir St. Orange Grove, took place on the 11 of December 2011
- Trial 2: Anaconda St. Huntingdale took place over two days from the 16 to 17 of January 2012.
- Trial 3: Mills Rd. West Gosnells took place on the 16 of January 2014.

A number of cores and samples were tested using different methods such as, rutting, fatigue, water resistance, modulus and indirect tensile strength tests performed at different temperatures.

Validation testing of the study was carried out utilising the following methodology a shown in Figure 6.1.

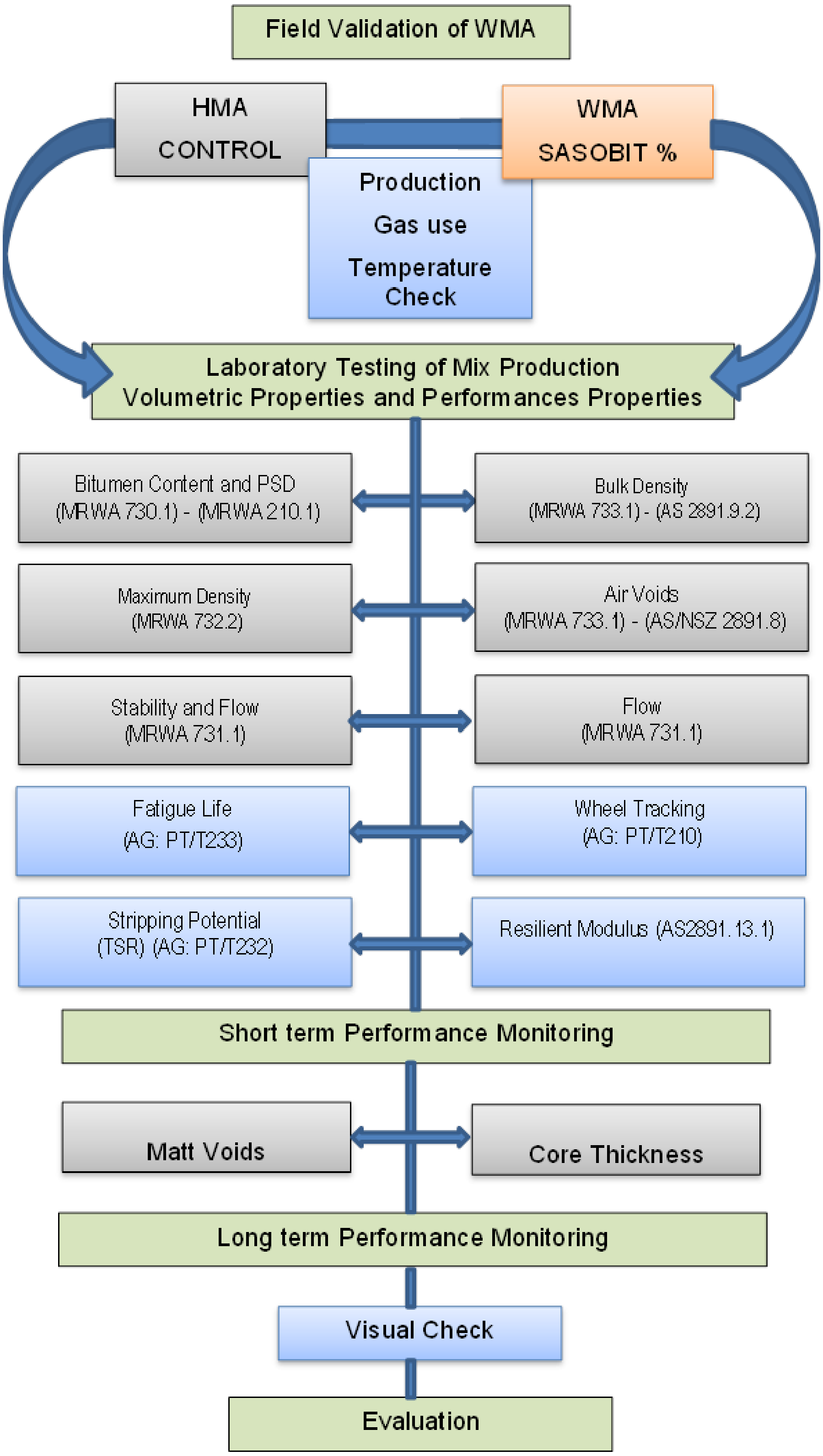


Figure 6.1 Testing Methodology

6.1 Trail Testing

6.1.1 Trial production testing

The general objective of the first two trials was to compare HMA to WMA performance under the same road conditions. Performance was measured through an intensive testing of the volumetric properties, performance and field densities of both mixes. The field densities were determined according to the wet coring MRWA 701.1 and preparation of asphalt for testing method MRWA 705.1 was used. The air voids were calculated according to MRWA 733.1 and these methods were used for all trial sites testing.

Production took place at BGC Hazelmere asphalt plant where a continuous plant was used for the production of HMA and WMA. With a production capability of 85 tonne per hour and was equipped with a baghouse dust collector. Figure 6.2 shows BGC asphalt plant.

Figure 6.2 Asphalt mix plant used for HMA and WMA

At trial site No 1 a total of 404 tonnes of AC 14/75 mix was produced of which 202 tonnes were HMA and 202 tonnes were WMA with a production rate of 85 tonnes per hour. The site was approximately 24 km from the plant and required a 30 to 40 minute travel time. The HMA control section was produced at 170 °C and compacted between 140 – 150 °C. WMA with a 1.5 % of Sasobit mixing temperature was 140 °C and was compacted between 120 to 130 °C.

At trial site No 2 a total 620 tonnes of AC 10/50 mix was produced of which 300 tonnes were HMA and 320 were WMA with a production rate of 85 tonnes per hour. The site was approximately 23 km from the plant and required a 30 to 40 minute travel time. The HMA control section was produced between 170 °C and compacted at between 140 – 150 °C. WMA with 1.5% of Sasobit with a mixing temperature of 140 °C and was compacted between 120 °C to 130 °C.

At trial site No 3 a total of 400 tonnes of AC 10/50 of only WMA was produced with a production rate of 85 tonnes per hour. The site was approximately 25 km from the plant and required a 35 to 45 minute travel time. WMA with 4% of Sasobit with a mixing temperature of 140 °C and was compacted between 120 to 130 °C. Due to the modify bitumen and mix laboratory results that showed a high performance within the ranges of 3% to 6%, the 4% of Sasobit was selected, to fit the purpose and the air voids requirement. Also, there were restrictions in compaction (no vibratory roller allowed) due to gas pipes in the area. Figure 6.3 and Figure 6.4 shows production temperature for HMA and WMA respectively.

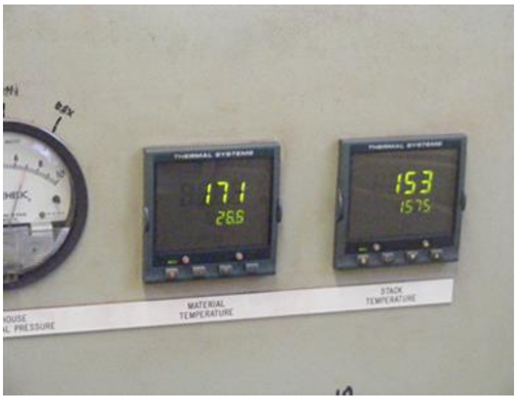


Figure 6.3 HMA production temperature

Figure 6.4 WMA production temperature

6.1.2 Pavement construction

Trial site No. 1 was located at Reservoir Street in Orange Grove. This section has a medium volume of traffic with more than 40% of heavy vehicles. An aerial view of the site is presented in Figure 6.5**,** while Figure 6.6 and Figure 6.7 show aerial views of the WMA section and HMA control section sites.

Figure 6.5 Trial 1 (site aerial view)

Figure 6.6 WMA control section

Figure 6.7 HMA control section

The condition of the surface, prior to the asphalt mix placements, showed distress and exhibited severe alligator and longitudinal cracking. Photos of the site before treatment are shown in Figure 6.8 and 6.9.

Figure 6.8 Alligator cracking

Figure 6.9 Longitudinal cracking

The 404 tonnes produced were placed in one lift with a compacted thickness of 40 mm in an area of 4,200 m^2 of which 2,100 m^2 was HMA and the other 2,100 m^2 was WMA. A conventional paver, a 9-tonne vibratory breakdown roller, a 12-tonne pneumatic tired roller, and a 7-tonne static steel finish roller were used to construct the pavement. Figure 6.10 shows the paver during placement.

Figure 6.10 Paver operations

Trial site No. 2 was located at Anaconda Street in Huntingdale. This section has a medium volume of local traffic with a low heavy vehicle volume. An aerial view of the site is presented in Figure 6.11**,** while Figure 6.12 and Figure 6.13 show the HMA section and WMA section respectively.

Figure 6.11 Trial 2 (site aerial view)

Figure 6.12 WMA control section

Figure 6.13 HMA control section

The 620 tonnes were placed in one lift as a wearing course, with a compacted thickness of 30 mm, in an area of 5,661 m^2, of which 2,295 m^2 was HMA and 3,366 m^2 was WMA. A conventional paver, a 9-tonne vibratory breakdown roller, a 12-tonne pneumatic tired roller, and a 7-tonne static steel finish roller were used to construct the pavement. Figure 6.14 shows paver loading, and Figure 6.15 shows WMA compaction.

Figure 6.14 Paver loading

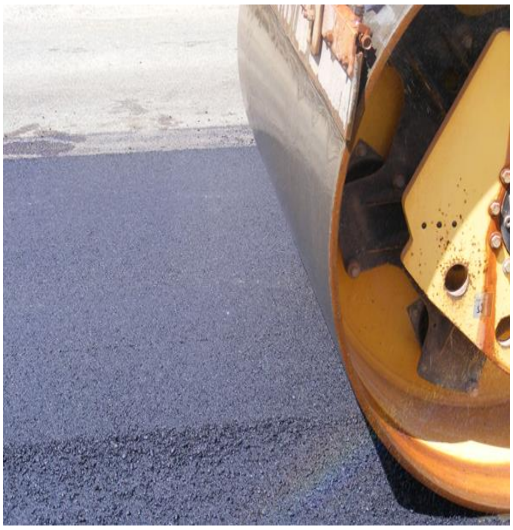


Figure 6.15 Compaction roller

Trial site No. 3 was located at Mills Road West in Gosnells. This section has a high volume of traffic with a 20% of heavy vehicles. An aerial view of the WMA site is presented in Figure 6.16.

Figure 6.16 WMA site (4% Sasobit)

The condition of the surface prior to the asphalt mix placing showed distress, particularly cracking which is evidence of possible issues with the base course. Photos of the site before treatment are shown in Figure 6.17 and Figure 6.18

Figure 6.17 Longitudinal cracking

Figure 6.18 Distressed surface

The 400 tonnes of WMA were placed in one lift as a wearing course, with a compacted thickness of 40 mm, in an area of 3,212 m^2. A conventional paver, a 9-tonne vibratory breakdown roller, a 12-tonne pneumatic tired roller, and a 7-tonne static steel finish roller were used to construct the pavement. Figure 6.19 shows compaction operation, and Figure 6.20 shows the paver during placement.

Figure 6.19 Roller in action

Figure 6.20 Paving operations

6.1.3 Temperature monitoring of HMA and WMA mixes

The temperatures for both the HMA and the WMA were continuously monitored during construction, using a digital thermometer with a probe. Figure 6.21 and Figure 6.22 show mix temperatures in the truck of WMA and

HMA mixes respectively. Figure 6.23 and Figure 6.24 show mix temperatures of the compacted surface of HMA and WMA mixes respectively.

Figure 6.21 WMA temperature in the truck

Figure 6.22 HMA temperature in the truck

Figure 6.23 WMA surface temperature

Figure 6.24 HMA surface temperature

6.1.4 Gas consumption WMA/HMA

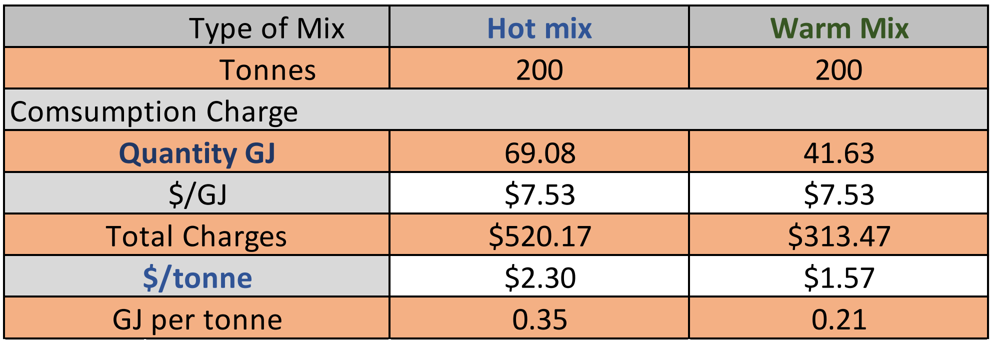
The reduction in fuel consumption and energy used in asphalt plants and at paving because of the reduced production temperatures in comparison to HMA are important benefits in asphalt production. Plus, there is the additional benefit of reducing the need of non-renewable energy sources.

6.1.5 WMA energy use

Sustainability is dependent on and varies according to the WMA technology chosen. In Western Australia, there are two WMA technologies available: Sasobit (organic additive) used for this study, and the Double Barrel Green foaming process developed by Astec.

In 2012, the Infrastructure Sustainability Council of Australia (ISCA) presented the ISCA rating scheme which is a rating scheme for sustainability performance to evaluate planning, design, construction and operation of infrastructure assets. For this study, gas calculations were performed considering the production of WMA and to assess the possible reduction in gas consumption of WMA compared to the conventional HMA.

Table 6.1 presents the gas production consumption per tonne which indicates that to produce the same amount of asphalt – 200 tonnes – WMA requires only 41.630 GJ in comparison to HMA that required 69.080 GJ. Therefore, the difference in cost of producing WMA is a reduction of $1.03 per tonne.



Type of Mix	**Hot mix**	**Warm Mix**
Tonnes	200	200
Comsumption Charge		
Quantity GJ	69.08	41.63
$/GJ	$7.53	$7.53
Total Charges	$520.17	$313.47
$/tonne	$2.30	$1.57
GJ per tonne	0.35	0.21

Table 6.1 Gas consumption HMA/WMA

Figure 6.25 presents the gas usage for the production of HMA and WMA which clearly indicates a lower gas consumption to produce WMA mainly due to the fact that it has a lower production temperature (30 ºC lower).

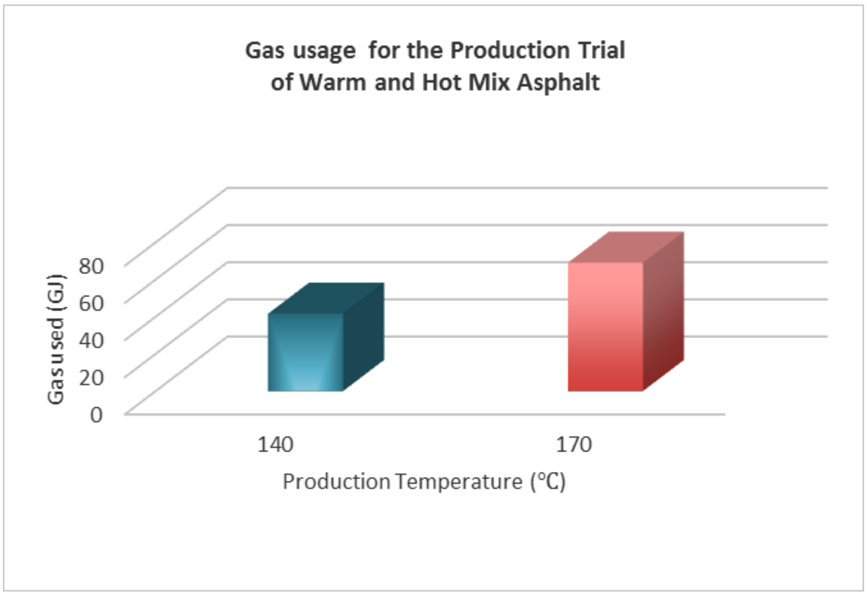


Figure 6.25 Gas used for WMA/HMA

It needs to be noted that the additional cost of the WMA technologies - considered a drawback - could offset the savings in the reduction in gas consumption as cost increases depending on the price of the additive/materials and the investment in plant equipment modification or installation costs.

The production cost per tonne including the additive Sasobit is presented in Table 6.2 and Table 6.3 presents the production cost without Sasobit. These indicate that that to produce WMA with Sasobit is $ 3.80 per tonne more expensive than production without.

	Mix Type	Bitumen %	10mm %	7mm %	5mm %	Dust %	Sasobit %	Lime %	TOTAL
	AC 10mm	5.6	18.7	14.2	18.9	41.2	0.084	1.4	100
TONS	1	0.056	0.187	0.142	0.189	0.412	0.00084	0.014	1
COST	PER TON	$765.0	$24.8	$25.8	$24.8	$8.9	$4,500.0	$380.0	
COST	INPUT	$42.8	$4.6	$3.7	$4.7	$3.7	$3.8	$5.3	**$68.6**

Table 6.2 Cost production of WMA with Sasobit (1.5%)

	Mix Type	Bitumen %	10mm %	7mm %	5mm %	Dust %	Sasobit %	Lime %	TOTAL
	AC 10mm	5.6	18.7	14.2	18.9	41.2	0	1.4	100
TONS	1	0.056	0.187	0.142	0.189	0.412	0	0.014	1
COST	PER TON	$765.0	$24.8	$25.8	$24.8	$8.9	$4,500.0	$380.0	
COST	INPUT	$42.8	$4.6	$3.7	$4.7	$3.7	$0.0	$5.3	**$64.8**

Table 6.3 Cost production of HMA

It is important to mention that some of the WMA additives are a by-product of other production processes, for example the wax used to produce Sasobit which is a by-product of Fisher-Tropsch process. The wax could become waste material if not used in the road construction industry. Therefore, the use of this product reduces waste material and pollution from the production of other WMA additives making an indirect contribution to the environment.

Another alternative to produce WMA is the use of Reclaimed Asphalt Pavement (RAP), with the benefit to the environment as it can reduce GHG emissions as less fuel is required, as well as, preserving other resources.

6.2 Testing data analysis and results (trial site No. 1)

At trial site No. 1, two samples were taken from the plant production of the HMA and WMA mixes, to test the volumetric properties and quality control. The test asphalt report for HMA and WMA are presented in Appendix F.
Table 6.4 show material grading results.

		Mix	AC14/75 Warm Mix	AC14/75 Warm Mix	AC14/75 Hot Mix	AC14/75 Hot Mix
		Date	11/12/2011	11/12/2011	11/12/2011	11/12/2011
		Report No	875	876	877	878
Particle Size Distribution MRWA 210.1	AS Sieve (mm)	Specifications				
	26.5					
	19	**100**	100.0	100	100	100
	13.20	**91 - 100**	97.5	97.0	97.5	96.8
	9.5	**72 - 86**	79.5	79.2	79.5	80.3
	6.7	**59 - 73**	66.0	67.4	66.0	65.4
	4.75	**48 - 62**	56.2	54.3	56.2	55.4
	2.36	**34 - 44**	40.2	38.5	40.2	39.8
	1.18	**26 - 36**	31.1	30.28	31.08	31.12
	0.600	**20 - 28**	23.1	22.88	23.15	22.66
	0.300	**13 - 21**	16.4	16.27	16.41	15.86
	0.150	**9 - 14**	10.5	10.48	10.50	9.55
	0.075	**4 - 7**	5.4	5.65	5.43	4.94

Table 6.4 Grading results of WMA and HMA (trial site 1)

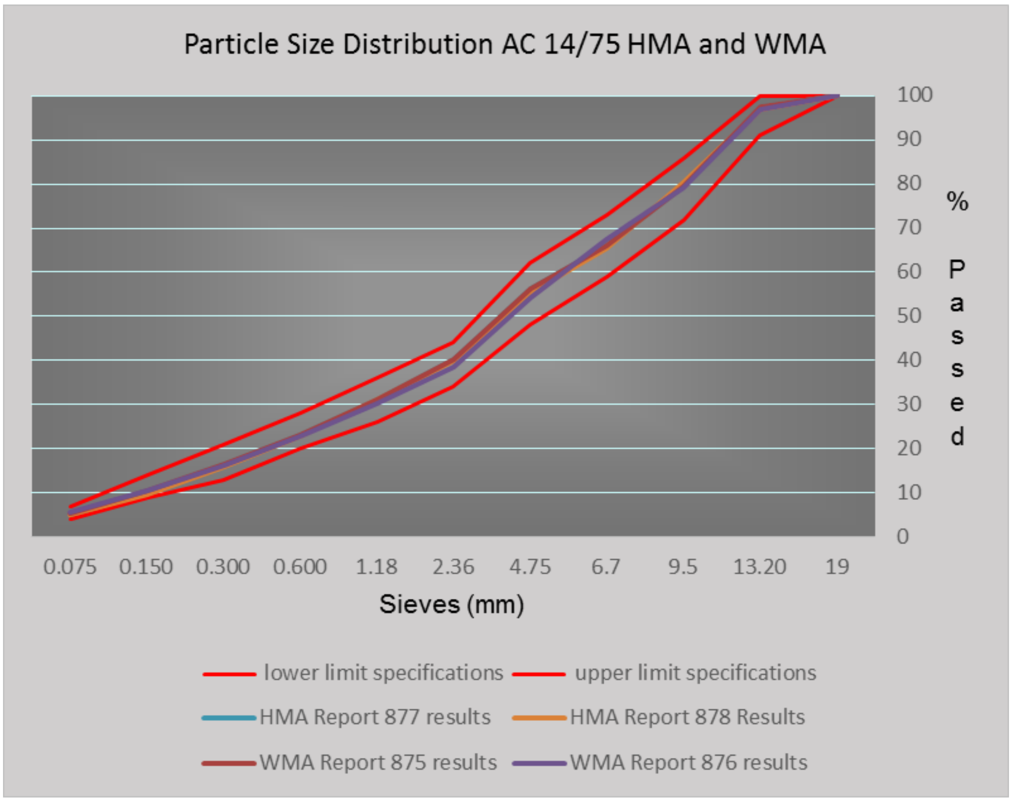


Figure 6.26 PSD for HMA and WMA (trial 1)

Table 6.4 and Figure 6.26 indicate that, in order to achieve optimum quality control, all the materials used in this research were rigorously tested and kept in different stock piles to avoid segregation and to keep consistency. The results show that both mixes – the HMA and the WMA – met all the specifications with no significant differences observed.

6.2.1 Binder content and volumetric properties

The binder content and volumetric properties data was compiled from the results of the quality control tests performed on the mix sample at the plant. Results are shown in Table 6.5**.**

Method	Test	Spec	WMA	WMA	HMA	HMA
MRWA 730.1	Bitumen Content (%)	**4.4 - 5.0**	4.8	4.7	4.8	4.6
MRWA 732.2	Rice Density (t/m^3)		2.471	2.475	2.477	2.485
MRWA 733.1	Bulk Density (t/m^3)		2.339	2.333	2.345	2.335
MRWA 733.1	Air Voids (%)	**4.0 - 6.0**	5.3	5.7	5.8	6.0
MRWA 731.1	Marshall Flow (mm)	**2.0 - 4.0**	3.00	3.25	2.00	3.00
MRWA 731.1	Marshall Stability (kN)	**>8.0**	16.5	18.9	16.5	16.5
MRWA 733.1	V.M.A. (%)		16.0	16.4	16.6	16.9
MRWA 733.1	V.F.B. (%)		66.5	65.0	65.3	64.3

Table 6.5 Binder content and volumetric properties test results (trial 1)

All test results show that both HMA and WMA mixes were within the specification tolerances, and no discernible differences were observed. Even though some mixes showed higher air voids, the specifications were still met. The laboratory production samples confirm that the plant production of both mixes is similar.

Table 6.6 through to Table 6.13 present the average results of the four mixes, which show a minimum standard deviation with a slight difference in values. This demonstrates that WMA can obtain volumetric property values similar to the HMA mix, and meet all the specifications.

Bitumen Content (%)					
N° of tests	Average	**4.7**	Min	4.6	Difference
4	Standard Dev	0.09	Max	4.8	0.2

Table 6.6 Binder content (trial 1)

Maximum Density (t/m3)					
N° of tests	Average	**2.477**	Min	2.471	Difference
4	Standard Dev	0.006	Max	2.485	0.014

Table 6.7 Maximum density (trial 1)

Bulk Density (t/m3)					
N° of tests	Average	**2.338**	Min	2.333	Difference
4	Standard Dev	0.005	Max	2.345	0.012

Table 6.8 Bulk density (trial 1)

Air Voids (%)					
N° of tests	Average	**5.7**	Min	5.3	Difference
4	Standard Dev	0.3	Max	6.0	1.3

Table 6.9 Air voids average (trial 1)

Marshall Flow (mm)					
N° of tests	Average	**2.81**	Min	16.5	Difference
4	Standard Dev	1.2	Max	18.9	2.4

Table 6.10 Marshall Flow (trial 1)

Marshall Stability (KN)					
N° of tests	Average	**17.1**	Min	16.5	Difference
4	Standard Dev	1.2	Max	18.9	2.4

Table 6.11 Marshall Stability (trial 1)

VMA (%)					
N° of tests	Average	**16.5**	Min	16.0	Difference
4	Standard Dev	0.4	Max	16.9	0.9

Table 6.12 Voids in mineral aggregate (trial 1)

VFB (%)					
N° of tests	Average	**65.3**	Min	64.3	Difference
4	Standard Dev	0.9	Max	66.5	2.2

Table 6.13 Voids filled with bitumen (trial 1)

6.2.2 Compaction results

6.2.2.1 Air voids of field cores

Twenty-four field cores (twelve HMA and twelve WMA) of the completed asphalt layer were taken at random locations, as seen in. Figure 6.28 shows the extracted core; all were sampled according to Main Roads methods. Compaction test reports from trial 1 are presented in Appendix G.

Figure 6.29 shows the in-situ air void values of the field cores of HMA and WMA.

Figure 6.27 Extraction of cores

Figure 6.28 WMA core

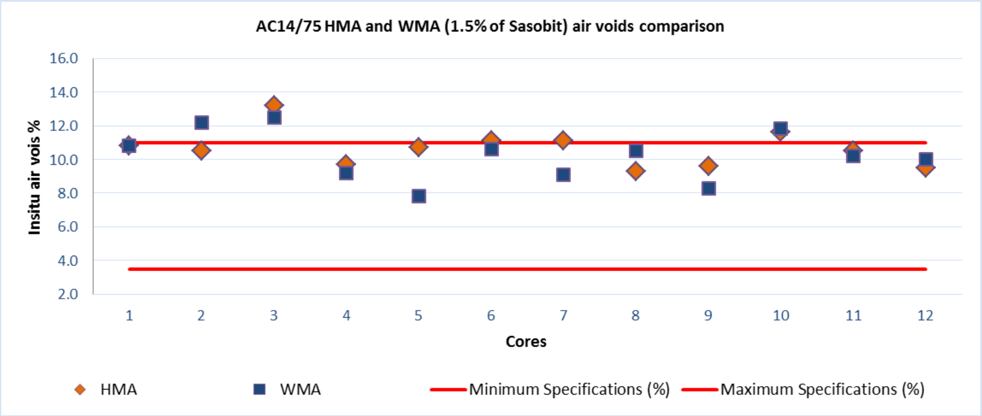


Figure 6.29 In-situ air voids comparison between HMA and WMA (trial 1)

The air void average for HMA was 10.6% and for WMA 10.3%. This verifies that in-situ field compaction was achieved. The results show that the air voids were close to the maximum specification of 11%, even considering that some single cores were out of the specification for both mixes; this was probably due to the distress present on the working surface prior to the asphalt placement. Both mixes require a suitable working surface to obtain durable and long-term wearing course asphalt.

6.3 Testing data analysis and results (trial site No. 2)

At trial site No. 2, two samples were taken from the plant production of the HMA and WMA mixes, to test the volumetric properties and quality control. The asphalt reports are presented in Appendix H. Table 6.14 shows material grading results.

	Mix	AC10/50 WMA	AC10/50 WMA	AC10/50 HMA	AC10/50 HMA
	Date	17/01/2012	17/01/2012	18/01/2012	18/01/2012
	Report No	73	75	74	76
AS Sieve (mm)	Specifications				
26.5					
19		100.0	100	100	100
13.20	**100**	100.0	100	100	100
9.5	**90 - 100**	97.2	95.7	97.5	97.3
6.7	**73 - 87**	78.7	76.1	77.0	78.0
4.75	**57 - 71**	64.7	64.6	61.4	62.1
2.36	**40 - 50**	44.3	46.7	47.9	48.8
1.18	**30 - 40**	35.03	36.47	37.63	36.19
0.600	**23 - 31**	26.16	26.10	26.46	25.41
0.300	**15- 23**	18.72	17.73	17.40	17.03
0.150	**10-15**	11.30	10.81	10.69	10.61
0.075	**3-6**	5.71	5.68	4.82	5.05

Table 6.14 Grading results of WMA and HMA (trial site 2)

Figure 6.30 indicates that, to achieve optimum quality control, all the materials used in this research were rigorously tested and kept in different stock piles to avoid segregation and to keep consistency. The results show that both mixes – the HMA and the WMA – met all the specifications with no significant differences observed.

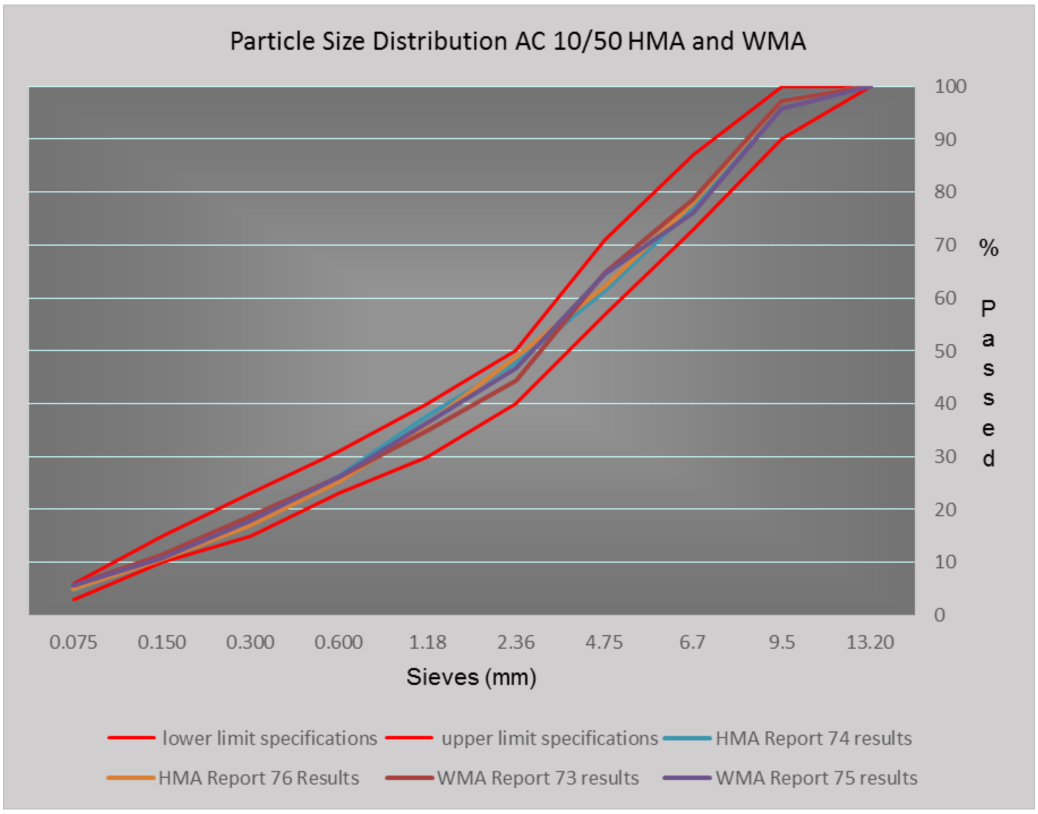


Figure 6.30 PSD for HMA and WMA (trial 2)

6.3.1 Binder content and volumetric properties

The binder content and volumetric properties data was compiled from the results of the quality control tests performed on the mix sample at the plant. Results are shown in Table 6.15.

Method	Test	**Spec**	AC10/50 WMA	AC10/50 WMA	AC10/50 HMA	AC10/50 HMA
MRWA 730.1	Bitumen Content (%)	**5.3-5.9**	5.6	5.4	5.5	5.7
MRWA 732.2	Rice Density (t/m^3)		2.455	2.467	2.456	2.454
MRWA 733.1	Bulk Density (t/m^3)		2.317	2.319	2.321	2.324
MRWA 733.1	Air Voids (%)	**4.0-6.0**	5.6	6.0	5.5	5.3
MRWA 731.1	Marshall Flow (mm)	**2.0-4.0**	2.75	2.50	3.00	2.25
MRWA 731.1	Marshall Stability (kN)	**>6.5**	11.2	12.8	11.0	12.3
MRWA 733.1	V.M.A. (%)	**>15**	18.3	18.2	18.0	18.5
MRWA 733.1	V.F.B. (%)		69.3	67.0	69.4	71.4

Table 6.15 Binder content and volumetric properties test results (trial 2)

All test results show that both HMA and WMA mixes were within the specifications tolerances, and no discernible differences were observed. The laboratory production samples confirm that plant production of both mixes is similar.

Table 6.16 through to Table 6.23 present the average results of four mixes. The results indicate a minimum standard deviation with a slight difference in values. This demonstrates that WMA can obtain volumetric results similar to the HMA mix, and meet all the specifications.

Bitumen Content (%)					
N° of tests	Average	**5.6**	Min	5.4	Difference
4	Standard Dev	0.13	Max	5.7	0.3

Table 6.16 Bitumen content (trial 2)

Maximum Density (t/m3)					
N° of tests	Average	**2.458**	Min	2.454	Difference
4	Standard Dev	0.006	Max	2.467	0.012

Table 6.17 Maximum density (trial 2)

Bulk Density (t/m3)					
N° of tests	Average	**2.320**	Min	2.317	Difference
4	Standard Dev	0.003	Max	2.324	0.007

Table 6.18 Bulk density (trial 2)

Air Voids (%)					
N° of tests	Average	**5.6**	Min	5.3	Difference
4	Standard Dev	0.3	Max	6.0	0.7

Table 6.19 In-situ air voids (trial 2)

Marshall Flow (mm)					
N° of tests	Average	**2.63**	Min	2.3	Difference
4	Standard Dev	0.32	Max	3.0	0.8

Table 6.20 Marshall Flow (trail 2)

Marshall Stability (kN)					
N° of tests	Average	**11.85**	Min	11.0	Difference
4	Standard Dev	0.9	Max	12.8	1.8

Table 6.21 Marshall Stability (trail 2)

VMA (%)					
N° of tests	Average	**18.2**	Min	18.0	Difference
4	Standard Dev	0.2	Max	18.5	0.6

Table 6.22 Voids in mineral aggregate (trial 2)

VFB (%)					
N° of tests	Average	**69.3**	Min	67.0	Difference
4	Standard Dev	1.8	Max	71.4	4.5

Table 6.23 Voids filled with bitumen (trial 2)

6.3.2 Compaction results

6.3.2.1 Air voids of field cores

Twenty four field cores (twelve HMA and twelve WMA) of the completed asphalt layer were taken at random locations and were sampled according to MRWA methods. Compaction test reports are presented in Appendix I. Figure 6.31 shows the in-situ air voids values of the field cores of HMA and WMA.

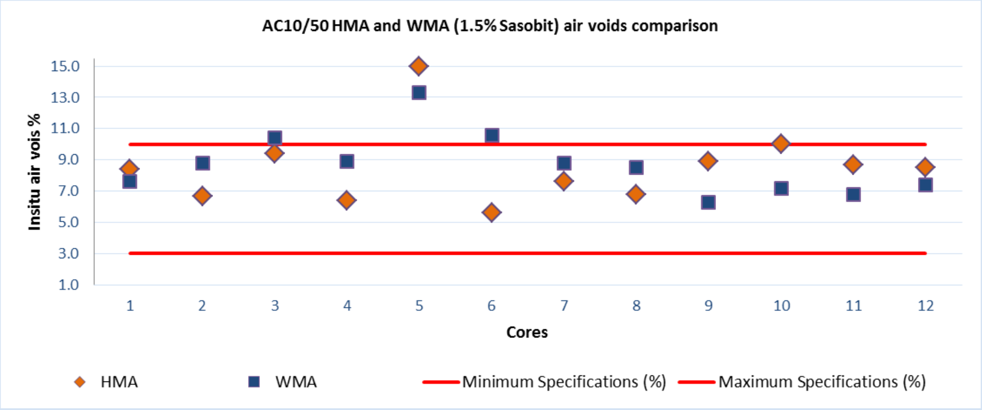


Figure 6.31 In-situ air voids comparison between HMA and WMA (trial 2)

The air void average for HMA was 8.1% (slightly better), and 8.7% for WMA. This verifies that in-situ field compaction was achieved. Even considering the high air voids, the average result met the specifications in both mixes.

6.4 Testing data analysis and results (trial site No. 3)

Two samples were taken from the plant production of the WMA mixes for trial site No 3, to test the volumetric properties, performance and quality control. The asphalt test reports for WMA with 4% of Sasobit are presented in Appendix J. Table 6.24 show materials grading results.

		Mix	AC10/50 WMA 4% Sasobit	AC10/50 WMA 4% Sasobit
		Date	16/01/2014	16/01/2014
		Report No	31	32
Particle Size Distribution MRWA 210.1	AS Sieve (mm)	Specifications		
	26.5		100.0	100
	19		100.0	100
	13.20	**100**	100.0	100
	9.5	**90 - 100**	97.5	96.2
	6.7	**73 - 87**	79.8	77.1
	4.75	**57 - 71**	65.9	64.7
	2.36	**40 - 50**	44.2	43.3
	1.18	**30 - 40**	33.91	32.57
	0.600	**23 - 31**	25.82	24.73
	0.300	**15- 23**	18.16	17.31
	0.150	**10-15**	11.43	10.94
	0.075	**3-6**	5.33	5.26

Table 6.24 Grading results of WMA with 4% Sasobit (trial site 3)

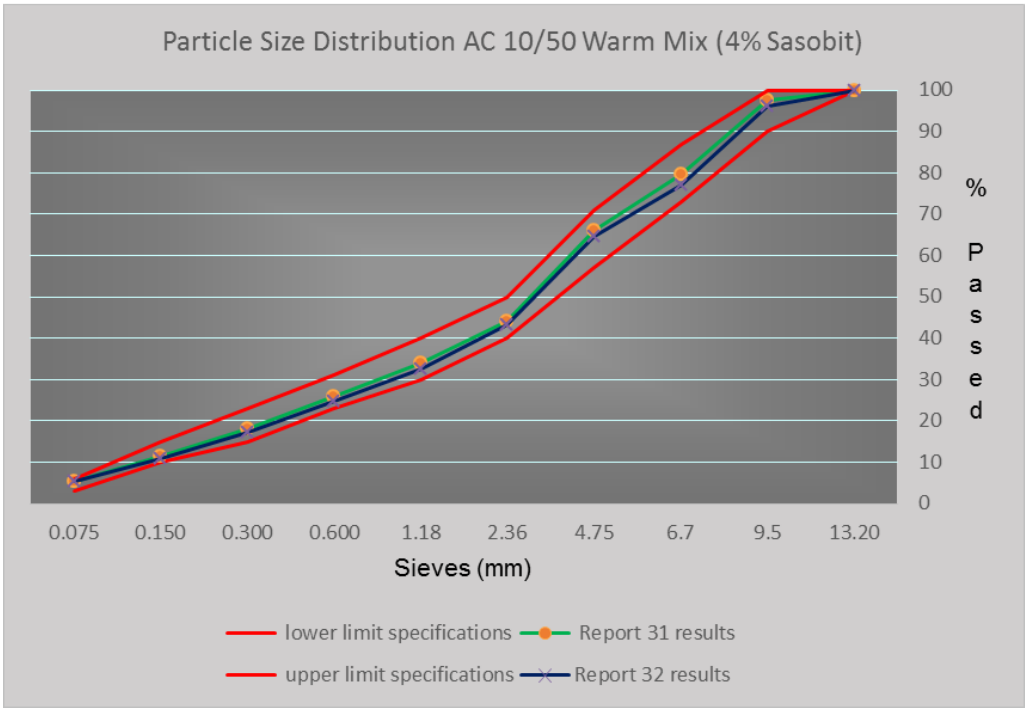


Figure 6.32 PSD average results of WMA (4% Sasobit)

Figure 6.32 indicates that the WMA mixes met all the grading specifications. It needs to be noted that for the three trials the same stockpile of aggregates was used to avoid differences in the material densities.

6.4.1 Binder content and volumetric properties

The binder content and volumetric property data was compiled from the results of the quality control tests performed on the mix sample at the plant. Results are shown in Table 6.25. All test results show that the WMA mixes were within the specification tolerances, showing the consistency of the material.

Method	Test	**Spec**	WMA 4% Sasobit	WMA 4% Sasobit
MRWA 730.1	Bitumen Content (%)	**5.3 - 5.9**	5.5	5.4
MRWA 732.2	Rice Density (t/m^3)		2.455	2.467
MRWA 733.1	Bulk Density (t/m^3)		2.323	2.325
MRWA 733.1	Air Voids (%)	**4.0 - 6.0**	5.4	5.7
MRWA 731.1	Marshall Flow (mm)	**2.0 - 4.0**	3.00	3.00
MRWA 731.1	Marshall Stability (kN)	**>6.5**	13.1	14.2
MRWA 733.1	V.M.A. (%)	**>15**	17.8	17.8
MRWA 733.1	V.F.B. (%)		69.8	67.8

Table 6.25 Binder content and volumetric properties test results (trial 3)

The WMA with 4% Sasobit was expected to provide low air voids, following the laboratory tendency results of 4.6% (3% Sasobit) and 4.3% (6% Sasobit). WMA with 4% Sasobit only showed slightly lower air voids in comparison to the hot mix. Thus, trials are important to validate the results of the production mix plant; they may not represent the volumetric values obtained from the laboratory results.

6.4.2 Compaction results

6.4.2.1 Air voids of field cores

Twelve field cores of WMA of the completed asphalt layer were taken at random locations according to MRWA methods. The reports are presented in Appendix K.

Figure 6.33 shows sample cores and Figure 6.34 shows core thickness. Figure 5.94 shows the in-situ air void values of the field cores of WMA.

Figure 6.33 Sample cores

Figure 6.34 Core thickness

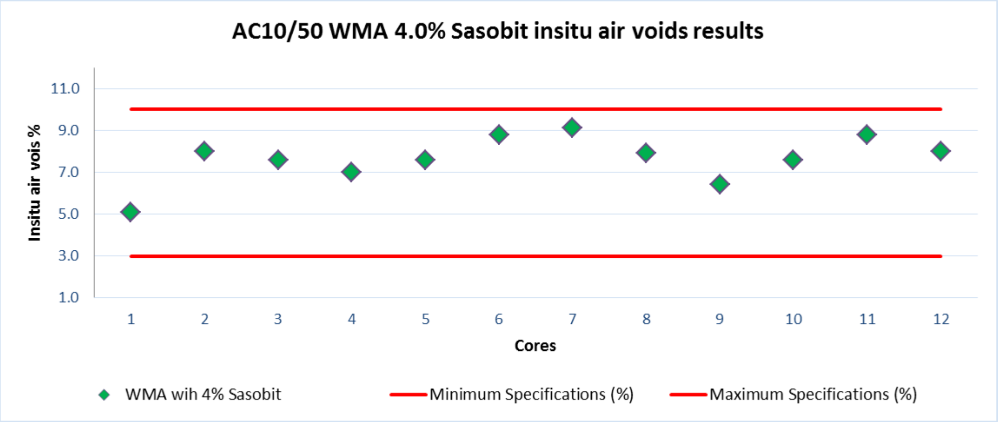


Figure 6.35 In-situ air voids results of WMA (4% Sasobit)

From Figure 6.35, it can be seen that the in-situ air voids met the specifications, with an average of 7.6%. The effect can be clearly observed of the 4% Sasobit in the mix, reflected in the consistency of the air void content. Even considering the condition of the working surface showed signs of distress prior to placement and that compaction was performed only with a static roller due to vibration restrictions (gas pipes in the area).

6.5 Performance tests

In addition to the volumetric testing performed for trial site No. 3, four performance tests (Indirect Tensile Strength, moisture sensitivity, wheel tracking, and fatigue) were conducted using plant production mix samples.
All the test results from the sample production are presented in Appendix L.

6.5.1 Indirect Tensile Strength

Indirect tensile strength testing was performed according to AS 2891.13.1-1995 (see section 4.8.1 for method procedure) for which four specimens were produced. The results of the testing are presented in Figure 6.36.

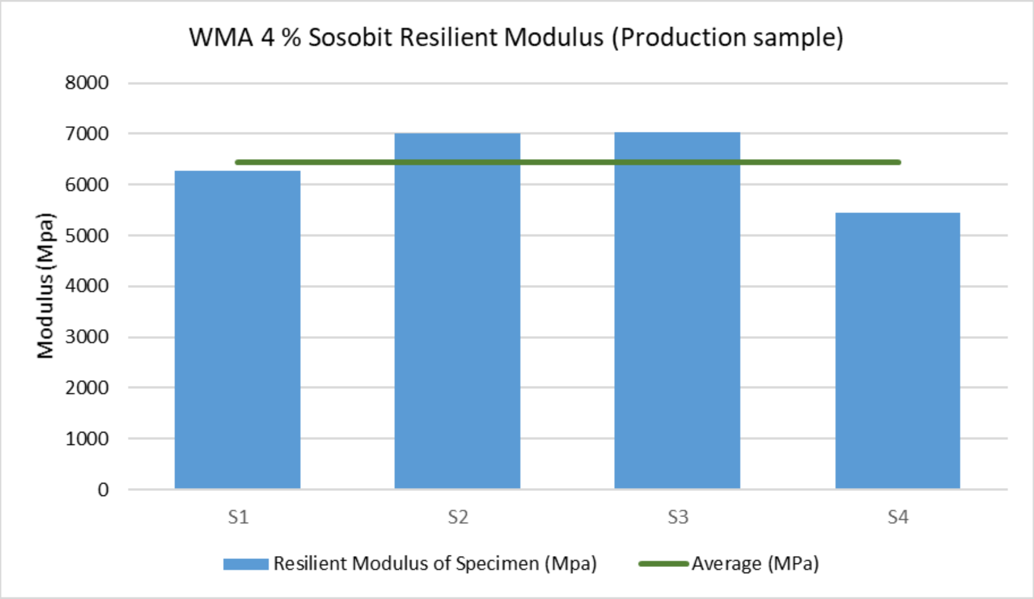


Figure 6.36 Indirect tensile strength testing results

The resilient modulus average was 6,200 MPa which indicates a high modulus for the AC 10 mm density, which is higher than the typical value of 4,500 MPa, according to Austroads, 2012. This result proves that the addition of 4% Sasobit produces a stiff mix.

6.5.2 Moisture Sensitivity

Moisture sensitivity testing of the plant production mix was performed in the laboratory according to AGPT/T232 where the conditioning and strength testing was carried out later on. Six specimens were produced for testing and the results are presented in Table 6.26 including the freeze/thaw cycle.

Test method used	Results	Results	Results	Average Results
AGPT/T232				
Dry set air voids (%)	8.1	7.7	8.3	8.0
(T1, T2 T3)				
Dry tensile strength at 25 °C (kPa)	1035	1025	1001	1020
(T1, T2 T3)				
Wet set air voids (%)	7.8	8.4	8	8.1
(T4, T5, T6)				
Wet tensile strength at 25 °C (kPa)	900	858	920	893
(T4, T5, T6)				
Tensile Strength ratio (%)	87.5			

Table 6.26 Test results of moisture sensitivity

Figure 6.37 and Figure 6.38 show results of dry and wet tensile strength and Figure 6.39 presents the dry and wet average tensile strength and TSR results. The results indicate that the tensile strength ratio was 87.5%. WMA mixes exceeded the minimum Tensile Strength Ratio (TSR) requirement of 80%, which is indicative that the moisture sensitivity was not a concern for the mixes. This proves that even the plant-produced mixes at lower temperatures can achieve the requirements of TSR. It needs to be noted that an increase in the percentage of Sasobit does not improve the TSR value in comparison to HMA.

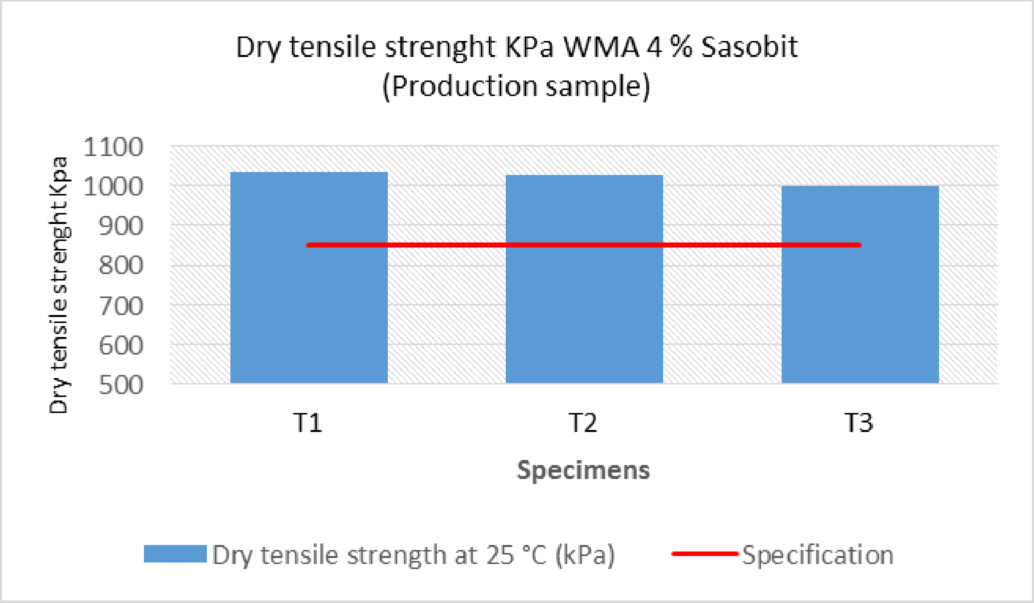


Figure 6.37 Dry tensile strength results

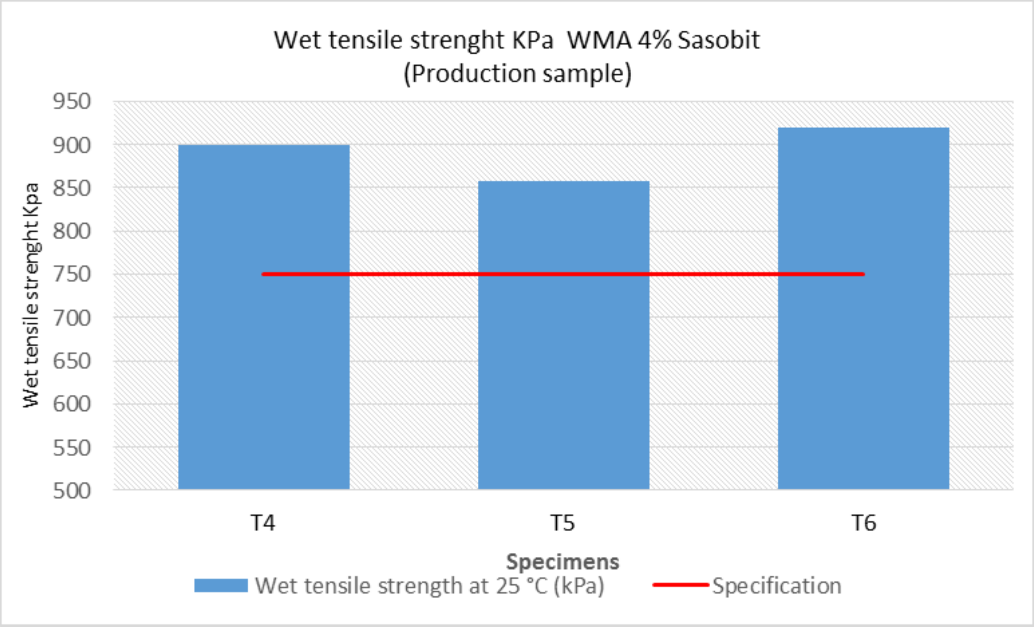


Figure 6.38 Wet tensile strength results

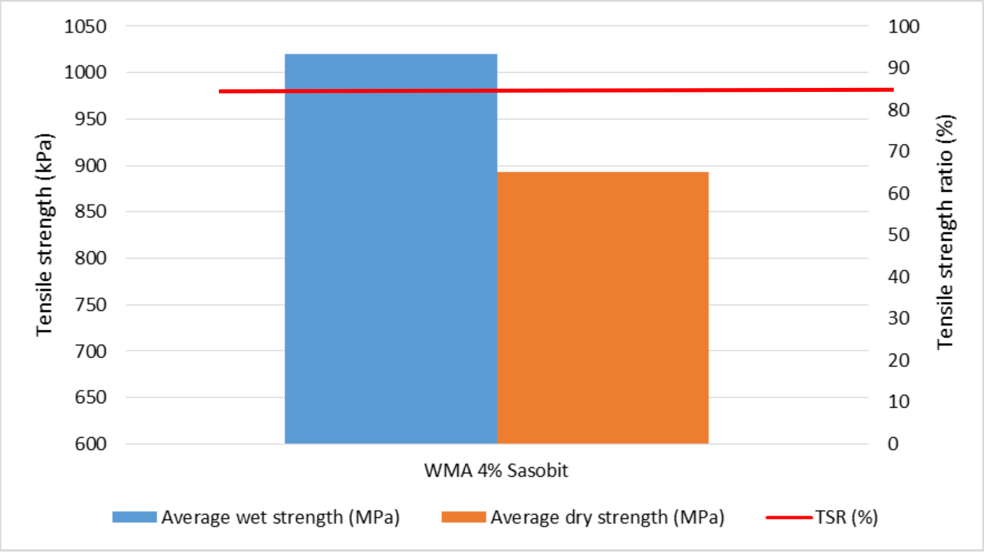


Figure 6.39 Tensile strength result

6.5.3 Wheel tracking

Slabs of the plant production mixes were constructed according with method AGPT/T220 (see section 5.8.3 for method procedure). All the slabs comply with the target air void of 5.0 ± 1.0% and the results are presented in Figure 6.40.

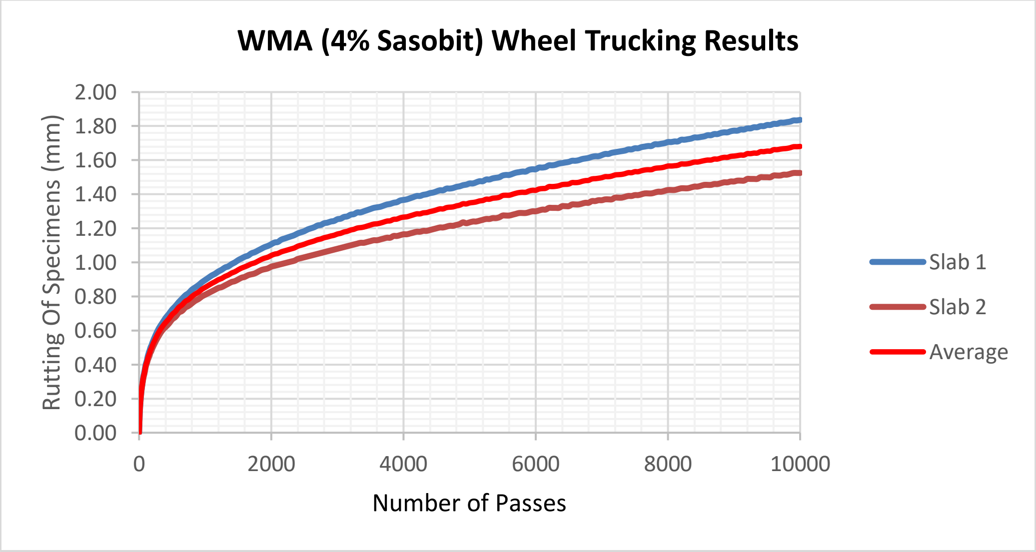


Figure 6.40 Wheel tracking testing average results at 60° C

From Figure 6.40 it can be observed that the tracking average depth of the mixes was 1.6 mm, indicating that the mix with 4% of Sasobit has a high rutting resistance, therefore less deformation of the mix. This type of mix is suitable for heavy traffic roads.

6.5.4 Fatigue

Nine beams for fatigue testing were produced from the plant production mixes, as seen in Figure 6.41 and performed according to method AGPT/T233 (see section 5.8.4 for method procedure). The nine beams were produced for a more extensive fatigue characterisation which requires testing triplicate beams. Figure 6.42 presents the nine beam results and Figure 6.43 presents the average flexural stiffness results.

The average value of the initial flexural stiffness is 6932 MPa (as seen in Table 6.27) and for the fatigue resistance (cycle count) is 208089 cycles. The strain level required to fail the beam was 400 µƐ.

Mix	Beam Nº	Initial Flexural Stiffness (MPa)	Termination Stiffness (50% of the initial Stiffness (MPa)	Strain (Peak to Peakt)µƐ	Phase Angle (deg)	Cycle count of 1000000
WMA Sasobit (4.0%)	1	6177	3088	399	27.3	208730
WMA Sasobit (4.0%)	2	6824	3412	400	26.4	216700
WMA Sasobit (4.0%)	3	6746	3373	400	27.3	143450
WMA Sasobit (4.0%)	4	7491	3745	399	24.7	257890
WMA Sasobit (4.0%)	5	8051	4025	400	25.8	256210
WMA Sasobit	6	8090	4045	399	26.7	261510

(4.0%)						
WMA Sasobit (4.0%)	7	6495	3247	399	28.6	100260
WMA Sasobit (4.0%)	8	6469	3235	401	27.0	192470
WMA Sasobit (4.0%)	9	6044	3022	399	27.0	235584
Average		6932	3466	400	27	208089

Table 6.27 Flexural stiffness - fatigue resistant test results

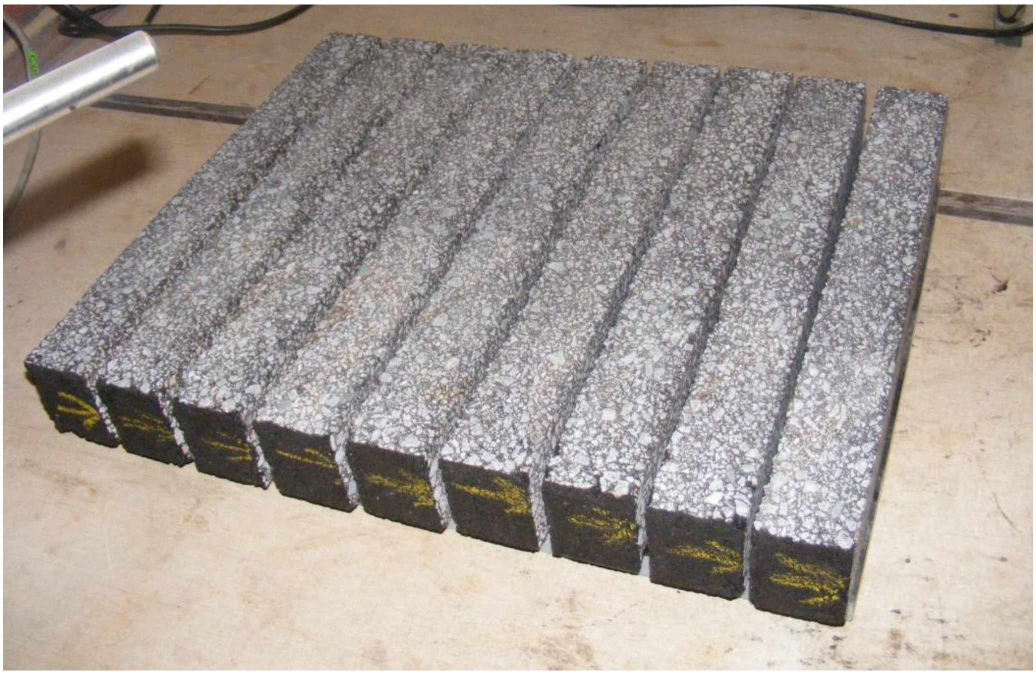


Figure 6.41 Nine beams for fatigue testing

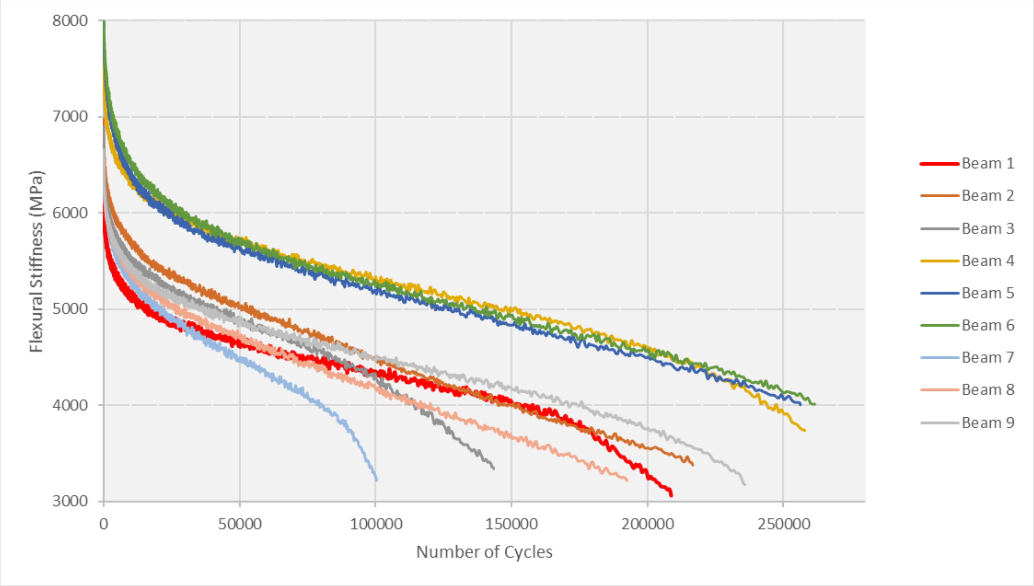


Figure 6.42 Flexural stiffness testing results at 20ºC

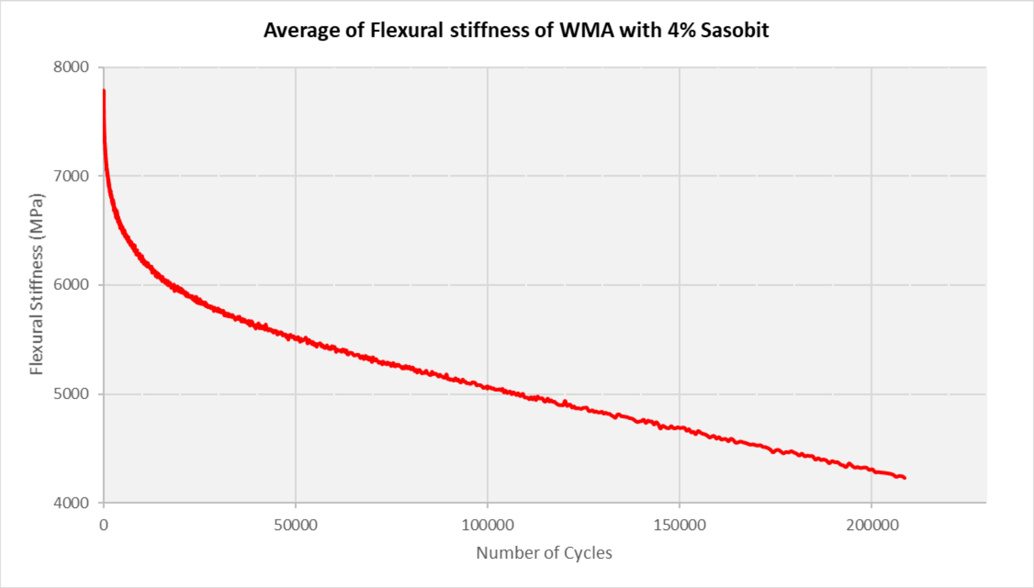


Figure 6.43 Average Flexural stiffness results at 20ºC

The results indicate that in the WMA, the effect of 4% Sasobit on fatigue life is minor compare to HMA. However, the effect on Flexural Stiffness increased. The test result verifies that the WMA with 4% Sasobit enhanced the stiffness.

It needs to be noted that Fatigue testing was performed with the purpose of comparison between HMA and WMA. For structural pavement design with Sasobit, it is necessary to perform extensive testing at different strain levels and temperatures. Therefore, more beams are required.

6.6 Summary of laboratory testing

A summary of the laboratory testing performed on the plant production mixes for the HMA and the WMA field validation sites is presented as follows:

- All binder content and aggregate grading of both the HMA and the WMA complied with all the specifications.
- Volumetric properties were within the target air void range, with similar values for both the HMA and the WMA and no discernible differences between the mixes.
- Marshall Stability and flow results were satisfactory and within the specifications.
- Values of WMA mixes (with 4% of Sasobit) for the indirect tensile modulus were high in comparison to standard hot mixes.
- Moisture sensitivity values of the WMA achieved the specifications.
- Wheel tracking testing results showed low average depth.
- Fatigue results are indicative of a high-fatigue resistance.

6.7 In service performance

Several site visits were made from 2011 to 2017, and both the HMA and the WMA appeared to be performing well after so many years as no signs of distress such as:

- Deformation: rutting, shoving, depression and corrugations.
- Surface texture: flushing, ravelling. Stripping, delamination and polishing.

However, WMA showed a smaller amount of distress in comparison to HMA, after being exposed to the same elements throughout the years.

Trial site No 1:

The following general observations can be made on the performance of both mixtures.

- In the first year, there were no signs of any form of deterioration on both mixes.
- Within the next couple of years, some slight surface distress was observed on both the HMA and WMA. Cracking appeared in both mixes, as seen in Figure 6.44 and Figure 6.45 for HMA and WMA correspondingly.

Figure 6.44 HMA surface 2014

Figure 6.45 WMA surface 2014

- It was observed that, from the period of 2016 to 2017, some sections of HMA had visible cracks which were not observed as severe on the WMA section, as shown in Figure 6.46 and Figure 6.47 respectively. See Appendix M 1 through to M 8 for chronological trial photos.

Figure 6.46 HMA section severe cracking

Figure 6.47 WMA cracked surface

Trial site No. 2:

- Both sections appeared to be performing well after the first couple of years. This is seen in Figure 6.48 for the WMA section, while the HMA section is shown in Figure 6.49
- Both sections showed minimum distress after four years in service, with more visible deformations on the HMA than the WMA. See Appendix M 9 through to M 16 for chronological trial photos.

Figure 6.48 WMA section after 2 years

Figure 6.49 HMA section after 2 years

Trial site No. 3:

- It was noticed that some cracking had appeared in the WMA with 4% Sasobit after the second winter, presented in Figure 6.50

Figure 6.50 WMA with some cracking

Figure 6.51 WMA surface after 5 years

- After five years in service, the WMA appeared to be in good condition (Figure 6.51) even though it was placed in a deteriorated working platform.

It can be concluded that both mixes have performed well; however, the WMA through the years showed no signs of water penetration after being exposed to the elements, with heavy rain in winter and high temperatures in summer. Despite this, it appears not to have been adversely affected in its performance. See Appendix M 17 through to M 28 for chronological trial photos. Further investigation throughout the years was not carried out. Site testing such as, rutting, field densities and the falling weight deflectometer (FWD) test, were not performed due to the cost involved.

7 Conclusions and Recommendations

The overall objective of this study was to test, evaluate and validate the production of WMA with organic additive Sasobit, in comparison to HMA, using local materials and equipment, under Western Australian conditions. The WMA results show a fluctuating performance of the mixes in numerous samples of dense-graded hot mix asphalt control, and with Sasobit at different percentages. The study presents the assessment of the extensive testing, performed both in-situ and in a laboratory, at various mixing and compaction temperatures. Testing was performed to determine the volumetric properties (bulk density, maximum density and air voids) and performance (resilient modulus, fatigue resistance, moisture sensitivity, stability and flow, rut resistance, and dynamic modulus) of the mixes.

In general terms, the results obtained showed that, by using the same aggregates and binder without altering the HMA mix design, WMA with Sasobit presented similar properties to the HMA mixes. Based on the tests results of this research, the following conclusions are drawn, in regard to:

Mix production

- Perform all modifications necessary to the asphalt plant to adapt the WMA technology used to obtain an optimal mix. The additional cost is dependent on the technology chosen.
- Adding the additive Sasobit in liquid form ensured a homogenous mix.
- Fuel (natural gas) consumption was reduced by 25% for the production of WMA with Sasobit, compared to the conventional hot mixes

Binder

- Sasobit significantly lowers the viscosity of the binder, possibly due to the fact that the wax dissolves in the binder as it re-crystallises at mid-range temperatures.
- Binder aging in WMA mixes is less in comparison to HMA, possibly due to lower short-term conditioning temperatures used in WMA.

Volumetric properties

- WMA with Sasobit maximum density showed no significant difference at different mixing temperatures in comparison to HMA.
- Bulk density showed no significant difference at the rate of 1.5% Sasobit in comparison to HMA. However, at the rate of 3% to 6% an increase in the bulk density is significant. Therefore, better workability was obtained.
- Air voids at a percentage of 1.5% showed no substantial difference to control HMA. It needs to be noted that, regardless of the lower temperature for the production of WMA, both met the specified air void target. For 3% and 6% Sasobit, the bulk density increased, therefore the air voids decreased making the WMA a stiffer mix.

Improved compaction was noticed at temperatures as low as 125 °C for the mixes produced with 3% Sasobit and above. However, the workability of the WMA is notably higher for mixes with 3% and above, compared to those of HMA.

Performance Testing

- WMA low temperatures at production did not affect the moisture sensitivity in comparison to HMA. It needs to be noted that an anti-stripping agent should be used because Sasobit is not an anti-stripping agent like other WMA technologies. The anti-stripping agent prevents the stripping of the mix.
- The resilient modulus of the control mix and the WMA with 1.5% were similar, and both results were under the typical values. WMA showed a clear higher resilient modulus with 3% Sasobit, and even higher with 6% Sasobit. Therefore, increasing the Sasobit amount in the bitumen results in an increased resilient modulus value.
- Rutting resistance measured by the wheel tracking test showed similar values for both mixes, the control and the WMA with 1.5% Sasobit, both achieving the specifications. The WMA with 3% Sasobit and 6% Sasobit showed minimal deformation. Therefore, the addition of Sasobit decreases the rutting potential of the asphalt mix.
- Fatigue values for the control HMA and WMA with 1.5% Sasobit showed similar results: the typical values for those mixes. However, at the higher rates of 3% and 6% Sasobit, fatigue resistance increases.
- Dynamic modulus results showed that the stiffness of the control and the 1.5% Sasobit WMA had no significant differences. For WMA with 3% and 6% Sasobit, the dynamic modulus increased resulting in a stiff mix.

HMA and WMA should be expected to perform equally. However, WMA improved performance compared to HMA is entirely dependent on the percentage of the additive Sasobit added to the mix.

Benefits of using WMA with Sasobit

- One of the most important benefits of WMA is in relation to the reduction of the production and placing temperatures, in comparison to conventional HMA mixes.
- The addition of Sasobit lowers the air voids, therefore improving compaction of the mixes, and thus the workability.
- Oxidation of the asphalt is avoided with adequate percentages of air voids in the compacted asphalt mixes. Density is increased. Air voids are more consistent with WMA.
- To produce WMA, less energy is required; therefore, it is possible to save on fuel consumption.
- WMA mixes can be transported at greater distances from the location where they are produced, without having a negative effect on the workability at placement and compaction, if the mix is produced within the range of 150 to 160 °C. These are higher than regular temperatures for WMA production, but still lower than HMA production temperatures.
- The lower temperature possible at production and paving of WMA benefits the asphalt workers, so that they are not exposed to high temperatures and they absorb fewer emissions.

The findings of this research positively encourage the implementation of WMA in WA, as it has the potential to be a viable alternative to conventional HMA. WMA offers several benefits, in particular:

- The ability to enhance compaction (workability)
- To be produced and placed at lower temperatures
- Achieve and comply with all specifications.
- Energy consumption is reduced.

- Suitable to use in cold weather conditions.
- Can be open to traffic earlier than HMA.

All of these benefits have resulted in a rapid increase in the use of WMA, especially in the USA where specifications have been adopted to allow the use on public roads.

The monitoring of the performance of WMA, over five years of construction projects, has shown that with an optimal mix design, production and compaction of WMA with Sasobit performs equally, and in some instances better, than conventional HMA.

7.1 Recommendations for future research

Considering that WMA technologies are relatively new, there are several areas that need to be evaluated further to assist with its implementation in Western Australia. It is recommended that:

- A methodology is established for the determination of an optimum temperature for a particular technology to ensure the quality and to encourage further use of the technologies.
- All WMA sites built for different traffic conditions are monitored by the respective road authorities, to assess their lifetime performance. Through lifetime monitoring, it would be possible to evaluate the real performance of WMA under Western Australian conditions.

It is recommended that the following be completed:

- Research and evaluate in detail the cost of WMA with different technologies, considering its life cycle in comparison to HMA.

- Evaluate the performance of WMA with different technologies containing recycled asphalt pavement.
- Evaluate the performance of WMA binders and mixes with modified polymers, for example crumb rubber.
- Evaluate the performance of Stone Mastic Asphalt (SMA) mixes containing WMA (following the European trend).
- Research the emission reduction to obtain a true value of the benefit obtained through the use of WMA.

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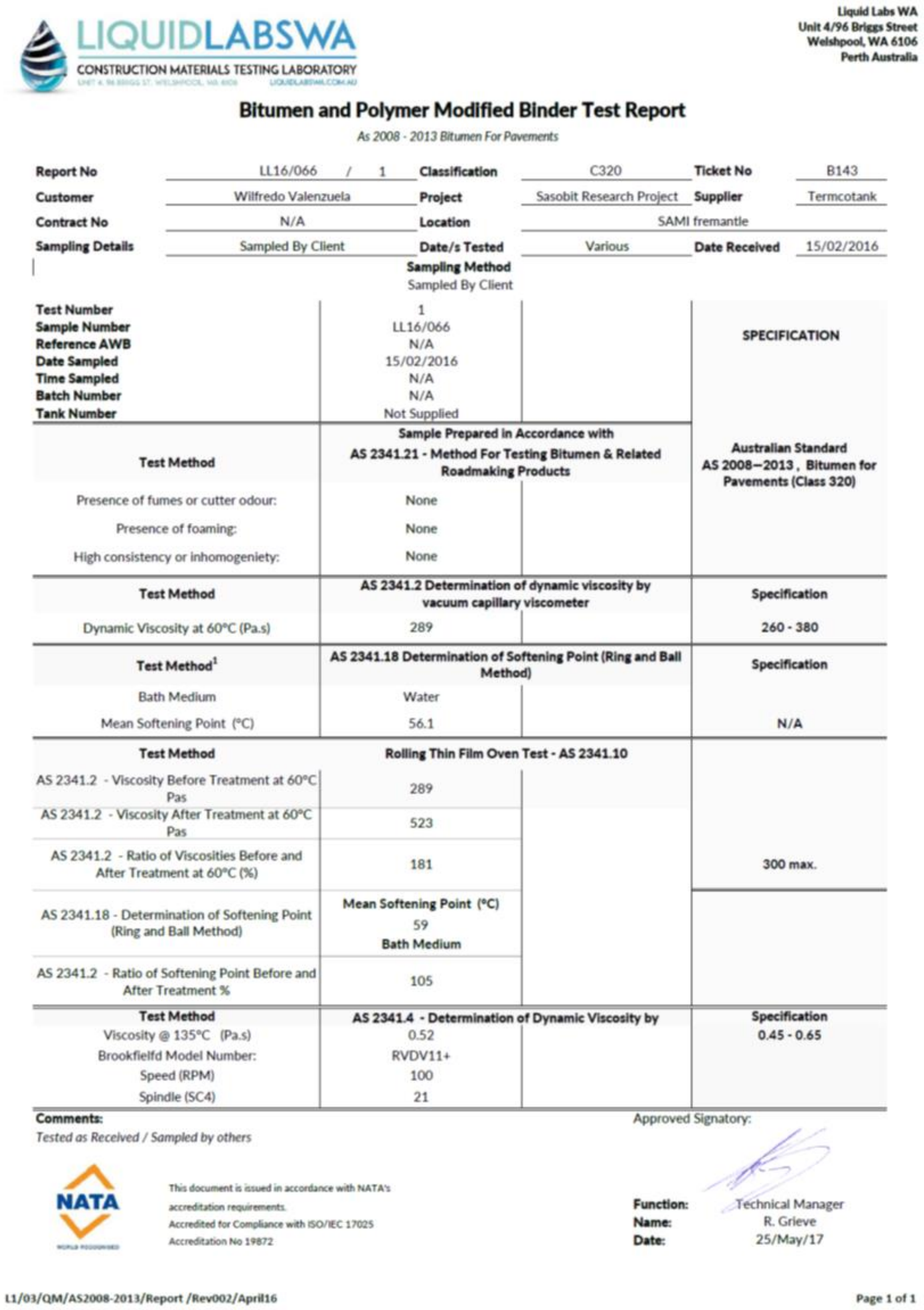
Appendix A Binder Test Results



LIQUIDLABSWA
CONSTRUCTION MATERIALS TESTING LABORATORY

Liquid Labs WA
Unit 4/96 Briggs Street
Welshpool, WA 6106
Perth Australia

Bitumen and Polymer Modified Binder Test Report

As 2008 - 2013 Bitumen For Pavements

Report No	LL16/066 / 1	**Classification**	C320	**Ticket No**	B143
Customer	Wilfredo Valenzuela	**Project**	Sasobit Research Project	**Supplier**	Termcotank
Contract No	N/A	**Location**	SAMI fremantle		
Sampling Details	Sampled By Client	**Date/s Tested**	Various	**Date Received**	15/02/2016

Sampling Method
Sampled By Client

Test Number	1		**SPECIFICATION**
Sample Number	LL16/066		
Reference AWB	N/A		
Date Sampled	15/02/2016		
Time Sampled	N/A		
Batch Number	N/A		
Tank Number	Not Supplied		
Test Method	**Sample Prepared in Accordance with** **AS 2341.21 - Method For Testing Bitumen & Related Roadmaking Products**		**Australian Standard AS 2008—2013 , Bitumen for Pavements (Class 320)**
Presence of fumes or cutter odour:	None		
Presence of foaming:	None		
High consistency or inhomogeniety:	None		
Test Method	**AS 2341.2 Determination of dynamic viscosity by vacuum capillary viscometer**		**Specification**
Dynamic Viscosity at 60°C (Pa.s)	289		**260 - 380**
Test Method[1]	**AS 2341.18 Determination of Softening Point (Ring and Ball Method)**		**Specification**
Bath Medium	Water		
Mean Softening Point (°C)	56.1		**N/A**
Test Method	**Rolling Thin Film Oven Test - AS 2341.10**		
AS 2341.2 - Viscosity Before Treatment at 60°C Pas	289		
AS 2341.2 - Viscosity After Treatment at 60°C Pas	523		
AS 2341.2 - Ratio of Viscosities Before and After Treatment at 60°C (%)	181		**300 max.**
AS 2341.18 - Determination of Softening Point (Ring and Ball Method)	**Mean Softening Point (°C)** 59 **Bath Medium**		
AS 2341.2 - Ratio of Softening Point Before and After Treatment %	105		
Test Method	**AS 2341.4 - Determination of Dynamic Viscosity by**		**Specification**
Viscosity @ 135°C (Pa.s)	0.52		**0.45 - 0.65**
Brookfielfd Model Number:	RVDV11+		
Speed (RPM)	100		
Spindle (SC4)	21		

Comments:
Tested as Received / Sampled by others

Approved Signatory:

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Function: Technical Manager
Name: R. Grieve
Date: 25/May/17

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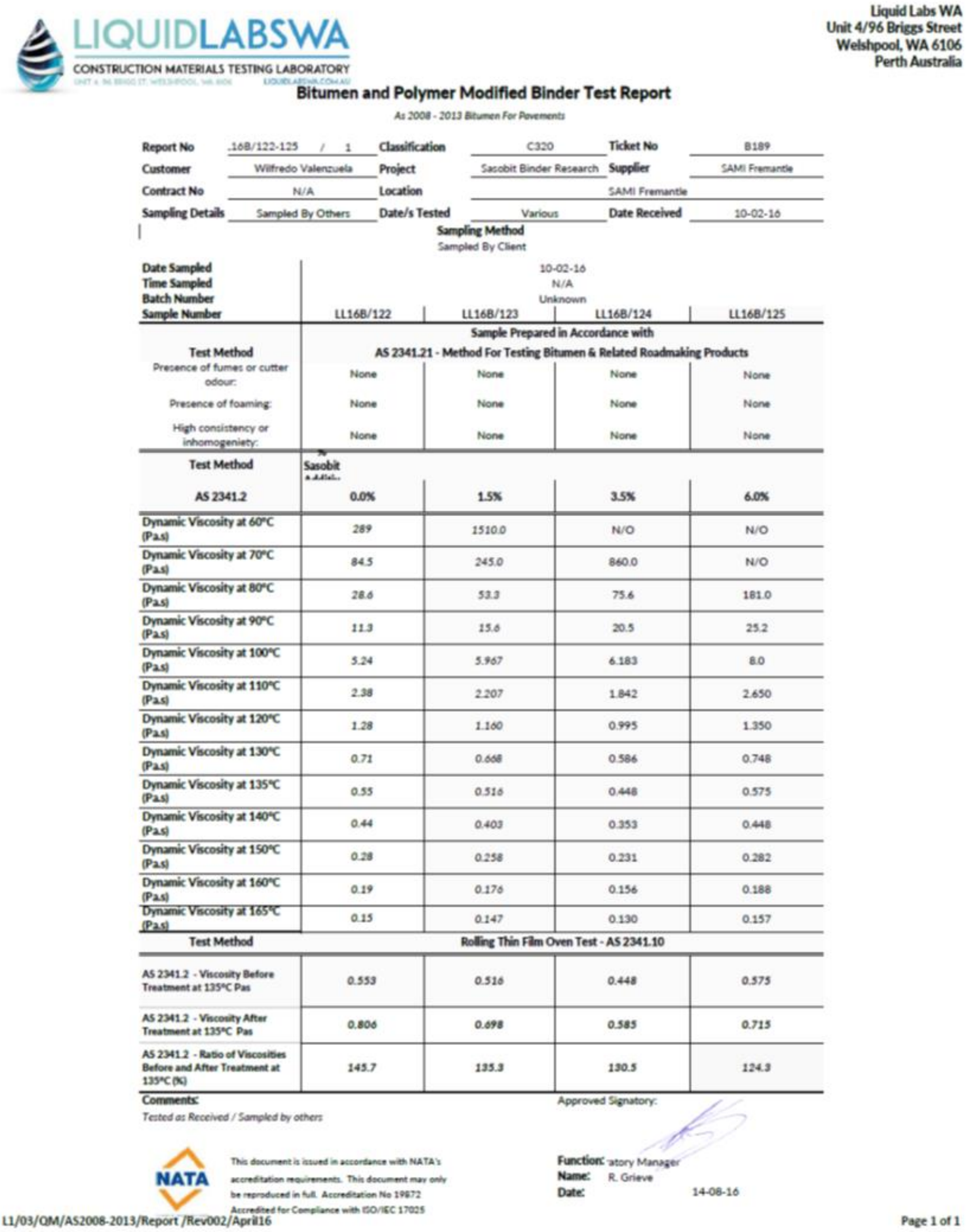

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Perth Australia

Bitumen and Polymer Modified Binder Test Report

As 2008 - 2013 Bitumen For Pavements

Report No	.16B/122-125 / 1	**Classification**	C320	**Ticket No**	B189
Customer	Wilfredo Valenzuela	**Project**	Sasobit Binder Research	**Supplier**	SAMI Fremantle
Contract No	N/A	**Location**	SAMI Fremantle		
Sampling Details	Sampled By Others	**Date/s Tested**	Various	**Date Received**	10-02-16

Sampling Method
Sampled By Client

Date Sampled	10-02-16			
Time Sampled	N/A			
Batch Number	Unknown			
Sample Number	LL16B/122	LL16B/123	LL16B/124	LL16B/125
Test Method	**Sample Prepared in Accordance with AS 2341.21 - Method For Testing Bitumen & Related Roadmaking Products**			
Presence of fumes or cutter odour:	None	None	None	None
Presence of foaming:	None	None	None	None
High consistency or inhomogeniety:	None	None	None	None
Test Method	**% Sasobit**			
AS 2341.2	**0.0%**	**1.5%**	**3.5%**	**6.0%**
Dynamic Viscosity at 60°C (Pa.s)	*289*	*1510.0*	N/O	N/O
Dynamic Viscosity at 70°C (Pa.s)	*84.5*	*245.0*	860.0	N/O
Dynamic Viscosity at 80°C (Pa.s)	*28.6*	*53.3*	75.6	181.0
Dynamic Viscosity at 90°C (Pa.s)	*11.3*	*15.6*	20.5	25.2
Dynamic Viscosity at 100°C (Pa.s)	*5.24*	*5.967*	6.183	8.0
Dynamic Viscosity at 110°C (Pa.s)	*2.38*	*2.207*	1.842	2.650
Dynamic Viscosity at 120°C (Pa.s)	*1.28*	*1.160*	0.995	1.350
Dynamic Viscosity at 130°C (Pa.s)	*0.71*	*0.668*	0.586	0.748
Dynamic Viscosity at 135°C (Pa.s)	*0.55*	*0.516*	0.448	0.575
Dynamic Viscosity at 140°C (Pa.s)	*0.44*	*0.403*	0.353	0.448
Dynamic Viscosity at 150°C (Pa.s)	*0.28*	*0.258*	0.231	0.282
Dynamic Viscosity at 160°C (Pa.s)	*0.19*	*0.176*	0.156	0.188
Dynamic Viscosity at 165°C (Pa.s)	*0.15*	*0.147*	0.130	0.157
Test Method	**Rolling Thin Film Oven Test - AS 2341.10**			
AS 2341.2 - Viscosity Before Treatment at 135°C Pas	*0.553*	*0.516*	*0.448*	*0.575*
AS 2341.2 - Viscosity After Treatment at 135°C Pas	***0.806***	***0.698***	***0.585***	***0.715***
AS 2341.2 - Ratio of Viscosities Before and After Treatment at 135°C (%)	***145.7***	***135.3***	***130.5***	***124.3***

Comments:
Tested as Received / Sampled by others

Approved Signatory:

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Function: atory Manager
Name: R. Grieve
Date: 14-08-16

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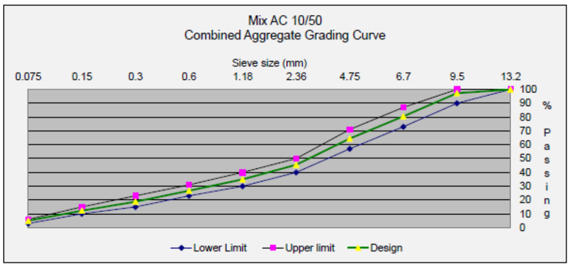
Appendix B Mix Design

AC10mm

Design Worksheet

AC 10/50

																					Design
	20mm		14mm	%	10mm	%	10/7mm	%	7mm	%	5mm	%	Sand	%	Dust	%	Lime	%	Oxide		Total
SIEVE						**19.8**				**15**		**20**				**43.6**		**1.5**			**100**
mm		**0.0**		**0.0**		**18.7**		**0.0**		**14.2**		**18.9**		**0.0**		**41.2**		**1.4**		**0.0**	**100.0**
26.5	100.0	0.0	100.0	0.0	100.0	19.8	100.0	0.0	100.0	15.0	100.0	20.0	100.0	0.0	100.0	43.6	100.0	1.5	100.0	0.0	**99.9**
19	92.3	0.0	100.0	0.0	100.0	19.8	100.0	0.0	100.0	15.0	100.0	20.0	100.0	0.0	100.0	43.6	100.0	1.5	100.0	0.0	**99.9**
13.2	55.2	0.0	91.5	0.0	100.0	19.8	100.0	0.0	100.0	15.0	100.0	20.0	100.0	0.0	100.0	43.6	100.0	1.5	100.0	0.0	**99.9**
9.5	18.4	0.0	22.6	0.0	86.7	17.2	91.8	0.0	100.0	15.0	100.0	20.0	100.0	0.0	100.0	43.6	100.0	1.5	100.0	0.0	**97.3**
6.7	7.8	0.0	6.1	0.0	8.9	1.8	48.0	0.0	91.0	13.7	100.0	20.0	100.0	0.0	100.0	43.6	100.0	1.5	100.0	0.0	**80.5**
4.75	4.9	0.0	2.9	0.0	0.8	0.2	15.1	0.0	24.9	3.7	77.4	15.5	100.0	0.0	100.0	43.6	100.0	1.5	100.0	0.0	**64.5**
2.36	2.5	0.0	1.6	0.0	0.4	0.1	2.9	0.0	5.4	0.8	1.9	0.4	100.0	0.0	98.0	42.7	100.0	1.5	100.0	0.0	**45.5**
1.18	2.0	0.0	1.4	0.0	0.3	0.1	1.8	0.0	3.7	0.5	1.2	0.2	100.0	0.0	74.8	32.6	100.0	1.5	100.0	0.0	**35.0**
0.6	2.0	0.0	1.4	0.0	1.0	0.2	1.8	0.0	3.7	0.5	1.2	0.2	93.7	0.0	55.6	24.2	100.0	1.5	100.0	0.0	**26.7**
0.3	2.0	0.0	1.4	0.0	1.0	0.2	1.8	0.0	3.7	0.5	1.2	0.2	31.6	0.0	37.3	16.3	100.0	1.5	100.0	0.0	**18.7**
0.15	2.0	0.0	1.4	0.0	1.0	0.2	1.8	0.0	3.7	0.5	1.2	0.2	1.7	0.0	22.5	9.8	100.0	1.5	100.0	0.0	**12.3**
0.075	0.7	0.0	0.6	0.0	0.2	0.0	0.8	0.0	1.5	0.2	0.9	0.2	0.2	0.0	7.0	3.1	100.0	1.5	100.0	0.0	**5.0**

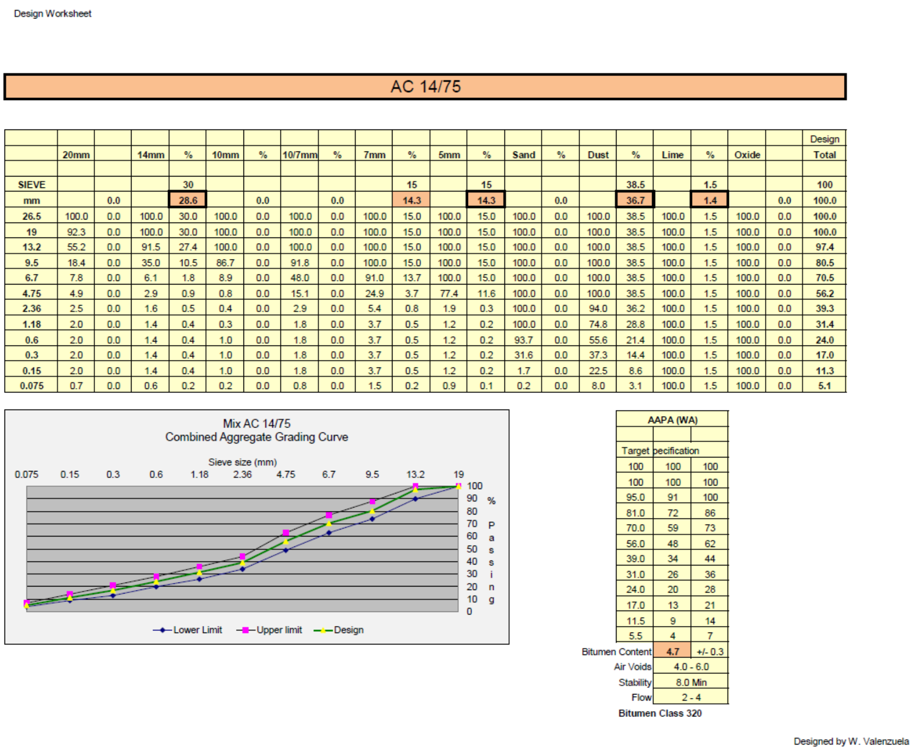


	AAPA (WA)		
	Target	pecification	
	100	100	100
	100	100	100
	100.0	100	100
	95.0	90	100
	80.0	73	87
	64.0	57	71
	45.0	40	50
	35.0	30	40
	27.0	23	31
	19.0	15	23
	12.5	10	15
	4.5	3	6
Bitumen Content		5.6	+/- 0.3
Air Voids		4.0-6.0	
Stability		6.5 Min	
Flow		2 - 4	

Bitumen Class 320

Designed by W. Valenzuela

AC 14mm



Design Worksheet

AC 14/75

	20mm		14mm	%	10mm	%	10/7mm	%	7mm	%	5mm	%	Sand	%	Dust	%	Lime	%	Oxide		Design Total
SIEVE				30						15		15				38.5		1.5			100
mm		0.0		28.6		0.0		0.0		14.3		14.3		0.0		36.7		1.4		0.0	100.0
26.5	100.0	0.0	100.0	30.0	100.0	0.0	100.0	0.0	100.0	15.0	100.0	15.0	100.0	0.0	100.0	38.5	100.0	1.5	100.0	0.0	**100.0**
19	92.3	0.0	100.0	30.0	100.0	0.0	100.0	0.0	100.0	15.0	100.0	15.0	100.0	0.0	100.0	38.5	100.0	1.5	100.0	0.0	**100.0**
13.2	55.2	0.0	91.5	27.4	100.0	0.0	100.0	0.0	100.0	15.0	100.0	15.0	100.0	0.0	100.0	38.5	100.0	1.5	100.0	0.0	**97.4**
9.5	18.4	0.0	35.0	10.5	86.7	0.0	91.8	0.0	100.0	15.0	100.0	15.0	100.0	0.0	100.0	38.5	100.0	1.5	100.0	0.0	**80.5**
6.7	7.8	0.0	6.1	1.8	8.9	0.0	48.0	0.0	91.0	13.7	100.0	15.0	100.0	0.0	100.0	38.5	100.0	1.5	100.0	0.0	**70.5**
4.75	4.9	0.0	2.9	0.9	0.8	0.0	15.1	0.0	24.9	3.7	77.4	11.6	100.0	0.0	100.0	38.5	100.0	1.5	100.0	0.0	**56.2**
2.36	2.5	0.0	1.6	0.5	0.4	0.0	2.9	0.0	5.4	0.8	1.9	0.3	100.0	0.0	94.0	36.2	100.0	1.5	100.0	0.0	**39.3**
1.18	2.0	0.0	1.4	0.4	0.3	0.0	1.8	0.0	3.7	0.5	1.2	0.2	100.0	0.0	74.8	28.8	100.0	1.5	100.0	0.0	**31.4**
0.6	2.0	0.0	1.4	0.4	1.0	0.0	1.8	0.0	3.7	0.5	1.2	0.2	93.7	0.0	55.6	21.4	100.0	1.5	100.0	0.0	**24.0**
0.3	2.0	0.0	1.4	0.4	1.0	0.0	1.8	0.0	3.7	0.5	1.2	0.2	31.6	0.0	37.3	14.4	100.0	1.5	100.0	0.0	**17.0**
0.15	2.0	0.0	1.4	0.4	1.0	0.0	1.8	0.0	3.7	0.5	1.2	0.2	1.7	0.0	22.5	8.6	100.0	1.5	100.0	0.0	**11.3**
0.075	0.7	0.0	0.6	0.2	0.2	0.0	0.8	0.0	1.5	0.2	0.9	0.1	0.2	0.0	8.0	3.1	100.0	1.5	100.0	0.0	**5.1**

Mix AC 14/75
Combined Aggregate Grading Curve

AAPA (WA)		
Target	pecification	
100	100	100
100	100	100
95.0	91	100
81.0	72	86
70.0	59	73
56.0	48	62
39.0	34	44
31.0	26	36
24.0	20	28
17.0	13	21
11.5	9	14
5.5	4	7

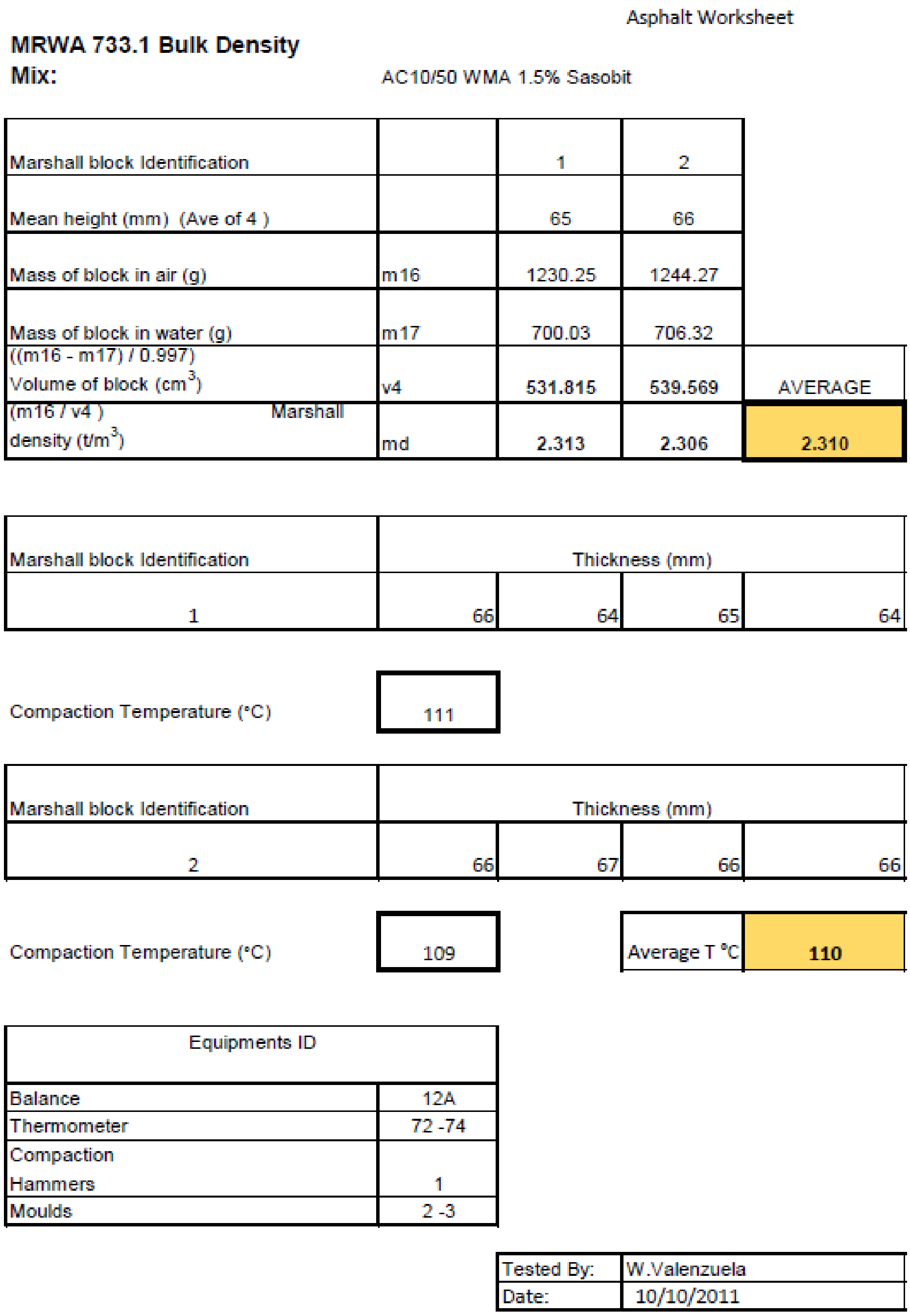
Bitumen Content	4.7	+/- 0.3
Air Voids	4.0 - 6.0	
Stability	8.0 Min	
Flow	2 - 4	

Bitumen Class 320

Designed by W. Valenzuela

Appendix C WMA Compaction Temperature Determination

Density at 110°C



Asphalt Worksheet

MRWA 733.1 Bulk Density

Mix: AC10/50 WMA 1.5% Sasobit

Marshall block Identification		1	2	
Mean height (mm) (Ave of 4)		65	66	
Mass of block in air (g)	m16	1230.25	1244.27	
Mass of block in water (g)	m17	700.03	706.32	
((m16 - m17) / 0.997) Volume of block (cm^3)	v4	531.815	539.569	AVERAGE
(m16 / v4) Marshall density (t/m^3)	md	2.313	2.306	2.310

Marshall block Identification	Thickness (mm)			
1	66	64	65	64

Compaction Temperature (°C) 111

Marshall block Identification	Thickness (mm)			
2	66	67	66	66

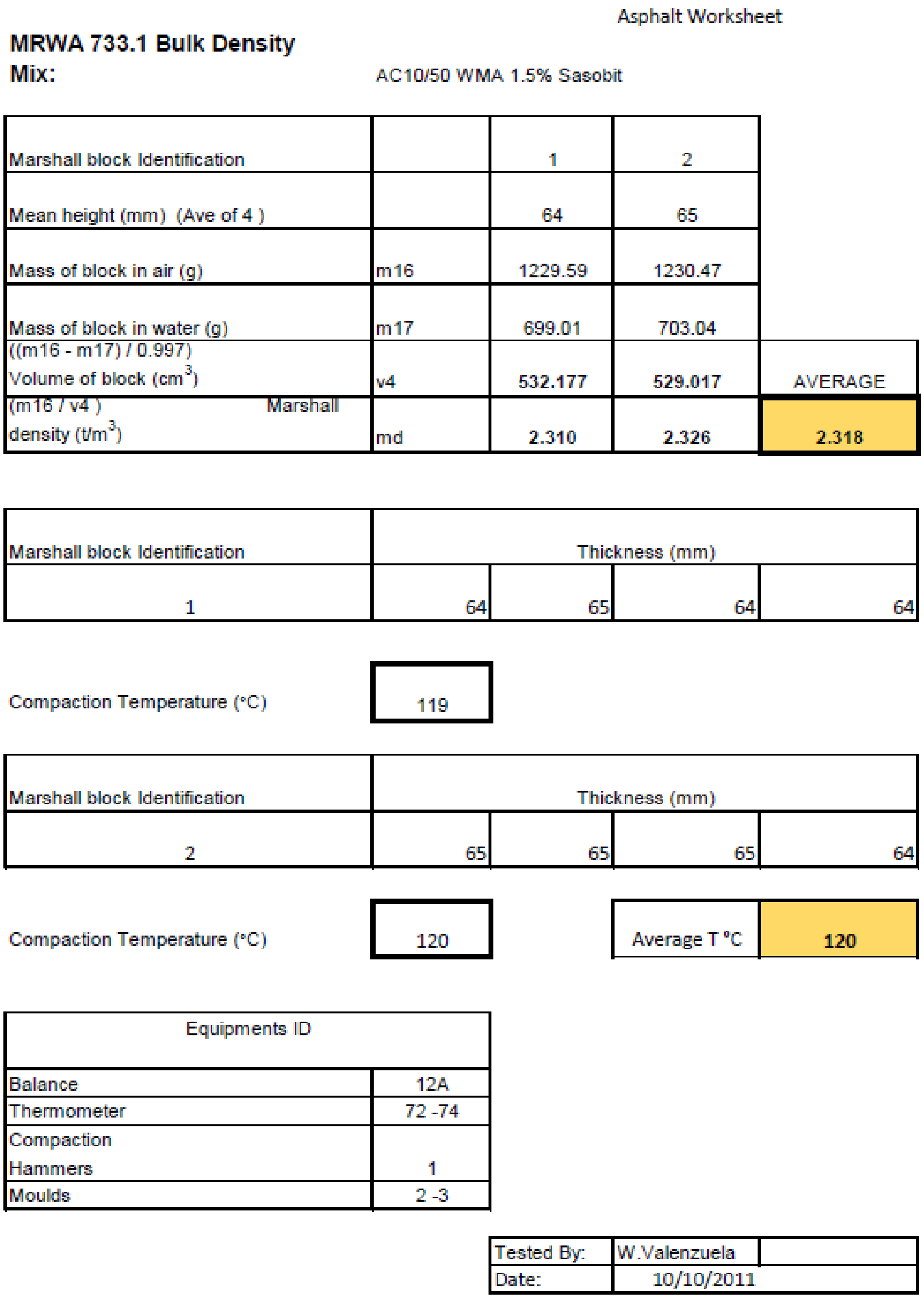
Compaction Temperature (°C) 109

Average T °C 110

Equipments ID	
Balance	12A
Thermometer	72 -74
Compaction Hammers	1
Moulds	2 -3

Tested By:	W.Valenzuela
Date:	10/10/2011

Density at 120°C



Asphalt Worksheet

MRWA 733.1 Bulk Density

Mix: AC10/50 WMA 1.5% Sasobit

Marshall block Identification		1	2	
Mean height (mm) (Ave of 4)		64	65	
Mass of block in air (g)	m16	1229.59	1230.47	
Mass of block in water (g)	m17	699.01	703.04	
((m16 - m17) / 0.997) Volume of block (cm^3)	v4	532.177	529.017	AVERAGE
(m16 / v4) Marshall density (t/m^3)	md	2.310	2.326	2.318

Marshall block Identification	Thickness (mm)			
1	64	65	64	64

Compaction Temperature (°C) 119

Marshall block Identification	Thickness (mm)			
2	65	65	65	64

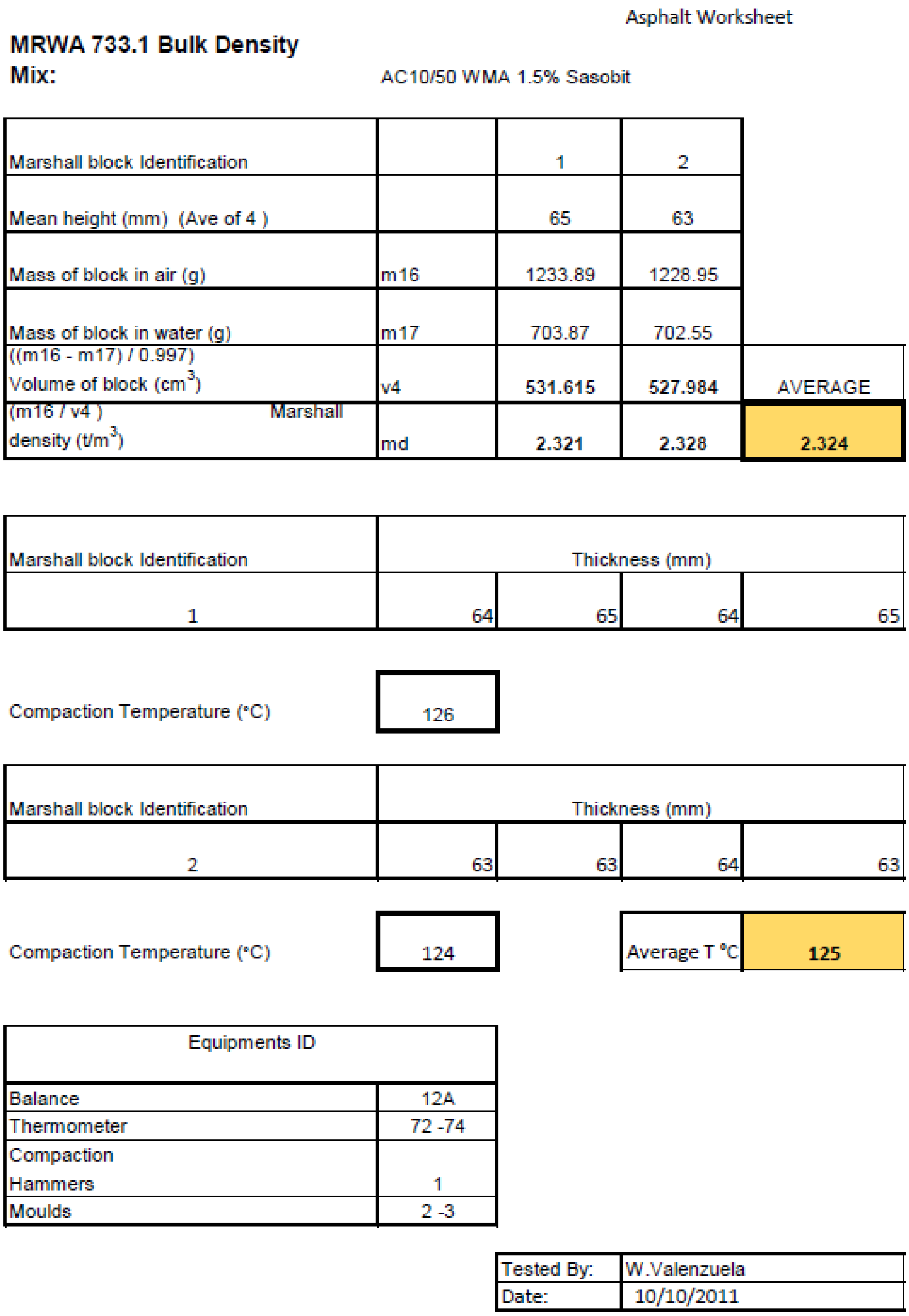
Compaction Temperature (°C) 120

Average T °C 120

Equipments ID	
Balance	12A
Thermometer	72 -74
Compaction Hammers	1
Moulds	2 -3

Tested By:	W.Valenzuela
Date:	10/10/2011

Density at 125°C



Asphalt Worksheet

MRWA 733.1 Bulk Density

Mix: AC10/50 WMA 1.5% Sasobit

Marshall block Identification		1	2	
Mean height (mm) (Ave of 4)		65	63	
Mass of block in air (g)	m16	1233.89	1228.95	
Mass of block in water (g)	m17	703.87	702.55	
((m16 - m17) / 0.997) Volume of block (cm^3)	v4	**531.615**	**527.984**	AVERAGE
(m16 / v4) Marshall density (t/m^3)	md	**2.321**	**2.328**	**2.324**

Marshall block Identification	Thickness (mm)			
1	64	65	64	65

Compaction Temperature (°C) 126

Marshall block Identification	Thickness (mm)			
2	63	63	64	63

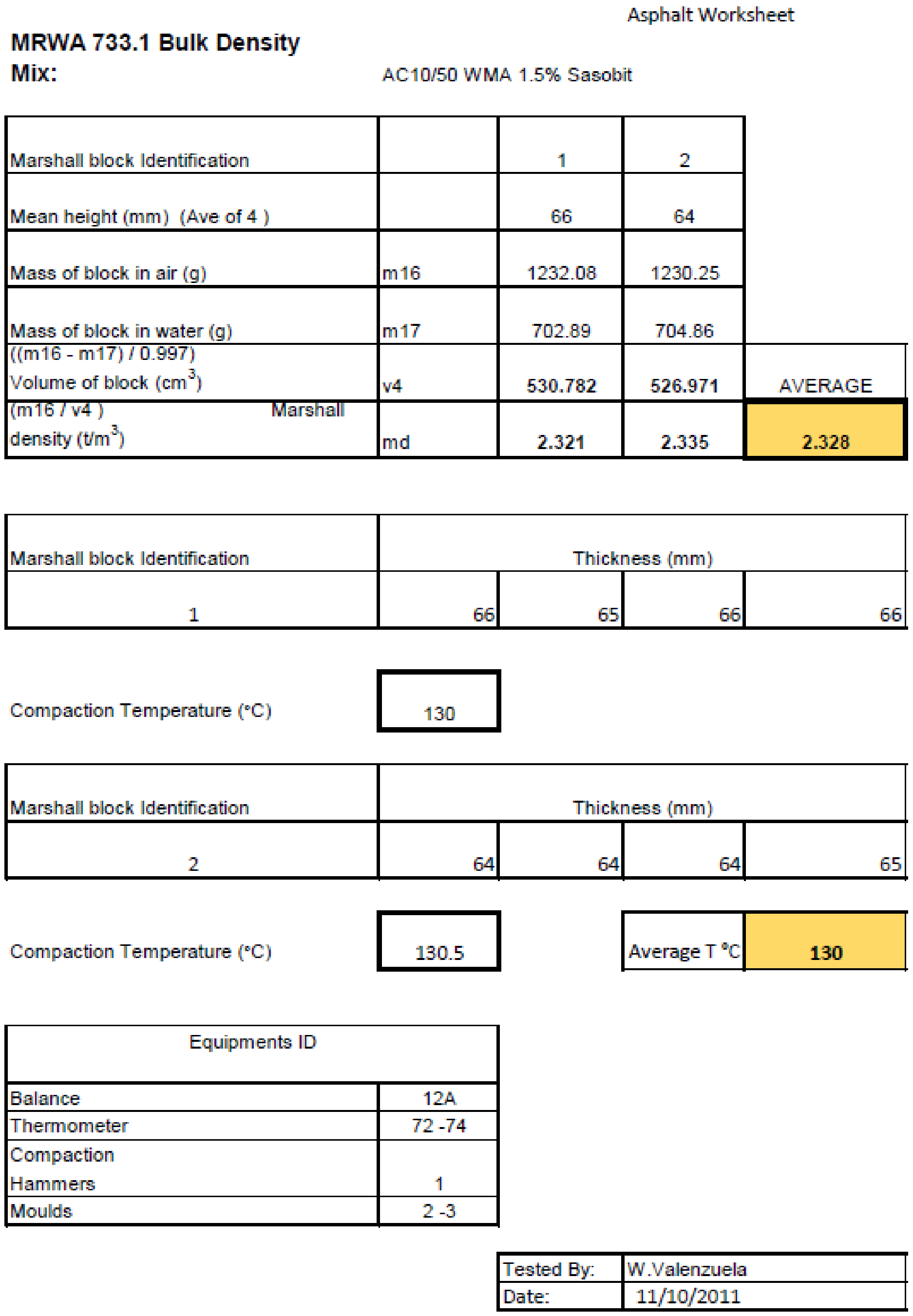
Compaction Temperature (°C) 124

Average T °C **125**

Equipments ID	
Balance	12A
Thermometer	72 -74
Compaction Hammers	1
Moulds	2 -3

Tested By:	W.Valenzuela
Date:	10/10/2011

Density at 130°C



Asphalt Worksheet

MRWA 733.1 Bulk Density

Mix: AC10/50 WMA 1.5% Sasobit

Marshall block Identification		1	2	
Mean height (mm) (Ave of 4)		66	64	
Mass of block in air (g)	m16	1232.08	1230.25	
Mass of block in water (g)	m17	702.89	704.86	
((m16 - m17) / 0.997) Volume of block (cm^3)	v4	530.782	526.971	AVERAGE
(m16 / v4) Marshall density (t/m^3)	md	**2.321**	**2.335**	**2.328**

Marshall block Identification	Thickness (mm)			
1	66	65	66	66

Compaction Temperature (°C) 130

Marshall block Identification	Thickness (mm)			
2	64	64	64	65

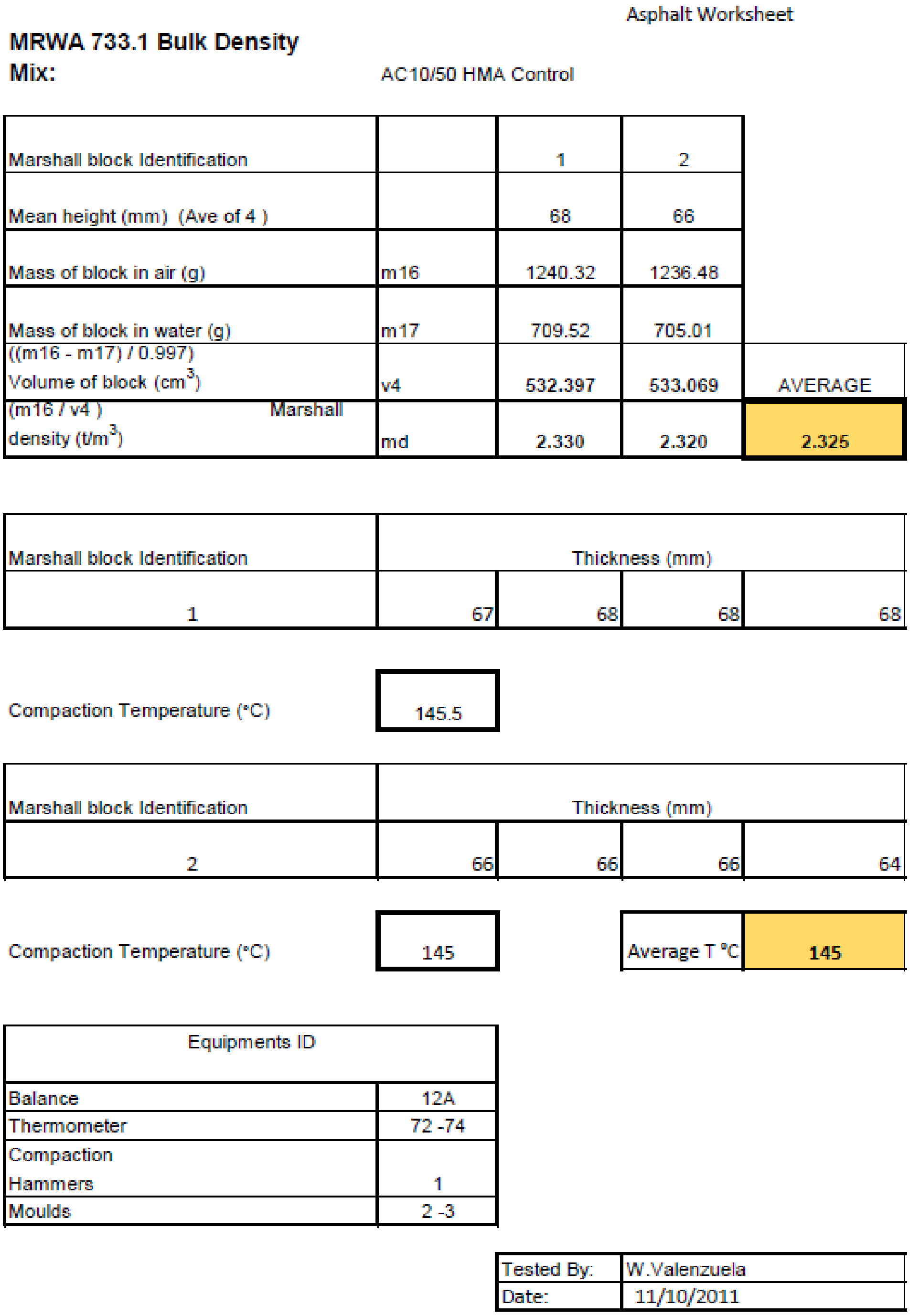
Compaction Temperature (°C) 130.5

Average T °C **130**

Equipments ID	
Balance	12A
Thermometer	72 -74
Compaction Hammers	1
Moulds	2 -3

Tested By:	W.Valenzuela
Date:	11/10/2011

Density at 145°C



Asphalt Worksheet

MRWA 733.1 Bulk Density

Mix: AC10/50 HMA Control

Marshall block Identification		1	2	
Mean height (mm) (Ave of 4)		68	66	
Mass of block in air (g)	m16	1240.32	1236.48	
Mass of block in water (g)	m17	709.52	705.01	
((m16 - m17) / 0.997) Volume of block (cm^3)	v4	532.397	533.069	AVERAGE
(m16 / v4) Marshall density (t/m^3)	md	**2.330**	**2.320**	**2.325**

Marshall block Identification	Thickness (mm)			
1	67	68	68	68

Compaction Temperature (°C) 145.5

Marshall block Identification	Thickness (mm)			
2	66	66	66	64

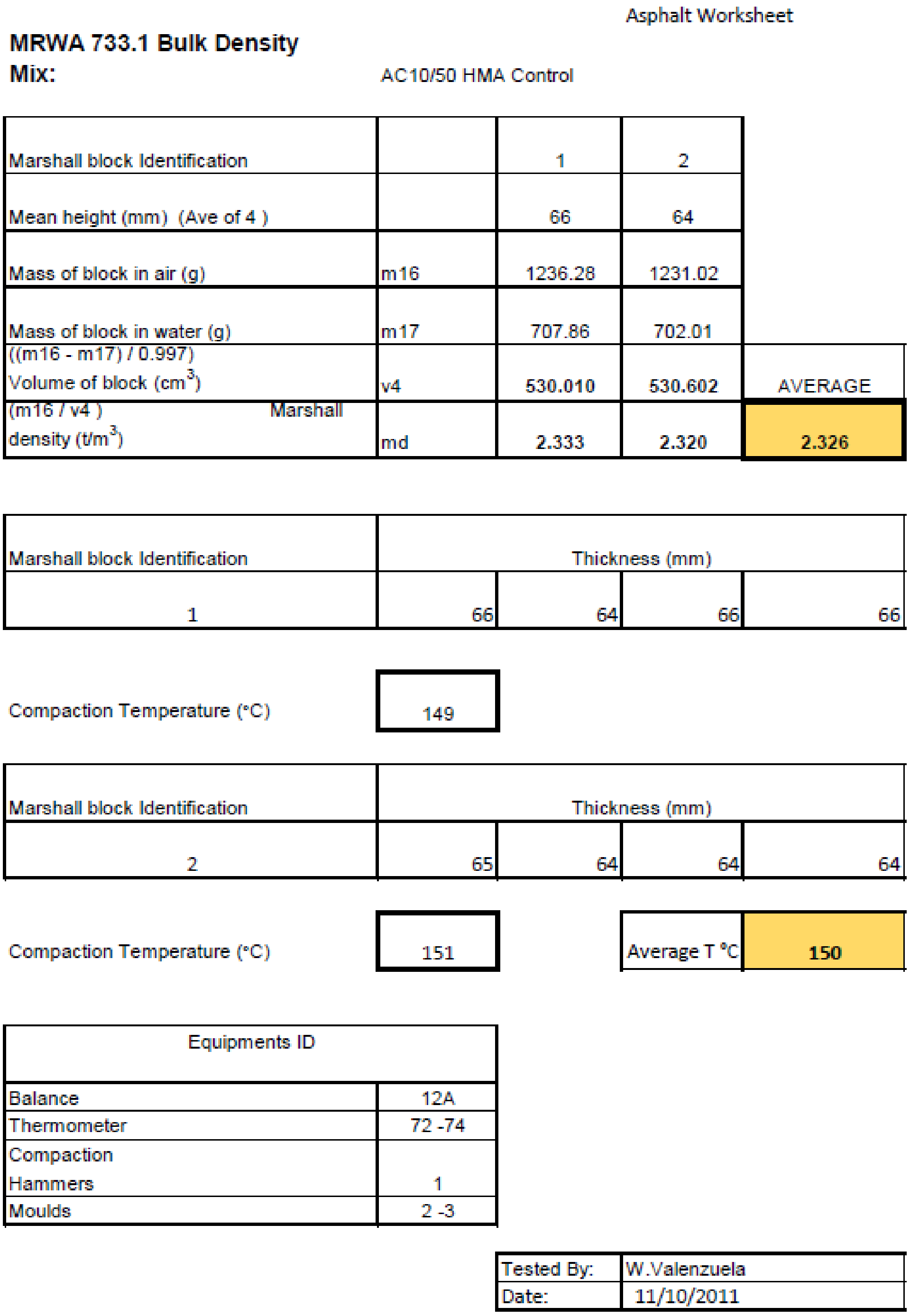
Compaction Temperature (°C) 145

Average T °C **145**

Equipments ID	
Balance	12A
Thermometer	72 -74
Compaction Hammers	1
Moulds	2 -3

Tested By:	W.Valenzuela
Date:	11/10/2011

Density at 150°C



Asphalt Worksheet

MRWA 733.1 Bulk Density

Mix: AC10/50 HMA Control

Marshall block Identification		1	2	
Mean height (mm) (Ave of 4)		66	64	
Mass of block in air (g)	m16	1236.28	1231.02	
Mass of block in water (g)	m17	707.86	702.01	
((m16 - m17) / 0.997) Volume of block (cm^3)	v4	530.010	530.602	AVERAGE
(m16 / v4) Marshall density (t/m^3)	md	2.333	2.320	**2.326**

Marshall block Identification	Thickness (mm)			
1	66	64	66	66

Compaction Temperature (°C) 149

Marshall block Identification	Thickness (mm)			
2	65	64	64	64

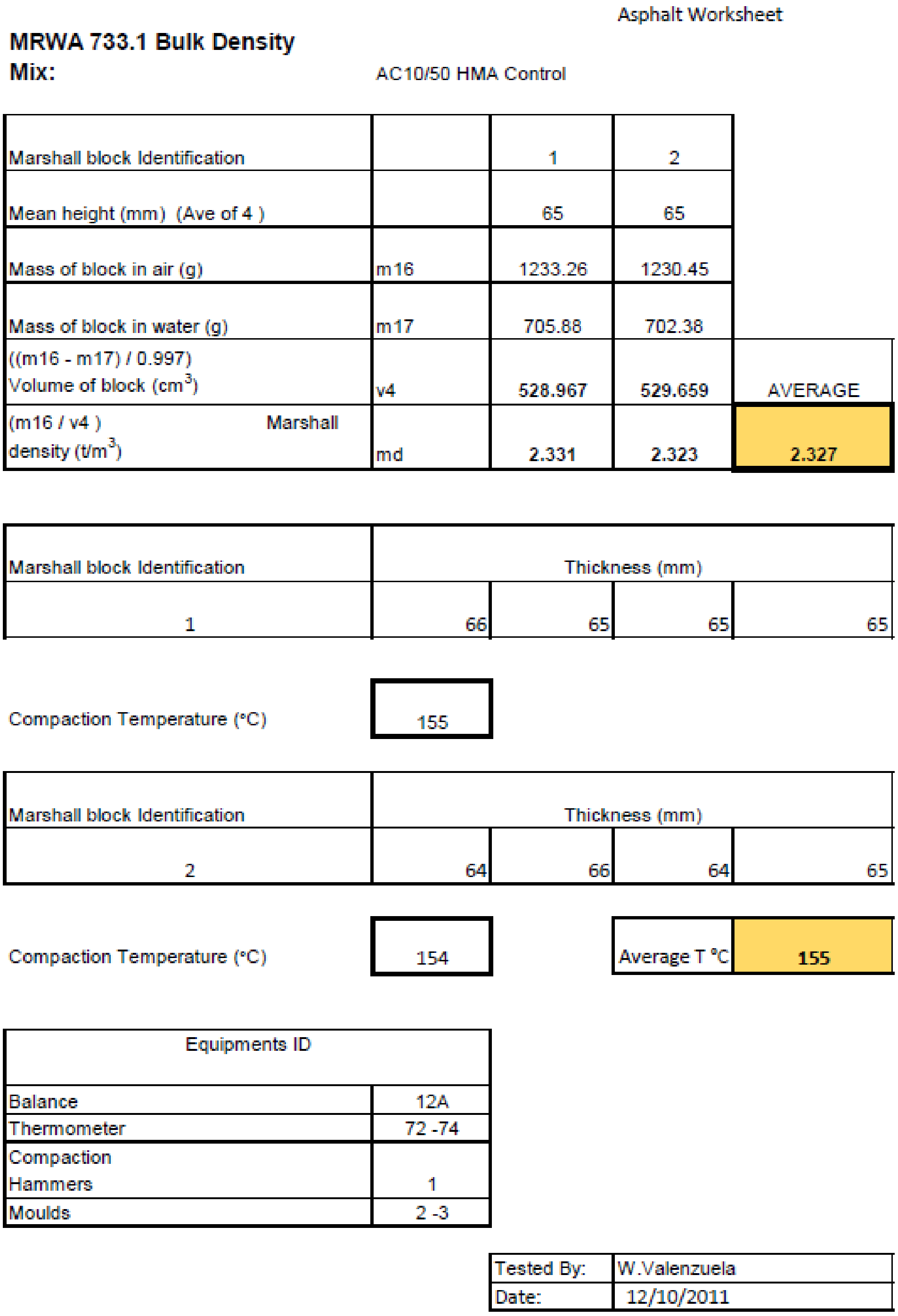
Compaction Temperature (°C) 151

Average T °C **150**

Equipments ID	
Balance	12A
Thermometer	72 -74
Compaction Hammers	1
Moulds	2 -3

Tested By:	W.Valenzuela
Date:	11/10/2011

Density at 155°C



Asphalt Worksheet

MRWA 733.1 Bulk Density

Mix: AC10/50 HMA Control

Marshall block Identification		1	2	
Mean height (mm) (Ave of 4)		65	65	
Mass of block in air (g)	m16	1233.26	1230.45	
Mass of block in water (g)	m17	705.88	702.38	
((m16 - m17) / 0.997) Volume of block (cm^3)	v4	528.967	529.659	AVERAGE
(m16 / v4) Marshall density (t/m^3)	md	**2.331**	**2.323**	**2.327**

Marshall block Identification	Thickness (mm)			
1	66	65	65	65

Compaction Temperature (°C) 155

Marshall block Identification	Thickness (mm)			
2	64	66	64	65

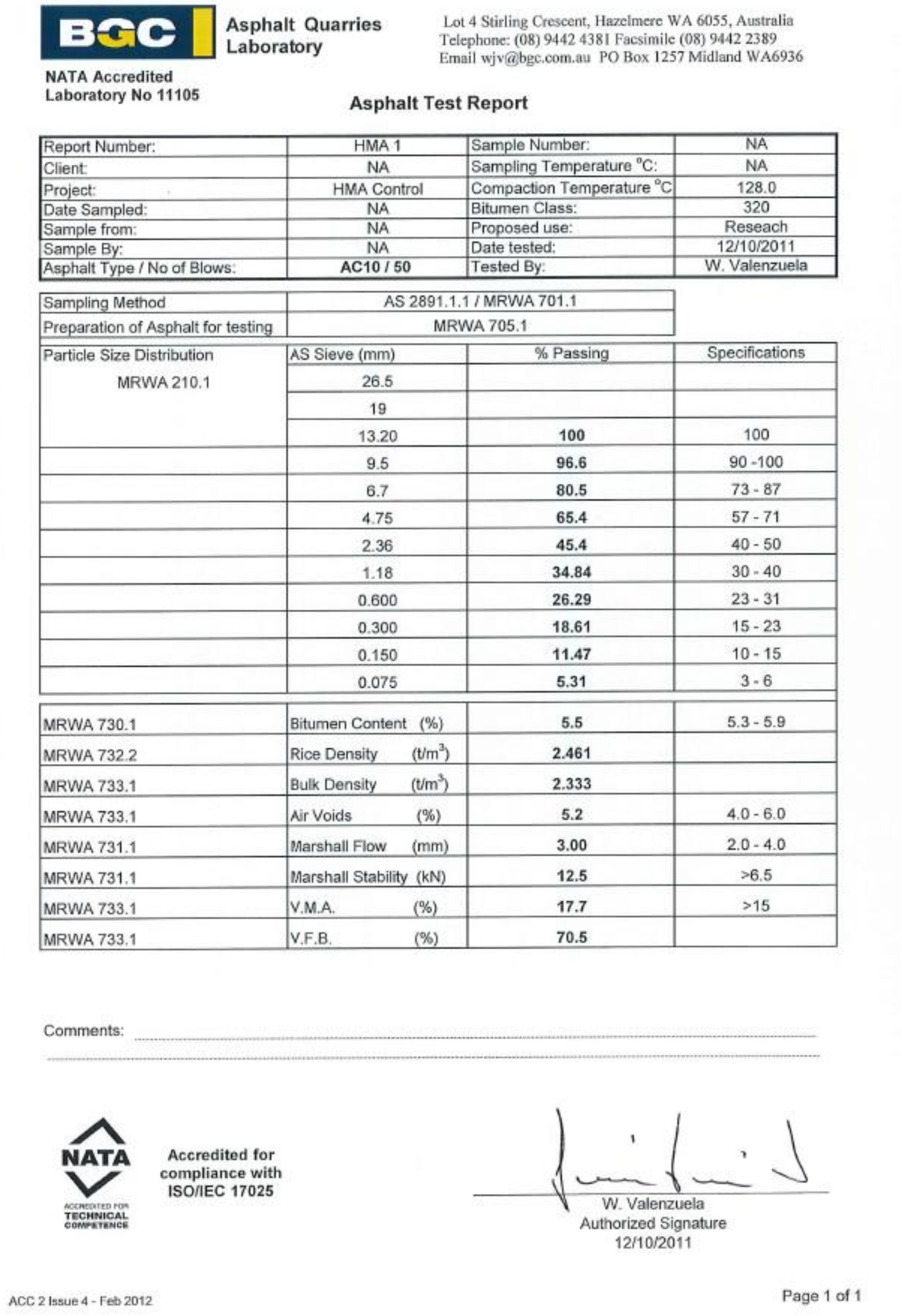
Compaction Temperature (°C) 154

Average T °C **155**

Equipments ID	
Balance	12A
Thermometer	72 -74
Compaction Hammers	1
Moulds	2 -3

Tested By:	W.Valenzuela
Date:	12/10/2011

Appendix D Asphalt Reports



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NATA Accredited
Laboratory No 11105

Asphalt Test Report

Report Number:	HMA 1	Sample Number:	NA
Client:	NA	Sampling Temperature °C:	NA
Project:	HMA Control	Compaction Temperature °C	128.0
Date Sampled:	NA	Bitumen Class:	320
Sample from:	NA	Proposed use:	Reseach
Sample By:	NA	Date tested:	12/10/2011
Asphalt Type / No of Blows:	**AC10 / 50**	Tested By:	W. Valenzuela

Sampling Method	AS 2891.1.1 / MRWA 701.1
Preparation of Asphalt for testing	MRWA 705.1

Particle Size Distribution	AS Sieve (mm)	% Passing	Specifications
MRWA 210.1	26.5		
	19		
	13.20	**100**	100
	9.5	**96.6**	90 -100
	6.7	**80.5**	73 - 87
	4.75	**65.4**	57 - 71
	2.36	**45.4**	40 - 50
	1.18	**34.84**	30 - 40
	0.600	**26.29**	23 - 31
	0.300	**18.61**	15 - 23
	0.150	**11.47**	10 - 15
	0.075	**5.31**	3 - 6

MRWA 730.1	Bitumen Content (%)	**5.5**	5.3 - 5.9
MRWA 732.2	Rice Density (t/m³)	**2.461**	
MRWA 733.1	Bulk Density (t/m³)	**2.333**	
MRWA 733.1	Air Voids (%)	**5.2**	4.0 - 6.0
MRWA 731.1	Marshall Flow (mm)	**3.00**	2.0 - 4.0
MRWA 731.1	Marshall Stability (kN)	**12.5**	>6.5
MRWA 733.1	V.M.A. (%)	**17.7**	>15
MRWA 733.1	V.F.B. (%)	**70.5**	

Comments: ....

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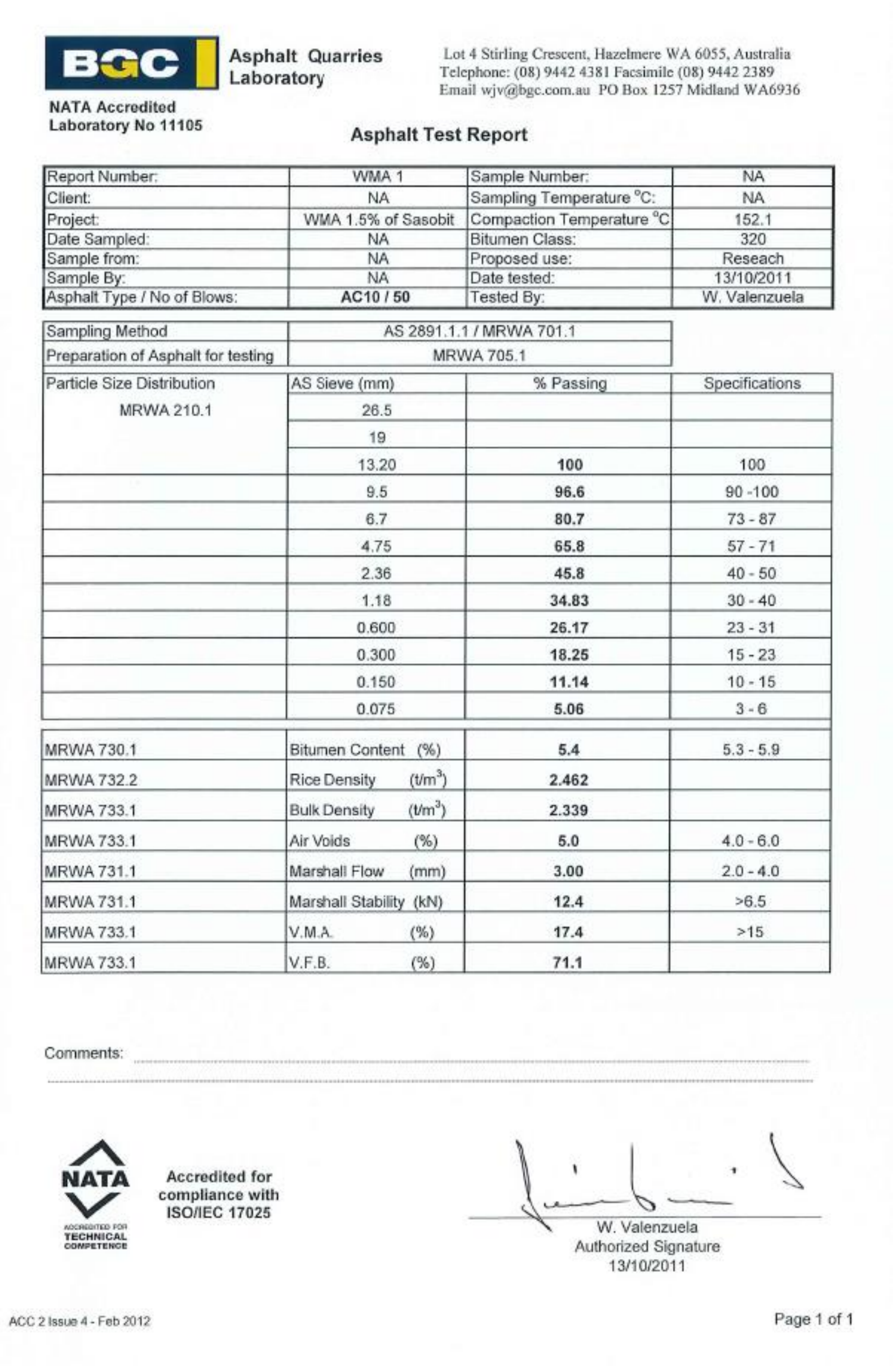

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NATA Accredited
Laboratory No 11105

Asphalt Test Report

Report Number:	WMA 1	Sample Number:	NA
Client:	NA	Sampling Temperature °C:	NA
Project:	WMA 1.5% of Sasobit	Compaction Temperature °C	152.1
Date Sampled:	NA	Bitumen Class:	320
Sample from:	NA	Proposed use:	Reseach
Sample By:	NA	Date tested:	13/10/2011
Asphalt Type / No of Blows:	**AC10 / 50**	Tested By:	W. Valenzuela

Sampling Method	AS 2891.1.1 / MRWA 701.1
Preparation of Asphalt for testing	MRWA 705.1

Particle Size Distribution	AS Sieve (mm)	% Passing	Specifications
MRWA 210.1	26.5		
	19		
	13.20	**100**	100
	9.5	**96.6**	90 -100
	6.7	**80.7**	73 - 87
	4.75	**65.8**	57 - 71
	2.36	**45.8**	40 - 50
	1.18	**34.83**	30 - 40
	0.600	**26.17**	23 - 31
	0.300	**18.25**	15 - 23
	0.150	**11.14**	10 - 15
	0.075	**5.06**	3 - 6

MRWA 730.1	Bitumen Content (%)	**5.4**	5.3 - 5.9
MRWA 732.2	Rice Density (t/m^3)	**2.462**	
MRWA 733.1	Bulk Density (t/m^3)	**2.339**	
MRWA 733.1	Air Voids (%)	**5.0**	4.0 - 6.0
MRWA 731.1	Marshall Flow (mm)	**3.00**	2.0 - 4.0
MRWA 731.1	Marshall Stability (kN)	**12.4**	>6.5
MRWA 733.1	V.M.A. (%)	**17.4**	>15
MRWA 733.1	V.F.B. (%)	**71.1**	

Comments: ....

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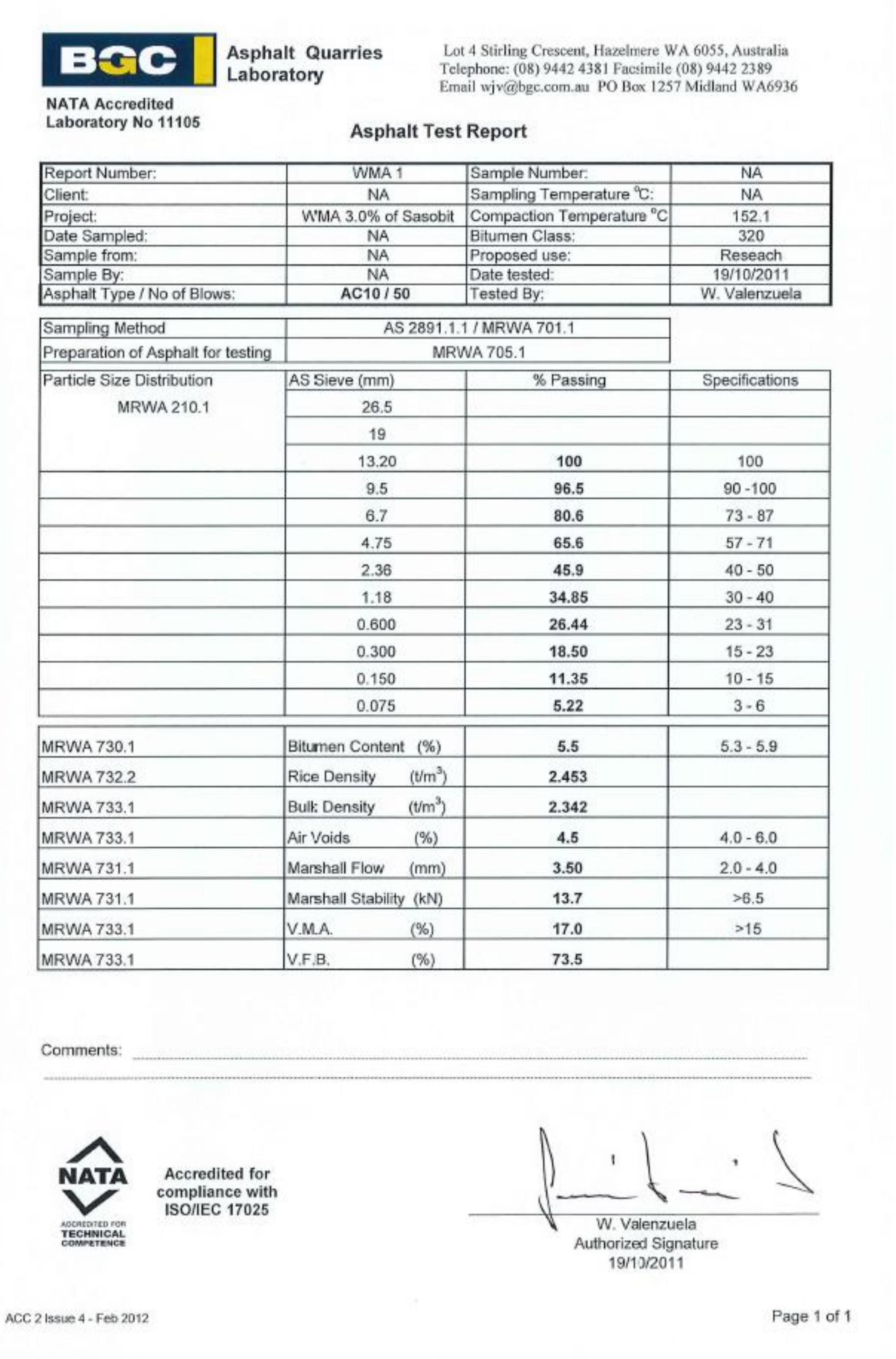

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Laboratory No 11105

Asphalt Test Report

Report Number:	WMA 1	Sample Number:	NA
Client:	NA	Sampling Temperature °C:	NA
Project:	WMA 3.0% of Sasobit	Compaction Temperature °C	152.1
Date Sampled:	NA	Bitumen Class:	320
Sample from:	NA	Proposed use:	Reseach
Sample By:	NA	Date tested:	19/10/2011
Asphalt Type / No of Blows:	**AC10 / 50**	Tested By:	W. Valenzuela

Sampling Method	AS 2891.1.1 / MRWA 701.1
Preparation of Asphalt for testing	MRWA 705.1

Particle Size Distribution	AS Sieve (mm)	% Passing	Specifications
MRWA 210.1	26.5		
	19		
	13.20	**100**	100
	9.5	**96.5**	90 -100
	6.7	**80.6**	73 - 87
	4.75	**65.6**	57 - 71
	2.36	**45.9**	40 - 50
	1.18	**34.85**	30 - 40
	0.600	**26.44**	23 - 31
	0.300	**18.50**	15 - 23
	0.150	**11.35**	10 - 15
	0.075	**5.22**	3 - 6

MRWA 730.1	Bitumen Content (%)	**5.5**	5.3 - 5.9
MRWA 732.2	Rice Density (t/m^3)	**2.453**	
MRWA 733.1	Bulk Density (t/m^3)	**2.342**	
MRWA 733.1	Air Voids (%)	**4.5**	4.0 - 6.0
MRWA 731.1	Marshall Flow (mm)	**3.50**	2.0 - 4.0
MRWA 731.1	Marshall Stability (kN)	**13.7**	>6.5
MRWA 733.1	V.M.A. (%)	**17.0**	>15
MRWA 733.1	V.F.B. (%)	**73.5**	

Comments: ....

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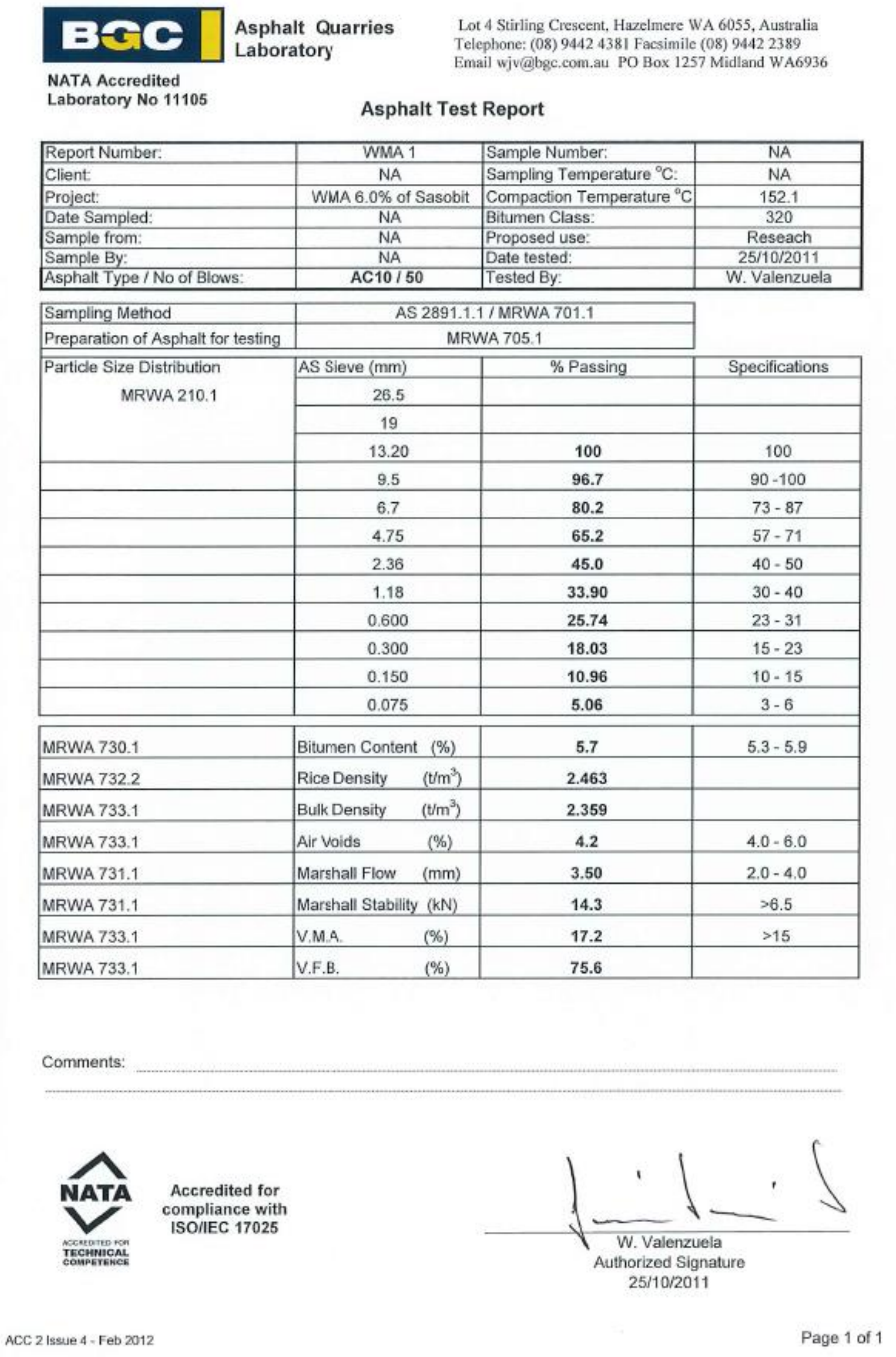

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Laboratory No 11105

Asphalt Test Report

Report Number:	WMA 1	Sample Number:	NA
Client:	NA	Sampling Temperature °C:	NA
Project:	WMA 6.0% of Sasobit	Compaction Temperature °C	152.1
Date Sampled:	NA	Bitumen Class:	320
Sample from:	NA	Proposed use:	Reseach
Sample By:	NA	Date tested:	25/10/2011
Asphalt Type / No of Blows:	**AC10 / 50**	Tested By:	W. Valenzuela

Sampling Method	AS 2891.1.1 / MRWA 701.1
Preparation of Asphalt for testing	MRWA 705.1

Particle Size Distribution	AS Sieve (mm)	% Passing	Specifications
MRWA 210.1	26.5		
	19		
	13.20	**100**	100
	9.5	**96.7**	90 -100
	6.7	**80.2**	73 - 87
	4.75	**65.2**	57 - 71
	2.36	**45.0**	40 - 50
	1.18	**33.90**	30 - 40
	0.600	**25.74**	23 - 31
	0.300	**18.03**	15 - 23
	0.150	**10.96**	10 - 15
	0.075	**5.06**	3 - 6

MRWA 730.1	Bitumen Content (%)	**5.7**	5.3 - 5.9
MRWA 732.2	Rice Density (t/m^3)	**2.463**	
MRWA 733.1	Bulk Density (t/m^3)	**2.359**	
MRWA 733.1	Air Voids (%)	**4.2**	4.0 - 6.0
MRWA 731.1	Marshall Flow (mm)	**3.50**	2.0 - 4.0
MRWA 731.1	Marshall Stability (kN)	**14.3**	>6.5
MRWA 733.1	V.M.A. (%)	**17.2**	>15
MRWA 733.1	V.F.B. (%)	**75.6**	

Comments: ....

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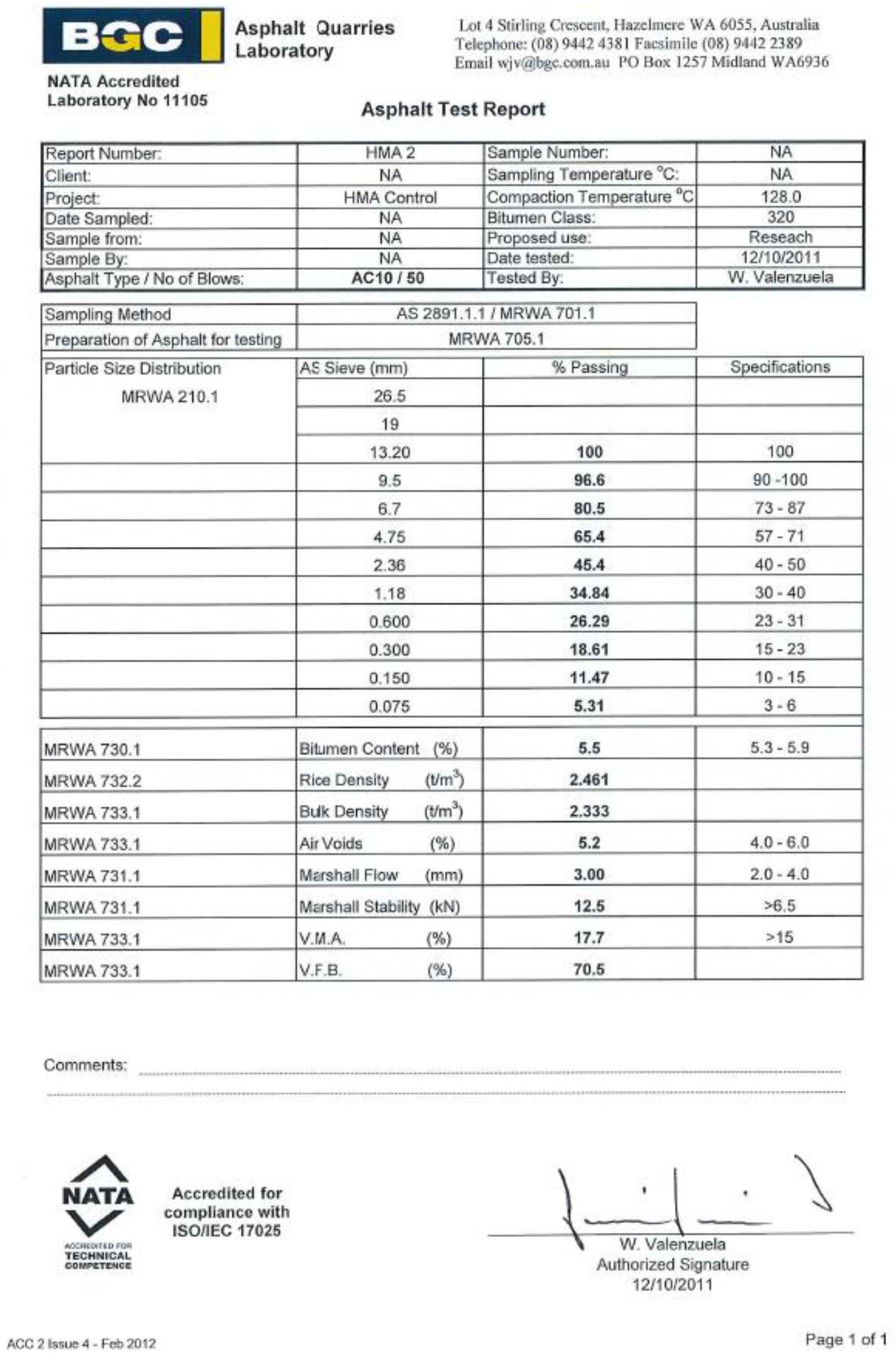

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Asphalt Test Report

Report Number:	HMA 2	Sample Number:	NA
Client:	NA	Sampling Temperature °C:	NA
Project:	HMA Control	Compaction Temperature °C	128.0
Date Sampled:	NA	Bitumen Class:	320
Sample from:	NA	Proposed use:	Reseach
Sample By:	NA	Date tested:	12/10/2011
Asphalt Type / No of Blows:	**AC10 / 50**	Tested By:	W. Valenzuela

Sampling Method	AS 2891.1.1 / MRWA 701.1
Preparation of Asphalt for testing	MRWA 705.1

Particle Size Distribution	AS Sieve (mm)	% Passing	Specifications
MRWA 210.1	26.5		
	19		
	13.20	**100**	100
	9.5	**96.6**	90 -100
	6.7	**80.5**	73 - 87
	4.75	**65.4**	57 - 71
	2.36	**45.4**	40 - 50
	1.18	**34.84**	30 - 40
	0.600	**26.29**	23 - 31
	0.300	**18.61**	15 - 23
	0.150	**11.47**	10 - 15
	0.075	**5.31**	3 - 6

MRWA 730.1	Bitumen Content (%)	**5.5**	5.3 - 5.9
MRWA 732.2	Rice Density (t/m^3)	**2.461**	
MRWA 733.1	Bulk Density (t/m^3)	**2.333**	
MRWA 733.1	Air Voids (%)	**5.2**	4.0 - 6.0
MRWA 731.1	Marshall Flow (mm)	**3.00**	2.0 - 4.0
MRWA 731.1	Marshall Stability (kN)	**12.5**	>6.5
MRWA 733.1	V.M.A. (%)	**17.7**	>15
MRWA 733.1	V.F.B. (%)	**70.5**	

Comments: ....

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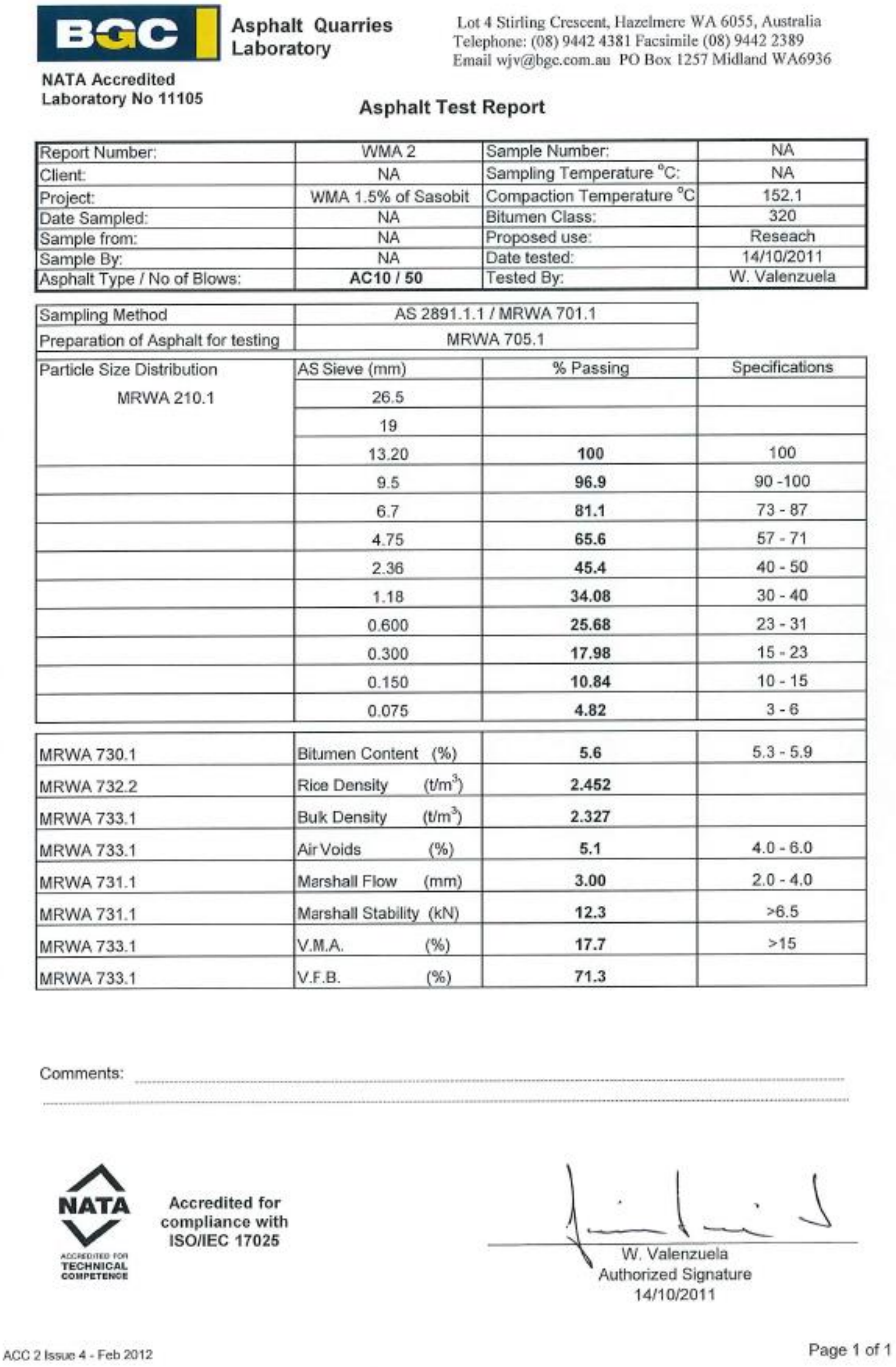

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Laboratory No 11105

Asphalt Test Report

Report Number:	WMA 2	Sample Number:	NA
Client:	NA	Sampling Temperature °C:	NA
Project:	WMA 1.5% of Sasobit	Compaction Temperature °C	152.1
Date Sampled:	NA	Bitumen Class:	320
Sample from:	NA	Proposed use:	Reseach
Sample By:	NA	Date tested:	14/10/2011
Asphalt Type / No of Blows:	**AC10 / 50**	Tested By:	W. Valenzuela

Sampling Method	AS 2891.1.1 / MRWA 701.1
Preparation of Asphalt for testing	MRWA 705.1

Particle Size Distribution	AS Sieve (mm)	% Passing	Specifications
MRWA 210.1	26.5		
	19		
	13.20	**100**	100
	9.5	**96.9**	90 -100
	6.7	**81.1**	73 - 87
	4.75	**65.6**	57 - 71
	2.36	**45.4**	40 - 50
	1.18	**34.08**	30 - 40
	0.600	**25.68**	23 - 31
	0.300	**17.98**	15 - 23
	0.150	**10.84**	10 - 15
	0.075	**4.82**	3 - 6

MRWA 730.1	Bitumen Content (%)	**5.6**	5.3 - 5.9
MRWA 732.2	Rice Density (t/m^3)	**2.452**	
MRWA 733.1	Bulk Density (t/m^3)	**2.327**	
MRWA 733.1	Air Voids (%)	**5.1**	4.0 - 6.0
MRWA 731.1	Marshall Flow (mm)	**3.00**	2.0 - 4.0
MRWA 731.1	Marshall Stability (kN)	**12.3**	>6.5
MRWA 733.1	V.M.A. (%)	**17.7**	>15
MRWA 733.1	V.F.B. (%)	**71.3**	

Comments: ……………………………………………………………………

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14/10/2011

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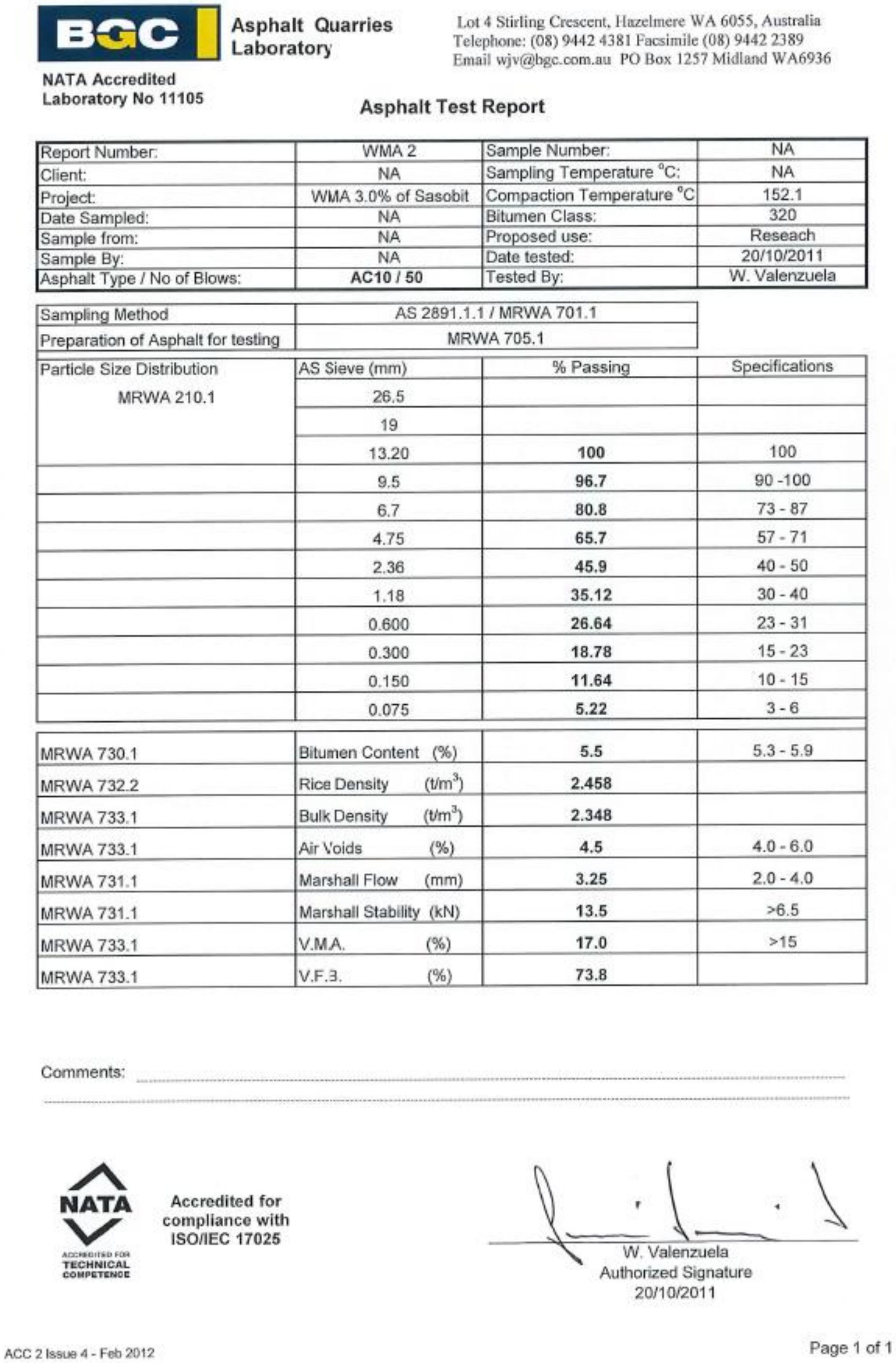

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Laboratory No 11105

Asphalt Test Report

Report Number:	WMA 2	Sample Number:	NA
Client:	NA	Sampling Temperature °C:	NA
Project:	WMA 3.0% of Sasobit	Compaction Temperature °C	152.1
Date Sampled:	NA	Bitumen Class:	320
Sample from:	NA	Proposed use:	Reseach
Sample By:	NA	Date tested:	20/10/2011
Asphalt Type / No of Blows:	**AC10 / 50**	Tested By:	W. Valenzuela

Sampling Method	AS 2891.1.1 / MRWA 701.1
Preparation of Asphalt for testing	MRWA 705.1

Particle Size Distribution	AS Sieve (mm)	% Passing	Specifications
MRWA 210.1	26.5		
	19		
	13.20	**100**	100
	9.5	**96.7**	90 -100
	6.7	**80.8**	73 - 87
	4.75	**65.7**	57 - 71
	2.36	**45.9**	40 - 50
	1.18	**35.12**	30 - 40
	0.600	**26.64**	23 - 31
	0.300	**18.78**	15 - 23
	0.150	**11.64**	10 - 15
	0.075	**5.22**	3 - 6

MRWA 730.1	Bitumen Content (%)	**5.5**	5.3 - 5.9
MRWA 732.2	Rice Density (t/m^3)	**2.458**	
MRWA 733.1	Bulk Density (t/m^3)	**2.348**	
MRWA 733.1	Air Voids (%)	**4.5**	4.0 - 6.0
MRWA 731.1	Marshall Flow (mm)	**3.25**	2.0 - 4.0
MRWA 731.1	Marshall Stability (kN)	**13.5**	>6.5
MRWA 733.1	V.M.A. (%)	**17.0**	>15
MRWA 733.1	V.F.B. (%)	**73.8**	

Comments: ....

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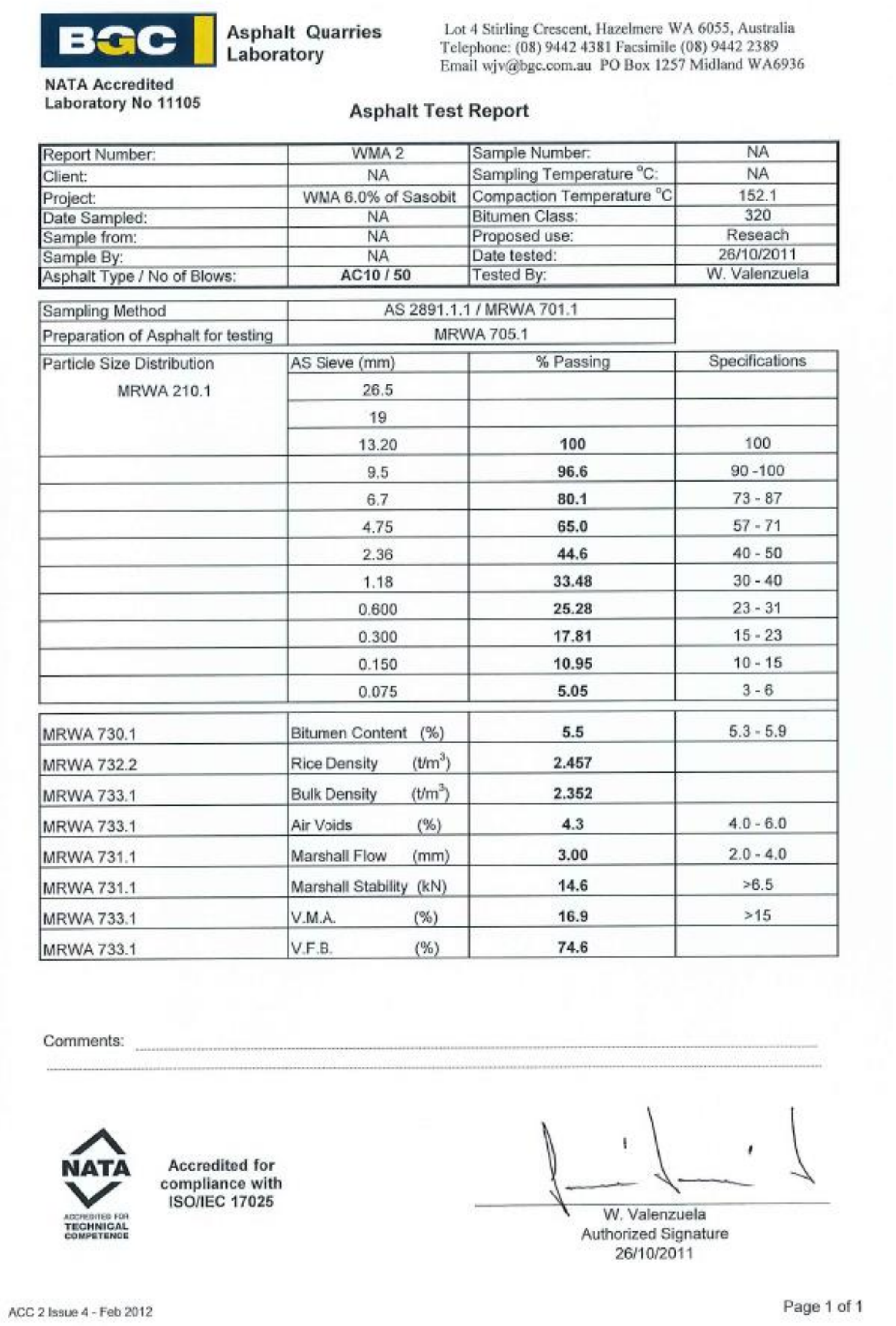

BGC **Asphalt Quarries Laboratory**

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Laboratory No 11105

Asphalt Test Report

Report Number:	WMA 2	Sample Number:	NA
Client:	NA	Sampling Temperature °C:	NA
Project:	WMA 6.0% of Sasobit	Compaction Temperature °C	152.1
Date Sampled:	NA	Bitumen Class:	320
Sample from:	NA	Proposed use:	Reseach
Sample By:	NA	Date tested:	26/10/2011
Asphalt Type / No of Blows:	**AC10 / 50**	Tested By:	W. Valenzuela

Sampling Method	AS 2891.1.1 / MRWA 701.1
Preparation of Asphalt for testing	MRWA 705.1

Particle Size Distribution	AS Sieve (mm)	% Passing	Specifications
MRWA 210.1	26.5		
	19		
	13.20	**100**	100
	9.5	**96.6**	90 -100
	6.7	**80.1**	73 - 87
	4.75	**65.0**	57 - 71
	2.36	**44.6**	40 - 50
	1.18	**33.48**	30 - 40
	0.600	**25.28**	23 - 31
	0.300	**17.81**	15 - 23
	0.150	**10.95**	10 - 15
	0.075	**5.05**	3 - 6

MRWA 730.1	Bitumen Content (%)	**5.5**	5.3 - 5.9
MRWA 732.2	Rice Density (t/m^3)	**2.457**	
MRWA 733.1	Bulk Density (t/m^3)	**2.352**	
MRWA 733.1	Air Voids (%)	**4.3**	4.0 - 6.0
MRWA 731.1	Marshall Flow (mm)	**3.00**	2.0 - 4.0
MRWA 731.1	Marshall Stability (kN)	**14.6**	>6.5
MRWA 733.1	V.M.A. (%)	**16.9**	>15
MRWA 733.1	V.F.B. (%)	**74.6**	

Comments: ....

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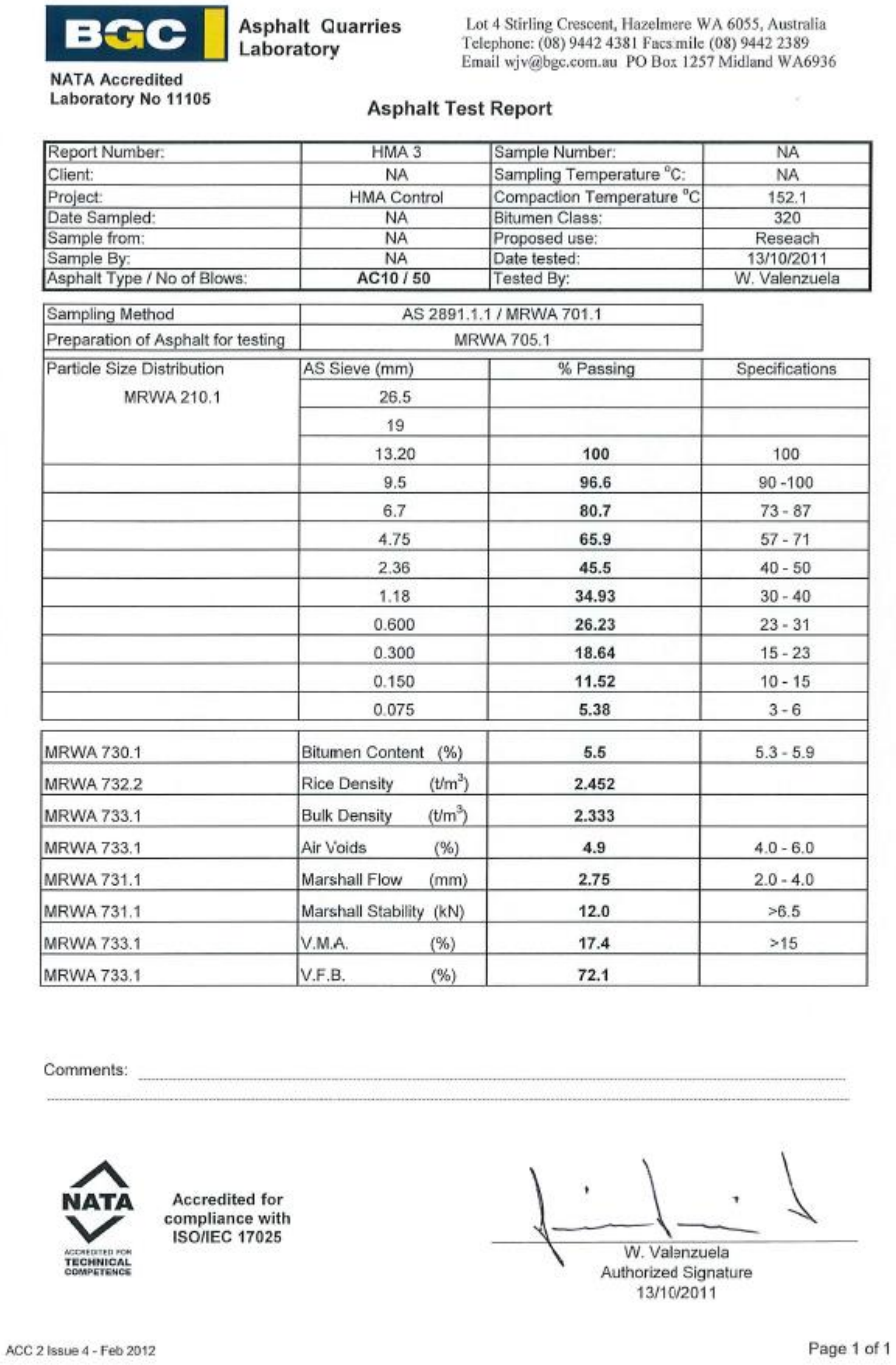

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Asphalt Test Report

Report Number:	HMA 3	Sample Number:	NA
Client:	NA	Sampling Temperature °C:	NA
Project:	HMA Control	Compaction Temperature °C	152.1
Date Sampled:	NA	Bitumen Class:	320
Sample from:	NA	Proposed use:	Reseach
Sample By:	NA	Date tested:	13/10/2011
Asphalt Type / No of Blows:	**AC10 / 50**	Tested By:	W. Valenzuela

Sampling Method	AS 2891.1.1 / MRWA 701.1
Preparation of Asphalt for testing	MRWA 705.1

Particle Size Distribution	AS Sieve (mm)	% Passing	Specifications
MRWA 210.1	26.5		
	19		
	13.20	**100**	100
	9.5	**96.6**	90 -100
	6.7	**80.7**	73 - 87
	4.75	**65.9**	57 - 71
	2.36	**45.5**	40 - 50
	1.18	**34.93**	30 - 40
	0.600	**26.23**	23 - 31
	0.300	**18.64**	15 - 23
	0.150	**11.52**	10 - 15
	0.075	**5.38**	3 - 6

MRWA 730.1	Bitumen Content (%)	**5.5**	5.3 - 5.9
MRWA 732.2	Rice Density (t/m^3)	**2.452**	
MRWA 733.1	Bulk Density (t/m^3)	**2.333**	
MRWA 733.1	Air Voids (%)	**4.9**	4.0 - 6.0
MRWA 731.1	Marshall Flow (mm)	**2.75**	2.0 - 4.0
MRWA 731.1	Marshall Stability (kN)	**12.0**	>6.5
MRWA 733.1	V.M.A. (%)	**17.4**	>15
MRWA 733.1	V.F.B. (%)	**72.1**	

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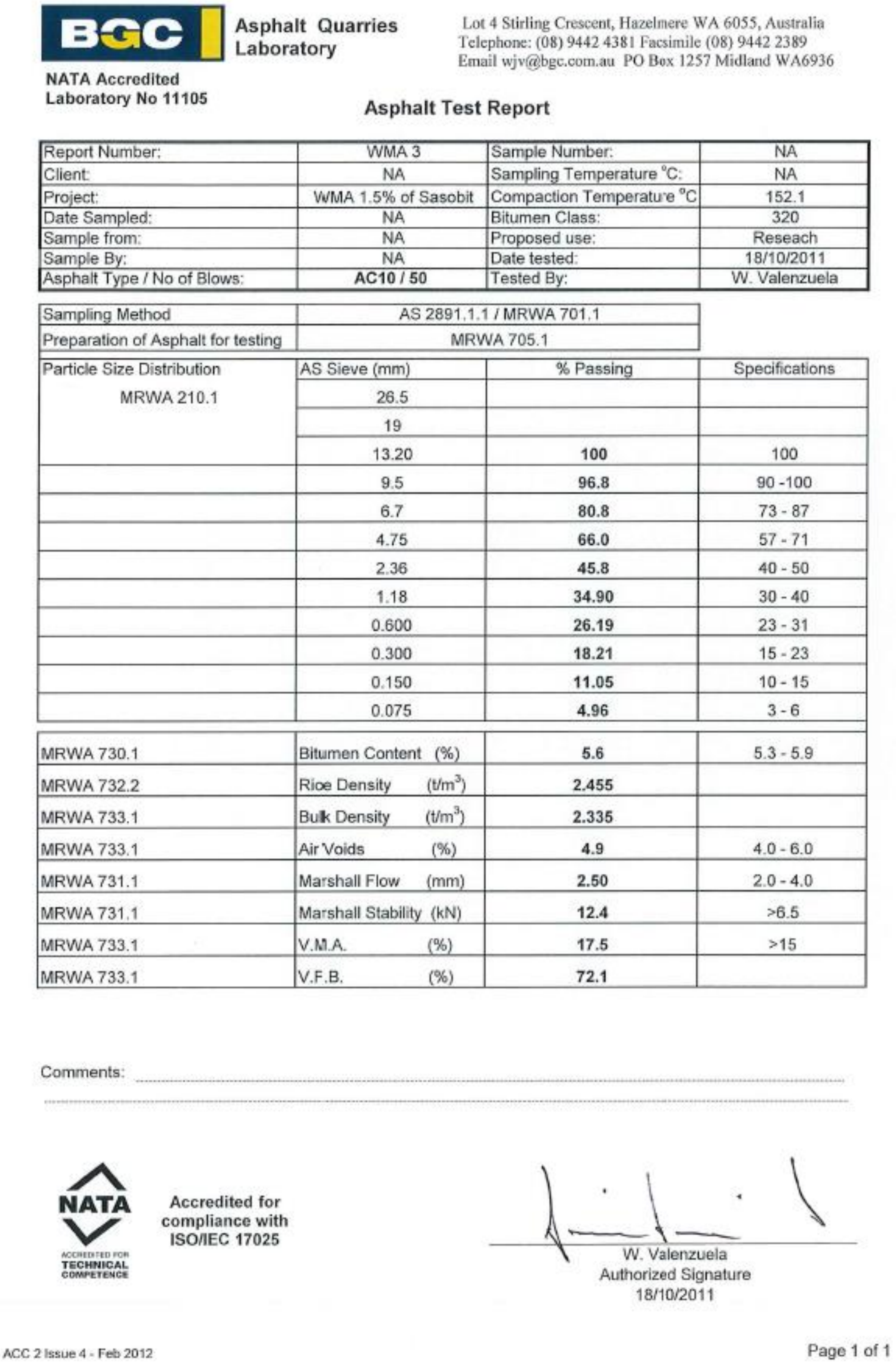

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Asphalt Test Report

Report Number:	WMA 3	Sample Number:	NA
Client:	NA	Sampling Temperature °C:	NA
Project:	WMA 1.5% of Sasobit	Compaction Temperature °C	152.1
Date Sampled:	NA	Bitumen Class:	320
Sample from:	NA	Proposed use:	Reseach
Sample By:	NA	Date tested:	18/10/2011
Asphalt Type / No of Blows:	**AC10 / 50**	Tested By:	W. Valenzuela

Sampling Method	AS 2891.1.1 / MRWA 701.1
Preparation of Asphalt for testing	MRWA 705.1

Particle Size Distribution	AS Sieve (mm)	% Passing	Specifications
MRWA 210.1	26.5		
	19		
	13.20	**100**	100
	9.5	**96.8**	90 -100
	6.7	**80.8**	73 - 87
	4.75	**66.0**	57 - 71
	2.36	**45.8**	40 - 50
	1.18	**34.90**	30 - 40
	0.600	**26.19**	23 - 31
	0.300	**18.21**	15 - 23
	0.150	**11.05**	10 - 15
	0.075	**4.96**	3 - 6

MRWA 730.1	Bitumen Content (%)	**5.6**	5.3 - 5.9
MRWA 732.2	Rice Density (t/m^3)	**2.455**	
MRWA 733.1	Bulk Density (t/m^3)	**2.335**	
MRWA 733.1	Air Voids (%)	**4.9**	4.0 - 6.0
MRWA 731.1	Marshall Flow (mm)	**2.50**	2.0 - 4.0
MRWA 731.1	Marshall Stability (kN)	**12.4**	>6.5
MRWA 733.1	V.M.A. (%)	**17.5**	>15
MRWA 733.1	V.F.B. (%)	**72.1**	

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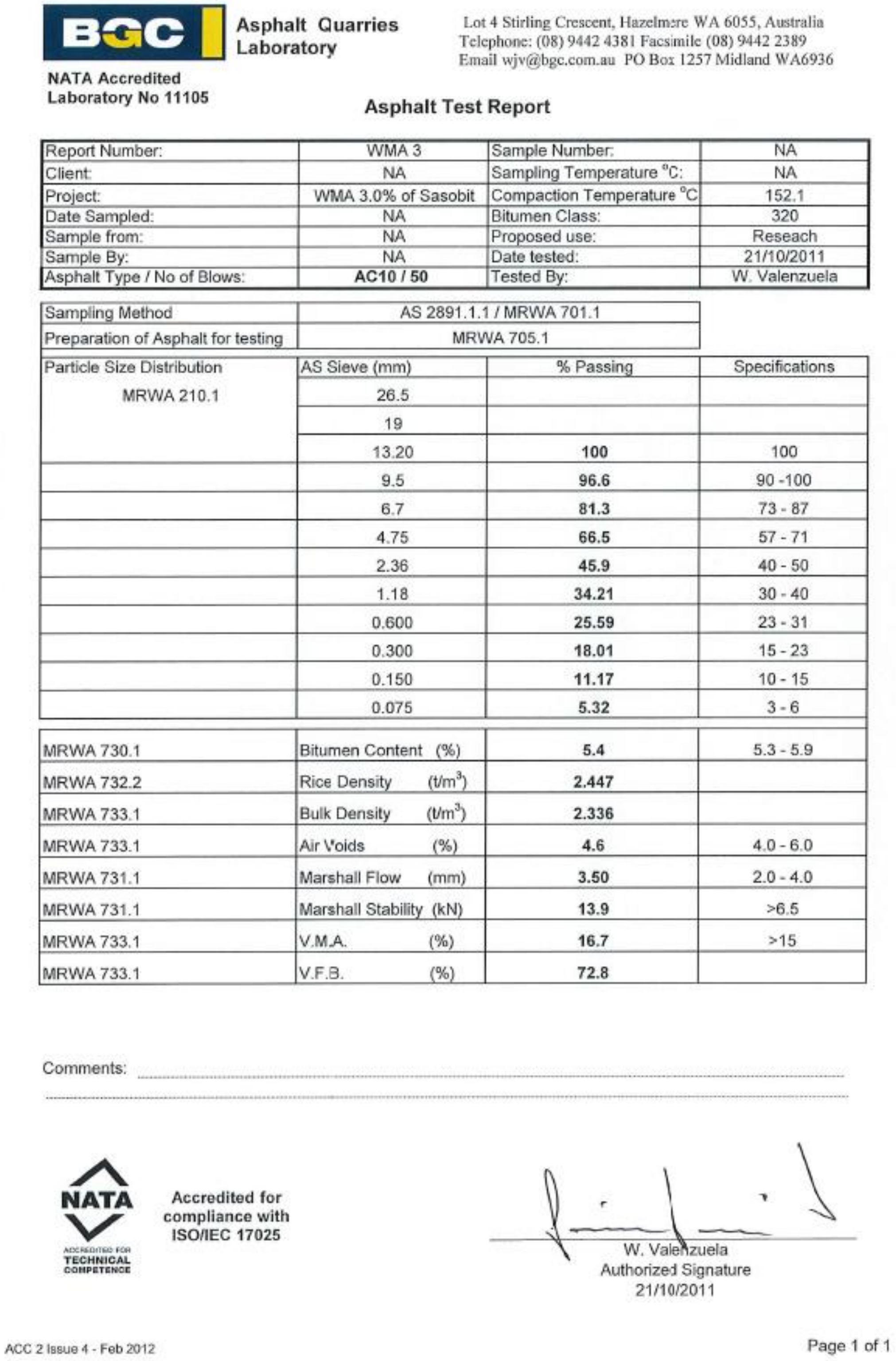

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Asphalt Test Report

Report Number:	WMA 3	Sample Number:	NA
Client:	NA	Sampling Temperature °C:	NA
Project:	WMA 3.0% of Sasobit	Compaction Temperature °C	152.1
Date Sampled:	NA	Bitumen Class:	320
Sample from:	NA	Proposed use:	Reseach
Sample By:	NA	Date tested:	21/10/2011
Asphalt Type / No of Blows:	**AC10 / 50**	Tested By:	W. Valenzuela

Sampling Method	AS 2891.1.1 / MRWA 701.1
Preparation of Asphalt for testing	MRWA 705.1

Particle Size Distribution	AS Sieve (mm)	% Passing	Specifications
MRWA 210.1	26.5		
	19		
	13.20	**100**	100
	9.5	**96.6**	90 -100
	6.7	**81.3**	73 - 87
	4.75	**66.5**	57 - 71
	2.36	**45.9**	40 - 50
	1.18	**34.21**	30 - 40
	0.600	**25.59**	23 - 31
	0.300	**18.01**	15 - 23
	0.150	**11.17**	10 - 15
	0.075	**5.32**	3 - 6

MRWA 730.1	Bitumen Content (%)	**5.4**	5.3 - 5.9
MRWA 732.2	Rice Density (t/m³)	**2.447**	
MRWA 733.1	Bulk Density (t/m³)	**2.336**	
MRWA 733.1	Air Voids (%)	**4.6**	4.0 - 6.0
MRWA 731.1	Marshall Flow (mm)	**3.50**	2.0 - 4.0
MRWA 731.1	Marshall Stability (kN)	**13.9**	>6.5
MRWA 733.1	V.M.A. (%)	**16.7**	>15
MRWA 733.1	V.F.B. (%)	**72.8**	

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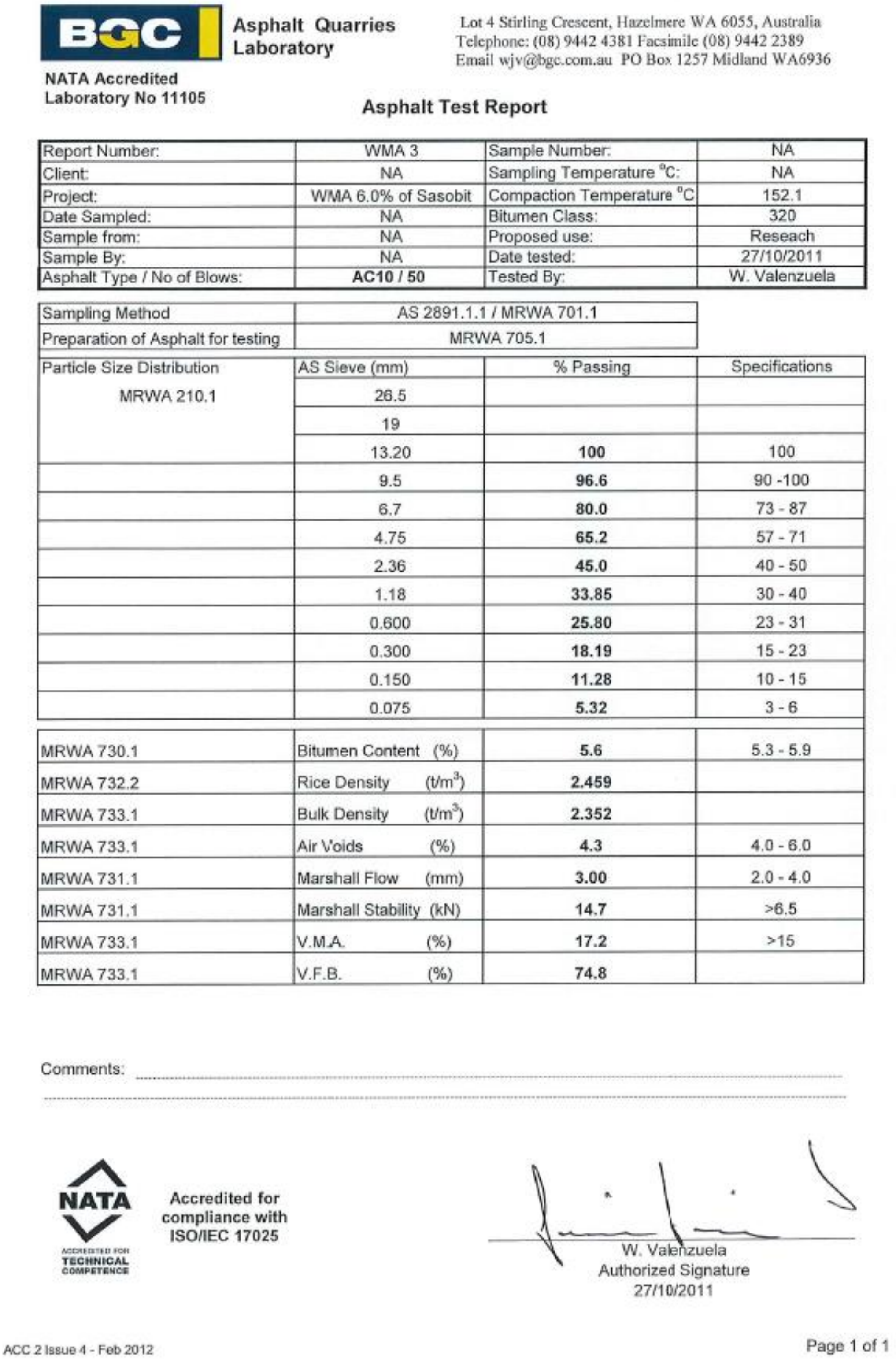

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Asphalt Test Report

Report Number:	WMA 3	Sample Number:	NA
Client:	NA	Sampling Temperature °C:	NA
Project:	WMA 6.0% of Sasobit	Compaction Temperature °C	152.1
Date Sampled:	NA	Bitumen Class:	320
Sample from:	NA	Proposed use:	Reseach
Sample By:	NA	Date tested:	27/10/2011
Asphalt Type / No of Blows:	**AC10 / 50**	Tested By:	W. Valenzuela

Sampling Method	AS 2891.1.1 / MRWA 701.1
Preparation of Asphalt for testing	MRWA 705.1

Particle Size Distribution	AS Sieve (mm)	% Passing	Specifications
MRWA 210.1	26.5		
	19		
	13.20	**100**	100
	9.5	**96.6**	90 -100
	6.7	**80.0**	73 - 87
	4.75	**65.2**	57 - 71
	2.36	**45.0**	40 - 50
	1.18	**33.85**	30 - 40
	0.600	**25.80**	23 - 31
	0.300	**18.19**	15 - 23
	0.150	**11.28**	10 - 15
	0.075	**5.32**	3 - 6

MRWA 730.1	Bitumen Content (%)	**5.6**	5.3 - 5.9
MRWA 732.2	Rice Density (t/m^3)	**2.459**	
MRWA 733.1	Bulk Density (t/m^3)	**2.352**	
MRWA 733.1	Air Voids (%)	**4.3**	4.0 - 6.0
MRWA 731.1	Marshall Flow (mm)	**3.00**	2.0 - 4.0
MRWA 731.1	Marshall Stability (kN)	**14.7**	>6.5
MRWA 733.1	V.M.A. (%)	**17.2**	>15
MRWA 733.1	V.F.B. (%)	**74.8**	

Comments: ....

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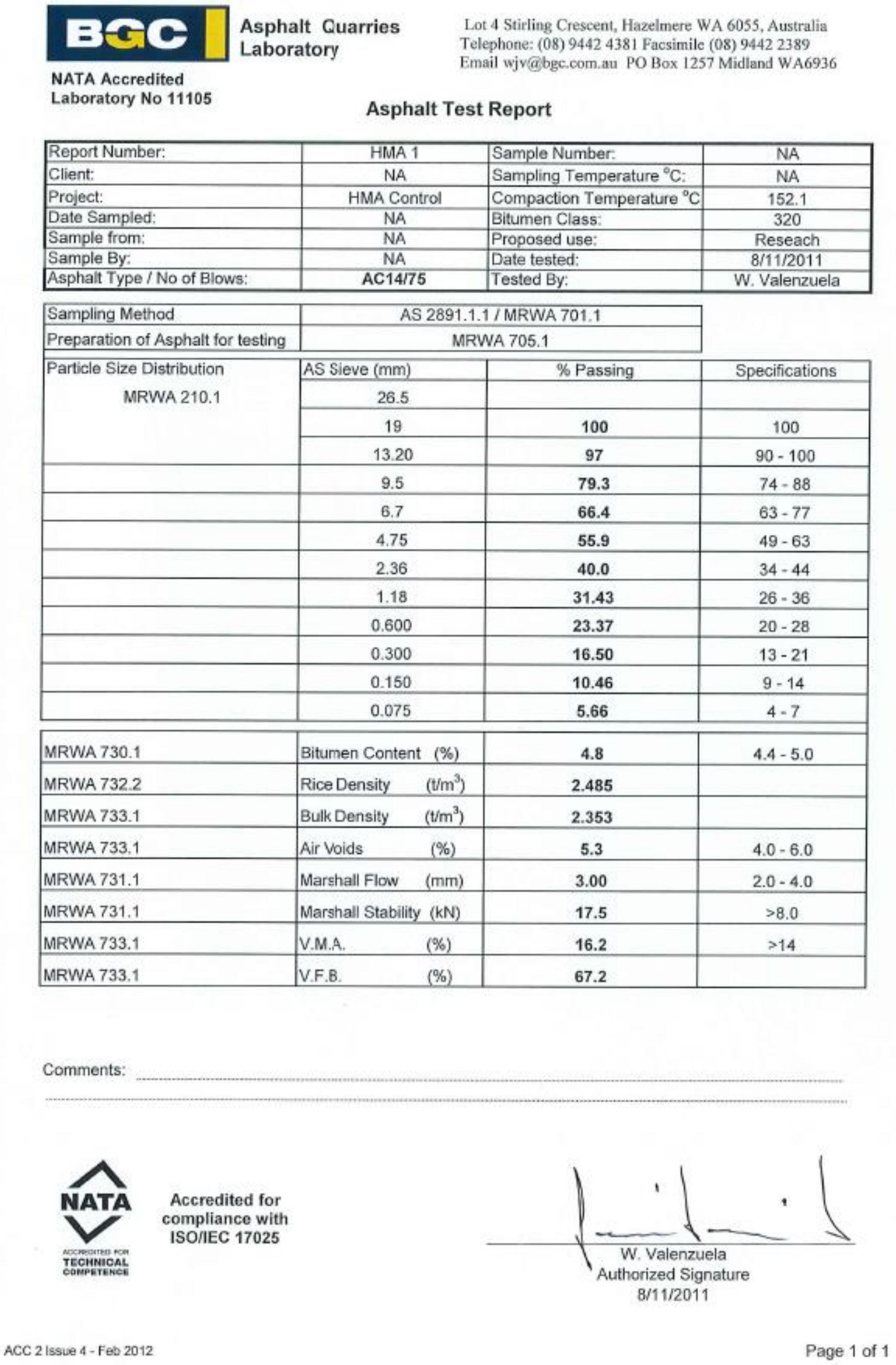

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Asphalt Test Report

Report Number:	HMA 1	Sample Number:	NA
Client:	NA	Sampling Temperature °C:	NA
Project:	HMA Control	Compaction Temperature °C	152.1
Date Sampled:	NA	Bitumen Class:	320
Sample from:	NA	Proposed use:	Reseach
Sample By:	NA	Date tested:	8/11/2011
Asphalt Type / No of Blows:	**AC14/75**	Tested By:	W. Valenzuela

Sampling Method	AS 2891.1.1 / MRWA 701.1
Preparation of Asphalt for testing	MRWA 705.1

Particle Size Distribution	AS Sieve (mm)	% Passing	Specifications
MRWA 210.1	26.5		
	19	**100**	100
	13.20	**97**	90 - 100
	9.5	**79.3**	74 - 88
	6.7	**66.4**	63 - 77
	4.75	**55.9**	49 - 63
	2.36	**40.0**	34 - 44
	1.18	**31.43**	26 - 36
	0.600	**23.37**	20 - 28
	0.300	**16.50**	13 - 21
	0.150	**10.46**	9 - 14
	0.075	**5.66**	4 - 7

MRWA 730.1	Bitumen Content (%)	**4.8**	4.4 - 5.0
MRWA 732.2	Rice Density (t/m^3)	**2.485**	
MRWA 733.1	Bulk Density (t/m^3)	**2.353**	
MRWA 733.1	Air Voids (%)	**5.3**	4.0 - 6.0
MRWA 731.1	Marshall Flow (mm)	**3.00**	2.0 - 4.0
MRWA 731.1	Marshall Stability (kN)	**17.5**	>8.0
MRWA 733.1	V.M.A. (%)	**16.2**	>14
MRWA 733.1	V.F.B. (%)	**67.2**	

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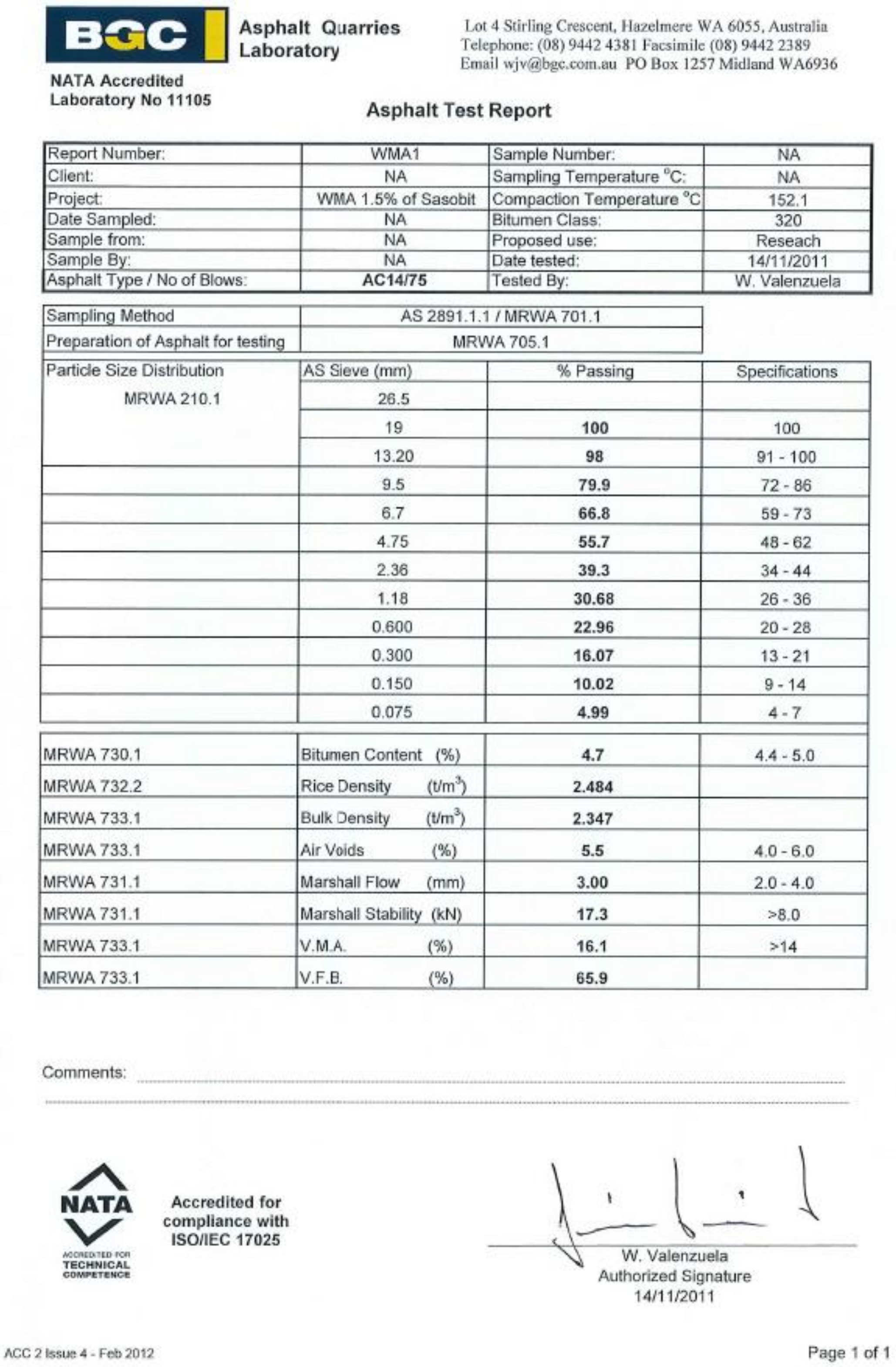

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Asphalt Test Report

Report Number:	WMA1	Sample Number:	NA
Client:	NA	Sampling Temperature °C:	NA
Project:	WMA 1.5% of Sasobit	Compaction Temperature °C	152.1
Date Sampled:	NA	Bitumen Class:	320
Sample from:	NA	Proposed use:	Reseach
Sample By:	NA	Date tested:	14/11/2011
Asphalt Type / No of Blows:	**AC14/75**	Tested By:	W. Valenzuela

Sampling Method	AS 2891.1.1 / MRWA 701.1
Preparation of Asphalt for testing	MRWA 705.1

Particle Size Distribution	AS Sieve (mm)	% Passing	Specifications
MRWA 210.1	26.5		
	19	**100**	100
	13.20	**98**	91 - 100
	9.5	**79.9**	72 - 86
	6.7	**66.8**	59 - 73
	4.75	**55.7**	48 - 62
	2.36	**39.3**	34 - 44
	1.18	**30.68**	26 - 36
	0.600	**22.96**	20 - 28
	0.300	**16.07**	13 - 21
	0.150	**10.02**	9 - 14
	0.075	**4.99**	4 - 7

MRWA 730.1	Bitumen Content (%)	**4.7**	4.4 - 5.0
MRWA 732.2	Rice Density (t/m^3)	**2.484**	
MRWA 733.1	Bulk Density (t/m^3)	**2.347**	
MRWA 733.1	Air Voids (%)	**5.5**	4.0 - 6.0
MRWA 731.1	Marshall Flow (mm)	**3.00**	2.0 - 4.0
MRWA 731.1	Marshall Stability (kN)	**17.3**	>8.0
MRWA 733.1	V.M.A. (%)	**16.1**	>14
MRWA 733.1	V.F.B. (%)	**65.9**	

Comments: ....

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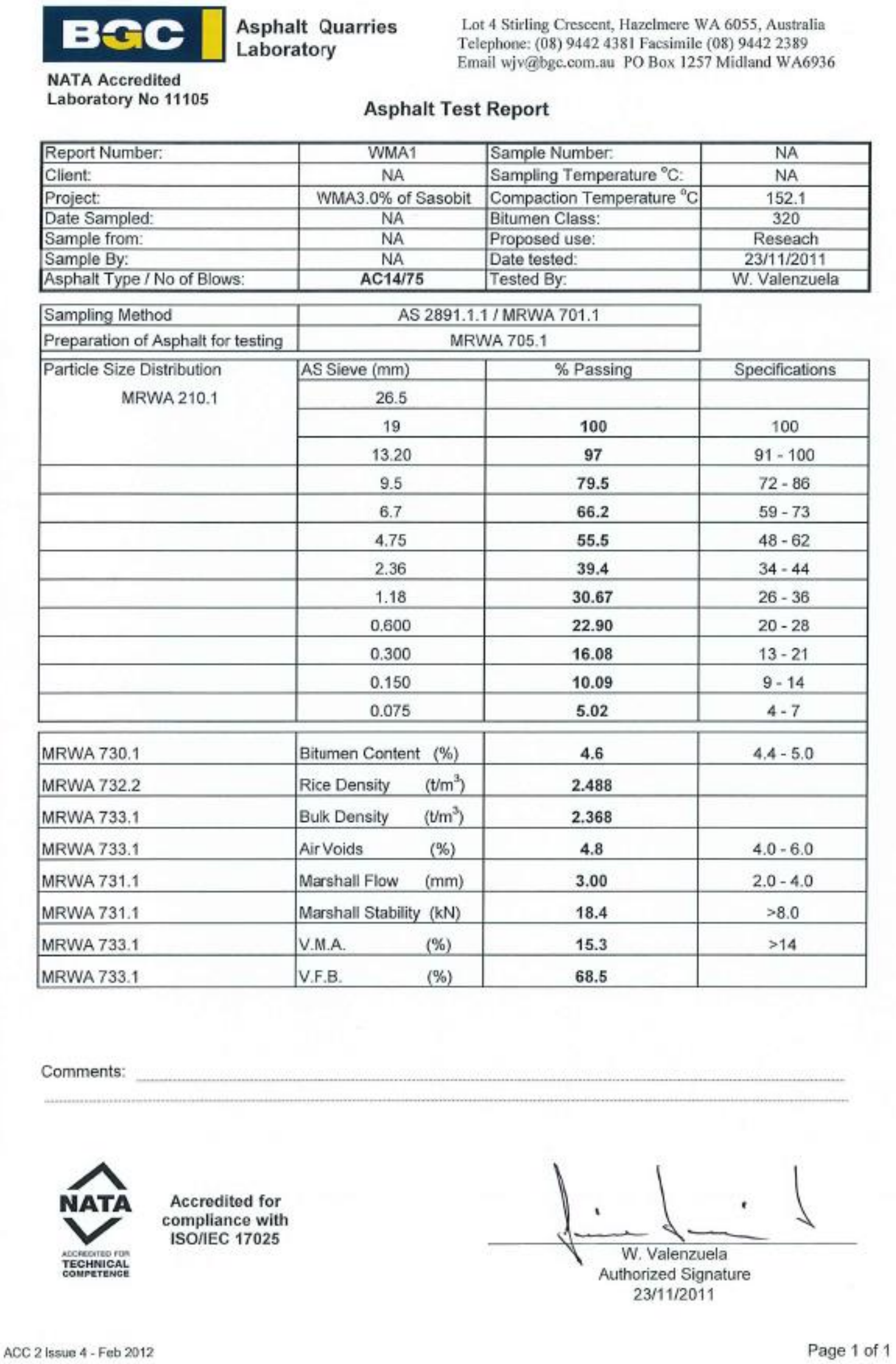

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Asphalt Test Report

Report Number:	WMA1	Sample Number:	NA
Client:	NA	Sampling Temperature °C:	NA
Project:	WMA3.0% of Sasobit	Compaction Temperature °C	152.1
Date Sampled:	NA	Bitumen Class:	320
Sample from:	NA	Proposed use:	Reseach
Sample By:	NA	Date tested:	23/11/2011
Asphalt Type / No of Blows:	**AC14/75**	Tested By:	W. Valenzuela

Sampling Method	AS 2891.1.1 / MRWA 701.1
Preparation of Asphalt for testing	MRWA 705.1

Particle Size Distribution	AS Sieve (mm)	% Passing	Specifications
MRWA 210.1	26.5		
	19	**100**	100
	13.20	**97**	91 - 100
	9.5	**79.5**	72 - 86
	6.7	**66.2**	59 - 73
	4.75	**55.5**	48 - 62
	2.36	**39.4**	34 - 44
	1.18	**30.67**	26 - 36
	0.600	**22.90**	20 - 28
	0.300	**16.08**	13 - 21
	0.150	**10.09**	9 - 14
	0.075	**5.02**	4 - 7

MRWA 730.1	Bitumen Content (%)	**4.6**	4.4 - 5.0
MRWA 732.2	Rice Density (t/m^3)	**2.488**	
MRWA 733.1	Bulk Density (t/m^3)	**2.368**	
MRWA 733.1	Air Voids (%)	**4.8**	4.0 - 6.0
MRWA 731.1	Marshall Flow (mm)	**3.00**	2.0 - 4.0
MRWA 731.1	Marshall Stability (kN)	**18.4**	>8.0
MRWA 733.1	V.M.A. (%)	**15.3**	>14
MRWA 733.1	V.F.B. (%)	**68.5**	

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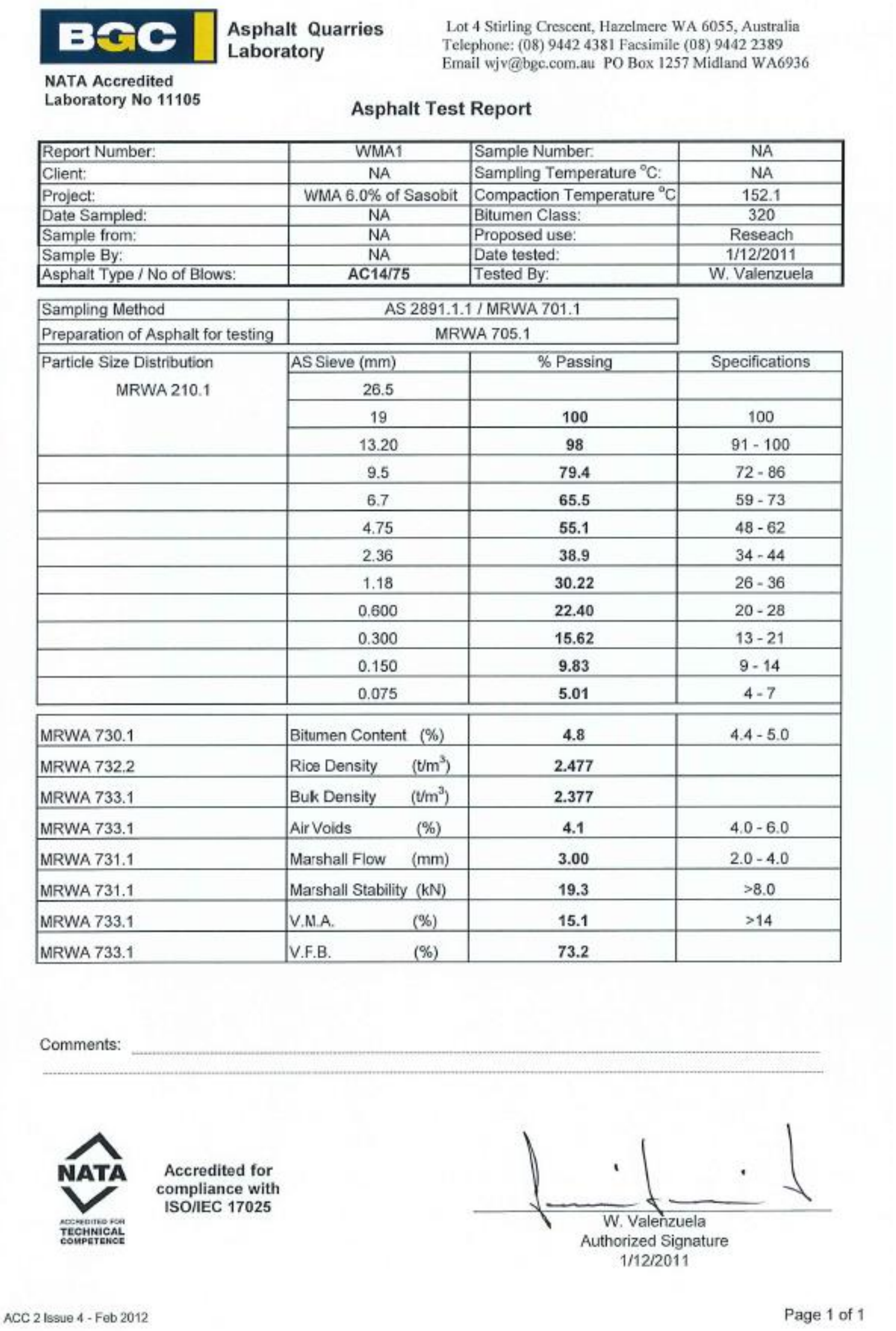

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Asphalt Test Report

Report Number:	WMA1	Sample Number:	NA
Client:	NA	Sampling Temperature °C:	NA
Project:	WMA 6.0% of Sasobit	Compaction Temperature °C	152.1
Date Sampled:	NA	Bitumen Class:	320
Sample from:	NA	Proposed use:	Reseach
Sample By:	NA	Date tested:	1/12/2011
Asphalt Type / No of Blows:	**AC14/75**	Tested By:	W. Valenzuela

Sampling Method	AS 2891.1.1 / MRWA 701.1
Preparation of Asphalt for testing	MRWA 705.1

Particle Size Distribution	AS Sieve (mm)	% Passing	Specifications
MRWA 210.1	26.5		
	19	**100**	100
	13.20	**98**	91 - 100
	9.5	**79.4**	72 - 86
	6.7	**65.5**	59 - 73
	4.75	**55.1**	48 - 62
	2.36	**38.9**	34 - 44
	1.18	**30.22**	26 - 36
	0.600	**22.40**	20 - 28
	0.300	**15.62**	13 - 21
	0.150	**9.83**	9 - 14
	0.075	**5.01**	4 - 7

MRWA 730.1	Bitumen Content (%)	**4.8**	4.4 - 5.0
MRWA 732.2	Rice Density (t/m^3)	**2.477**	
MRWA 733.1	Bulk Density (t/m^3)	**2.377**	
MRWA 733.1	Air Voids (%)	**4.1**	4.0 - 6.0
MRWA 731.1	Marshall Flow (mm)	**3.00**	2.0 - 4.0
MRWA 731.1	Marshall Stability (kN)	**19.3**	>8.0
MRWA 733.1	V.M.A. (%)	**15.1**	>14
MRWA 733.1	V.F.B. (%)	**73.2**	

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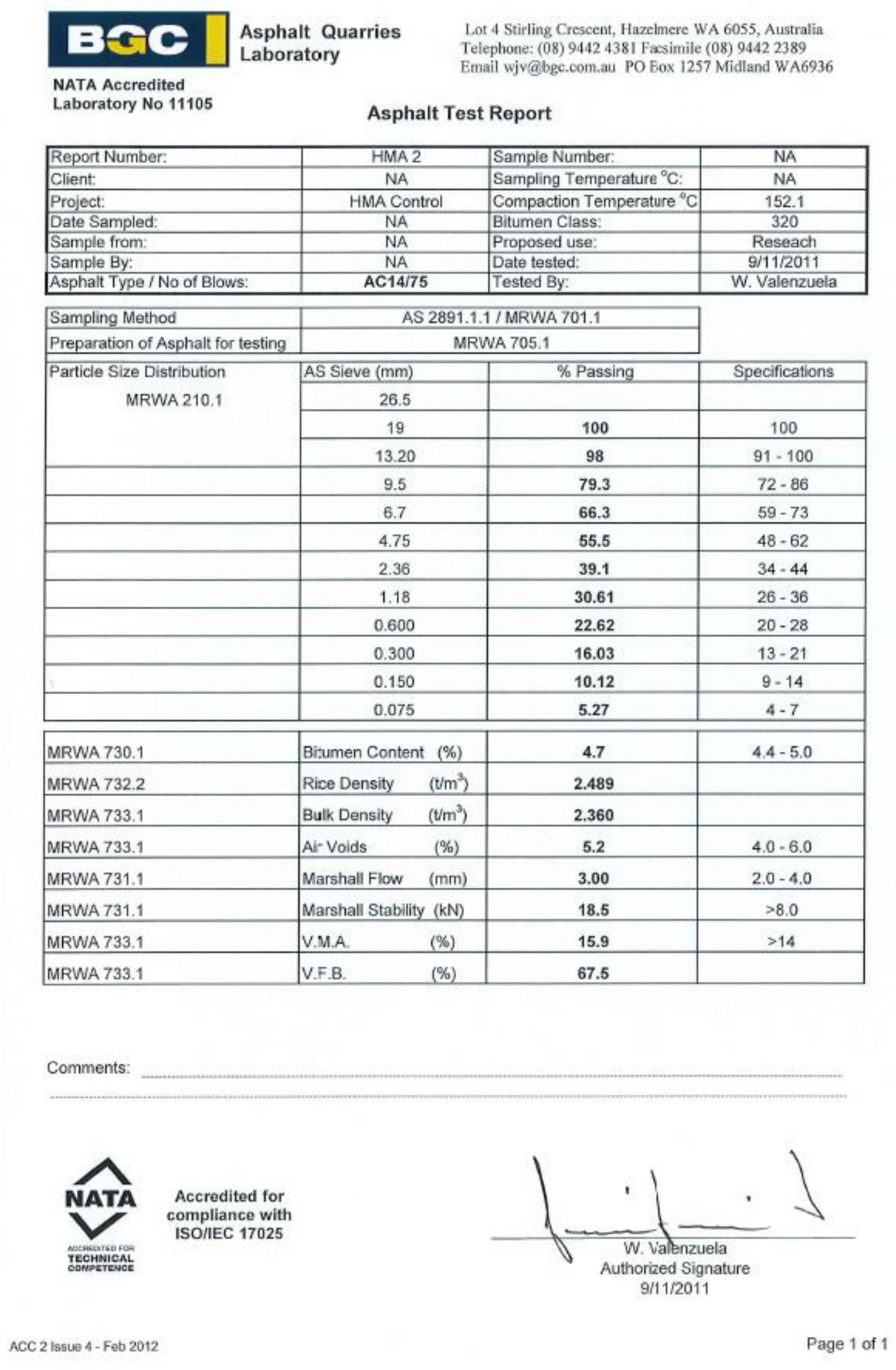

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Laboratory No 11105

Asphalt Test Report

Report Number:	HMA 2	Sample Number:	NA
Client:	NA	Sampling Temperature °C:	NA
Project:	HMA Control	Compaction Temperature °C	152.1
Date Sampled:	NA	Bitumen Class:	320
Sample from:	NA	Proposed use:	Reseach
Sample By:	NA	Date tested:	9/11/2011
Asphalt Type / No of Blows:	**AC14/75**	Tested By:	W. Valenzuela

Sampling Method	AS 2891.1.1 / MRWA 701.1
Preparation of Asphalt for testing	MRWA 705.1

Particle Size Distribution	AS Sieve (mm)	% Passing	Specifications
MRWA 210.1	26.5		
	19	**100**	100
	13.20	**98**	91 - 100
	9.5	**79.3**	72 - 86
	6.7	**66.3**	59 - 73
	4.75	**55.5**	48 - 62
	2.36	**39.1**	34 - 44
	1.18	**30.61**	26 - 36
	0.600	**22.62**	20 - 28
	0.300	**16.03**	13 - 21
	0.150	**10.12**	9 - 14
	0.075	**5.27**	4 - 7

MRWA 730.1	Bitumen Content (%)	**4.7**	4.4 - 5.0
MRWA 732.2	Rice Density (t/m^3)	**2.489**	
MRWA 733.1	Bulk Density (t/m^3)	**2.360**	
MRWA 733.1	Air Voids (%)	**5.2**	4.0 - 6.0
MRWA 731.1	Marshall Flow (mm)	**3.00**	2.0 - 4.0
MRWA 731.1	Marshall Stability (kN)	**18.5**	>8.0
MRWA 733.1	V.M.A. (%)	**15.9**	>14
MRWA 733.1	V.F.B. (%)	**67.5**	

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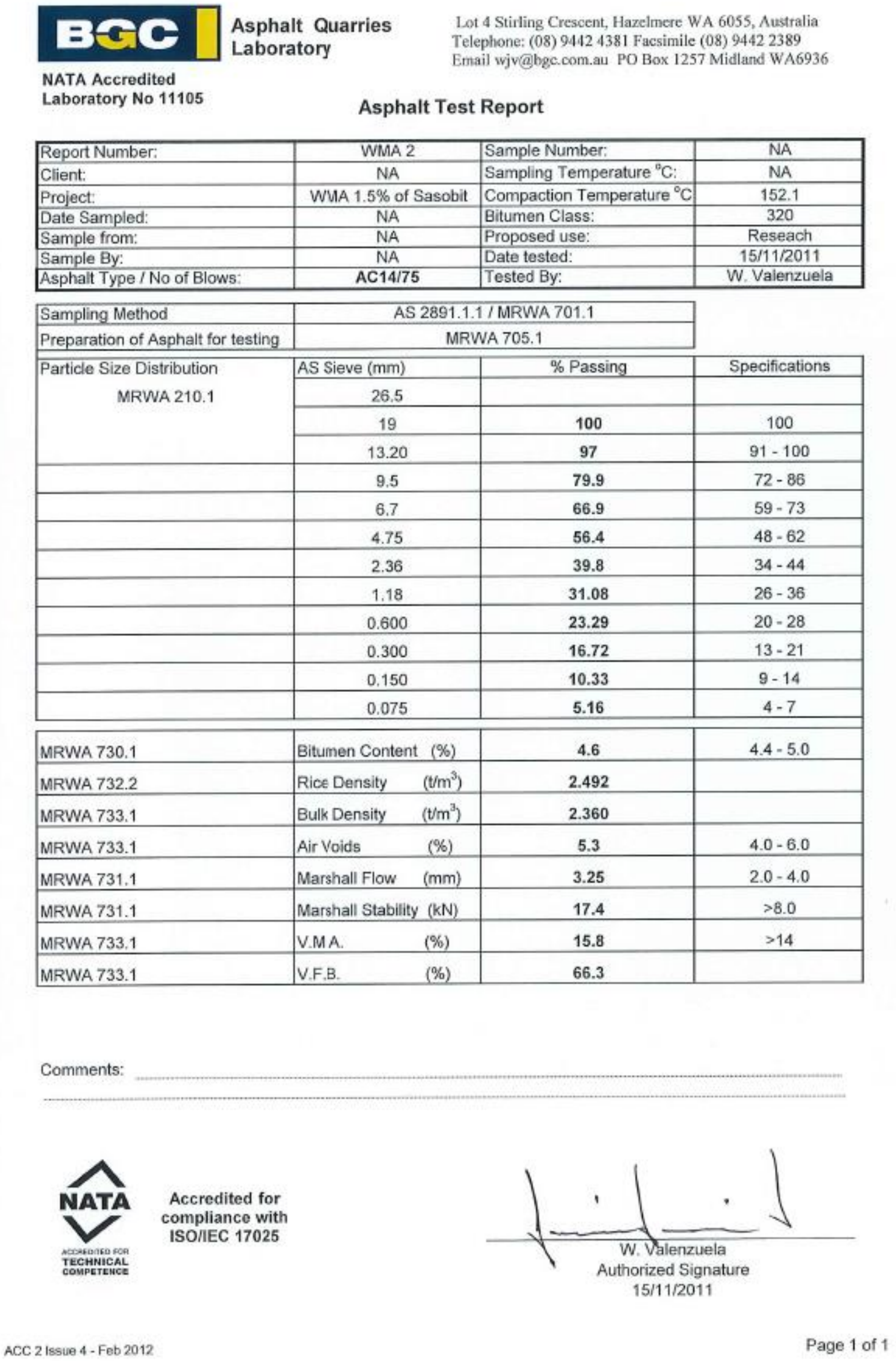

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Asphalt Test Report

Report Number:	WMA 2	Sample Number:	NA
Client:	NA	Sampling Temperature °C:	NA
Project:	WMA 1.5% of Sasobit	Compaction Temperature °C	152.1
Date Sampled:	NA	Bitumen Class:	320
Sample from:	NA	Proposed use:	Reseach
Sample By:	NA	Date tested:	15/11/2011
Asphalt Type / No of Blows:	**AC14/75**	Tested By:	W. Valenzuela

Sampling Method	AS 2891.1.1 / MRWA 701.1
Preparation of Asphalt for testing	MRWA 705.1

Particle Size Distribution	AS Sieve (mm)	% Passing	Specifications
MRWA 210.1	26.5		
	19	**100**	100
	13.20	**97**	91 - 100
	9.5	**79.9**	72 - 86
	6.7	**66.9**	59 - 73
	4.75	**56.4**	48 - 62
	2.36	**39.8**	34 - 44
	1.18	**31.08**	26 - 36
	0.600	**23.29**	20 - 28
	0.300	**16.72**	13 - 21
	0.150	**10.33**	9 - 14
	0.075	**5.16**	4 - 7

MRWA 730.1	Bitumen Content (%)	**4.6**	4.4 - 5.0
MRWA 732.2	Rice Density (t/m^3)	**2.492**	
MRWA 733.1	Bulk Density (t/m^3)	**2.360**	
MRWA 733.1	Air Voids (%)	**5.3**	4.0 - 6.0
MRWA 731.1	Marshall Flow (mm)	**3.25**	2.0 - 4.0
MRWA 731.1	Marshall Stability (kN)	**17.4**	>8.0
MRWA 733.1	V.M.A. (%)	**15.8**	>14
MRWA 733.1	V.F.B. (%)	**66.3**	

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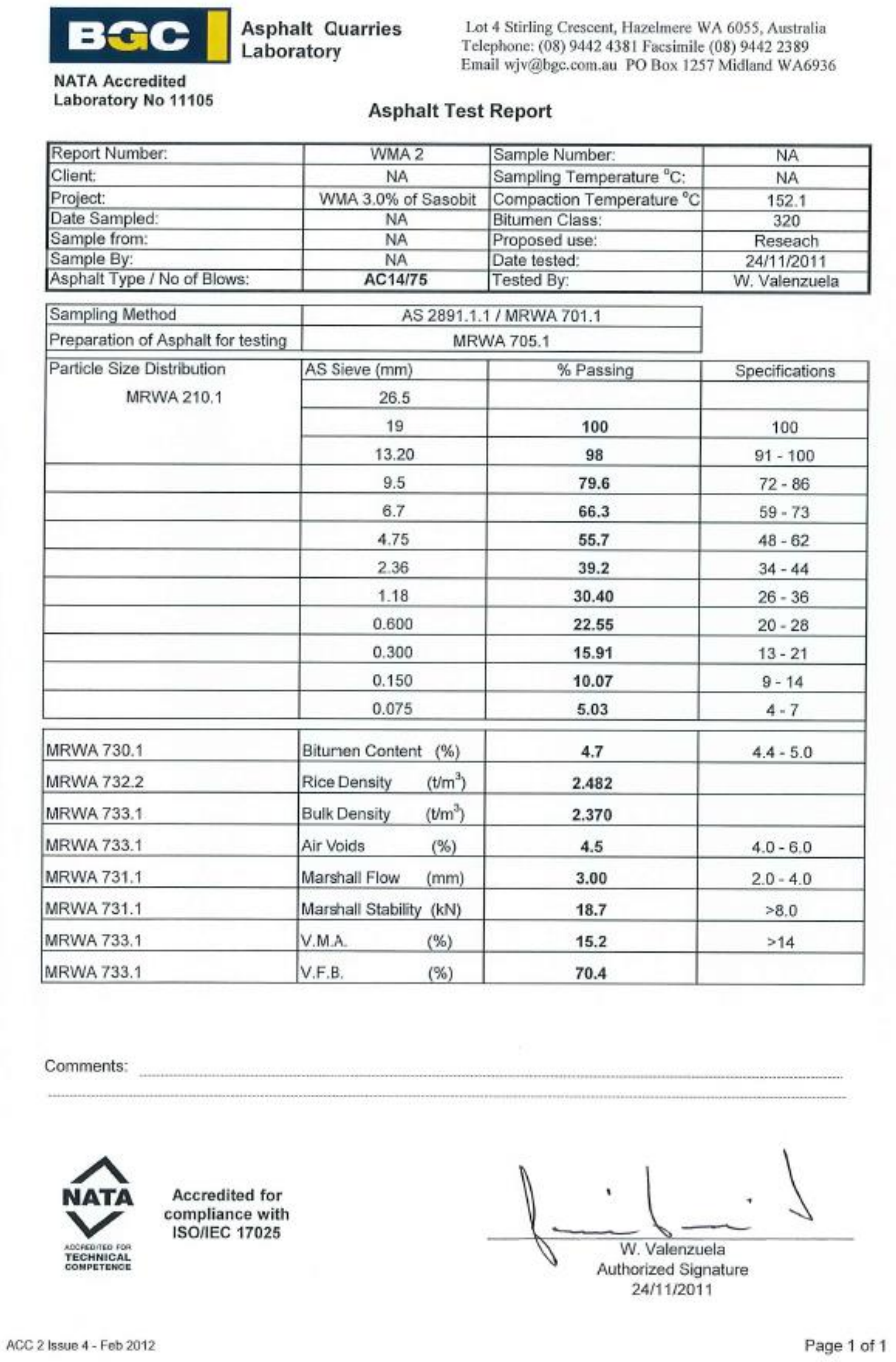

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Asphalt Test Report

Report Number:	WMA 2	Sample Number:	NA
Client:	NA	Sampling Temperature °C:	NA
Project:	WMA 3.0% of Sasobit	Compaction Temperature °C	152.1
Date Sampled:	NA	Bitumen Class:	320
Sample from:	NA	Proposed use:	Reseach
Sample By:	NA	Date tested:	24/11/2011
Asphalt Type / No of Blows:	**AC14/75**	Tested By:	W. Valenzuela

Sampling Method	AS 2891.1.1 / MRWA 701.1
Preparation of Asphalt for testing	MRWA 705.1

Particle Size Distribution	AS Sieve (mm)	% Passing	Specifications
MRWA 210.1	26.5		
	19	**100**	100
	13.20	**98**	91 - 100
	9.5	**79.6**	72 - 86
	6.7	**66.3**	59 - 73
	4.75	**55.7**	48 - 62
	2.36	**39.2**	34 - 44
	1.18	**30.40**	26 - 36
	0.600	**22.55**	20 - 28
	0.300	**15.91**	13 - 21
	0.150	**10.07**	9 - 14
	0.075	**5.03**	4 - 7

MRWA 730.1	Bitumen Content (%)	**4.7**	4.4 - 5.0
MRWA 732.2	Rice Density (t/m^3)	**2.482**	
MRWA 733.1	Bulk Density (t/m^3)	**2.370**	
MRWA 733.1	Air Voids (%)	**4.5**	4.0 - 6.0
MRWA 731.1	Marshall Flow (mm)	**3.00**	2.0 - 4.0
MRWA 731.1	Marshall Stability (kN)	**18.7**	>8.0
MRWA 733.1	V.M.A. (%)	**15.2**	>14
MRWA 733.1	V.F.B. (%)	**70.4**	

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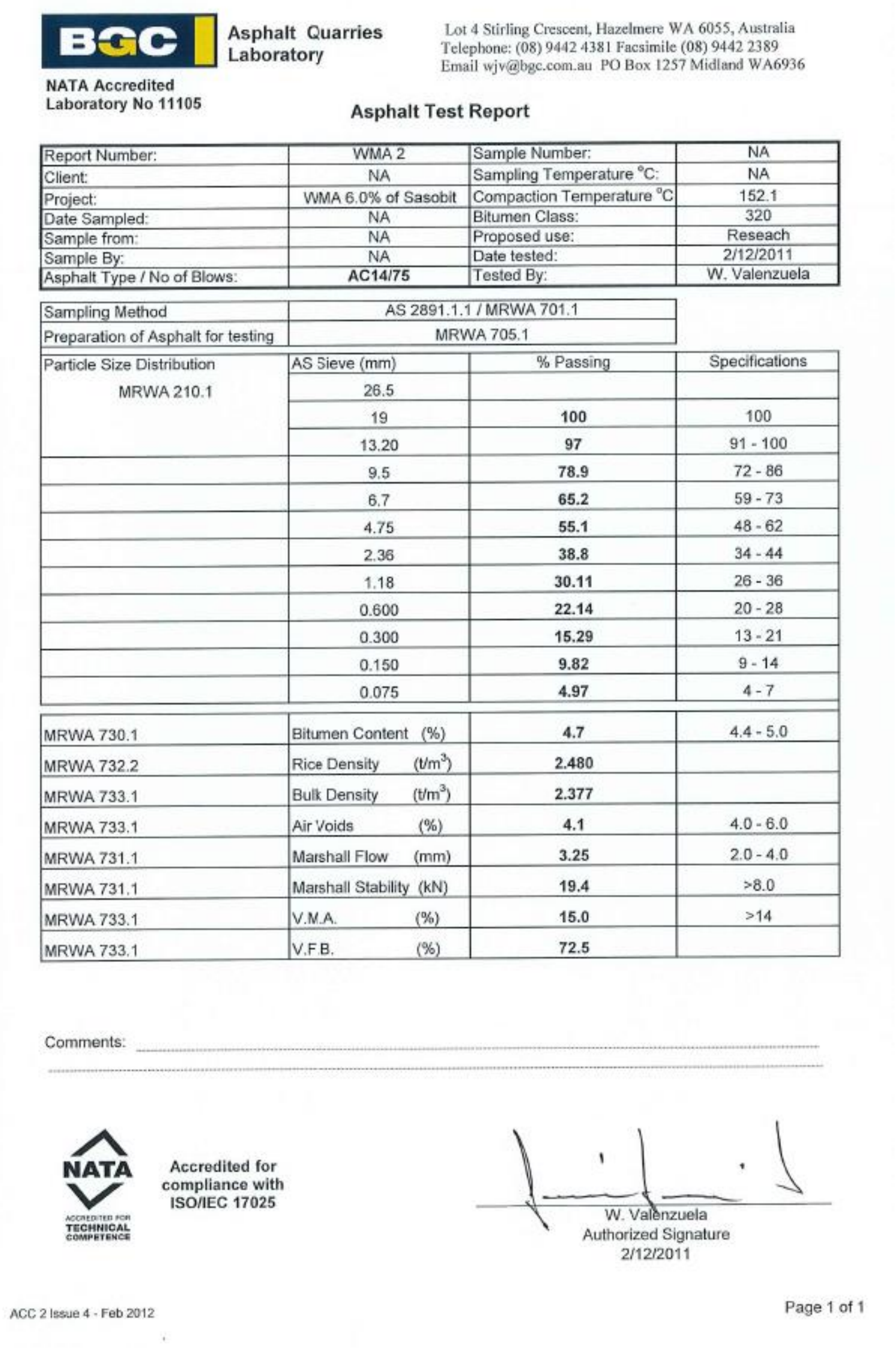

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Asphalt Test Report

Report Number:	WMA 2	Sample Number:	NA
Client:	NA	Sampling Temperature °C:	NA
Project:	WMA 6.0% of Sasobit	Compaction Temperature °C	152.1
Date Sampled:	NA	Bitumen Class:	320
Sample from:	NA	Proposed use:	Reseach
Sample By:	NA	Date tested:	2/12/2011
Asphalt Type / No of Blows:	**AC14/75**	Tested By:	W. Valenzuela

Sampling Method	AS 2891.1.1 / MRWA 701.1
Preparation of Asphalt for testing	MRWA 705.1

Particle Size Distribution	AS Sieve (mm)	% Passing	Specifications
MRWA 210.1	26.5		
	19	**100**	100
	13.20	**97**	91 - 100
	9.5	**78.9**	72 - 86
	6.7	**65.2**	59 - 73
	4.75	**55.1**	48 - 62
	2.36	**38.8**	34 - 44
	1.18	**30.11**	26 - 36
	0.600	**22.14**	20 - 28
	0.300	**15.29**	13 - 21
	0.150	**9.82**	9 - 14
	0.075	**4.97**	4 - 7

MRWA 730.1	Bitumen Content (%)	**4.7**	4.4 - 5.0
MRWA 732.2	Rice Density (t/m^3)	**2.480**	
MRWA 733.1	Bulk Density (t/m^3)	**2.377**	
MRWA 733.1	Air Voids (%)	**4.1**	4.0 - 6.0
MRWA 731.1	Marshall Flow (mm)	**3.25**	2.0 - 4.0
MRWA 731.1	Marshall Stability (kN)	**19.4**	>8.0
MRWA 733.1	V.M.A. (%)	**15.0**	>14
MRWA 733.1	V.F.B. (%)	**72.5**	

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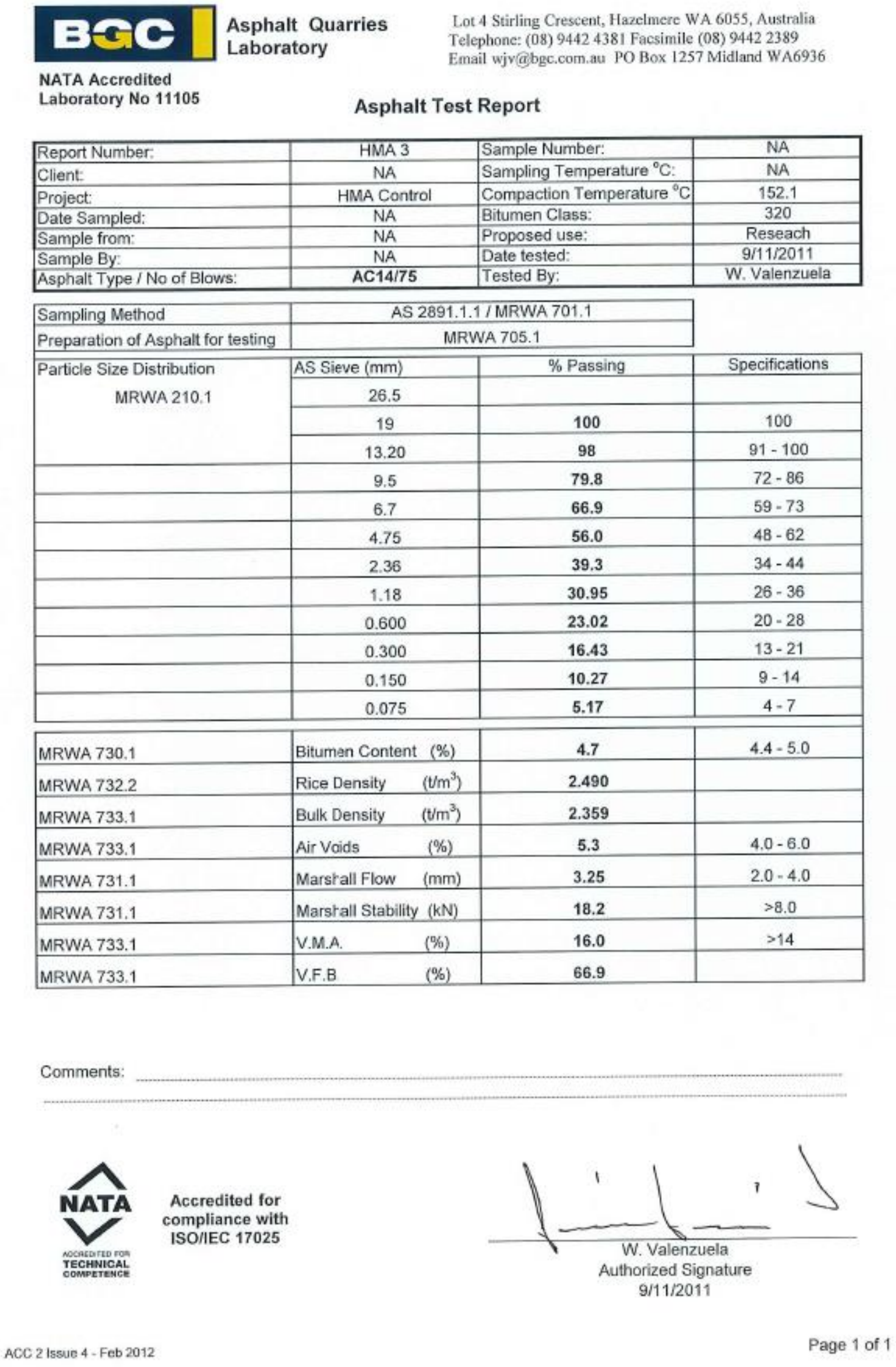

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Asphalt Test Report

Report Number:	HMA 3	Sample Number:	NA
Client:	NA	Sampling Temperature °C:	NA
Project:	HMA Control	Compaction Temperature °C	152.1
Date Sampled:	NA	Bitumen Class:	320
Sample from:	NA	Proposed use:	Reseach
Sample By:	NA	Date tested:	9/11/2011
Asphalt Type / No of Blows:	**AC14/75**	Tested By:	W. Valenzuela

Sampling Method	AS 2891.1.1 / MRWA 701.1
Preparation of Asphalt for testing	MRWA 705.1

Particle Size Distribution	AS Sieve (mm)	% Passing	Specifications
MRWA 210.1	26.5		
	19	**100**	100
	13.20	**98**	91 - 100
	9.5	**79.8**	72 - 86
	6.7	**66.9**	59 - 73
	4.75	**56.0**	48 - 62
	2.36	**39.3**	34 - 44
	1.18	**30.95**	26 - 36
	0.600	**23.02**	20 - 28
	0.300	**16.43**	13 - 21
	0.150	**10.27**	9 - 14
	0.075	**5.17**	4 - 7

MRWA 730.1	Bitumen Content (%)	**4.7**	4.4 - 5.0
MRWA 732.2	Rice Density (t/m^3)	**2.490**	
MRWA 733.1	Bulk Density (t/m^3)	**2.359**	
MRWA 733.1	Air Voids (%)	**5.3**	4.0 - 6.0
MRWA 731.1	Marshall Flow (mm)	**3.25**	2.0 - 4.0
MRWA 731.1	Marshall Stability (kN)	**18.2**	>8.0
MRWA 733.1	V.M.A. (%)	**16.0**	>14
MRWA 733.1	V.F.B (%)	**66.9**	

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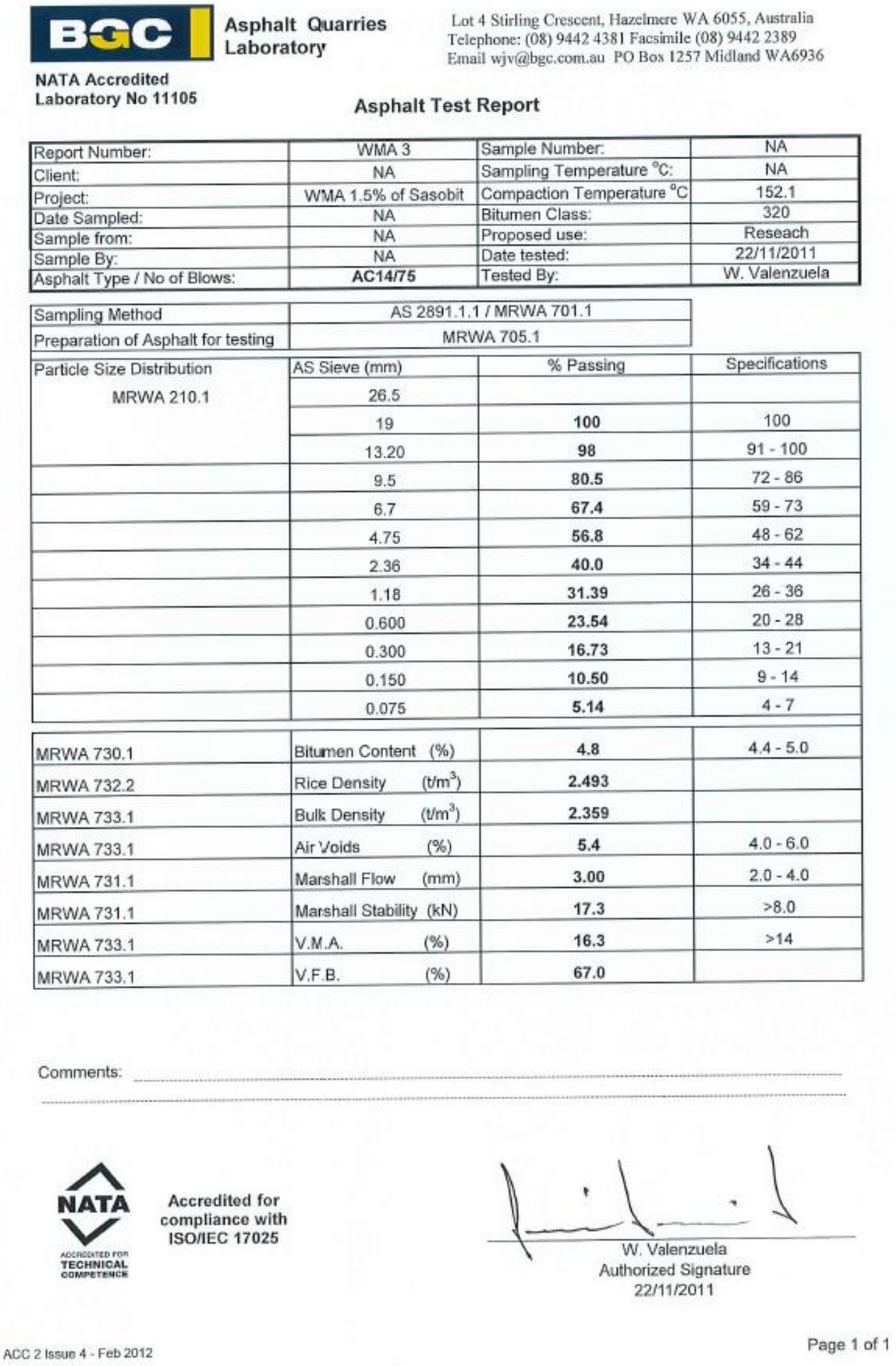

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Asphalt Test Report

Report Number:	WMA 3	Sample Number:	NA
Client:	NA	Sampling Temperature °C:	NA
Project:	WMA 1.5% of Sasobit	Compaction Temperature °C	152.1
Date Sampled:	NA	Bitumen Class:	320
Sample from:	NA	Proposed use:	Reseach
Sample By:	NA	Date tested:	22/11/2011
Asphalt Type / No of Blows:	**AC14/75**	Tested By:	W. Valenzuela

Sampling Method	AS 2891.1.1 / MRWA 701.1
Preparation of Asphalt for testing	MRWA 705.1

Particle Size Distribution	AS Sieve (mm)	% Passing	Specifications
MRWA 210.1	26.5		
	19	**100**	100
	13.20	**98**	91 - 100
	9.5	**80.5**	72 - 86
	6.7	**67.4**	59 - 73
	4.75	**56.8**	48 - 62
	2.36	**40.0**	34 - 44
	1.18	**31.39**	26 - 36
	0.600	**23.54**	20 - 28
	0.300	**16.73**	13 - 21
	0.150	**10.50**	9 - 14
	0.075	**5.14**	4 - 7

MRWA 730.1	Bitumen Content (%)	**4.8**	4.4 - 5.0
MRWA 732.2	Rice Density (t/m³)	**2.493**	
MRWA 733.1	Bulk Density (t/m³)	**2.359**	
MRWA 733.1	Air Voids (%)	**5.4**	4.0 - 6.0
MRWA 731.1	Marshall Flow (mm)	**3.00**	2.0 - 4.0
MRWA 731.1	Marshall Stability (kN)	**17.3**	>8.0
MRWA 733.1	V.M.A. (%)	**16.3**	>14
MRWA 733.1	V.F.B. (%)	**67.0**	

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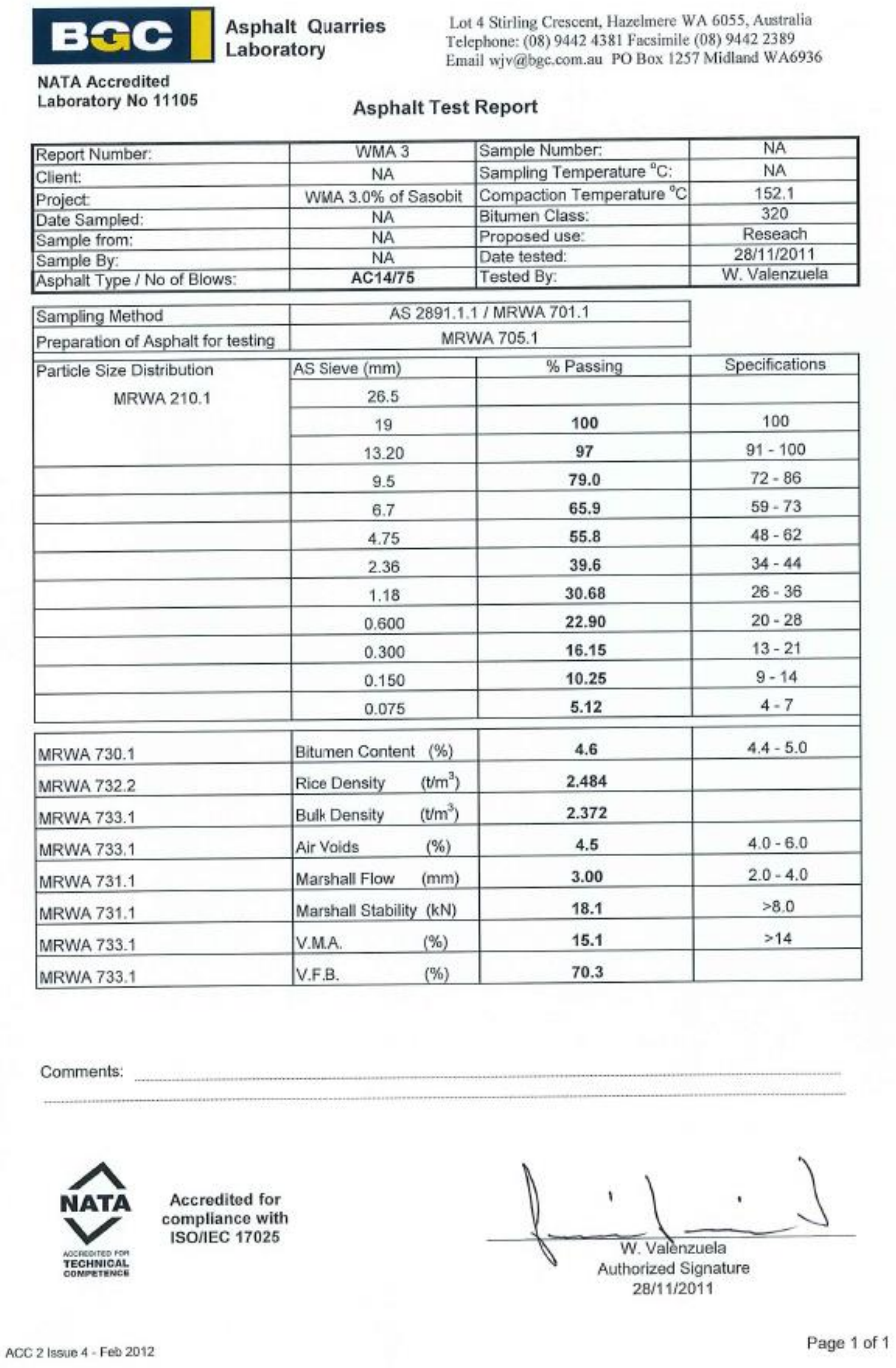

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Asphalt Test Report

Report Number:	WMA 3	Sample Number:	NA
Client:	NA	Sampling Temperature °C:	NA
Project:	WMA 3.0% of Sasobit	Compaction Temperature °C	152.1
Date Sampled:	NA	Bitumen Class:	320
Sample from:	NA	Proposed use:	Reseach
Sample By:	NA	Date tested:	28/11/2011
Asphalt Type / No of Blows:	**AC14/75**	Tested By:	W. Valenzuela

Sampling Method	AS 2891.1.1 / MRWA 701.1
Preparation of Asphalt for testing	MRWA 705.1

Particle Size Distribution	AS Sieve (mm)	% Passing	Specifications
MRWA 210.1	26.5		
	19	**100**	100
	13.20	**97**	91 - 100
	9.5	**79.0**	72 - 86
	6.7	**65.9**	59 - 73
	4.75	**55.8**	48 - 62
	2.36	**39.6**	34 - 44
	1.18	**30.68**	26 - 36
	0.600	**22.90**	20 - 28
	0.300	**16.15**	13 - 21
	0.150	**10.25**	9 - 14
	0.075	**5.12**	4 - 7

MRWA 730.1	Bitumen Content (%)	**4.6**	4.4 - 5.0
MRWA 732.2	Rice Density (t/m^3)	**2.484**	
MRWA 733.1	Bulk Density (t/m^3)	**2.372**	
MRWA 733.1	Air Voids (%)	**4.5**	4.0 - 6.0
MRWA 731.1	Marshall Flow (mm)	**3.00**	2.0 - 4.0
MRWA 731.1	Marshall Stability (kN)	**18.1**	>8.0
MRWA 733.1	V.M.A. (%)	**15.1**	>14
MRWA 733.1	V.F.B. (%)	**70.3**	

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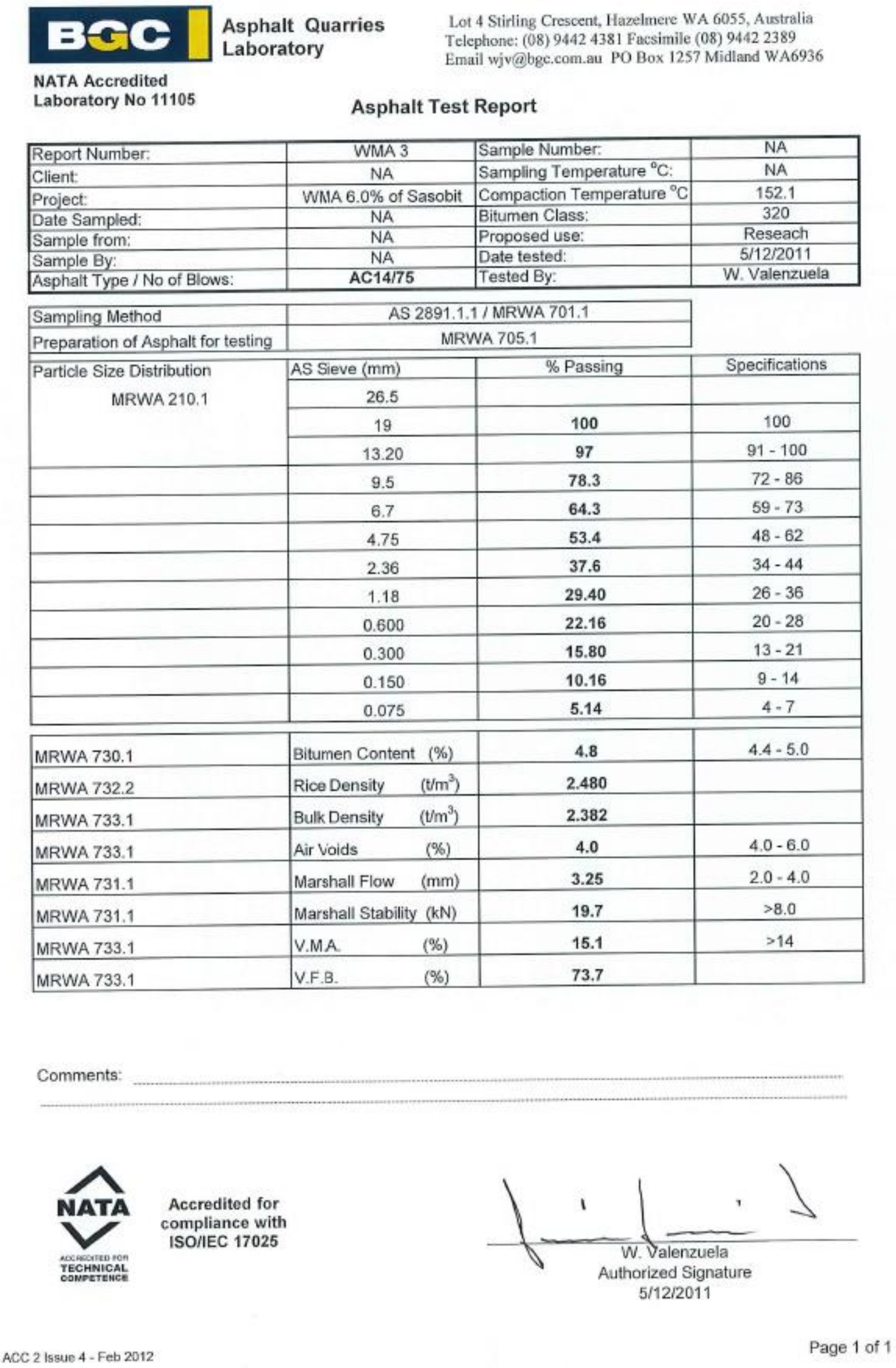

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Asphalt Test Report

Report Number:	WMA 3	Sample Number:	NA
Client:	NA	Sampling Temperature °C:	NA
Project:	WMA 6.0% of Sasobit	Compaction Temperature °C	152.1
Date Sampled:	NA	Bitumen Class:	320
Sample from:	NA	Proposed use:	Reseach
Sample By:	NA	Date tested:	5/12/2011
Asphalt Type / No of Blows:	**AC14/75**	Tested By:	W. Valenzuela

Sampling Method	AS 2891.1.1 / MRWA 701.1
Preparation of Asphalt for testing	MRWA 705.1

Particle Size Distribution	AS Sieve (mm)	% Passing	Specifications
MRWA 210.1	26.5		
	19	**100**	100
	13.20	**97**	91 - 100
	9.5	**78.3**	72 - 86
	6.7	**64.3**	59 - 73
	4.75	**53.4**	48 - 62
	2.36	**37.6**	34 - 44
	1.18	**29.40**	26 - 36
	0.600	**22.16**	20 - 28
	0.300	**15.80**	13 - 21
	0.150	**10.16**	9 - 14
	0.075	**5.14**	4 - 7

MRWA 730.1	Bitumen Content (%)	**4.8**	4.4 - 5.0
MRWA 732.2	Rice Density (t/m^3)	**2.480**	
MRWA 733.1	Bulk Density (t/m^3)	**2.382**	
MRWA 733.1	Air Voids (%)	**4.0**	4.0 - 6.0
MRWA 731.1	Marshall Flow (mm)	**3.25**	2.0 - 4.0
MRWA 731.1	Marshall Stability (kN)	**19.7**	>8.0
MRWA 733.1	V.M.A. (%)	**15.1**	>14
MRWA 733.1	V.F.B. (%)	**73.7**	

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Appendix E Performance test results

Resilient Modulus

Specimen Information
AC 10mm HMA Control
4 cylinders

Results	Pulse 1	Pulse 2	Pulse 3	Pulse 4	Pulse 5	Mean	Std Dev	%CV
Resilient modulus (MPa)	5146	4402	4208	4133	4098	4397	388.91	8.84
Recovered horizontal strain (μ€)	32.81	43.56	45.74	46.48	47.37	43.19	5.34	12.37
Peak loading force (N)	1638	1860	1867	1864	1883	1822	92.61	5.08
10% to 90% rise time (ms)	14	27	26	26	26	24	4.87	20.17
Load time (ms)	226	256	255	255	257	249.7	11.78	4.72
Phase delay at 90% (ms)	16	18	19	18	19	17.9	0.88	4.93
Resilient horiz. deform. #1 (μm)	1.93	2.32	2.5	2.49	2.6	2.37	0.24	10..02
Resilient horiz. deform. #2 (μm)	1.35	2.04	2.07	2.16	2.14	1.95	0.3	15.51
Seating force (N)	20	21	20	21	21	20	0.67	3.3

Results	Pulse 1	Pulse 2	Pulse 3	Pulse 4	Pulse 5	Mean	Std Dev	%CV
Resilient modulus (MPa)	5015	4780	4762	4787	4725	4814	103	2.14
Recovered horizontal strain (μ€)	42.92	44.78	45.12	45.07	45.75	44.73	0.96	2.14
Peak loading force (N)	2068	2057	2064	2073	2077	2068	7.03	0.34
10% to 90% rise time (ms)	38	38	37	37	37	37	0.76	2.04
Load time (ms)	193	190	190	188	188	189.7	1.87	0.99
Phase delay at 90% (ms)	13	14	14	13	13	13.3	0.45	3.37
Resilient horiz. deform. #1 (μm)	2.44	2.52	2.59	2.56	2.56	2.53	0.05	2.1
Resilient horiz. deform. #2 (μm)	1.84	1.94	1.91	1.93	2	1.93	0.05	2.7
Seating force (N)	19	19	20	20	21	20	0.65	3.31

Results	Pulse 1	Pulse 2	Pulse 3	Pulse 4	Pulse 5	Mean	Std Dev	%CV
Resilient modulus (MPa)	5410	5304	5116	5160	4959	5190	155.69	3
Recovered horizontal strain (μ€)	42.88	44.07	45.14	44.81	46.64	44.71	1.24	2.77
Peak loading force (N)	2240	2256	2230	2232	2233	2238	9.71	0.43
10% to 90% rise time (ms)	35	36	35	35	35	36	0.24	0.68
Load time (ms)	206	200	201	200	200	201.4	2.26	1.12
Phase delay at 90% (ms)	14	13	14	15	15	14.4	0.66	4.56
Resilient horiz. deform. #1 (μm)	2.24	2.39	2.39	2.38	2.53	2.39	0.09	3.97
Resilient horiz. deform. #2 (μm)	2.05	2.01	2.12	2.1	2.12	2.08	0.04	2.15
Seating force (N)	20	20	20	20	20	20	0.1	0.5

Results	Pulse 1	Pulse 2	Pulse 3	Pulse 4	Pulse 5	Mean	Std Dev	%CV
Resilient modulus (MPa)	4400	4256	4154	41.21	4100	4206	110.94	2.64
Recovered horizontal strain (μ€)	42.15	43.33	44.35	44.77	44.99	43.92	1.05	2.4
Peak loading force (N)	1793	1783	1780	1783	1783	1784	4.24	0.24
10% to 90% rise time (ms)	39	39	38	39	38	39	0.39	1.01
Load time (ms)	151	150	152	152	151	151.4	0.6	0.4
Phase delay at 90% (ms)	19	22	22	20	22	20.8	1.01	4.87
Resilient horiz. deform. #1 (μm)	2.93	2.93	2.97	2.97	3.12	3.01	0.08	2.74
Resilient horiz. deform. #2 (μm)	1.27	1.39	1.46	1.46	1.36	1.37	0.06	4.37
Seating force (N)	20	20	20	20	20	20	0.24	1.18

Specimen Information
AC10mm WMA 1.5% Sasobit
2 cylinders

Results	Pulse 1	Pulse 2	Pulse 3	Pulse 4	Pulse 5	Mean	Std Dev	%CV
Resilient modulus (MPa)	3904	4362	4110	3956	3971	4061	165.46	4.07
Recovered horizontal strain (µ€)	12.98	54.85	57.64	61.86	63.24	50.11	18.8	37.52
Peak loading force (N)	492	2321	2298	2374	2436	1984	747.8	37.69
10% to 90% rise time (ms)	25	17	16	16	17	18	3.3	18.18
Load time (ms)	139	180	175	179	189	172.4	17.51	10.15
Phase delay at 90% (ms)	12	16	17	17	17	15.7	1.95	12.4
Resilient horiz. deform. #1 (µm)	0.61	3.26	3.41	3.67	3.65	2.92	1.16	39.9
Resilient horiz. deform. #2 (µm)	0.69	2.22	2.36	2.52	2.67	2.09	0.72	34.31
Seating force (N)	20	21	20	21	20	20	0.54	2.64

Results	Pulse 1	Pulse 2	Pulse 3	Pulse 4	Pulse 5	Mean	Std Dev	%CV
Resilient modulus (MPa)	5884	4849	4693	4682	4489	4919	495.63	10.08
Recovered horizontal strain (µ€)	35.35	44.45	46.25	47.16	49.44	44.53	4.86	10.92
Peak loading force (N)	2018	2091	2106	2142	2153	2102	47.7	2.27
10% to 90% rise time (ms)	34	32	32	30	29	31	1.55	4.92
Load time (ms)	180	190	190	189	190	187.9	3.99	2.12
Phase delay at 90% (ms)	12	20	11	12	13	13.6	3.14	23.18
Resilient horiz. deform. #1 (µm)	2.34	2.77	2.74	2.79	2.86	2.7	0.18	6.82
Resilient horiz. deform. #2 (µm)	1.2	1.67	1.88	1.92	2.09	1.75	0.31	17.58
Seating force (N)	17	20	17	21	20	19	1.64	8.67

Specimen Information

AC 10mm WMA 3.0% Sasobit

3 cylinders

Results	Pulse 1	Pulse 2	Pulse 3	Pulse 4	Pulse 5	Mean	Std Dev	%CV
Resilient modulus (MPa)	5588	5421	5369	5253	5220	5370	131.27	2.44
Recovered horizontal strain (µ€)	45.24	47.12	47.34	48.33	48.61	47.33	47.33	2.51
Peak loading force (N)	2427	2453	2440	2438	2436	2436	2439	0.34
10% to 90% rise time (ms)	33	37	37	37	37	37	36	4.44
Load time (ms)	230	222	224	220	222	222	223.8	1.57
Phase delay at 90% (ms)	18	17	18	18	18	18	17.9	3.57
Resilient horiz. deform. #1 (µm)	2.21	2.37	2.42	2.45	2.52	2.52	2.39	4.38
Resilient horiz. deform. #2 (µm)	2.3	2.32	2.29	2.36	2.32	2.32	2.32	1.07
Seating force (N)	20	20	21	20	20	20	20	2.05

Results	Pulse 1	Pulse 2	Pulse 3	Pulse 4	Pulse 5	Mean	Std Dev	%CV
Resilient modulus (MPa)	5382	53.27	5256	5189	5275	5286	65.28	1.24
Recovered horizontal strain (µ€)	47.47	48.44	48.71	49.34	48.56	48.5	0.6	1.24
Peak loading force (N)	2459	2483	2464	2464	2465	2467	8.33	0.34
10% to 90% rise time (ms)	42	43	42	42	42	43	0.32	0.75
Load time (ms)	189	186	189	186	186	186.9	1.57	0.84
Phase delay at 90% (ms)	18	18	18	18	18	17.6	0	0
Resilient horiz. deform. #1 (µm)	2.73	2.81	2.88	2.94	0.82	2.84	0.07	2.47
Resilient horiz. deform. #2 (µm)	2	2.01	1.98	1.97	2.02	2	0.02	0.99
Seating force (N)	20	20	20	20	20	20	0.2	1.02

Results	Pulse 1	Pulse 2	Pulse 3	Pulse 4	Pulse 5	Mean	Std Dev	%CV
Resilient modulus (MPa)	5409	5210	5137	5185	5067	5201	114.57	2.2
Recovered horizontal strain (µ€)	47	48.59	49.16	48.81	50.04	48.72	0.99	2.03
Peak loading force (N)	2433	2423	2417	48.8124	2427	2425	5.35	0.22
10% to 90% rise time (ms)	43	42	42	42	42	42	0.51	1.19
Load time (ms)	178	177	179	180	182	179.2	1.6	0.89
Phase delay at 90% (ms)	17	18	18	18	18	17.8	0.6	2.37
Resilient horiz. deform. #1 (µm)	2.72	2.74	2.83	2.76	2.87	2.78	0.06	2.03
Resilient horiz. deform. #2 (µm)	1.95	2.08	2.05	2.08	2.1	2.05	0.05	2.6
Seating force (N)	20	20	19	20	21	20	0.47	2.35

Specimen Information

AC 10mm WMA 6.0% Sasobit

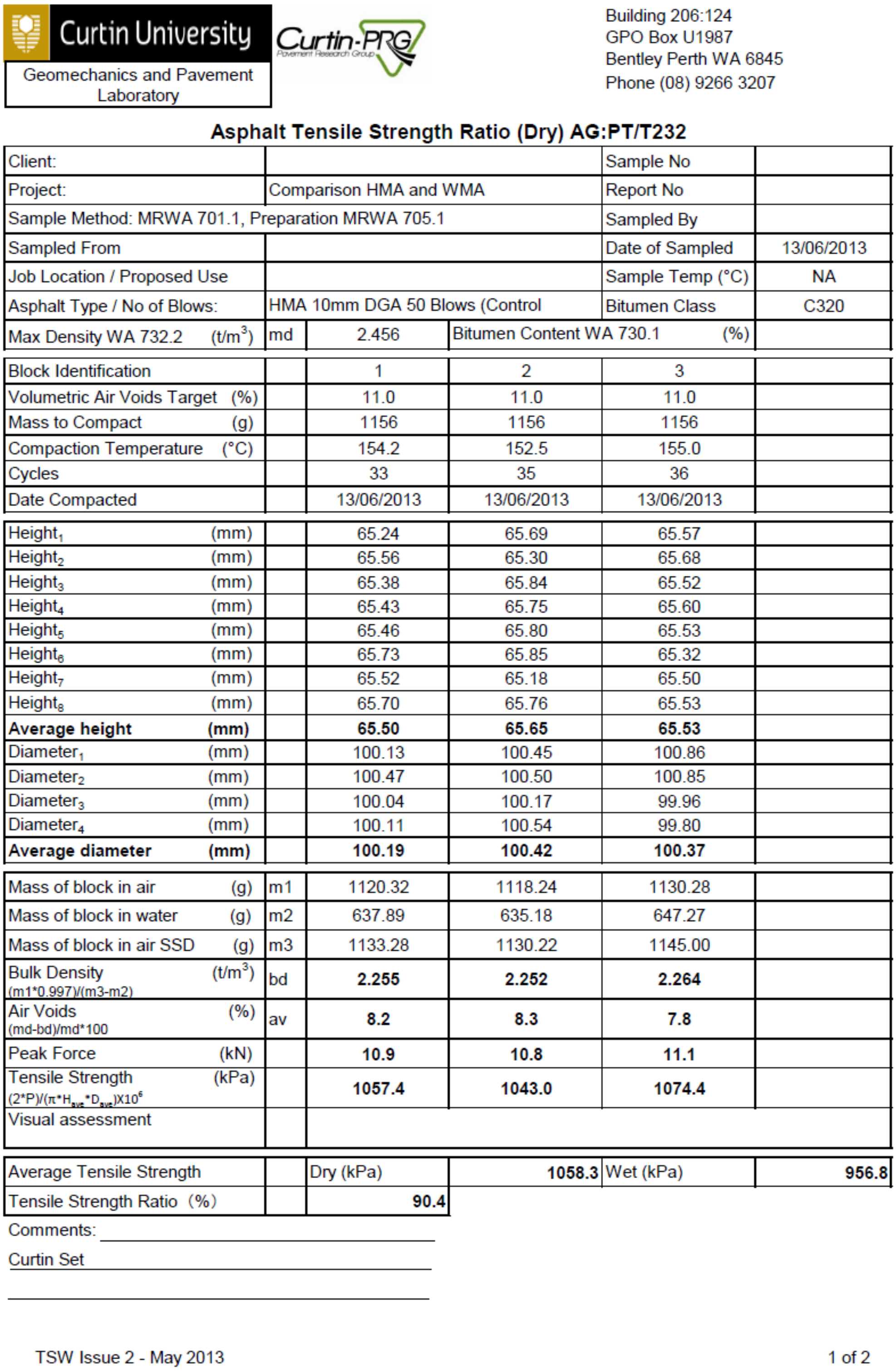
3 cylinders

Results	Pulse 1	Pulse 2	Pulse 3	Pulse 4	Pulse 5	Mean	Std Dev	%CV
Resilient modulus (MPa)	6800	6703	6598	6492	6461	6611	127.39	1.93
Recovered horizontal strain (µ€)	51.78	52.62	53.48	54.15	54.55	53.29	0.98	1.84
Peak loading force (N)	3363	3369	3370	3358	3359	3364	5.06	0.15
10% to 90% rise time (ms)	38	37	38	38	37	37	0.39	1.05
Load time (ms)	176	165	162	163	162	165.8	5.19	3.13
Phase delay at 90% (ms)	14	14	15	15	16	15	0.6	3.98
Resilient horiz. deform. #1 (µm)	2.92	2.9	2.92	3.05	3.02	2.96	0.06	2.06
Resilient horiz. deform. #2 (µm)	2.22	2.33	2.4	2.33	2.39	2.33	0.06	2.71
Seating force (N)	20	20	20	19	20	20	0.3	1.5

Results	Pulse 1	Pulse 2	Pulse 3	Pulse 4	Pulse 5	Mean	Std Dev	%CV
Resilient modulus (MPa)	6977	6881	6814	6707	6680	6812	109.93	1.61
Recovered horizontal strain (µ€)	48.14	48.8	49.27	50.06	50.28	49.31	0.79	1.61
Peak loading force (N)	3213	3212	3212	3212	3214	3231	0.52	0.02
10% to 90% rise time (ms)	42	41	42	41	2	41	0.39	0.95
Load time (ms)	154	154	154	154	155	154.6	0.32	0.21
Phase delay at 90% (ms)	16	15	14	16	16	15.5	0.64	4.12
Resilient horiz. deform. #1 (µm)	2.32	2.31	2.38	2.38	2.38	2.35	0.03	1.31
Resilient horiz. deform. #2 (µm)	2.47	2.54	2.53	2.61	2.62	2.55	0.05	2.14
Seating force (N)	20	20	20	19	20	20	0.26	1.3

Results	Pulse 1	Pulse 2	Pulse 3	Pulse 4	Pulse 5	Mean	Std Dev	%CV
Resilient modulus (MPa)	7278	7131	6997	6939	7060	7081	117.34	1.66
Recovered horizontal strain (µ€)	49.14	50.18	51.02	51.43	50.56	50.47	0.79	1.56
Peak loading force (N)	3411	3413	3405	3404	3405	3408	3.81	0.11
10% to 90% rise time (ms)	36	37	36	36	36	36	0.32	0.88
Load time (ms)	161	160	158	156	154	158.1	2	1.26
Phase delay at 90% (ms)	15	15	15	15	15	15.2	0	0
Resilient horiz. deform. #1 (µm)	3.22	3.21	3.27	3.35	3.34	3.28	0.06	1.74
Resilient horiz. deform. #2 (µm)	1.66	0.77	1.8	1.76	1.69	1.73	0.05	3.07
Seating force (N)	20	20	20	19	20	20	0.27	1.38

Moisture Sensitivity



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Asphalt Tensile Strength Ratio (Dry) AG:PT/T232

Client:		Sample No	
Project:	Comparison HMA and WMA	Report No	
Sample Method: MRWA 701.1, Preparation MRWA 705.1		Sampled By	
Sampled From		Date of Sampled	13/06/2013
Job Location / Proposed Use		Sample Temp (°C)	NA
Asphalt Type / No of Blows:	HMA 10mm DGA 50 Blows (Control	Bitumen Class	C320
Max Density WA 732.2 (t/m^3)	md 2.456	Bitumen Content WA 730.1 (%)	

Block Identification		1	2	3	
Volumetric Air Voids Target (%)		11.0	11.0	11.0	
Mass to Compact (g)		1156	1156	1156	
Compaction Temperature (°C)		154.2	152.5	155.0	
Cycles		33	35	36	
Date Compacted		13/06/2013	13/06/2013	13/06/2013	
Height$_1$ (mm)		65.24	65.69	65.57	
Height$_2$ (mm)		65.56	65.30	65.68	
Height$_3$ (mm)		65.38	65.84	65.52	
Height$_4$ (mm)		65.43	65.75	65.60	
Height$_5$ (mm)		65.46	65.80	65.53	
Height$_6$ (mm)		65.73	65.85	65.32	
Height$_7$ (mm)		65.52	65.18	65.50	
Height$_8$ (mm)		65.70	65.76	65.53	
Average height (mm)		**65.50**	**65.65**	**65.53**	
Diameter$_1$ (mm)		100.13	100.45	100.86	
Diameter$_2$ (mm)		100.47	100.50	100.85	
Diameter$_3$ (mm)		100.04	100.17	99.96	
Diameter$_4$ (mm)		100.11	100.54	99.80	
Average diameter (mm)		**100.19**	**100.42**	**100.37**	
Mass of block in air (g)	m1	1120.32	1118.24	1130.28	
Mass of block in water (g)	m2	637.89	635.18	647.27	
Mass of block in air SSD (g)	m3	1133.28	1130.22	1145.00	
Bulk Density (t/m^3) (m1*0.997)/(m3-m2)	bd	**2.255**	**2.252**	**2.264**	
Air Voids (%) (md-bd)/md*100	av	**8.2**	**8.3**	**7.8**	
Peak Force (kN)		**10.9**	**10.8**	**11.1**	
Tensile Strength (kPa) $(2*P)/(\pi*H_{ave}*D_{ave})X10^6$		**1057.4**	**1043.0**	**1074.4**	
Visual assessment					

Average Tensile Strength		Dry (kPa)	**1058.3**	Wet (kPa)	**956.8**
Tensile Strength Ratio (%)		**90.4**			

Comments: ____________________

Curtin Set

TSW Issue 2 - May 2013

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Curtin University

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Asphalt Tensile Strength Ratio (Wet) AG:PT/T232

Client:		Sample No	
Project:		Report No	
Sample Method: MRWA 701.1, Preparation MRWA 705.1		Sampled By	
Sampled From		Date Sampled	13/06/2013
Job Location / Proposed use:		Sample Temp (°C)	
Asphalt Type / No of Blows:	HMA 10mm DGA 50 Blows (Control	Bitumen Class:	C320
Max Density WA 732.2 (t/m^3) md	2.456	Bitumen Content WA 730.1 (%)	

Block Identification		4		5		6			
Volumetric Air Voids Target (%)		11.0		11.0		11.0			
Mass to Compact (g)		1156		1156		1156			
Compaction Temperature (°C)		153.5		150.0		148.0			
Cycles		33		46		37			
Date Compacted		13/06/2013		13/06/2013		13/06/2013			
Conditioning	**Measurements**	Before	After	Before	After	Before	After		
Freeze/Thaw	Height$_1$ (mm)	65.41	66.09	65.41	66.24	65.31	66.15		
Start:	Height$_2$ (mm)	65.34	65.92	65.31	66.01	65.19	65.89		
End:	Height$_3$ (mm)	65.18	66.36	65.19	66.49	65.22	66.52		
60°C Moisture	Height$_4$ (mm)	65.27	66.18	65.43	66.46	65.39	66.42		
Start:	Height$_5$ (mm)	65.33	65.92	65.28	65.99	65.48	66.19		
End:	Height$_6$ (mm)	65.29	66.34	65.33	66.50	65.29	66.46		
25°C Moisture	Height$_7$ (mm)	65.40	66.44	65.24	66.40	65.34	66.50		
End:	Height$_8$ (mm)	65.34	66.06	65.43	66.27	65.39	66.23		
Average height (mm)		**65.32**	**66.16**	**65.33**	**66.30**	**65.33**	**66.30**		
Diameter$_1$ (mm)		100.02	101.09	100.10	101.40	100.12	101.32		
Diameter$_2$ (mm)		100.09	101.29	100.09	101.54	100.21	101.66		
Diameter$_3$ (mm)		99.90	101.10	100.10	101.55	100.22	101.67		
Diameter$_4$ (mm)		100.03	101.05	100.80	102.07	100.18	101.45		
Average diameter (mm)		**100.01**	**101.13**	**100.27**	**101.64**	**100.18**	**101.53**		
Volume π*H*D^2/4000		513.12	531.49	515.88	537.90	514.95	536.68		

Mass of block in air (g)	m1	1108.32	1112.30	1112.98	
Mass of block in water (g)	m2	631.21	622.31	629.10	
Mass of block in air SSD (g)	m3	1119.20	1112.31	1120.12	
Volume Dry (m3-m2)/0.997	Vd	489.46	491.47	492.50	
Bulk density (m1/vd) (t/m3)	Bd	2.264	2.263	2.260	
% Air Voids (Md-Bd)/Md*100	AV	7.8	7.9	8.0	7.9
Volume Air (AV*Vd)/100 (cc)	Va	38.19	38.58	39.33	
Mass after saturation (g)	Mps	1140.17	1138.17	1137.18	
% Saturation (Mps-M1)/Va*100	Sp	83.4	67.0	61.5	
Swell ((Vmc-Vdm)/Vdm)*100		3.57824965	4.267836731	4.221018391	
Peak Force (kN)	P	9.7	9.8	10	
Tensile Strength (kPa) $(2*P)/(\pi*H_{after}*D_{after})*10^6$		**945**	**952**	**973**	
Visual assessment					

Comments:______________________________________

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Asphalt Tensile Strength Ratio (Dry) AG:PT/T232

Client:				Sample No	
Project:	Comparison HMA and WMA			Report No	
Sample Method: MRWA 701.1, Preparation MRWA 705.1				Sampled By	
Sampled From				Date of Sampled	13/06/2013
Job Location / Proposed Use				Sample Temp (°C)	140
Asphalt Type / No of Blows:	WMA AC10/50 (1.5% Sasobit)			Bitumen Class	C320
Max Density WA 732.2 (t/m^3)	md	2.456	Bitumen Content WA 730.1 (%)		
Block Identification		4	5	6	
Volumetric Air Voids Target (%)		11.0	11.0	11.0	
Mass to Compact (g)		1156	1156	1156	
Compaction Temperature (°C)		126.0	125.0	126.0	
Cycles		30	31	32	
Date Compacted		13/06/2013	13/06/2013	13/06/2013	
Height$_1$ (mm)		65.10	65.60	65.37	
Height$_2$ (mm)		65.20	65.55	65.30	
Height$_3$ (mm)		65.15	65.35	65.35	
Height$_4$ (mm)		65.10	65.48	65.40	
Height$_5$ (mm)		65.25	65.77	65.39	
Height$_6$ (mm)		65.16	65.55	95.38	
Height$_7$ (mm)		65.32	65.39	65.41	
Height$_8$ (mm)		65.24	65.40	65.49	
Average height (mm)		**65.19**	**65.51**	**69.14**	
Diameter$_1$ (mm)		100.10	100.14	100.11	
Diameter$_2$ (mm)		100.12	100.25	100.18	
Diameter$_3$ (mm)		100.25	100.20	100.09	
Diameter$_4$ (mm)		100.09	100.18	100.12	
Average diameter (mm)		**100.14**	**100.19**	**100.13**	
Mass of block in air (g)	m1	1125.30	1120.18	1125.39	
Mass of block in water (g)	m2	638.12	634.28	647.00	
Mass of block in air SSD (g)	m3	1133.29	1128.38	1144.38	
Bulk Density (t/m^3) (m1*0.997)/(m3-m2)	bd	**2.266**	**2.260**	**2.256**	
Air Voids (%) (md-bd)/md*100	av	**7.7**	**8.0**	**8.1**	**8.0**
Peak Force (kN)		**10.2**	**10.5**	**11.0**	
Tensile Strength (kPa) $(2*P)/(\pi*H_{ave}*D_{ave})X10^6$		**994.7**	**1018.4**	**1011.6**	
Visual assessment					
Average Tensile Strength		Dry (kPa)	**1008.2**	Wet (kPa)	**876.2**
Tensile Strength Ratio (%)		**86.9**			

Comments: ________________________________

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Asphalt Tensile Strength Ratio (Wet) AG:PT/T232

Client:			Sample No	
Project:			Report No	
Sample Method: MRWA 701.1, Preparation MRWA 705.1			Sampled By	
Sampled From			Date Sampled	13/06/2013
Job Location / Proposed use:			Sample Temp (°C)	140
Asphalt Type / No of Blows:	14mm DGA 75 blows		Bitumen Class:	C320
Max Density WA 732.2 (t/m^3)	md	2.456	Bitumen Content WA 730.1 (%)	

Block Identification		7	8	9	
Volumetric Air Voids Target (%)		11.0	11.0	11.0	
Mass to Compact (g)		1156	1156	1156	
Compaction Temperature (°C)		124.5	125.3	125.8	
Cycles		33	30	31	
Date Compacted		13/06/2013	13/06/2013	13/06/2013	

Conditioning	**Measurements**		Before	After	Before	After	Before	After		
Freeze/Thaw	Height$_1$ (mm)		65.28	65.64	65.30	65.65	65.13	65.10		
Start:	Height$_2$ (mm)		65.44	66.13	65.47	65.60	65.18	65.58		
End:	Height$_3$ (mm)		65.55	66.22	65.18	65.72	65.23	65.44		
60°C Moisture	Height$_4$ (mm)		65.39	66.01	65.37	65.57	65.14	65.80		
Start:	Height$_5$ (mm)		65.18	66.12	65.44	65.62	65.28	65.91		
End:	Height$_6$ (mm)		65.28	66.27	65.41	66.08	65.31	65.10		
25°C Moisture	Height$_7$ (mm)		65.33	65.99	65.19	65.78	65.29	65.50		
End:	Height$_8$ (mm)		65.28	65.98	65.24	65.88	65.24	65.45		
Average height	**(mm)**		**65.34**	**66.05**	**65.33**	**65.74**	**65.23**	**65.49**		
Diameter$_1$	(mm)		100.05	100.02	100.17	100.45	100.25	100.37		
Diameter$_2$	(mm)		100.10	99.97	100.04	100.45	100.21	100.28		
Diameter$_3$	(mm)		100.09	99.98	100.07	100.65	100.18	100.27		
Diameter$_4$	(mm)		99.99	100.08	100.37	100.08	100.15	100.44		
Average diameter	**(mm)**		**100.06**	**100.01**	**100.16**	**100.41**	**100.20**	**100.34**		
Volume $\pi*H*D^2/4000$			513.78	518.85	514.73	520.52	514.30	517.82		

Mass of block in air (g)	m1	1118.00	1110.02	1110.15	
Mass of block in water (g)	m2	625.00	625.00	623.35	
Mass of block in air SSD (g)	m3	1117.28	1117.28	1114.38	
Volume Dry (m3-m2)/0.997	Vd	493.76	493.76	492.51	
Bulk density (m1/vd) (t/m3)	Bd	2.264	2.248	2.254	
% Air Voids (Md-Bd)/Md*100	AV	7.8	8.5	8.2	8.2
Volume Air (AV*Vd)/100 (cc)	Va	38.55	41.80	40.49	
Mass after saturation (g)	Mps	1140.17	1138.17	1137.18	
% Saturation (Mps-M1)/Va*100	Sp	57.5	67.3	66.8	
Swell ((Vmc-Vdm)/Vdm)*100		0.986619075	1.123969766	0.684395293	
Peak Force (kN)	P	8.9	9.1	9	
Tensile Strength (kPa) $(2*P)/(\pi*H_{after}*D_{after})*10^6$		**867**	**885**	**877**	
Visual assessment					

Comments:______________________________

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Asphalt Tensile Strength Ratio (Dry) AG:PT/T232

Client:		Sample No	
Project:	Comparison HMA and WMA	Report No	
Sample Method: MRWA 701.1, Preparation MRWA 705.1		Sampled By	
Sampled From		Date of Sampled	16/06/2013
Job Location / Proposed Use		Sample Temp (°C)	140
Asphalt Type / No of Blows:	WMA AC10/50 (3.0% Sasobit)	Bitumen Class	C320

Max Density WA 732.2 (t/m^3)	md	2.456	Bitumen Content WA 730.1 (%)	

Block Identification		1	2	3	
Volumetric Air Voids Target (%)		11.0	11.0	11.0	
Mass to Compact (g)		1156	1156	1156	
Compaction Temperature (°C)		125.0	126.0	125.0	
Cycles		29	27	26	
Date Compacted		13/06/2013	13/06/2013	13/06/2013	
Height$_1$ (mm)		65.12	65.15	65.01	
Height$_2$ (mm)		65.08	65.34	65.08	
Height$_3$ (mm)		65.31	65.18	65.17	
Height$_4$ (mm)		65.10	65.31	65.29	
Height$_5$ (mm)		65.24	65.24	65.18	
Height$_6$ (mm)		65.37	65.38	65.14	
Height$_7$ (mm)		65.29	65.20	65.30	
Height$_8$ (mm)		65.31	65.14	65.26	
Average height (mm)		**65.23**	**65.24**	**65.18**	
Diameter$_1$ (mm)		100.08	100.20	100.12	
Diameter$_2$ (mm)		100.02	100.23	100.19	
Diameter$_3$ (mm)		100.06	100.28	100.22	
Diameter$_4$ (mm)		100.10	100.21	100.28	
Average diameter (mm)		**100.07**	**100.23**	**100.20**	
Mass of block in air (g)	m1	1132.12	1136.47	1128.31	
Mass of block in water (g)	m2	635.28	628.29	647.28	
Mass of block in air SSD (g)	m3	1133.02	1129.00	1145.62	
Bulk Density (t/m^3) (m1*0.997)/(m3-m2)	bd	**2.268**	**2.263**	**2.257**	
Air Voids (%) (md-bd)/md*100	av	**7.7**	**7.9**	**8.1**	**7.9**
Peak Force (kN)		**10.8**	**10.5**	**11.0**	
Tensile Strength (kPa) $(2*P)/(\pi*H_{ave}*D_{ave})X10^6$		**1053.4**	**1022.2**	**1072.2**	
Visual assessment					

Average Tensile Strength		Dry (kPa)	**1049.3**	Wet (kPa)	**937.6**
Tensile Strength Ratio (%)		**89.4**			

Comments: ______________________

Curtin Set ______________________

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Asphalt Tensile Strength Ratio (Wet) AG:PT/T232

Client:		Sample No	
Project:		Report No	
Sample Method: MRWA 701.1, Preparation MRWA 705.1		Sampled By	
Sampled From		Date Sampled	13/06/2013
Job Location / Proposed use:		Sample Temp (°C)	140
Asphalt Type / No of Blows:	WMA AC10/50 (3.0% Sasobit)	Bitumen Class:	C320
Max Density WA 732.2 (t/m^3) md	2.456	Bitumen Content WA 730.1 (%)	5.4

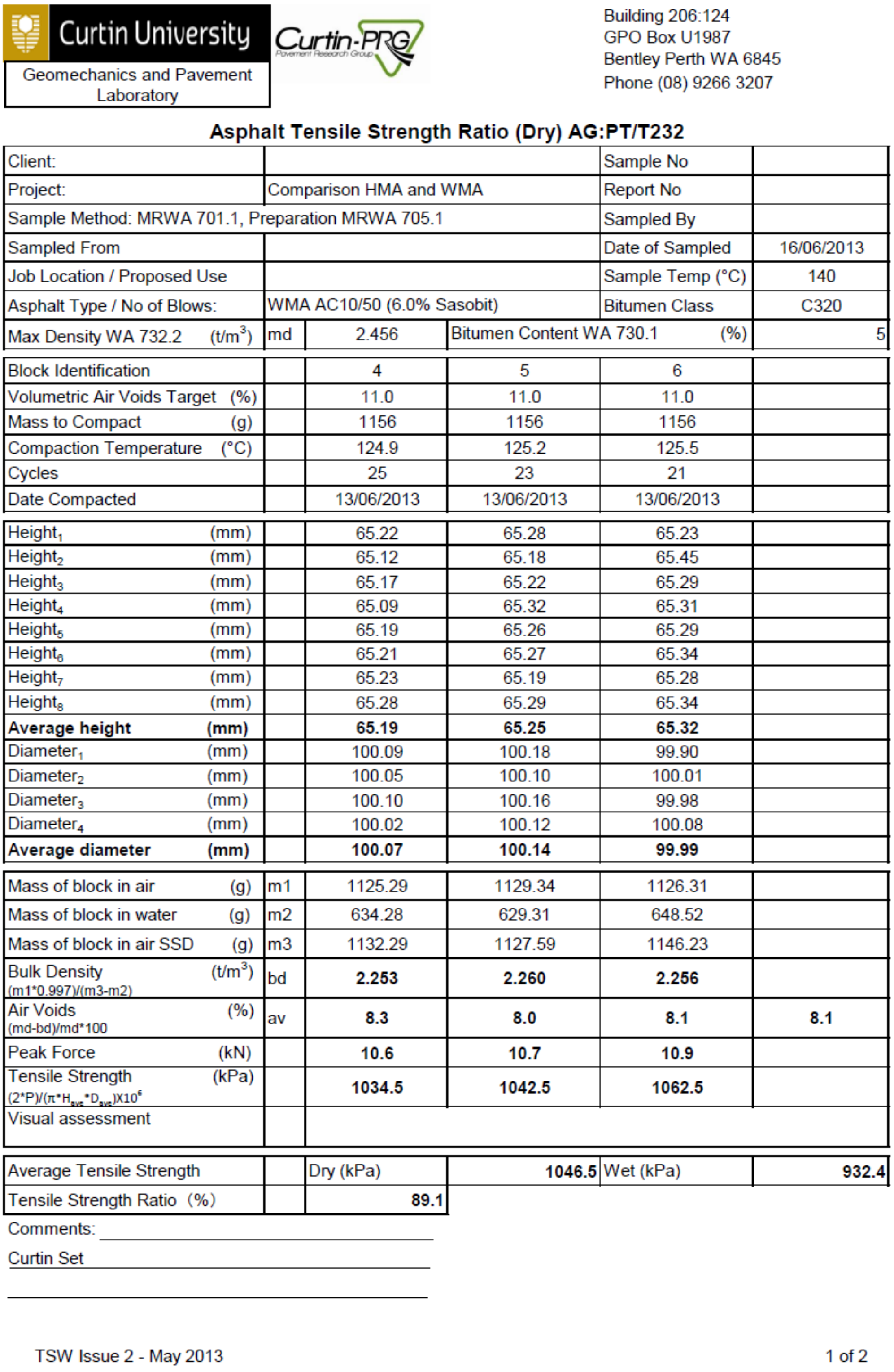
Block Identification		4	5	6	
Volumetric Air Voids Target (%)		11.0	11.0	11.0	
Mass to Compact (g)		1156	1156	1156	
Compaction Temperature (°C)		125.6	126.1	124.8	
Cycles		28	26	28	
Date Compacted		16/06/2013	16/06/2013	16/06/2013	

Conditioning	**Measurements**		Before	After	Before	After	Before	After		
Freeze/Thaw	Height$_1$ (mm)		65.32	65.79	65.18	65.76	65.48	66.06		
Start:	Height$_2$ (mm)		65.38	66.28	65.17	66.18	65.44	66.45		
End:	Height$_3$ (mm)		65.41	66.37	65.20	66.27	65.50	66.57		
60°C Moisture	Height$_4$ (mm)		65.39	66.16	65.20	66.08	65.51	66.39		
Start:	Height$_5$ (mm)		65.44	66.27	65.18	66.12	65.47	66.41		
End:	Height$_6$ (mm)		65.38	66.42	65.02	66.17	65.38	66.53		
25°C Moisture	Height$_7$ (mm)		65.47	66.14	65.19	65.97	65.51	66.29		
End:	Height$_8$ (mm)		65.29	66.13	65.23	66.18	65.49	66.44		
Average height (mm)			**65.39**	**66.20**	**65.17**	**66.09**	**65.47**	**66.39**		
Diameter$_1$ (mm)			99.98	100.20	100.08	100.44	100.10	100.45		
Diameter$_2$ (mm)			99.97	100.15	100.01	100.33	100.08	100.39		
Diameter$_3$ (mm)			100.01	100.16	100.07	100.36	100.05	100.33		
Diameter$_4$ (mm)			100.00	100.26	100.03	100.43	100.90	101.29		
Average diameter (mm)			**99.99**	**100.19**	**100.05**	**100.39**	**100.28**	**100.62**		
Volume $\pi*H*D^2/4000$			513.43	521.85	512.34	523.14	517.13	527.88		

Mass of block in air (g)	m1	1117.28	1113.27	1112.37	
Mass of block in water (g)	m2	623.18	624.18	621.30	
Mass of block in air SSD (g)	m3	1114.38	1116.02	1113.04	
Volume Dry (m3-m2)/0.997	Vd	492.68	493.32	493.22	
Bulk density (m1/vd) (t/m3)	Bd	2.268	2.257	2.255	
% Air Voids (Md-Bd)/Md*100	AV	7.7	8.1	8.2	8.0
Volume Air (AV*Vd)/100 (cc)	Va	37.76	40.03	40.30	
Mass after saturation (g)	Mps	1140.17	1138.17	1137.18	
% Saturation (Mps-M1)/Va*100	Sp	60.6	62.2	61.6	
Swell ((Vmc-Vdm)/Vdm)*100		1.639624362	2.107676804	2.079210095	
Peak Force (kN)	P	9.7	9.8	9.4	
Tensile Strength (kPa) $(2*P)/(\pi*H_{after}*D_{after})*10^6$		**945**	**957**	**911**	
Visual assessment					

Comments:____

Curtin Set



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Asphalt Tensile Strength Ratio (Dry) AG:PT/T232

Client:		Sample No	
Project:	Comparison HMA and WMA	Report No	
Sample Method: MRWA 701.1, Preparation MRWA 705.1		Sampled By	
Sampled From		Date of Sampled	16/06/2013
Job Location / Proposed Use		Sample Temp (°C)	140
Asphalt Type / No of Blows:	WMA AC10/50 (6.0% Sasobit)	Bitumen Class	C320
Max Density WA 732.2 (t/m^3)	md 2.456	Bitumen Content WA 730.1 (%)	5

Block Identification		4	5	6	
Volumetric Air Voids Target (%)		11.0	11.0	11.0	
Mass to Compact (g)		1156	1156	1156	
Compaction Temperature (°C)		124.9	125.2	125.5	
Cycles		25	23	21	
Date Compacted		13/06/2013	13/06/2013	13/06/2013	
Height$_1$ (mm)		65.22	65.28	65.23	
Height$_2$ (mm)		65.12	65.18	65.45	
Height$_3$ (mm)		65.17	65.22	65.29	
Height$_4$ (mm)		65.09	65.32	65.31	
Height$_5$ (mm)		65.19	65.26	65.29	
Height$_6$ (mm)		65.21	65.27	65.34	
Height$_7$ (mm)		65.23	65.19	65.28	
Height$_8$ (mm)		65.28	65.29	65.34	
Average height (mm)		**65.19**	**65.25**	**65.32**	
Diameter$_1$ (mm)		100.09	100.18	99.90	
Diameter$_2$ (mm)		100.05	100.10	100.01	
Diameter$_3$ (mm)		100.10	100.16	99.98	
Diameter$_4$ (mm)		100.02	100.12	100.08	
Average diameter (mm)		**100.07**	**100.14**	**99.99**	
Mass of block in air (g)	m1	1125.29	1129.34	1126.31	
Mass of block in water (g)	m2	634.28	629.31	648.52	
Mass of block in air SSD (g)	m3	1132.29	1127.59	1146.23	
Bulk Density (t/m^3) (m1*0.997)/(m3-m2)	bd	**2.253**	**2.260**	**2.256**	
Air Voids (%) (md-bd)/md*100	av	**8.3**	**8.0**	**8.1**	**8.1**
Peak Force (kN)		**10.6**	**10.7**	**10.9**	
Tensile Strength (kPa) $(2*P)/(\pi*H_{ave}*D_{ave})X10^6$		**1034.5**	**1042.5**	**1062.5**	
Visual assessment					

Average Tensile Strength		Dry (kPa)	**1046.5**	Wet (kPa)	**932.4**
Tensile Strength Ratio (%)		**89.1**			

Comments: ______________________

Curtin Set ______________________

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TSW Issue 2 - May 2013 1 of 2

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Asphalt Tensile Strength Ratio (Wet) AG:PT/T232

Client:		Sample No	
Project:		Report No	
Sample Method: MRWA 701.1, Preparation MRWA 705.1		Sampled By	
Sampled From		Date Sampled	13/06/2013
Job Location / Proposed use:		Sample Temp (°C)	140
Asphalt Type / No of Blows:	WMA AC10/50 (6.0% Sasobit)	Bitumen Class:	C320
Max Density WA 732.2 (t/m^3) md 2.456		Bitumen Content WA 730.1 (%)	5.4

Block Identification		7	8	9	
Volumetric Air Voids Target (%)		11.0	11.0	11.0	
Mass to Compact (g)		1156	1156	1156	
Compaction Temperature (°C)		125.6	126.1	124.8	
Cycles		24	23	21	
Date Compacted		16/06/2013	16/06/2013	16/06/2013	

Conditioning	**Measurements**		Before	After	Before	After	Before	After		
Freeze/Thaw	Height$_1$ (mm)		65.23	65.89	65.31	66.13	65.12	65.92		
Start:	Height$_2$ (mm)		65.18	66.38	65.29	66.65	65.08	66.42		
End:	Height$_3$ (mm)		65.14	66.47	65.34	66.83	65.13	66.60		
60°C Moisture	Height$_4$ (mm)		65.21	66.26	95.29	96.50	65.09	66.28		
Start:	Height$_5$ (mm)		65.29	66.37	65.17	66.41	65.10	66.32		
End:	Height$_6$ (mm)		65.32	66.52	65.28	66.64	65.19	66.53		
25°C Moisture	Height$_7$ (mm)		65.21	66.24	65.31	66.50	65.13	66.30		
End:	Height$_8$ (mm)		65.23	66.23	65.21	66.38	65.21	66.36		
Average height (mm)			**65.23**	**66.30**	**69.03**	**70.26**	**65.13**	**66.34**		
Diameter$_1$ (mm)			100.09	100.33	99.97	100.33	100.09	100.45		
Diameter$_2$ (mm)			100.02	100.28	99.99	100.37	100.08	100.46		
Diameter$_3$ (mm)			99.98	100.29	100.01	100.44	100.10	100.53		
Diameter$_4$ (mm)			100.03	100.39	100.00	100.48	100.08	100.56		
Average diameter (mm)			**100.03**	**100.32**	**99.99**	**100.40**	**100.09**	**100.50**		
Volume π*H*D^2/4000			512.59	524.02	542.04	556.25	512.44	526.28		

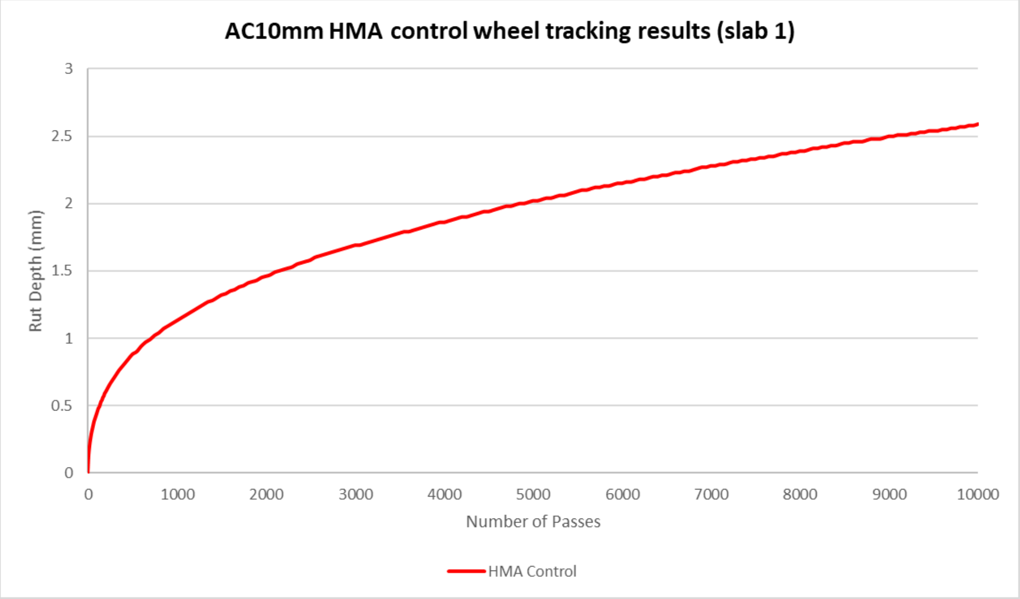
Mass of block in air (g)	m1	1115.26	1112.28	1113.21	
Mass of block in water (g)	m2	621.38	623.18	623.28	
Mass of block in air SSD (g)	m3	1113.29	1116.27	1114.25	
Volume Dry (m3-m2)/0.997	Vd	493.39	494.57	492.45	
Bulk density (m1/vd) (t/m3)	Bd	2.260	2.249	2.261	
% Air Voids (Md-Bd)/Md*100	AV	8.0	8.4	8.0	8.1
Volume Air (AV*Vd)/100 (cc)	Va	39.29	41.69	39.19	
Mass after saturation (g)	Mps	1140.17	1138.17	1137.18	
% Saturation (Mps-M1)/Va*100	Sp	63.4	62.1	61.2	
Swell ((Vmc-Vdm)/Vdm)*100		2.229217138	2.621800112	2.701806441	
Peak Force (kN)	P	9.6	9.9	9.7	
Tensile Strength (kPa) $(2 \cdot P)/(\pi \cdot H_{after} \cdot D_{after}) \cdot 10^6$		**937**	**913**	**947**	
Visual assessment					

Comments:________________________________

Curtin Set________________________________

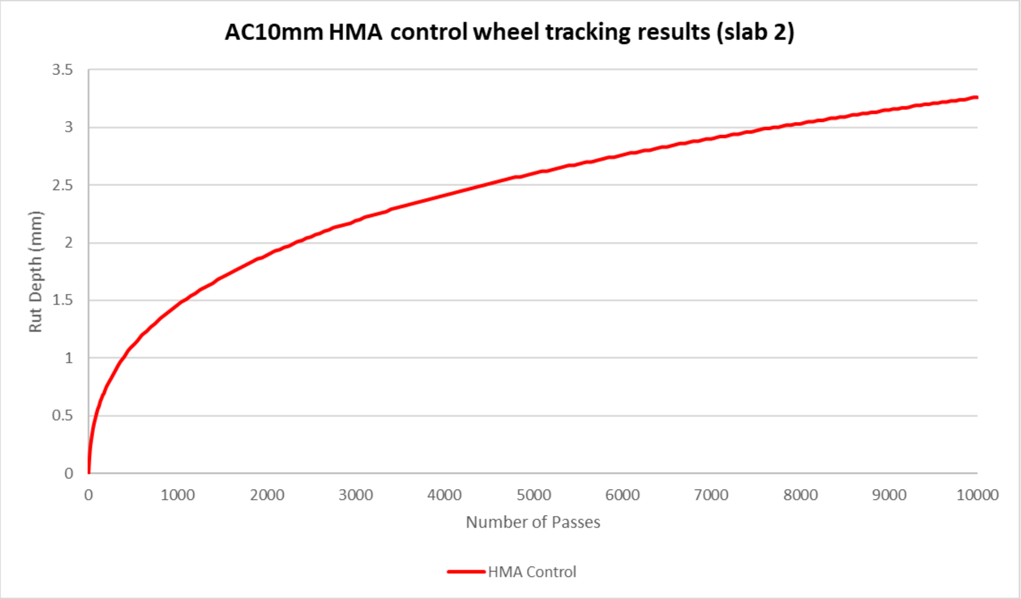
Wheel Tracking

Wheel tracking Test
Specimen Name: AC10mm Control Mix (slab 1)__
Date: 2/07/2013
Bitumen C320: 5.4%
Air voids 5.2%
Test Temperature: 60°C
Specimen Thickness: 50mm



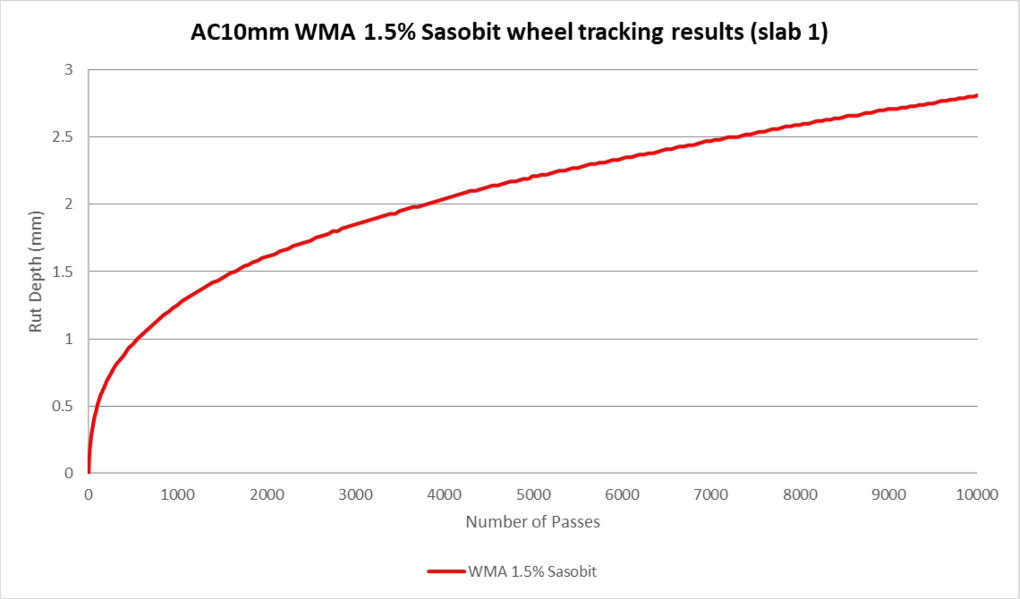
Test Finished At 10000 Passes
(5000.0 Load Cycles)
Final Rut depth = 2.6 mm

Wheel tracking Test
Specimen Name: AC10mm Control Mix (slab 2)
Date: 24/07/2013
Bitumen C320 5.4%
Air voids 5.1
Test Temperature: 60°C
Specimen Thickness: 50mm



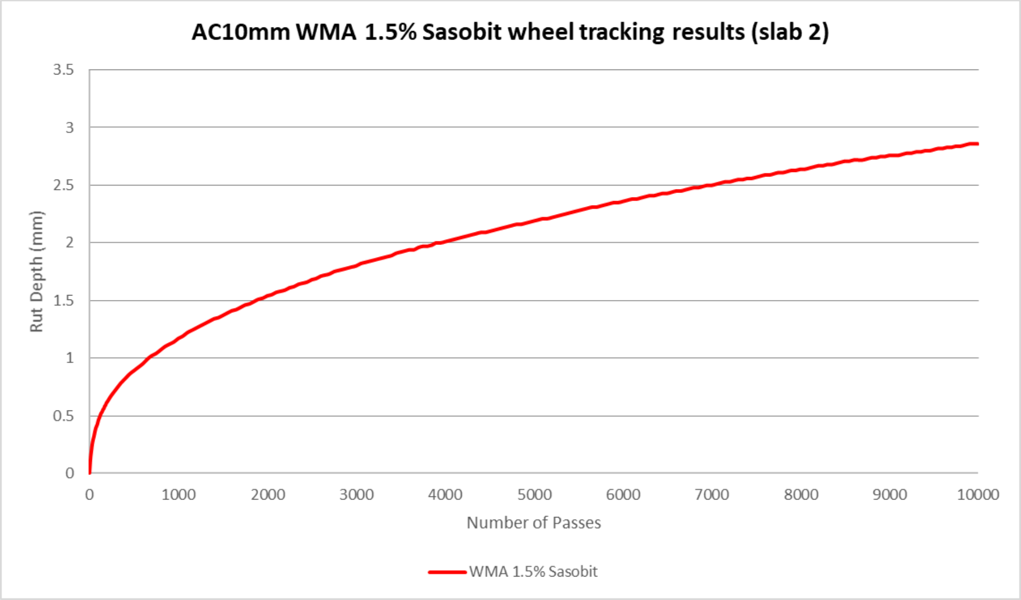
Test Finished At 10000
Passes (5000.0 Load Cycles)
Final Rut depth = 3.3 mm

Wheel tracking Test
Specimen Name: AC 10mm 1.5% Sasobit (slab 1)
Date: 21/06/2013
Bitumen C320 5.4%
Air voids 5.2%
Test Temperature: 60°C
Specimen Thickness: 50mm



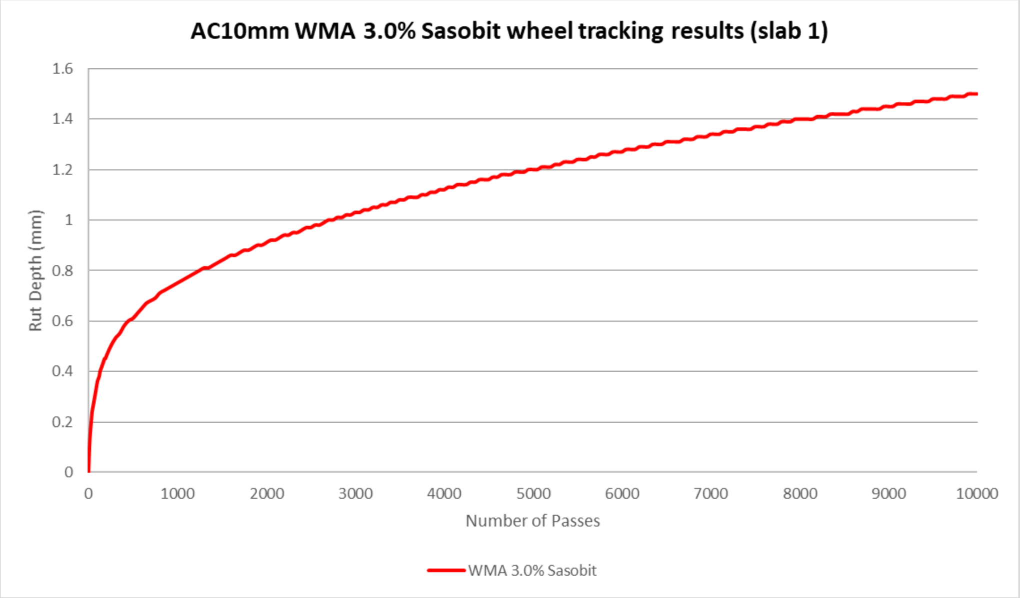
Test Finished At 10000
Passes (5000.0 Load Cycles)
Final Rut depth = 2.8 mm

Wheel tracking Test
Specimen Name: AC10mm 1.5% Sasobit (slab 2)
Date: 2/07/2013
Bitumen C320 5.4%
Air voids 5.1%
Test Temperature: 60°C
Specimen Thickness: 50mm



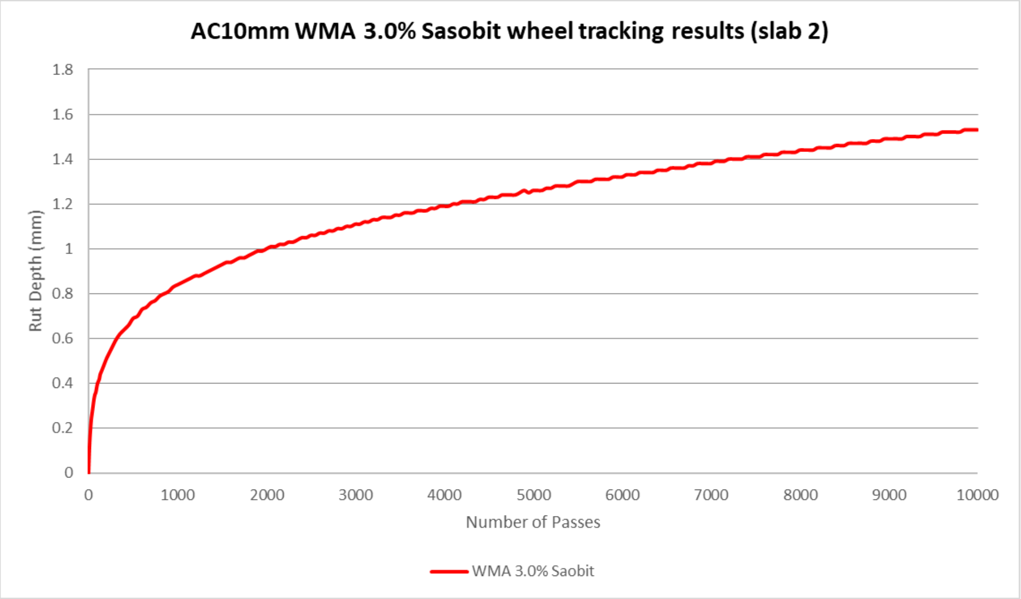
Test Finished At 10000
Passes (5000.0 Load Cycles)
Final Rut depth = 2.9 mm

Wheel tracking Test
Specimen Name: AC10mm 3.0% Sasobit (slab 1)
Date: 31/07/2013
Bitumen C320 5.4%
Air voids 5.1%
Test Temperature: 60°C
Specimen Thickness: 50mm



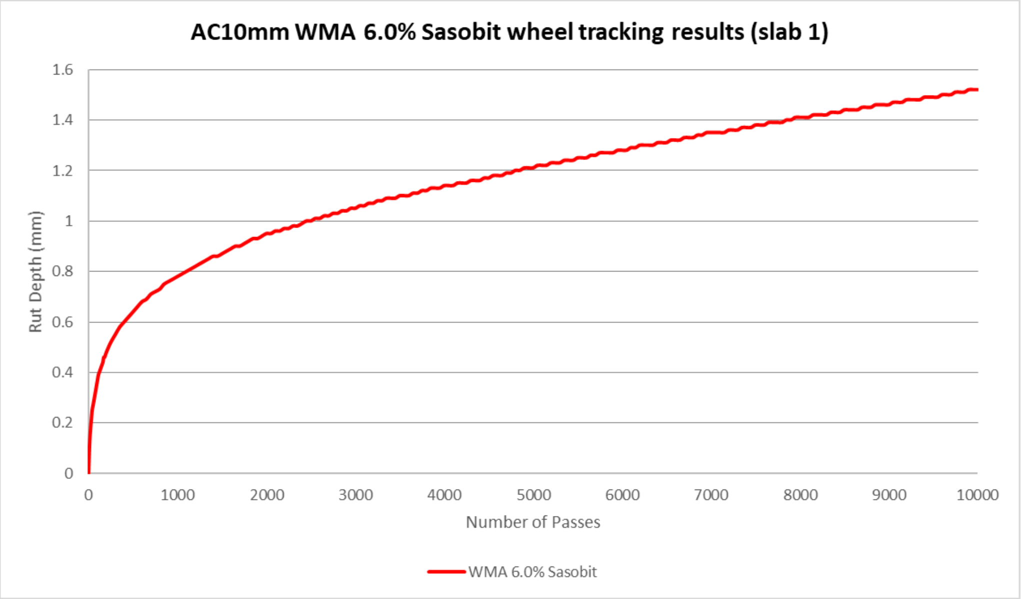
Test Finished At 10000
Passes (5000.0 Load Cycles)
Final Rut depth = 1.5 mm

Wheel tracking Test
Specimen Name: AC10mm 3.0% Sasobit (slab 2)
Date: 31/07/2013
Bitumen C320 5.4%
Air voids 5.2%
Test Temperature: 60°C
Specimen Thickness: 50mm



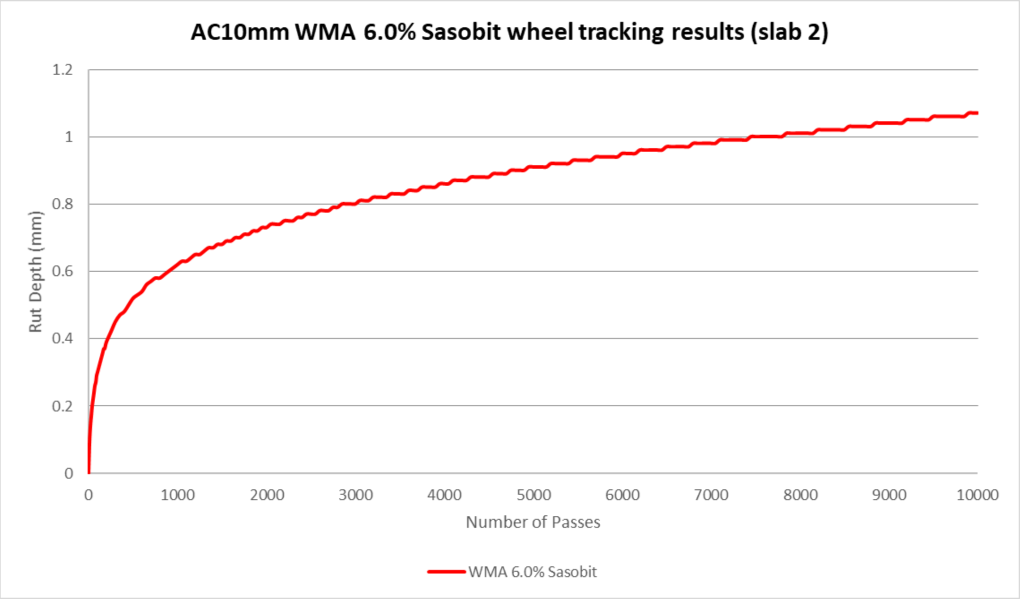
Test Finished At 10000
Passes (5000.0 Load Cycles)
Final Rut depth = 1.5 mm

Wheel tracking Test
Specimen Name:AC10mm 6.0% Sasobit (Slab 1)
Date: 1/08/2013
Bitumen C320 5.4%
Air voids 5.0%
Test Temperature: 60°C
Specimen Thickness: 50mm



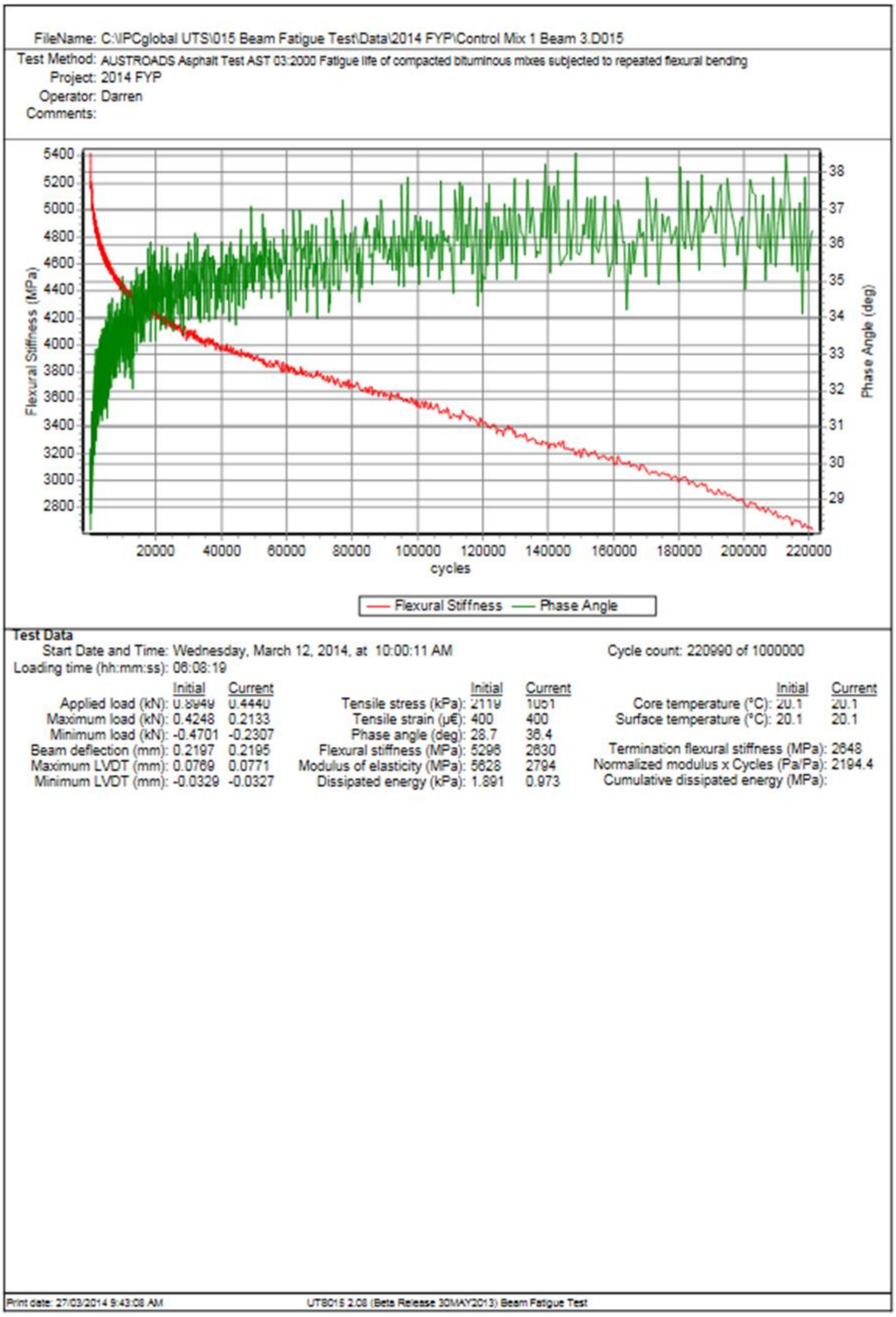
Test Finished At 10000
Passes (5000.0 Load Cycles)
Final Rut depth = 1.5 mm

Wheel tracking Test
Specimen Name: AC10-75 6.0% Sasobit (slab 2)
Date: 2/08/2013
Bitumen C320 5.4%
Air voids 5.1%
Test Temperature: 60°C
Specimen Thickness: 50mm



Test Finished At 10000
Passes (5000.0 Load Cycles)
Final Rut depth = 1.1 mm

Fatigue Resistance



FileName: C:\IPCglobal UTS\015 Beam Fatigue Test\Data\2014 FYP\Control Mix 1 Beam 3.D015

Test Method: AUSTROADS Asphalt Test AST 03:2000 Fatigue life of compacted bituminous mixes subjected to repeated flexural bending
Project: 2014 FYP
Operator: Darren
Comments:

Test Data

Start Date and Time: Wednesday, March 12, 2014, at 10:00:11 AM
Cycle count: 220990 of 1000000
Loading time (hh:mm:ss): 06:08:19

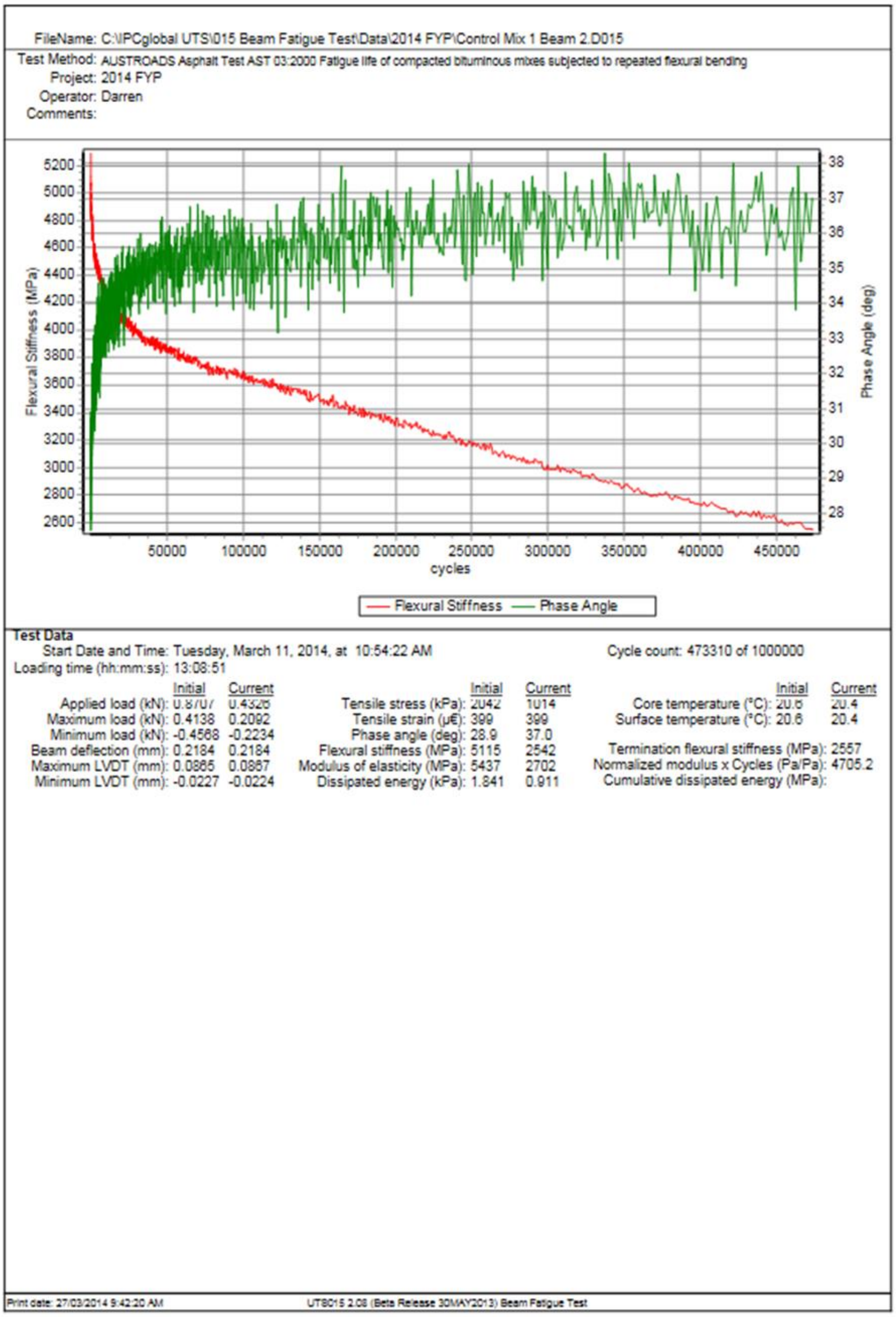
	Initial	Current
Applied load (kN):	0.8949	0.4440
Maximum load (kN):	0.4248	0.2133
Minimum load (kN):	-0.4701	-0.2307
Beam deflection (mm):	0.2197	0.2195
Maximum LVDT (mm):	0.0769	0.0771
Minimum LVDT (mm):	-0.0329	-0.0327

	Initial	Current
Tensile stress (kPa):	2119	1061
Tensile strain (μ€):	400	400
Phase angle (deg):	28.7	36.4
Flexural stiffness (MPa):	5296	2630
Modulus of elasticity (MPa):	5628	2794
Dissipated energy (kPa):	1.891	0.973

	Initial	Current
Core temperature (°C):	20.1	20.1
Surface temperature (°C):	20.1	20.1

Termination flexural stiffness (MPa): 2648
Normalized modulus x Cycles (Pa/Pa): 2194.4
Cumulative dissipated energy (MPa):

Print date: 27/03/2014 9:43:08 AM
UT8015 2.08 (Beta Release 30MAY2013) Beam Fatigue Test



FileName: C:\IPCglobal UTS\015 Beam Fatigue Test\Data\2014 FYP\Control Mix 1 Beam 2.D015

Test Method: AUSTROADS Asphalt Test AST 03:2000 Fatigue life of compacted bituminous mixes subjected to repeated flexural bending
Project: 2014 FYP
Operator: Darren
Comments:

Test Data

Start Date and Time: Tuesday, March 11, 2014, at 10:54:22 AM

Cycle count: 473310 of 1000000

Loading time (hh:mm:ss): 13:08:51

	Initial	Current
Applied load (kN):	0.8707	0.4326
Maximum load (kN):	0.4138	0.2092
Minimum load (kN):	-0.4568	-0.2234
Beam deflection (mm):	0.2184	0.2184
Maximum LVDT (mm):	0.0865	0.0867
Minimum LVDT (mm):	-0.0227	-0.0224

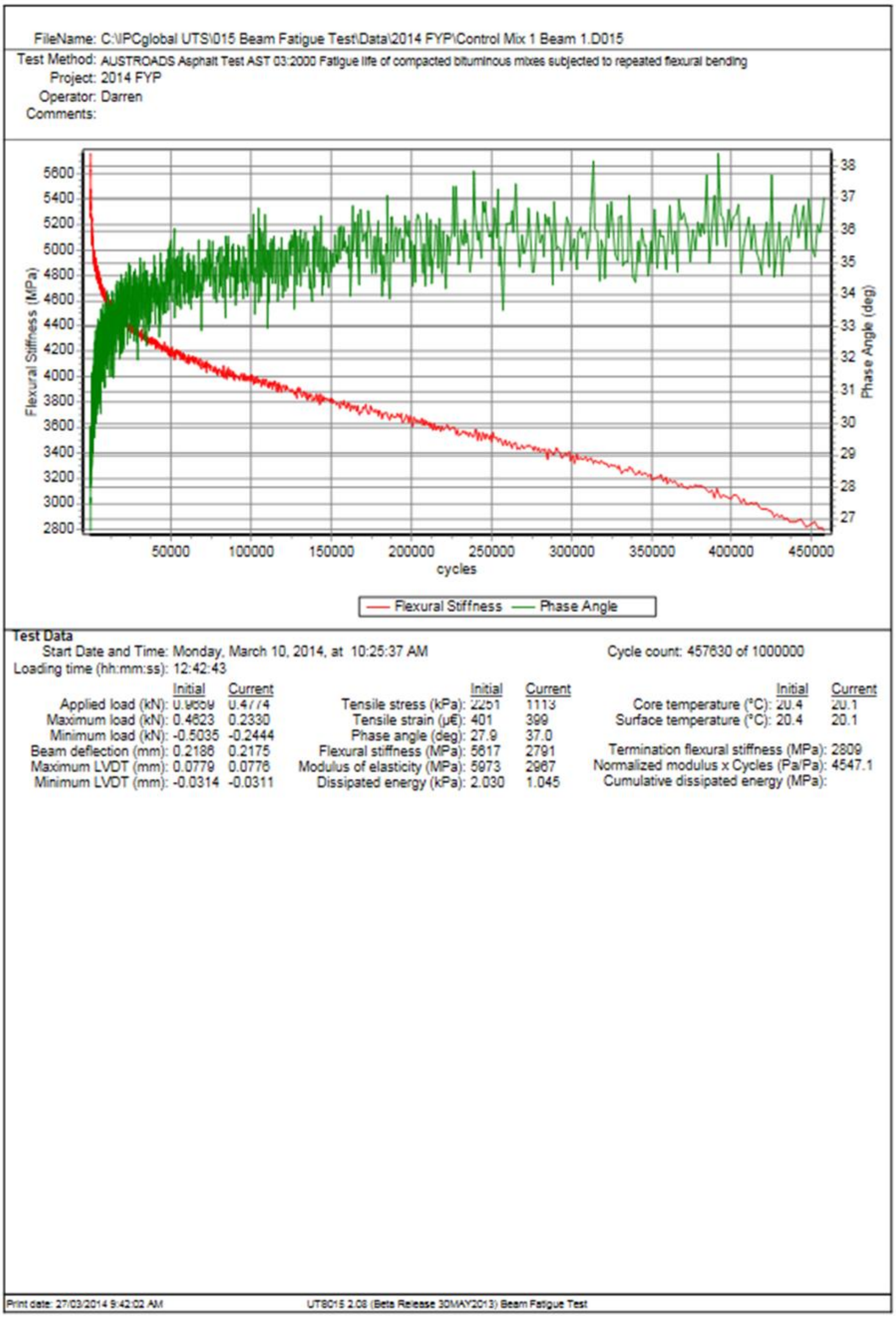
	Initial	Current
Tensile stress (kPa):	2042	1014
Tensile strain (µ€):	399	399
Phase angle (deg):	28.9	37.0
Flexural stiffness (MPa):	5115	2542
Modulus of elasticity (MPa):	5437	2702
Dissipated energy (kPa):	1.841	0.911

	Initial	Current
Core temperature (°C):	20.6	20.4
Surface temperature (°C):	20.6	20.4

Termination flexural stiffness (MPa): 2557
Normalized modulus x Cycles (Pa/Pa): 4705.2
Cumulative dissipated energy (MPa):

Print date: 27/03/2014 9:42:20 AM

UT8015 2.08 (Beta Release 30MAY2013) Beam Fatigue Test



FileName: C:\IPCglobal UTS\015 Beam Fatigue Test\Data\2014 FYP\Control Mix 1 Beam 1.D015

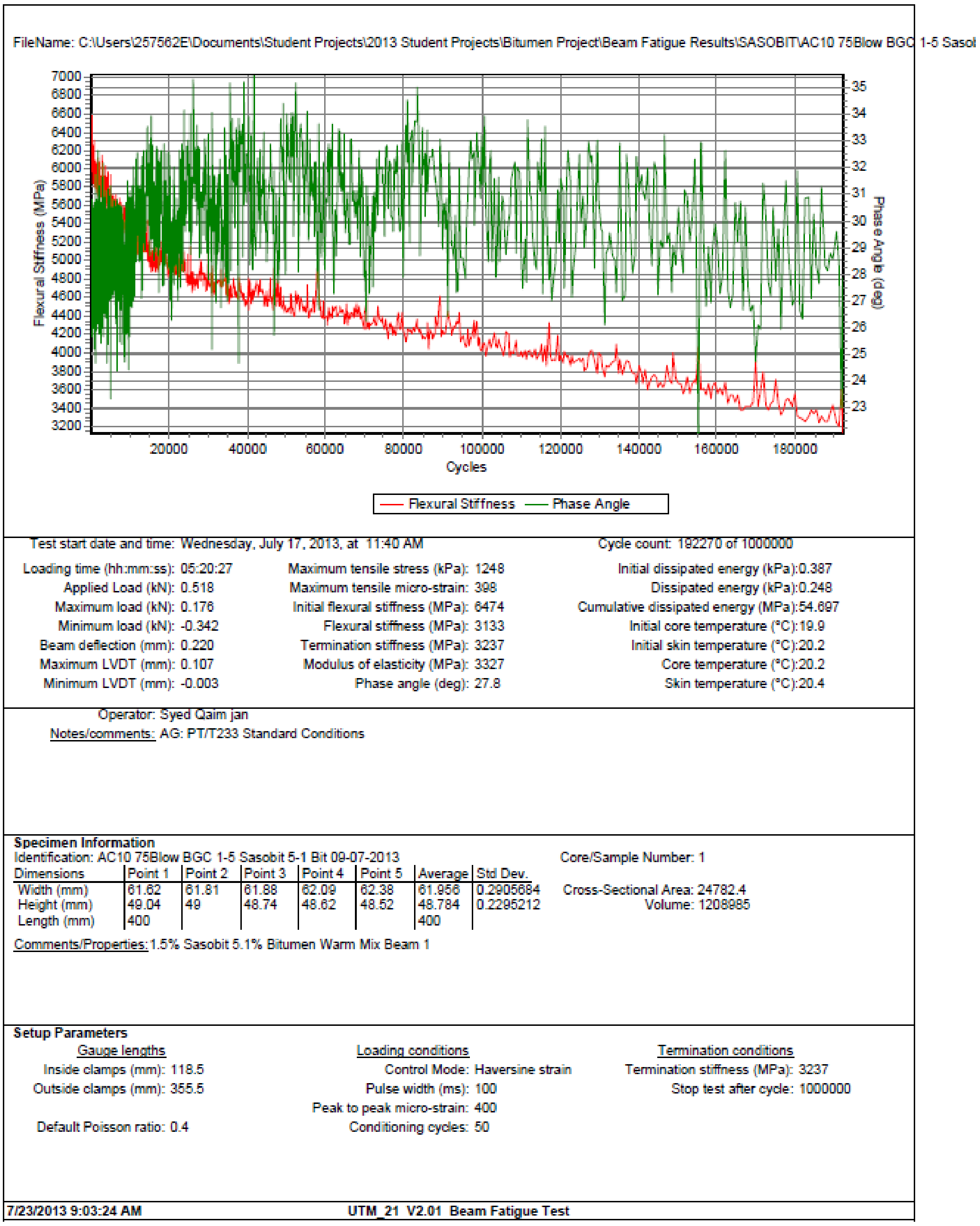
Test Method: AUSTROADS Asphalt Test AST 03:2000 Fatigue life of compacted bituminous mixes subjected to repeated flexural bending
Project: 2014 FYP
Operator: Darren
Comments:

Test Data

Start Date and Time: Monday, March 10, 2014, at 10:25:37 AM
Cycle count: 457630 of 1000000
Loading time (hh:mm:ss): 12:42:43

	Initial	Current		Initial	Current		Initial	Current
Applied load (kN):	0.9659	0.4774	Tensile stress (kPa):	2251	1113	Core temperature (°C):	20.4	20.1
Maximum load (kN):	0.4623	0.2330	Tensile strain (µ€):	401	399	Surface temperature (°C):	20.4	20.1
Minimum load (kN):	-0.5035	-0.2444	Phase angle (deg):	27.9	37.0			
Beam deflection (mm):	0.2186	0.2175	Flexural stiffness (MPa):	5617	2791	Termination flexural stiffness (MPa):	2809	
Maximum LVDT (mm):	0.0779	0.0776	Modulus of elasticity (MPa):	5973	2967	Normalized modulus x Cycles (Pa/Pa):	4547.1	
Minimum LVDT (mm):	-0.0314	-0.0311	Dissipated energy (kPa):	2.030	1.045	Cumulative dissipated energy (MPa):		

Print date: 27/03/2014 9:42:02 AM
UT8015 2.08 (Beta Release 30MAY2013) Beam Fatigue Test



FileName: C:\Users\257562E\Documents\Student Projects\2013 Student Projects\Bitumen Project\Beam Fatigue Results\SASOBIT\AC10 75Blow BGC 1-5 Sasol

Test start date and time: Wednesday, July 17, 2013, at 11:40 AM

Cycle count: 192270 of 1000000

Loading time (hh:mm:ss): 05:20:27
Applied Load (kN): 0.518
Maximum load (kN): 0.176
Minimum load (kN): -0.342
Beam deflection (mm): 0.220
Maximum LVDT (mm): 0.107
Minimum LVDT (mm): -0.003

Maximum tensile stress (kPa): 1248
Maximum tensile micro-strain: 398
Initial flexural stiffness (MPa): 6474
Flexural stiffness (MPa): 3133
Termination stiffness (MPa): 3237
Modulus of elasticity (MPa): 3327
Phase angle (deg): 27.8

Initial dissipated energy (kPa):0.387
Dissipated energy (kPa):0.248
Cumulative dissipated energy (MPa):54.697
Initial core temperature (°C):19.9
Initial skin temperature (°C):20.2
Core temperature (°C):20.2
Skin temperature (°C):20.4

Operator: Syed Qaim jan
Notes/comments: AG: PT/T233 Standard Conditions

Specimen Information
Identification: AC10 75Blow BGC 1-5 Sasobit 5-1 Bit 09-07-2013
Core/Sample Number: 1

Dimensions	Point 1	Point 2	Point 3	Point 4	Point 5	Average	Std Dev.
Width (mm)	61.62	61.81	61.88	62.09	62.38	61.956	0.2905684
Height (mm)	49.04	49	48.74	48.62	48.52	48.784	0.2295212
Length (mm)	400					400	

Cross-Sectional Area: 24782.4
Volume: 1208985

Comments/Properties: 1.5% Sasobit 5.1% Bitumen Warm Mix Beam 1

Setup Parameters

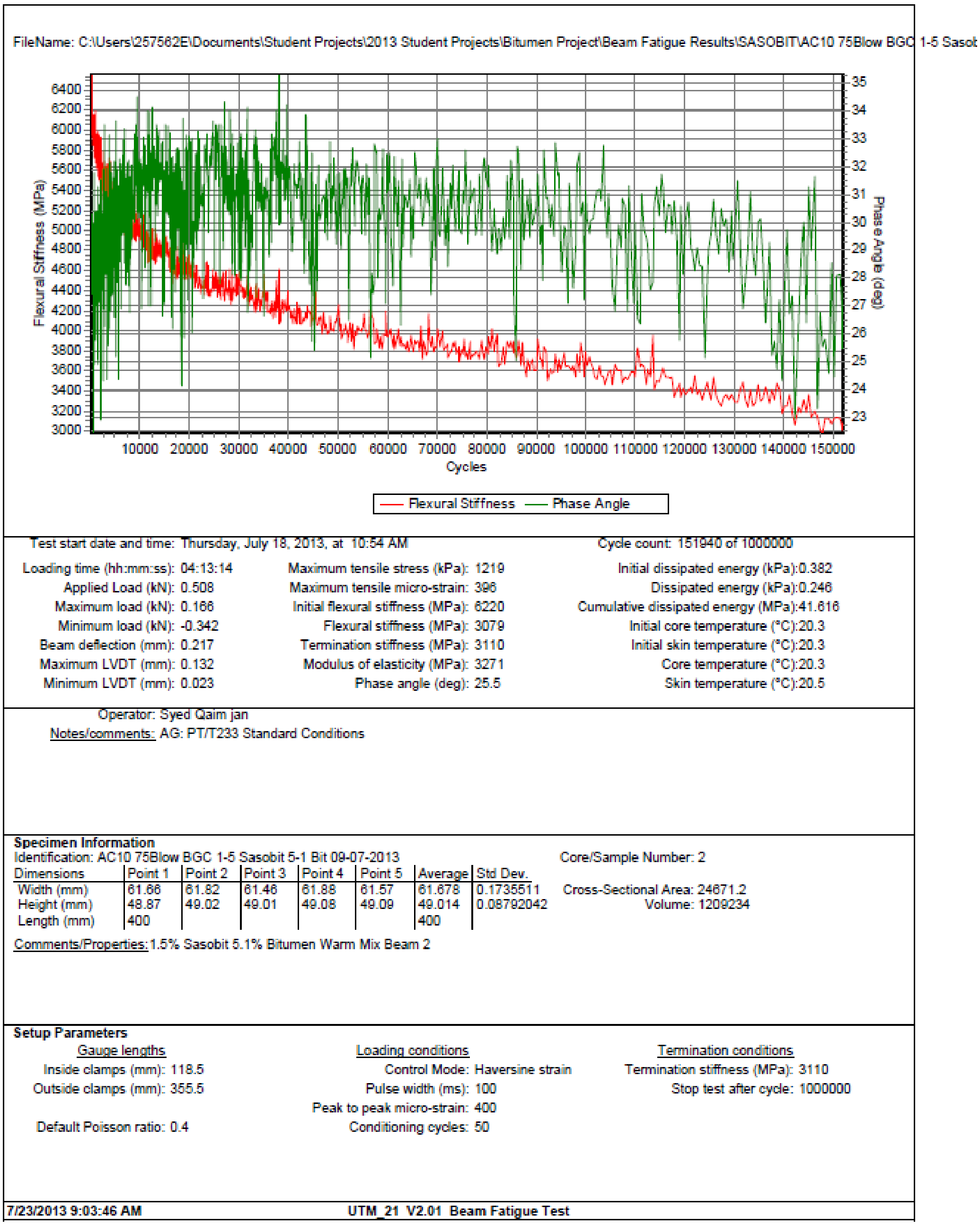
Gauge lengths
Inside clamps (mm): 118.5
Outside clamps (mm): 355.5

Default Poisson ratio: 0.4

Loading conditions
Control Mode: Haversine strain
Pulse width (ms): 100
Peak to peak micro-strain: 400
Conditioning cycles: 50

Termination conditions
Termination stiffness (MPa): 3237
Stop test after cycle: 1000000

7/23/2013 9:03:24 AM **UTM_21 V2.01 Beam Fatigue Test**



FileName: C:\Users\257562E\Documents\Student Projects\2013 Student Projects\Bitumen Project\Beam Fatigue Results\SASOBIT\AC10 75Blow BGC 1-5 Sasot

Test start date and time: Thursday, July 18, 2013, at 10:54 AM   Cycle count: 151940 of 1000000

Loading time (hh:mm:ss): 04:13:14
Applied Load (kN): 0.508
Maximum load (kN): 0.166
Minimum load (kN): -0.342
Beam deflection (mm): 0.217
Maximum LVDT (mm): 0.132
Minimum LVDT (mm): 0.023

Maximum tensile stress (kPa): 1219
Maximum tensile micro-strain: 396
Initial flexural stiffness (MPa): 6220
Flexural stiffness (MPa): 3079
Termination stiffness (MPa): 3110
Modulus of elasticity (MPa): 3271
Phase angle (deg): 25.5

Initial dissipated energy (kPa):0.382
Dissipated energy (kPa):0.246
Cumulative dissipated energy (MPa):41.616
Initial core temperature (°C):20.3
Initial skin temperature (°C):20.3
Core temperature (°C):20.3
Skin temperature (°C):20.5

Operator: Syed Qaim jan
Notes/comments: AG: PT/T233 Standard Conditions

Specimen Information
Identification: AC10 75Blow BGC 1-5 Sasobit 5-1 Bit 09-07-2013   Core/Sample Number: 2

Dimensions	Point 1	Point 2	Point 3	Point 4	Point 5	Average	Std Dev.
Width (mm)	61.66	61.82	61.46	61.88	61.57	61.678	0.1735511
Height (mm)	48.87	49.02	49.01	49.08	49.09	49.014	0.08792042
Length (mm)	400					400	

Cross-Sectional Area: 24671.2
Volume: 1209234

Comments/Properties: 1.5% Sasobit 5.1% Bitumen Warm Mix Beam 2

Setup Parameters

Gauge lengths
Inside clamps (mm): 118.5
Outside clamps (mm): 355.5

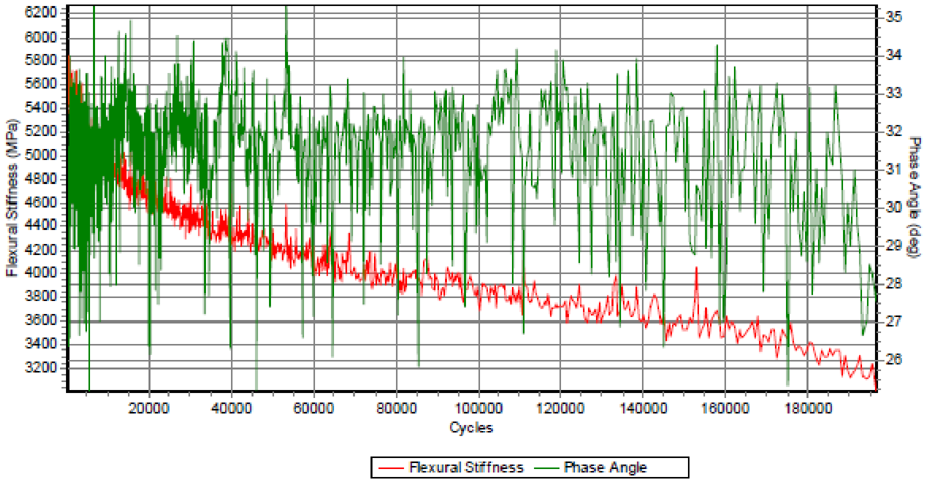
Default Poisson ratio: 0.4

Loading conditions
Control Mode: Haversine strain
Pulse width (ms): 100
Peak to peak micro-strain: 400
Conditioning cycles: 50

Termination conditions
Termination stiffness (MPa): 3110
Stop test after cycle: 1000000

7/23/2013 9:03:46 AM   **UTM_21 V2.01 Beam Fatigue Test**

FileName: C:\Users\257562E\Documents\Student Projects\2013 Student Projects\Bitumen Project\Beam Fatigue Results\SASOBIT\AC10 75Blow BGC 1-5 Saso



Test start date and time: Thursday, July 18, 2013, at 3:52 PM
Cycle count: 196700 of 1000000

Loading time (hh:mm:ss): 05:27:50
Applied Load (kN): 0.498
Maximum load (kN): 0.166
Minimum load (kN): -0.332
Beam deflection (mm): 0.218
Maximum LVDT (mm): 0.113
Minimum LVDT (mm): 0.004

Maximum tensile stress (kPa): 1193
Maximum tensile micro-strain: 396
Initial flexural stiffness (MPa): 6138
Flexural stiffness (MPa): 3010
Termination stiffness (MPa): 3069
Modulus of elasticity (MPa): 3197
Phase angle (deg): 27.6

Initial dissipated energy (kPa):0.380
Dissipated energy (kPa):0.248
Cumulative dissipated energy (MPa):54.552
Initial core temperature (°C):20.3
Initial skin temperature (°C):20.6
Core temperature (°C):20.0
Skin temperature (°C):20.3

Operator: Syed Qaim jan
Notes/comments: AG: PT/T233 Standard Conditions

Specimen Information
Identification: AC10 75Blow BGC 1-5 Sasobit 5-1 Bit 09-07-2013
Core/Sample Number: 3

Dimensions	Point 1	Point 2	Point 3	Point 4	Point 5	Average	Std Dev.
Width (mm)	61.49	61.92	62.17	62.46	62.69	62.146	0.4681132
Height (mm)	48.72	48.82	48.88	48.94	48.99	48.87	0.1053565
Length (mm)	400					400	

Cross-Sectional Area: 24858.4
Volume: 1214830

Comments/Properties: 1.5% Sasobit 5.1% Bitumen Warm Mix Beam 3

Setup Parameters

Gauge lengths
Inside clamps (mm): 118.5
Outside clamps (mm): 355.5

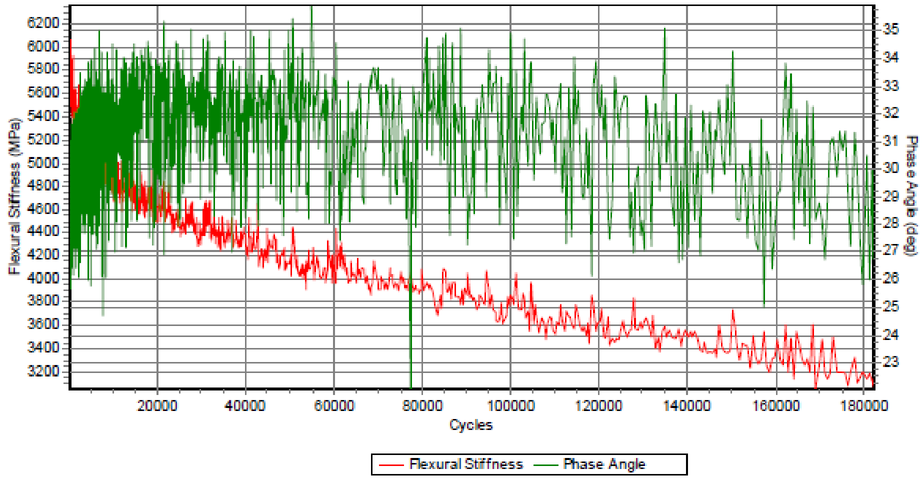
Default Poisson ratio: 0.4

Loading conditions
Control Mode: Haversine strain
Pulse width (ms): 100
Peak to peak micro-strain: 400
Conditioning cycles: 50

Termination conditions
Termination stiffness (MPa): 3069
Stop test after cycle: 1000000

7/23/2013 9:04:08 AM **UTM_21 V2.01 Beam Fatigue Test**

FileName: C:\Users\257562E\Documents\Student Projects\2013 Student Projects\Bitumen Project\Beam Fatigue Results\SASOBIT\AC10 75Blow BGC 3-0 Sasol



Test start date and time: Friday, July 19, 2013, at 1:01 PM

Cycle count: 182210 of 1000000

Loading time (hh:mm:ss): 05:03:41
Applied Load (kN): 0.508
Maximum load (kN): 0.166
Minimum load (kN): -0.342
Beam deflection (mm): 0.219
Maximum LVDT (mm): 0.133
Minimum LVDT (mm): 0.023

Maximum tensile stress (kPa): 1223
Maximum tensile micro-strain: 397
Initial flexural stiffness (MPa): 6228
Flexural stiffness (MPa): 3083
Termination stiffness (MPa): 3114
Modulus of elasticity (MPa): 3273
Phase angle (deg): 26.8

Initial dissipated energy (kPa):0.379
Dissipated energy (kPa):0.253
Cumulative dissipated energy (MPa):49.470
Initial core temperature (°C):19.7
Initial skin temperature (°C):19.8
Core temperature (°C):20.1
Skin temperature (°C):20.4

Operator: Syed Qaim jan
Notes/comments: AG: PT/T233 Standard Conditions

Specimen Information

Identification: AC10 75Blow BGC 3-0 Sasobit 5-1 Bit 15-07-2013

Core/Sample Number: 1

Dimensions	Point 1	Point 2	Point 3	Point 4	Point 5	Average	Std Dev.
Width (mm)	62.2	62.43	62.22	62.47	62.14	62.292	0.1478851
Height (mm)	48.94	48.66	48.69	48.44	48.71	48.688	0.1776795
Length (mm)	400					400	

Cross-Sectional Area: 24916.8
Volume: 1213149

Comments/Properties:3.0% Sasobit 5.1% Bitumen Warm Mix Beam 1

Setup Parameters

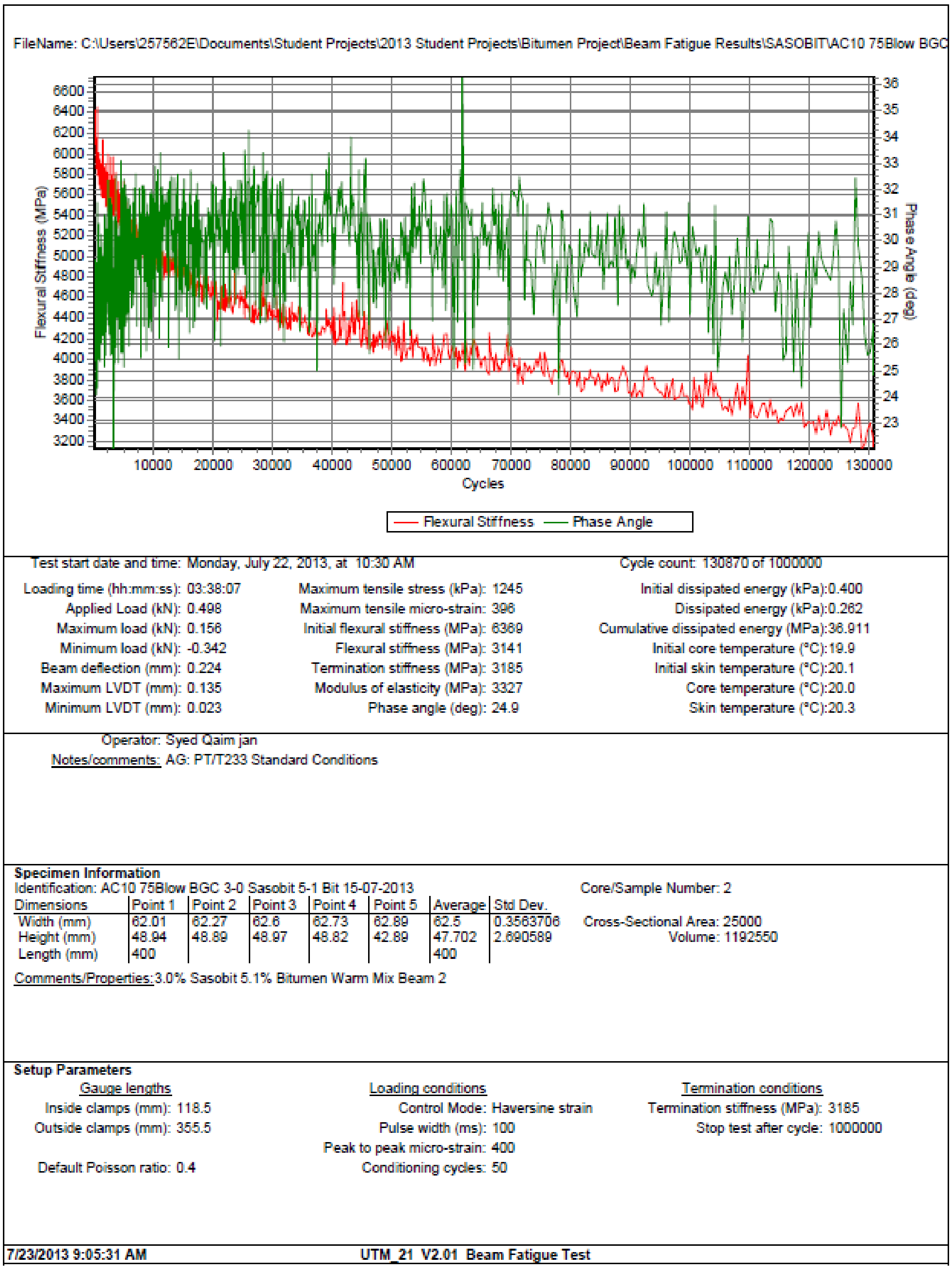
Gauge lengths
Inside clamps (mm): 118.5
Outside clamps (mm): 355.5

Default Poisson ratio: 0.4

Loading conditions
Control Mode: Haversine strain
Pulse width (ms): 100
Peak to peak micro-strain: 400
Conditioning cycles: 50

Termination conditions
Termination stiffness (MPa): 3114
Stop test after cycle: 1000000

7/23/2013 9:05:06 AM UTM_21 V2.01 Beam Fatigue Test



FileName: C:\Users\257562E\Documents\Student Projects\2013 Student Projects\Bitumen Project\Beam Fatigue Results\SASOBIT\AC10 75Blow BGC 3-0 Sasol

Test start date and time: Monday, July 22, 2013, at 10:30 AM

Cycle count: 130870 of 1000000

Loading time (hh:mm:ss): 03:38:07
Applied Load (kN): 0.498
Maximum load (kN): 0.156
Minimum load (kN): -0.342
Beam deflection (mm): 0.224
Maximum LVDT (mm): 0.135
Minimum LVDT (mm): 0.023

Maximum tensile stress (kPa): 1245
Maximum tensile micro-strain: 396
Initial flexural stiffness (MPa): 6369
Flexural stiffness (MPa): 3141
Termination stiffness (MPa): 3185
Modulus of elasticity (MPa): 3327
Phase angle (deg): 24.9

Initial dissipated energy (kPa):0.400
Dissipated energy (kPa):0.262
Cumulative dissipated energy (MPa):36.911
Initial core temperature (°C):19.9
Initial skin temperature (°C):20.1
Core temperature (°C):20.0
Skin temperature (°C):20.3

Operator: Syed Qaim jan

Notes/comments: AG: PT/T233 Standard Conditions

Specimen Information

Identification: AC10 75Blow BGC 3-0 Sasobit 5-1 Bit 15-07-2013

Core/Sample Number: 2

Dimensions	Point 1	Point 2	Point 3	Point 4	Point 5	Average	Std Dev.
Width (mm)	62.01	62.27	62.6	62.73	62.89	62.5	0.3563706
Height (mm)	48.94	48.89	48.97	48.82	42.89	47.702	2.690589
Length (mm)	400					400	

Cross-Sectional Area: 25000
Volume: 1192550

Comments/Properties:3.0% Sasobit 5.1% Bitumen Warm Mix Beam 2

Setup Parameters

Gauge lengths
Inside clamps (mm): 118.5
Outside clamps (mm): 355.5

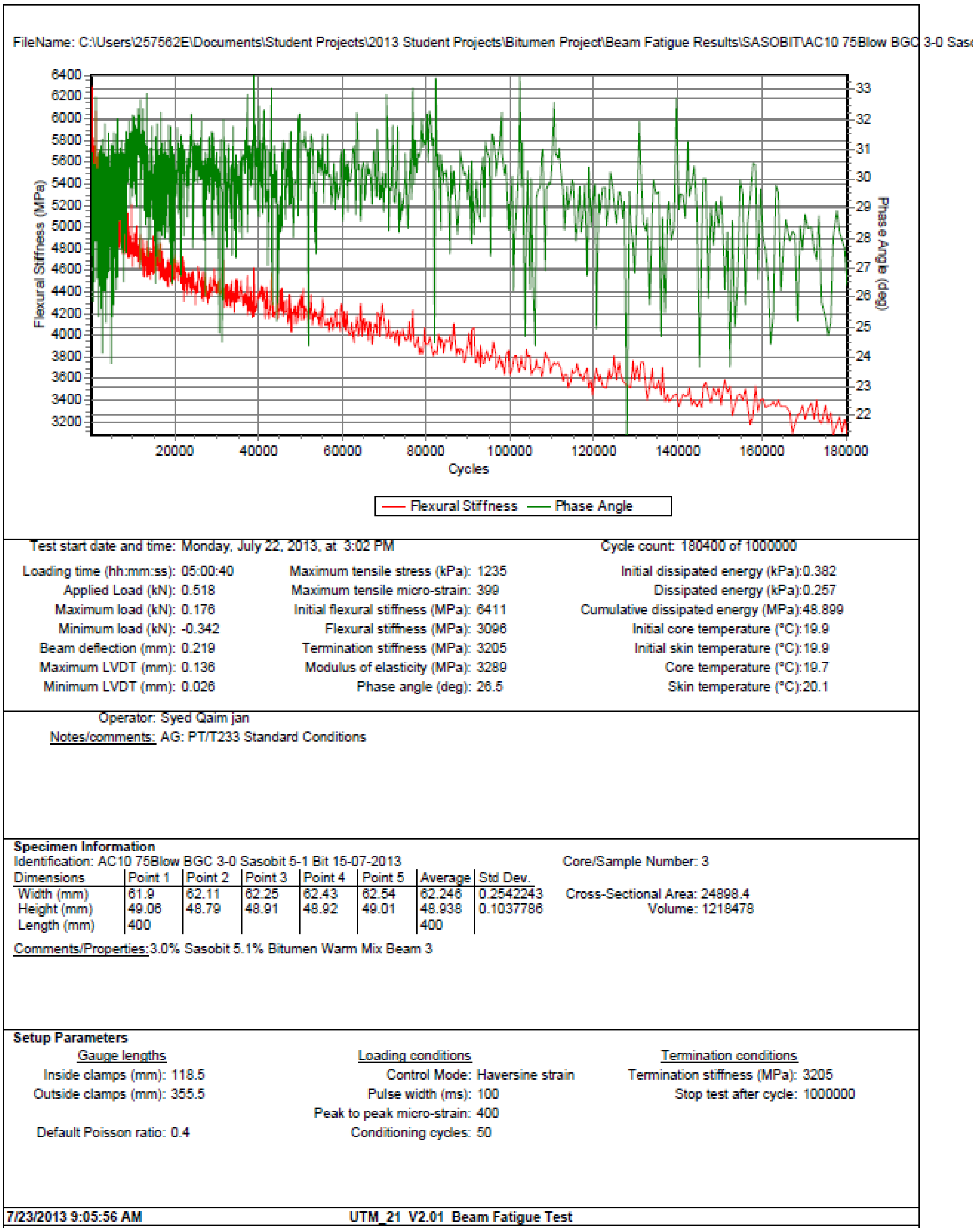
Default Poisson ratio: 0.4

Loading conditions
Control Mode: Haversine strain
Pulse width (ms): 100
Peak to peak micro-strain: 400
Conditioning cycles: 50

Termination conditions
Termination stiffness (MPa): 3185
Stop test after cycle: 1000000

7/23/2013 9:05:31 AM

UTM_21 V2.01 Beam Fatigue Test



Test start date and time: Monday, July 22, 2013, at 3:02 PM

Cycle count: 180400 of 1000000

Loading time (hh:mm:ss): 05:00:40
Applied Load (kN): 0.518
Maximum load (kN): 0.176
Minimum load (kN): -0.342
Beam deflection (mm): 0.219
Maximum LVDT (mm): 0.136
Minimum LVDT (mm): 0.026

Maximum tensile stress (kPa): 1235
Maximum tensile micro-strain: 399
Initial flexural stiffness (MPa): 6411
Flexural stiffness (MPa): 3096
Termination stiffness (MPa): 3205
Modulus of elasticity (MPa): 3289
Phase angle (deg): 26.5

Initial dissipated energy (kPa):0.382
Dissipated energy (kPa):0.257
Cumulative dissipated energy (MPa):48.899
Initial core temperature (°C):19.9
Initial skin temperature (°C):19.9
Core temperature (°C):19.7
Skin temperature (°C):20.1

Operator: Syed Qaim jan
Notes/comments: AG: PT/T233 Standard Conditions

Specimen Information
Identification: AC10 75Blow BGC 3-0 Sasobit 5-1 Bit 15-07-2013

Core/Sample Number: 3

Dimensions	Point 1	Point 2	Point 3	Point 4	Point 5	Average	Std Dev.
Width (mm)	61.9	62.11	62.25	62.43	62.54	62.246	0.2542243
Height (mm)	49.06	48.79	48.91	48.92	49.01	48.938	0.1037786
Length (mm)	400					400	

Cross-Sectional Area: 24898.4
Volume: 1218478

Comments/Properties: 3.0% Sasobit 5.1% Bitumen Warm Mix Beam 3

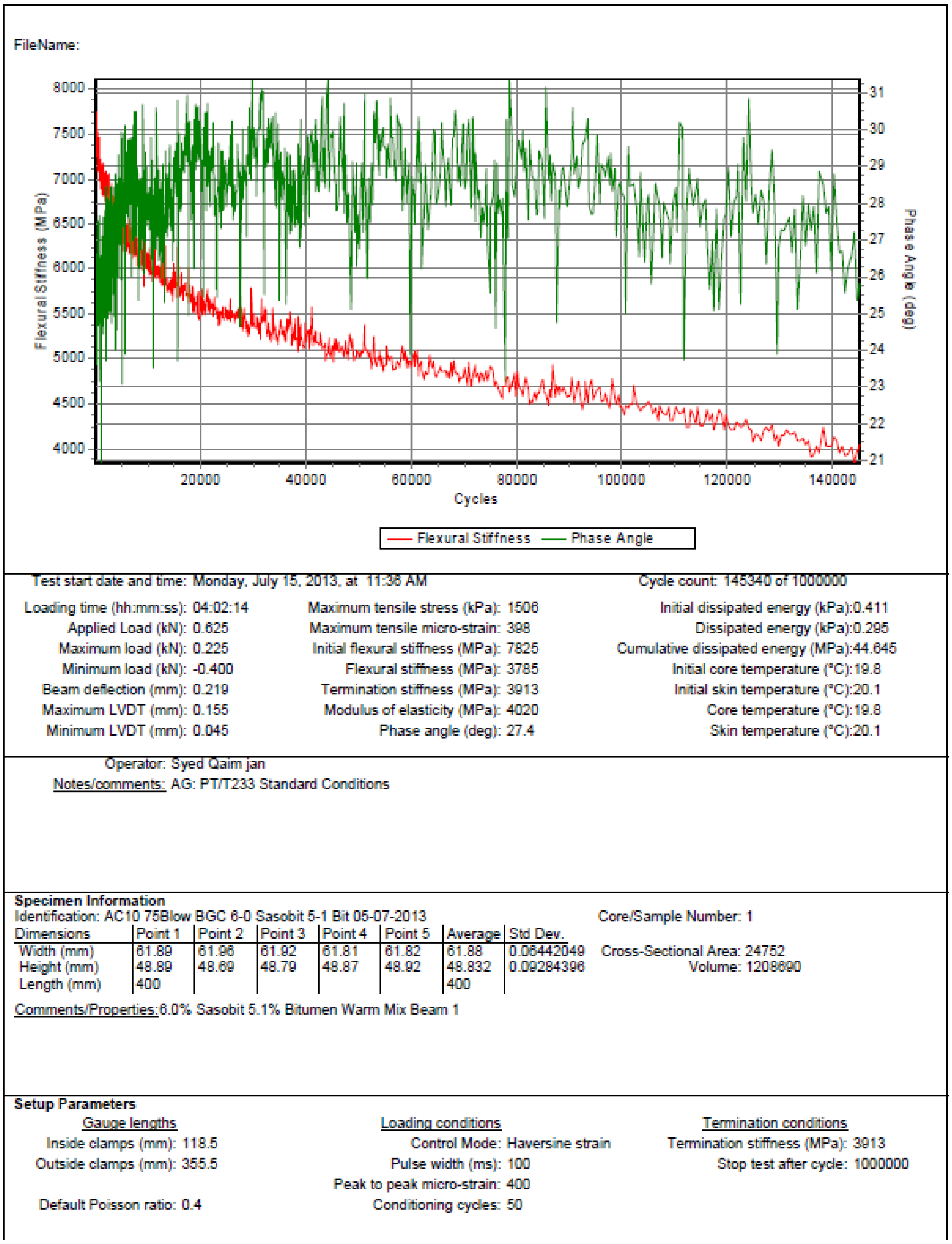
Setup Parameters

Gauge lengths
Inside clamps (mm): 118.5
Outside clamps (mm): 355.5
Default Poisson ratio: 0.4

Loading conditions
Control Mode: Haversine strain
Pulse width (ms): 100
Peak to peak micro-strain: 400
Conditioning cycles: 50

Termination conditions
Termination stiffness (MPa): 3205
Stop test after cycle: 1000000

7/23/2013 9:05:56 AM **UTM_21 V2.01 Beam Fatigue Test**



FileName:

Test start date and time: Monday, July 15, 2013, at 11:36 AM

Cycle count: 145340 of 1000000

Loading time (hh:mm:ss): 04:02:14
Applied Load (kN): 0.625
Maximum load (kN): 0.225
Minimum load (kN): -0.400
Beam deflection (mm): 0.219
Maximum LVDT (mm): 0.155
Minimum LVDT (mm): 0.045

Maximum tensile stress (kPa): 1506
Maximum tensile micro-strain: 398
Initial flexural stiffness (MPa): 7825
Flexural stiffness (MPa): 3785
Termination stiffness (MPa): 3913
Modulus of elasticity (MPa): 4020
Phase angle (deg): 27.4

Initial dissipated energy (kPa):0.411
Dissipated energy (kPa):0.295
Cumulative dissipated energy (MPa):44.645
Initial core temperature (°C):19.8
Initial skin temperature (°C):20.1
Core temperature (°C):19.8
Skin temperature (°C):20.1

Operator: Syed Qaim jan
Notes/comments: AG: PT/T233 Standard Conditions

Specimen Information

Identification: AC10 75Blow BGC 6-0 Sasobit 5-1 Bit 05-07-2013

Core/Sample Number: 1

Dimensions	Point 1	Point 2	Point 3	Point 4	Point 5	Average	Std Dev.
Width (mm)	61.89	61.96	61.92	61.81	61.82	61.88	0.06442049
Height (mm)	48.89	48.69	48.79	48.87	48.92	48.832	0.09284396
Length (mm)	400					400	

Cross-Sectional Area: 24752
Volume: 1208690

Comments/Properties:6.0% Sasobit 5.1% Bitumen Warm Mix Beam 1

Setup Parameters

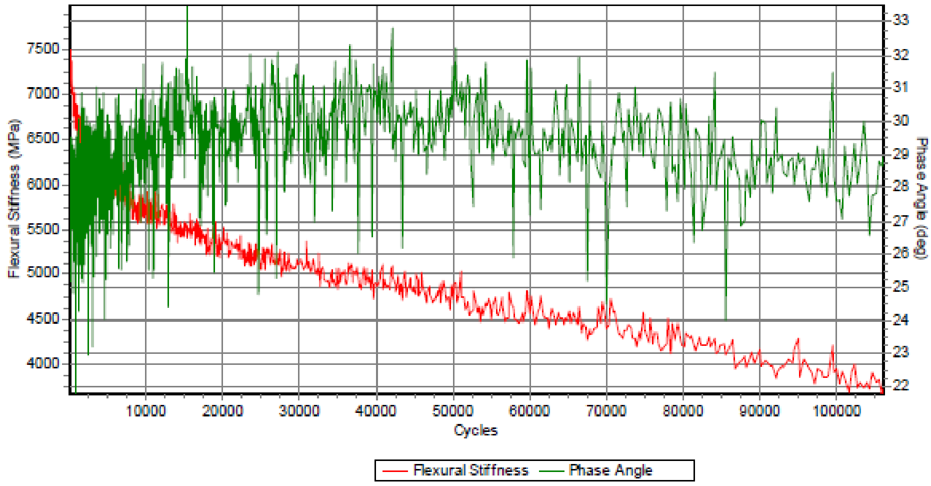
Gauge lengths
Inside clamps (mm): 118.5
Outside clamps (mm): 355.5

Default Poisson ratio: 0.4

Loading conditions
Control Mode: Haversine strain
Pulse width (ms): 100
Peak to peak micro-strain: 400
Conditioning cycles: 50

Termination conditions
Termination stiffness (MPa): 3913
Stop test after cycle: 1000000

FileName: C:\Users\257562E\Documents\Student Projects\2013 Student Projects\Bitumen Project\Beam Fatigue Results\SASOBIT\AC10 75Blow BGC 6-0 Sa



Test start date and time: Monday, July 15, 2013, at 6:03 PM

Cycle count: 106080 of 1000000

Loading time (hh:mm:ss): 02:56:48
Applied Load (kN): 0.615
Maximum load (kN): 0.225
Minimum load (kN): -0.391
Beam deflection (mm): 0.220
Maximum LVDT (mm): 0.137
Minimum LVDT (mm): 0.027

Maximum tensile stress (kPa): 1488
Maximum tensile micro-strain: 398
Initial flexural stiffness (MPa): 7565
Flexural stiffness (MPa): 3736
Termination stiffness (MPa): 3783
Modulus of elasticity (MPa): 3967
Phase angle (deg): 28.9

Initial dissipated energy (kPa):0.406
Dissipated energy (kPa):0.287
Cumulative dissipated energy (MPa):32.111
Initial core temperature (°C):19.9
Initial skin temperature (°C):20.2
Core temperature (°C):19.9
Skin temperature (°C):20.2

Operator: Syed Qaim jan
Notes/comments: AG: PT/T233 Standard Conditions

Specimen Information
Identification: AC10 75Blow BGC 6-0 Sasobit 5-1 Bit 05-07-2013

Core/Sample Number: 2

Dimensions	Point 1	Point 2	Point 3	Point 4	Point 5	Average	Std Dev.
Width (mm)	61.49	61.59	61.95	61.99	62.1	61.824	0.2673574
Height (mm)	48.72	48.66	48.86	48.82	48.79	48.77	0.08
Length (mm)	400					400	

Cross-Sectional Area: 24729.6
Volume: 1206063

Comments/Properties:6.0% Sasobit 5.1% Bitumen Warm Mix Beam 2

Setup Parameters

Gauge lengths
Inside clamps (mm): 118.5
Outside clamps (mm): 355.5

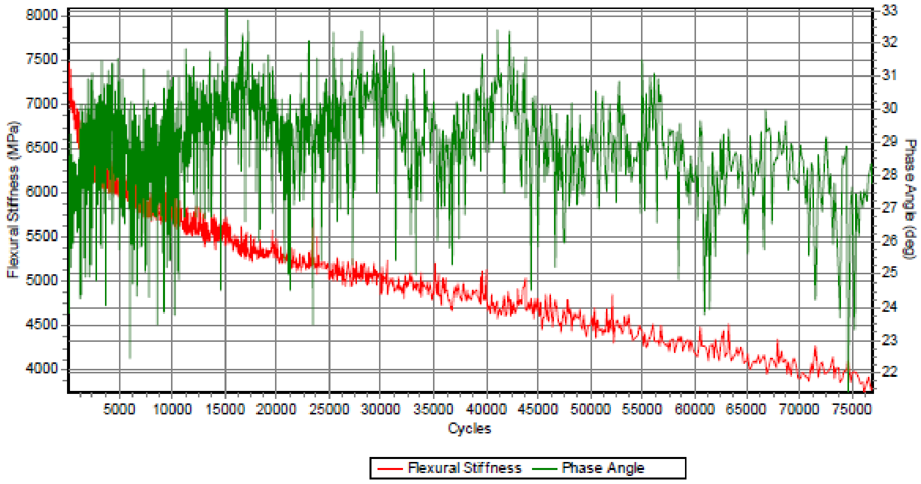
Default Poisson ratio: 0.4

Loading conditions
Control Mode: Haversine strain
Pulse width (ms): 100
Peak to peak micro-strain: 400
Conditioning cycles: 50

Termination conditions
Termination stiffness (MPa): 3783
Stop test after cycle: 1000000

7/23/2013 9:07:09 AM **UTM_21 V2.01 Beam Fatigue Test**

FileName: C:\Users\257562E\Documents\Student Projects\2013 Student Projects\Bitumen Project\Beam Fatigue Results\SASOBIT\AC10 75Blow BGC 6-0 Sas



Test start date and time: Tuesday, July 16, 2013, at 8:43 AM

Cycle count: 77000 of 1000000

Loading time (hh:mm:ss): 02:08:20
Applied Load (kN): 0.625
Maximum load (kN): 0.234
Minimum load (kN): -0.391
Beam deflection (mm): 0.219
Maximum LVDT (mm): 0.145
Minimum LVDT (mm): 0.036

Maximum tensile stress (kPa): 1507
Maximum tensile micro-strain: 397
Initial flexural stiffness (MPa): 6834
Flexural stiffness (MPa): 3792
Termination stiffness (MPa): 3813
Modulus of elasticity (MPa): 4026
Phase angle (deg): 27.8

Initial dissipated energy (kPa):0.377
Dissipated energy (kPa):0.296
Cumulative dissipated energy (MPa):23.576
Initial core temperature (°C):20.0
Initial skin temperature (°C):20.3
Core temperature (°C):19.7
Skin temperature (°C):19.7

Operator: Syed Qaim jan
Notes/comments: AG: PT/T233 Standard Conditions

Specimen Information
Identification: AC10 75Blow BGC 6-0 Sasobit 5-1 Bit 05-07-2013

Core/Sample Number: 3

Dimensions	Point 1	Point 2	Point 3	Point 4	Point 5	Average	Std Dev.
Width (mm)	61.85	61.93	62.14	61.96	61.98	61.972	0.1061603
Height (mm)	48.55	48.63	48.81	48.94	48.98	48.782	0.1883348
Length (mm)	400					400	

Cross-Sectional Area: 24788.8
Volume: 1209247

Comments/Properties:6.0% Sasobit 5.1% Bitumen Warm Mix Beam 3

Setup Parameters

Gauge lengths
Inside clamps (mm): 118.5
Outside clamps (mm): 355.5

Default Poisson ratio: 0.4

Loading conditions
Control Mode: Haversine strain
Pulse width (ms): 100
Peak to peak micro-strain: 400
Conditioning cycles: 50

Termination conditions
Termination stiffness (MPa): 3813
Stop test after cycle: 1000000

7/23/2013 9:02:36 AM **UTM_21 V2.01 Beam Fatigue Test**

Dynamic Modulus

Dynamic Modulus Results

HMA AC10mm Control	Cylinder 1			Cylinder 2			Cylinder 3		
Loading Rates (Hz)	10	1	0.1	10	1	0.1	10	1	0.1
Dynamic modulus (MPa)	16744	12571	8342	18161	13465	8836	17997	13617	9038
Phase angle (Degrees)	10.16	14.21	20.1	10.23	14.34	20.31	9.89	13.56	20.68
Average temperature (°C)	4.1	4.1	4	4.1	4.1	4.1	4	4.1	4.1
Average confining pressure (kPa)	0.7	0.7	0.7	0.7	0.7	0.6	0.7	0.7	0.7
Average micro-strain	99	99	102	99	101	103	100	101	106
Load drift (%)	0.1	0	0	9	0	0	9.7	0	0
Load standard error (%)	2.4	0.4	0.2	8.3	0.4	0.2	9.2	0.4	0.3
Average deformation drift (%)	-50.6	-91.9	-192.6	-69.1	-92.8	-197.4	-62.4	-76.2	-37.9
Average deformation standard error (%)	2.5	3.6	2.6	7.7	1.8	2.5	8.5	1.4	22.6
Deformation uniformity (%)	10.6	10.8	10.7	4.4	6.6	8.6	5.6	5.2	4.8
Phase uniformity (Degrees)	0.2	0.2	0.2	0.3	0.3	0.5	0.2	0.1	2.7

Dynamic Modulus Results

WMA AC10mm 1.5% Sasobit	Cylinder 1			Cylinder 2			Cylinder 3		
Loading Rates (Hz)	10	1	0.1	10	1	0.1	10	1	0.1
Dynamic modulus (MPa)	15470	11724	8203	16140	12360	8351	16998	12980	8900
Phase angle (Degrees)	10	13.3	17.84	10.03	9.18	18.12	9.89	13.5	19.55
Average temperature (°C)	4.1	4.1	4	4.1	4	4.1	4	4.1	4.1
Average confining pressure (kPa)	0.5	0.5	0.5	0.7	0.6	0.6	0.7	0.6	0.6
Average micro-strain	98	99	100	99	100	102	100	100	102
Load drift (%)	0.1	0	0	0.3	0.2	0.2	9.7	0.1	0.3
Load standard error (%)	2.1	0.5	0.3	2.7	2.7	0.2	9.2	0.4	0.3
Average deformation drift (%)	-49.3	-67.4	-125.3	-55.6	-70.2	-130.2	-62.4	-70.1	-115.2
Average deformation standard error (%)	2.1	1.5	2.1	4.2	2.4	2.3	8.5	1.4	2.4
Deformation uniformity (%)	13.6	12.2	10.1	10.2	12.1	10.9	5.6	8.2	9.8
Phase uniformity (Degrees)	0.1	0.1	0.2	0.2	0.3	0.4	0.2	0.1	0.1

Dynamic Modulus Results

WMA AC10mm 3% Sasobit	Cylinder 1			Cylinder 2			Cylinder 3		
Loading Rates (Hz)	10	1	0.1	10	1	0.1	10	1	0.1
Dynamic modulus (MPa)	20486	15779	11226	19572	14971	10566	17624	13343	9357
Phase angle (Degrees)	8.91	11.93	16.6	9.48	12.45	16.54	10.2	12.98	16.86
Average temperature (°C)	4.1	4.1	4	4.7	4.6	4.4	4	4	4.1
Average confining pressure (kPa)	0.6	0.6	0.6	0.6	0.6	0.6	0.7	0.7	0.6
Average micro-strain	88	102	104	92	101	104	103	101	102
Load drift (%)	9.8	0	0	9.6	0	0	9.3	0.1	0
Load standard error (%)	9.1	0.5	0.3	9.6	0.5	0.3	9.5	0.4	0.2
Average deformation drift (%)	-52.9	-55.7	-103.9	-54.7	-57.6	-99.6	-63.5	-61.3	-88.2
Average deformation standard error (%)	8.5	1.2	1.6	9.1	1.6	1.9	9.7	1.3	3.2
Deformation uniformity (%)	3.9	6	7.2	18.4	17.8	16.4	29.4	28	25.2
Phase uniformity (Degrees)	0.2	0.2	0.2	0.2	0.4	0.5	0.5	0.4	0.3

Dynamic Modulus Results

WMA AC10mm 6% Sasobit	Cylinder 1			Cylinder 2			Cylinder 3		
Loading Rates (Hz)	10	1	0.1	10	1	0.1	10	1	0.1
Dynamic modulus (MPa)	20548	16388	12119	18135	14223	10388	20191	15920	12003
Phase angle (Degrees)	8.3	10.86	14.37	8.97	11.77	15.42	7.67	10.2	13.35
Average temperature (°C)	4	4	4.1	4.1	4.1	4.1	4.1	4.1	4.1
Average confining pressure (kPa)	0.6	0.6	0.6	0.5	0.5	0.5	0.6	0.6	0.6
Average micro-strain	88	100	103	99	100	101	63	104	105
Load drift (%)	9.6	0.1	0	9.8	0.1	0	0.4	0	0
Load standard error (%)	9.3	0.5	0.3	9.4	0.4	0.2	2.3	0.5	0.2
Average deformation drift (%)	-45.1	-43.2	-76.9	-50.1	-45.8	-83.6	-24.3	-39.9	-66.2
Average deformation standard error (%)	8.9	1.5	1.9	8.9	1.2	1.6	4.5	1.7	1.5
Deformation uniformity (%)	36.4	34	33	9.4	10.6	11	8	2.6	0.9
Phase uniformity (Degrees)	0.1	0.2	0.2	0.3	0.2	0.2	0.3	0.4	0.4

Dynamic Modulus Results

HMA AC10mm Control	Cylinder 1			Cylinder 2			Cylinder 3		
Loading Rates (Hz)	10	1	0.1	10	1	0.1	10	1	0.1
Dynamic modulus (MPa)	7963	3959	1611	7386	3825	1567	7059	3712	1544
Phase angle (Degrees)	22.28	32.09	38.32	24.16	31.88	37.71	24.3	32.37	38.3
Average temperature (°C)	20.1	20.1	20.1	20.1	20.1	20.1	20.1	20.1	20
Average confining pressure (kPa)	0.4	0.4	0.4	0.3	0.3	0.3	0.4	0.4	0.4
Average micro-strain	95	96	98	99	96	99	98	94	98
Load drift (%)	0	0.2	0.2	0	-0.2	0	0.3	0	0.1
Load standard error (%)	2.1	0.6	0.5	2.2	0.6	0.3	2.1	0.6	0.3
Average deformation drift (%)	-342.4	-486.3	-464.1	-349	-477.4	-440.1	-326.2	-490.6	-512.4
Average deformation standard error (%)	38.3	6	5.5	6.7	6.7	5.5	5.8	6	5.8
Deformation uniformity (%)	15	13.9	13	13.3	14.3	14.8	8.3	7.8	7.1
Phase uniformity (Degrees)	2.5	0.4	0.6	0.6	0.8	0.8	0.4	0.1	0.3

Dynamic Modulus Results

WMA AC10mm 1.5% Sasobit	Cylinder 1			Cylinder 2			Cylinder 3		
Loading Rates (Hz)	10	1	0.1	10	1	0.1	10	1	0.1
Dynamic modulus (MPa)	6723	3805	1793.33	7001	3890	1680.12	6987	3912	1633
Phase angle (Degrees)	22.2	28.54	33.82	21.3	29.31	35.26	21.9	29.01	34.22
Average temperature (°C)	20	20	20	20	20.1	20	20.1	20	20.1
Average confining pressure (kPa)	0.5	0.5	0.4	0.6	0.6	0.6	0.6	0.6	0.5
Average micro-strain	96	94	96	98	96	98	97	95	97
Load drift (%)	0.3	0.3	0.2	0.3	0.2	0.2	0.4	0.1	0.3
Load standard error (%)	2	0.6	0.2	2.2	2.2	0.1	2.1	0.5	0.3
Average deformation drift (%)	-233.4	-339.6	-333.5	-280.1	-370.2	-340.1	-265.2	-345.12	-350.2
Average deformation standard error (%)	5	4.6	4.6	4.8	5	3.8	4.5	4.2	5
Deformation uniformity (%)	8.9	9.1	9.2	9.1	9.2	9	9.1	9.9	9.4
Phase uniformity (Degrees)	0.4	0.2	0.1	0.3	0.3	0.2	0.3	0.1	0.1

Dynamic Modulus Results

WMA AC10mm 3% Sasobit	Cylinder 1			Cylinder 2			Cylinder 3		
Loading Rates (Hz)	10	1	0.1	10	1	0.1	10	1	0.1
Dynamic modulus (MPa)	9163	5434	2777	7875	4573	2320	9041	5420	2848
Phase angle (Degrees)	19.87	25.72	31.25	20.87	26.31	31.18	19.56	25	30.09
Average temperature (°C)	20.1	20.1	20.1	20	20	20	19.9	19.9	20.2
Average confining pressure (kPa)	0.4	0.4	0.4	0.4	0.4	0.3	0.5	0.5	0.4
Average micro-strain	99	97	98	101	97	99	97	97	99
Load drift (%)	0.2	0.1	0	0.1	0	0	0.4	0	-0.3
Load standard error (%)	2.5	0.5	0.3	2.2	0.5	0.3	2.6	0.6	0.4
Average deformation drift (%)	-182.5	-262.3	-289.1	-182.8	-241.6	-239.2	-167.1	-240	-259.8
Average deformation standard error (%)	4.3	3.9	4.1	4.4	3.7	3.9	4.3	3.9	4.1
Deformation uniformity (%)	19.2	19	17.5	18.6	15.7	14.1	26.8	20.6	17.4
Phase uniformity (Degrees)	0.5	0.2	0.2	0.1	0.3	0.4	0.4	0.2	0.3

Dynamic Modulus Results

WMA AC10mm 6% Sasobit	Cylinder 1			Cylinder 2			Cylinder 3		
Loading Rates (Hz)	10	1	0.1	10	1	0.1	10	1	0.1
Dynamic modulus (MPa)	9868	6169	3441	9934	6398	3734	8571	5215	2767
Phase angle (Degrees)	17.97	23.07	28.16	16.82	21.4	26.37	19.28	24.54	29.56
Average temperature (°C)	20	20	20.1	20.1	20.1	20	20.1	20.1	20
Average confining pressure (kPa)	0.5	0.5	0.5	0.3	0.4	0.4	0.4	0.4	0.4
Average micro-strain	99	98	99	107	100	99	98	96	97
Load drift (%)	0.4	0	0	0.5	0	0.1	0.2	0	0.1
Load standard error (%)	2.5	0.5	0.3	2.4	0.4	0.3	2.1	0.4	0.3
Average deformation drift (%)	-136.5	-198	-245.9	-118.6	-168.9	-219.7	-158.1	-217.7	-237.5
Average deformation standard error (%)	3.7	3.2	3.3	3.7	2.9	3.1	3.6	4	3.5
Deformation uniformity (%)	34.9	33.8	32.1	1.4	0.6	2.3	10.9	10.6	10.7
Phase uniformity (Degrees)	0.5	0.2	0.2	0.2	0.3	0.3	0	0.1	0.2

Dynamic Modulus Results

HMA AC10mm Control	Cylinder 1				Cylinder 2				Cylinder 3			
Loading Rates (Hz)	10	1	0.1	0.01	10	1	0.1	0.01	10	1	0.1	0.01
Dynamic modulus (MPa)	1538	457.8	141.6	67.2	1159	342.3	110.5	58.3	1374	400.5	125	60.8
Phase angle (Degrees)	39.71	38.68	32.38	21.9	41.85	39.16	31.1	20.02	41.88	40.44	33.39	23.91
Average temperature (°C)	40	40.1	40	40.1	40.1	40.1	40.1	40.1	39.9	39.8	39.9	38.3
Average confining pressure (kPa)	0.1	0	0	0	0.1	0.1	0.1	0.1	0	0	0	0
Average micro-strain	96	102	104	91	96	101	100	91	118	101	102	92
Load drift (%)	-0.3	0.2	-1	10.4	-1	0.9	0.6	0.3	-0.3	0	0.4	-0.4
Load standard error (%)	6.7	0.9	1.2	6.9	9.3	1.9	1.5	2.6	7.3	1.5	1.4	2.5
Average deformation drift (%)	-330.3	-100.4	-18.2	22.6	-408.1	-155.1	-36.4	7.6	-548.7	-185.9	-41	59.2
Average deformation standard error (%)	9	3.2	4.2	7	10.2	4.3	4.7	5.8	12.4	3.8	4.2	6
Deformation uniformity (%)	5.9	3.6	0.6	5.8	17.3	16.3	16.3	16.8	22.5	20.7	18.6	17.8
Phase uniformity (Degrees)	0.2	0.4	0.6	0.7	1	0.5	0.4	0.9	0.9	1.6	1.4	0.9

Dynamic Modulus Results

WMA AC10mm 1.5% Sasobit	Cylinder 1				Cylinder 2				Cylinder 3			
Loading Rates (Hz)	10	1	0.1	0.01	10	1	0.1	0.01	10	1	0.1	0.01
Dynamic modulus (MPa)	1434	515.1	182.4	83.2	1292	409.6	129.1	59.2	1320	420.1	123.1	55.2
Phase angle (Degrees)	38.85	37.74	33.09	25.49	41.25	39.85	33.17	23.02	38.7	39.01	32.2	24.1
Average temperature (°C)	40.1	40.1	40.1	40.1	40.1	40.1	40	40.1	40.1	40.1	39.9	40.1
Average confining pressure (kPa)	0.1	0	0	0.1	0	0	0	0.1	0.2	0.2	0.2	0.1
Average micro-strain	93	95	95	87	93	97	96	85	95	94	98	91
Load drift (%)	0.6	1	-1.2	-3.6	-0.3	0.1	1	0.8	0.2	0.2	0.3	-1.5
Load standard error (%)	8.4	2.2	2.6	7.7	9.4	3.2	4.1	8.9	5.2	1.6	2.1	6.7
Average deformation drift (%)	-445.8	-207	-52.2	16.5	-555.7	-354.3	-107.9	34.7	-480.2	-175.2	-44.9	27.6
Average deformation standard error (%)	10.4	4.8	4.2	7.6	9.7	5.4	4.6	9.4	9.2	4.9	4.2	6.1
Deformation uniformity (%)	9.8	9.7	10.2	10.4	2.4	2.9	4.6	8.5	9.3	9.5	9.9	9.6
Phase uniformity (Degrees)	0.1	0.7	0.7	1	0.7	1	0.8	0.6	0.2	0.1	0.1	0.9

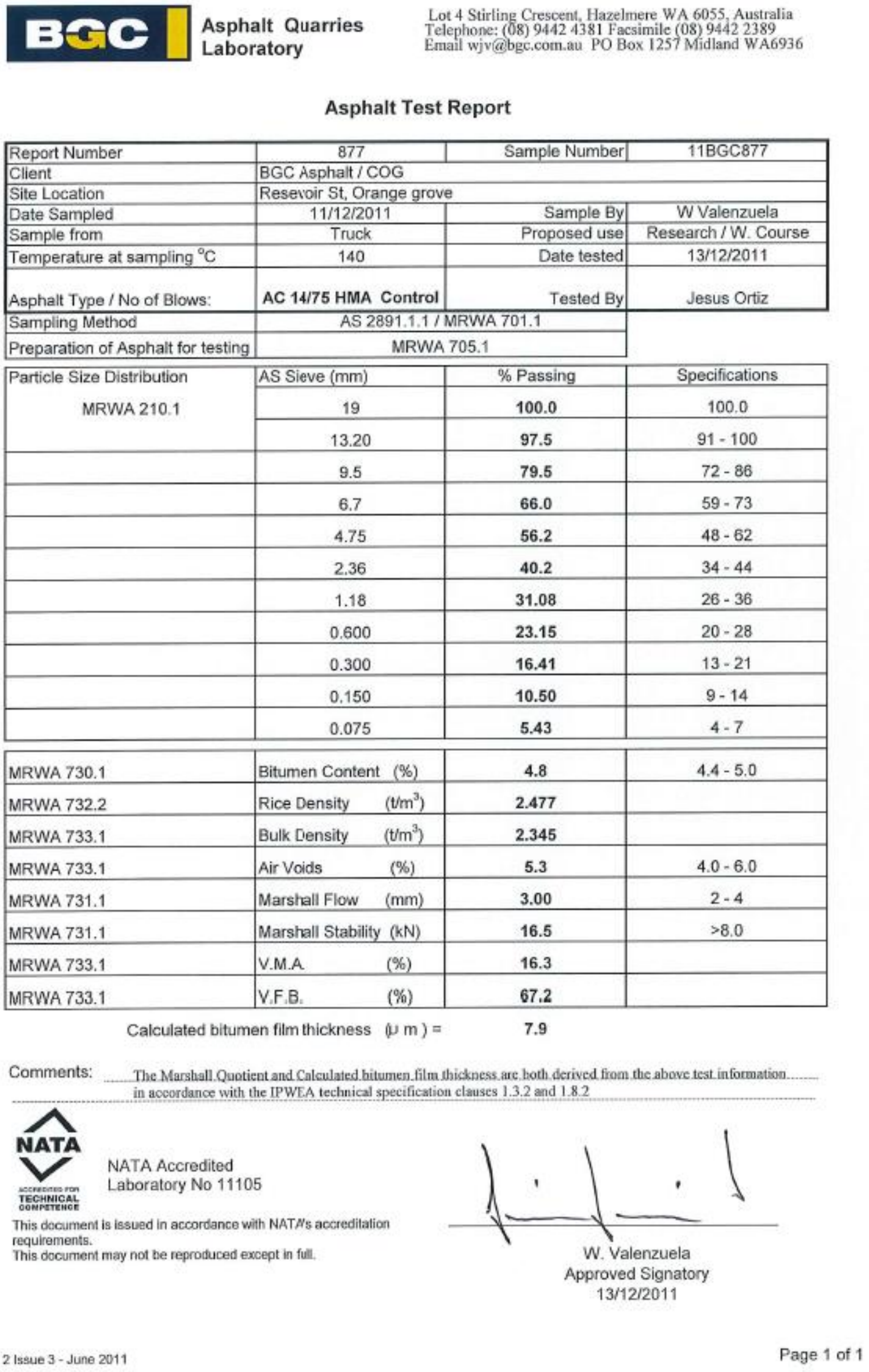
Dynamic Modulus Results

WMA AC10mm 3% Sasobit	Cylinder 1				Cylinder 2				Cylinder 3			
Loading Rates (Hz)	10	1	0.1	0.01	10	1	0.1	0.01	10	1	0.1	0.01
Dynamic modulus (MPa)	2119	829.37	301.4	130	1723	698.3	285.3	145.6	2134	885.1	352.2	171.9
Phase angle (Degrees)	36.36	37.11	34.14	28.54	36.37	36	32.1	28.57	35.13	35.02	31.74	25.69
Average temperature (°C)	40.1	40.1	40	40.1	40.1	40.1	40.1	40.1	40	40	40.1	40.1
Average confining pressure (kPa)	0	0	0	0	-0.1	0	0	0	-0.3	0	0	0
Average micro-strain	95	93	98	96	93	92	96	94	96	93	98	96
Load drift (%)	0.1	0.1	-0.4	4.5	-0.7	0.4	0	-3.2	-0.1	0.7	-0.3	1.2
Load standard error (%)	6.8	1.3	0.7	5.7	8	1.6	0.8	4	7.4	1.6	0.9	3.5
Average deformation drift (%)	-435.4	-231.6	-74.4	-8.4	-372.3	-173.3	-53.6	-94.6	-400.2	-189.2	-47.5	13.2
Average deformation standard error (%)	10.6	4.7	3.9	6.2	9.9	4.5	3.6	32.7	10.5	4.6	3.8	4.5
Deformation uniformity (%)	18.1	16.9	16.2	14.1	9.7	8.1	6.7	2.5	17.1	15.7	17.3	19.8
Phase uniformity (Degrees)	0	0.9	1.1	1.2	0.3	0.5	0.3	3.3	0.3	0.5	0.2	0.7

Dynamic Modulus Results

WMA AC10mm 6% Sasobit	Cylinder 1				Cylinder 2				Cylinder 3			
Loading Rates (Hz)	10	1	0.1	0.01	10	1	0.1	0.01	10	1	0.1	0.01
Dynamic modulus (MPa)	2612	1172	500.9	237.2	2027	829.8	351.5	186.9	2917	1358	572.8	268.9
Phase angle (Degrees)	33.56	34.64	32.96	28.93	34.66	34.65	31.88	26.58	30.42	32.55	32.2	28.89
Average temperature (°C)	40	40	40.1	40.1	40.1	40.2	40.1	40.1	40.2	40.4	40	40.1
Average confining pressure (kPa)	0	0	0	0	-0.2	0	0	0	0.1	0	0	0
Average micro-strain	97	91	94	100	130	93	96	89	94	92	98	97
Load drift (%)	0.7	0.6	0	-1.5	-0.5	0	-0.6	-0.7	0	0.4	-0.3	-0.6
Load standard error (%)	6.1	1.6	0.7	1.5	5	1.3	1.1	3.8	4.6	0.9	0.7	3.1
Average deformation drift (%)	-395.3	-247.7	-106.4	-27.6	-386.2	-127.1	-46	-1.6	-293.8	-171	-60.6	-9.8
Average deformation standard error (%)	9.3	5.1	4.3	5.1	9.6	3.7	3.7	4.3	8.2	4	3.3	3.8
Deformation uniformity (%)	12.6	10.6	10.1	8.6	6.9	3.9	1.4	1	9.3	9.8	9.3	8.4
Phase uniformity (Degrees)	0.1	0.6	0.8	0.8	0.2	0.4	0.3	0.3	0.2	0.2	0.5	0.7

Appendix F Production Asphalt Reports (trial 1)



BGC Asphalt Quarries Laboratory

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Asphalt Test Report

Report Number	877	Sample Number	11BGC877
Client	BGC Asphalt / COG		
Site Location	Resevoir St, Orange grove		
Date Sampled	11/12/2011	Sample By	W Valenzuela
Sample from	Truck	Proposed use	Research / W. Course
Temperature at sampling °C	140	Date tested	13/12/2011
Asphalt Type / No of Blows:	**AC 14/75 HMA Control**	Tested By	Jesus Ortiz
Sampling Method	AS 2891.1.1 / MRWA 701.1		
Preparation of Asphalt for testing	MRWA 705.1		

Particle Size Distribution	AS Sieve (mm)	% Passing	Specifications
MRWA 210.1	19	**100.0**	100.0
	13.20	**97.5**	91 - 100
	9.5	**79.5**	72 - 86
	6.7	**66.0**	59 - 73
	4.75	**56.2**	48 - 62
	2.36	**40.2**	34 - 44
	1.18	**31.08**	26 - 36
	0.600	**23.15**	20 - 28
	0.300	**16.41**	13 - 21
	0.150	**10.50**	9 - 14
	0.075	**5.43**	4 - 7

MRWA 730.1	Bitumen Content (%)	**4.8**	4.4 - 5.0
MRWA 732.2	Rice Density (t/m^3)	**2.477**	
MRWA 733.1	Bulk Density (t/m^3)	**2.345**	
MRWA 733.1	Air Voids (%)	**5.3**	4.0 - 6.0
MRWA 731.1	Marshall Flow (mm)	**3.00**	2 - 4
MRWA 731.1	Marshall Stability (kN)	**16.5**	>8.0
MRWA 733.1	V.M.A. (%)	**16.3**	
MRWA 733.1	V.F.B. (%)	**67.2**	

Calculated bitumen film thickness (µ m) = **7.9**

Comments: The Marshall Quotient and Calculated bitumen film thickness are both derived from the above test information in accordance with the IPWEA technical specification clauses 1.3.2 and 1.8.2

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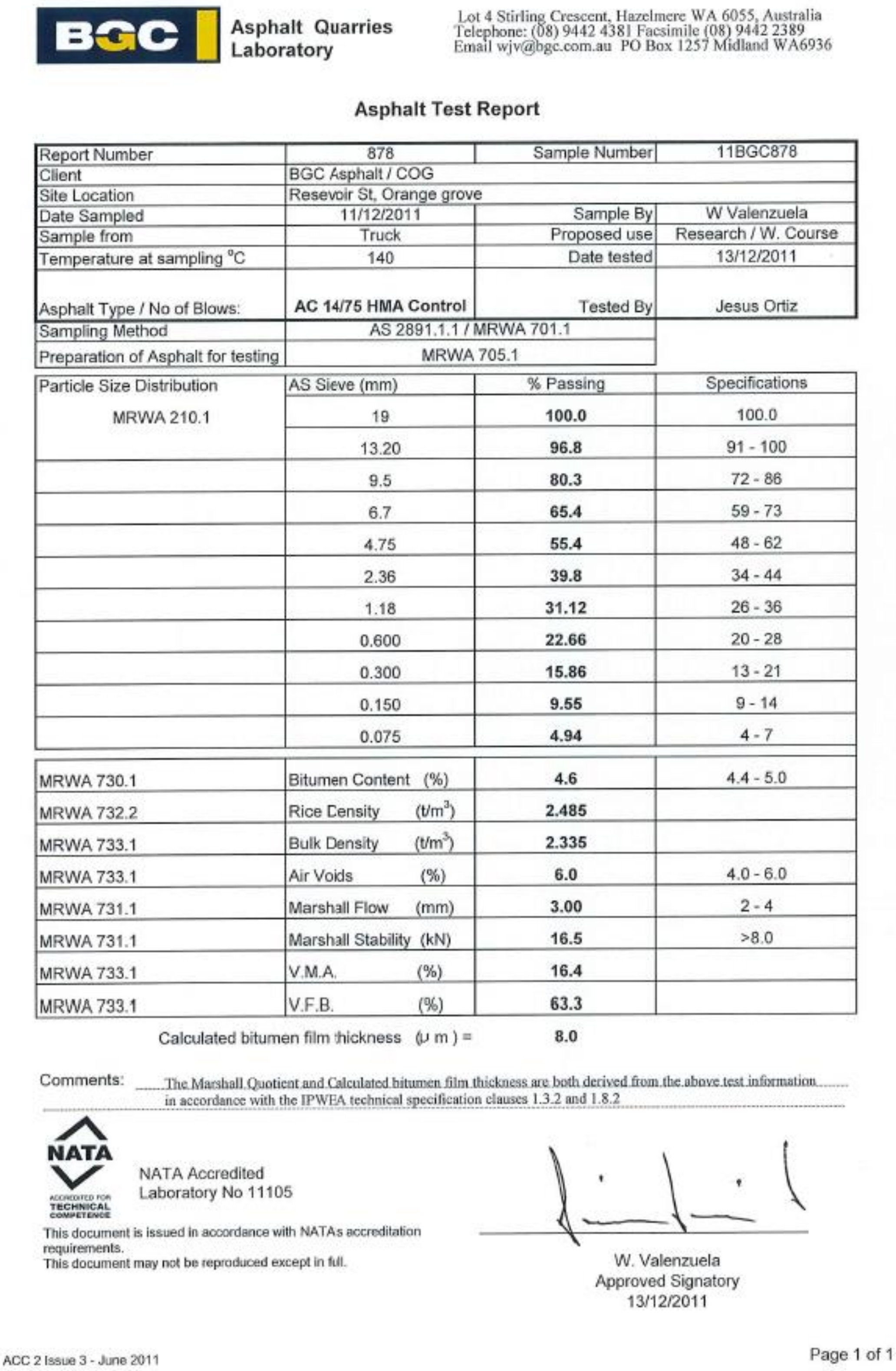

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Asphalt Test Report

Report Number	878	Sample Number	11BGC878
Client	BGC Asphalt / COG		
Site Location	Resevoir St, Orange grove		
Date Sampled	11/12/2011	Sample By	W Valenzuela
Sample from	Truck	Proposed use	Research / W. Course
Temperature at sampling °C	140	Date tested	13/12/2011
Asphalt Type / No of Blows:	**AC 14/75 HMA Control**	Tested By	Jesus Ortiz
Sampling Method	AS 2891.1.1 / MRWA 701.1		
Preparation of Asphalt for testing	MRWA 705.1		

Particle Size Distribution	AS Sieve (mm)	% Passing	Specifications
MRWA 210.1	19	**100.0**	100.0
	13.20	**96.8**	91 - 100
	9.5	**80.3**	72 - 86
	6.7	**65.4**	59 - 73
	4.75	**55.4**	48 - 62
	2.36	**39.8**	34 - 44
	1.18	**31.12**	26 - 36
	0.600	**22.66**	20 - 28
	0.300	**15.86**	13 - 21
	0.150	**9.55**	9 - 14
	0.075	**4.94**	4 - 7

MRWA 730.1	Bitumen Content (%)	**4.6**	4.4 - 5.0
MRWA 732.2	Rice Density (t/m^3)	**2.485**	
MRWA 733.1	Bulk Density (t/m^3)	**2.335**	
MRWA 733.1	Air Voids (%)	**6.0**	4.0 - 6.0
MRWA 731.1	Marshall Flow (mm)	**3.00**	2 - 4
MRWA 731.1	Marshall Stability (kN)	**16.5**	>8.0
MRWA 733.1	V.M.A. (%)	**16.4**	
MRWA 733.1	V.F.B. (%)	**63.3**	

Calculated bitumen film thickness (µ m) = **8.0**

Comments: The Marshall Quotient and Calculated bitumen film thickness are both derived from the above test information in accordance with the IPWEA technical specification clauses 1.3.2 and 1.8.2

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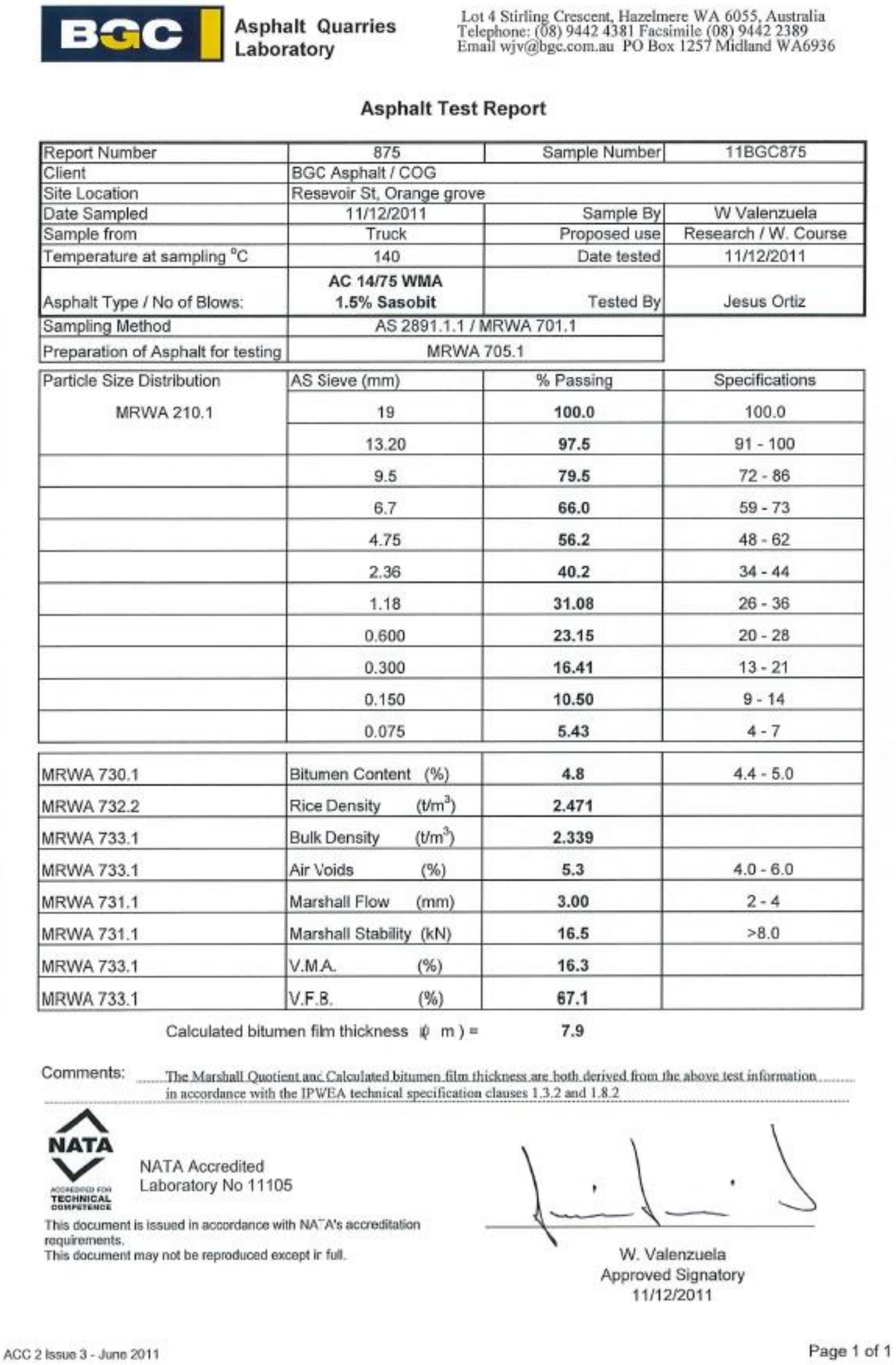

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Asphalt Test Report

Report Number	875	Sample Number	11BGC875
Client	BGC Asphalt / COG		
Site Location	Resevoir St, Orange grove		
Date Sampled	11/12/2011	Sample By	W Valenzuela
Sample from	Truck	Proposed use	Research / W. Course
Temperature at sampling °C	140	Date tested	11/12/2011
Asphalt Type / No of Blows:	**AC 14/75 WMA** **1.5% Sasobit**	Tested By	Jesus Ortiz
Sampling Method	AS 2891.1.1 / MRWA 701.1		
Preparation of Asphalt for testing	MRWA 705.1		

Particle Size Distribution	AS Sieve (mm)	% Passing	Specifications
MRWA 210.1	19	**100.0**	100.0
	13.20	**97.5**	91 - 100
	9.5	**79.5**	72 - 86
	6.7	**66.0**	59 - 73
	4.75	**56.2**	48 - 62
	2.36	**40.2**	34 - 44
	1.18	**31.08**	26 - 36
	0.600	**23.15**	20 - 28
	0.300	**16.41**	13 - 21
	0.150	**10.50**	9 - 14
	0.075	**5.43**	4 - 7

MRWA 730.1	Bitumen Content (%)	**4.8**	4.4 - 5.0
MRWA 732.2	Rice Density (t/m^3)	**2.471**	
MRWA 733.1	Bulk Density (t/m^3)	**2.339**	
MRWA 733.1	Air Voids (%)	**5.3**	4.0 - 6.0
MRWA 731.1	Marshall Flow (mm)	**3.00**	2 - 4
MRWA 731.1	Marshall Stability (kN)	**16.5**	>8.0
MRWA 733.1	V.M.A. (%)	**16.3**	
MRWA 733.1	V.F.B. (%)	**67.1**	

Calculated bitumen film thickness (µ m) = **7.9**

Comments: The Marshall Quotient anc Calculated bitumen film thickness are both derived from the above test information in accordance with the IPWEA technical specification clauses 1.3.2 and 1.8.2

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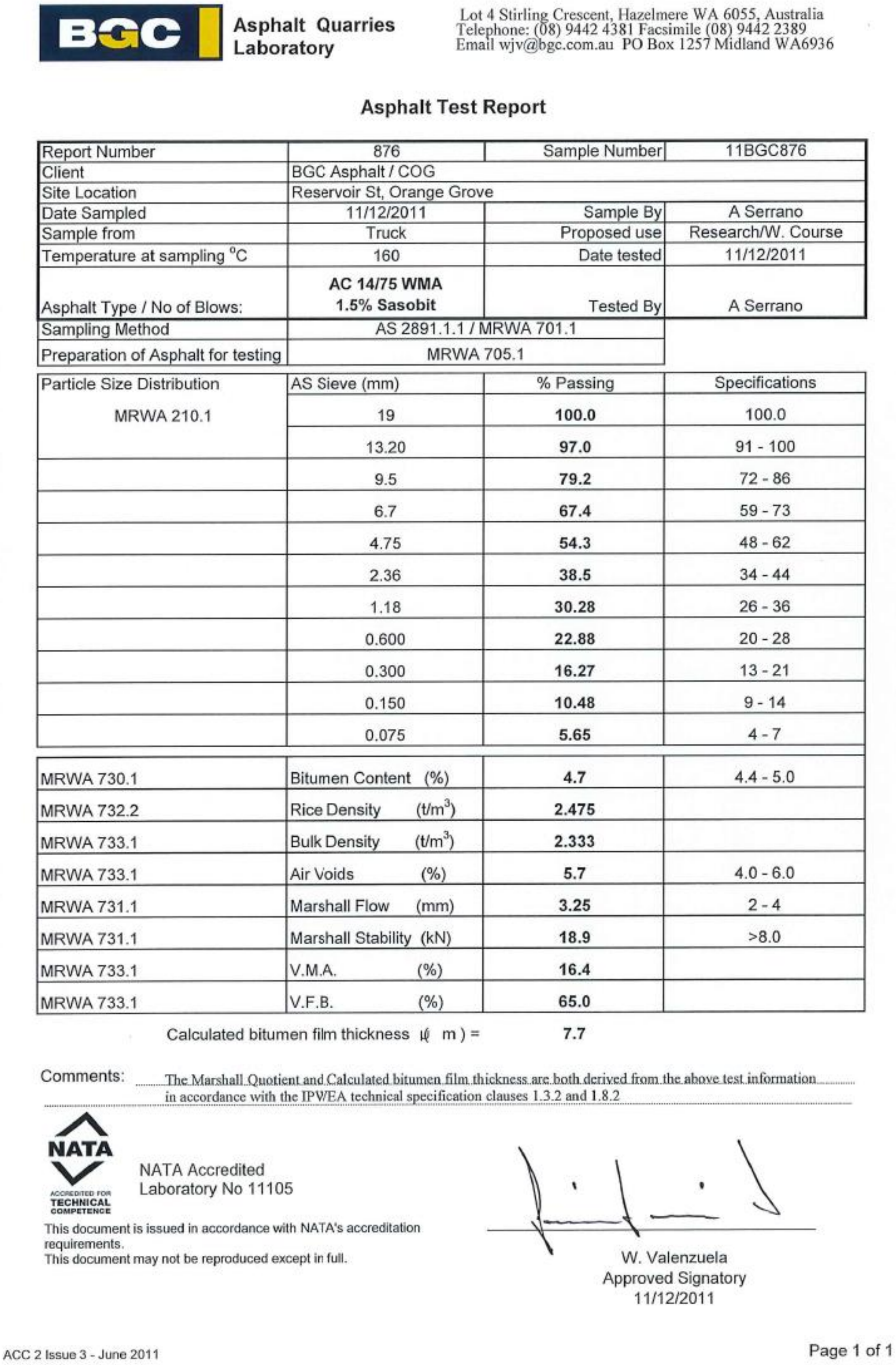

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Asphalt Test Report

Report Number	876	Sample Number	11BGC876
Client	BGC Asphalt / COG		
Site Location	Reservoir St, Orange Grove		
Date Sampled	11/12/2011	Sample By	A Serrano
Sample from	Truck	Proposed use	Research/W. Course
Temperature at sampling °C	160	Date tested	11/12/2011
Asphalt Type / No of Blows:	**AC 14/75 WMA** **1.5% Sasobit**	Tested By	A Serrano
Sampling Method	AS 2891.1.1 / MRWA 701.1		
Preparation of Asphalt for testing	MRWA 705.1		

Particle Size Distribution	AS Sieve (mm)	% Passing	Specifications
MRWA 210.1	19	**100.0**	100.0
	13.20	**97.0**	91 - 100
	9.5	**79.2**	72 - 86
	6.7	**67.4**	59 - 73
	4.75	**54.3**	48 - 62
	2.36	**38.5**	34 - 44
	1.18	**30.28**	26 - 36
	0.600	**22.88**	20 - 28
	0.300	**16.27**	13 - 21
	0.150	**10.48**	9 - 14
	0.075	**5.65**	4 - 7

MRWA 730.1	Bitumen Content (%)	**4.7**	4.4 - 5.0
MRWA 732.2	Rice Density (t/m^3)	**2.475**	
MRWA 733.1	Bulk Density (t/m^3)	**2.333**	
MRWA 733.1	Air Voids (%)	**5.7**	4.0 - 6.0
MRWA 731.1	Marshall Flow (mm)	**3.25**	2 - 4
MRWA 731.1	Marshall Stability (kN)	**18.9**	>8.0
MRWA 733.1	V.M.A. (%)	**16.4**	
MRWA 733.1	V.F.B. (%)	**65.0**	

Calculated bitumen film thickness (µ m) = **7.7**

Comments: The Marshall Quotient and Calculated bitumen film thickness are both derived from the above test information in accordance with the IPWEA technical specification clauses 1.3.2 and 1.8.2

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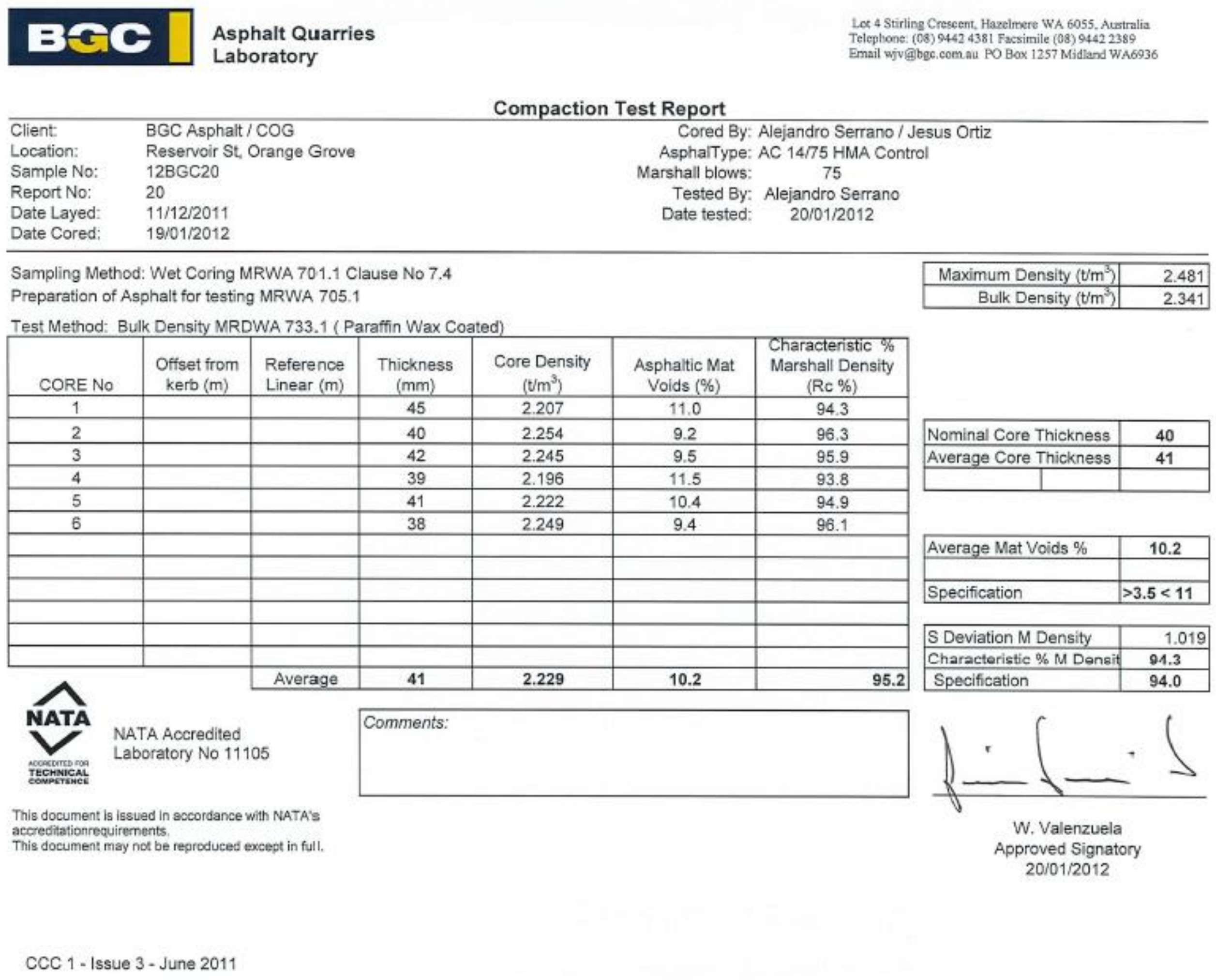
Appendix G Compaction Reports (trial 1)



BGC **Asphalt Quarries Laboratory**

Lot 4 Stirling Crescent, Hazelmere WA 6055, Australia
Telephone: (08) 9442 4381 Facsimile (08) 9442 2389
Email wjv@bgc.com.au PO Box 1257 Midland WA6936

Compaction Test Report

Client: BGC Asphalt / COG
Location: Reservoir St, Orange Grove
Sample No: 12BGC20
Report No: 20
Date Layed: 11/12/2011
Date Cored: 19/01/2012

Cored By: Alejandro Serrano / Jesus Ortiz
AsphalType: AC 14/75 HMA Control
Marshall blows: 75
Tested By: Alejandro Serrano
Date tested: 20/01/2012

Sampling Method: Wet Coring MRWA 701.1 Clause No 7.4
Preparation of Asphalt for testing MRWA 705.1

Maximum Density (t/m³)	2.481
Bulk Density (t/m³)	2.341

Test Method: Bulk Density MRDWA 733.1 (Paraffin Wax Coated)

CORE No	Offset from kerb (m)	Reference Linear (m)	Thickness (mm)	Core Density (t/m³)	Asphaltic Mat Voids (%)	Characteristic % Marshall Density (Rc %)
1			45	2.207	11.0	94.3
2			40	2.254	9.2	96.3
3			42	2.245	9.5	95.9
4			39	2.196	11.5	93.8
5			41	2.222	10.4	94.9
6			38	2.249	9.4	96.1
		Average	**41**	**2.229**	**10.2**	**95.2**

Nominal Core Thickness	**40**
Average Core Thickness	**41**

Average Mat Voids %	**10.2**
Specification	**>3.5 < 11**

S Deviation M Density	1.019
Characteristic % M Densit	**94.3**
Specification	**94.0**

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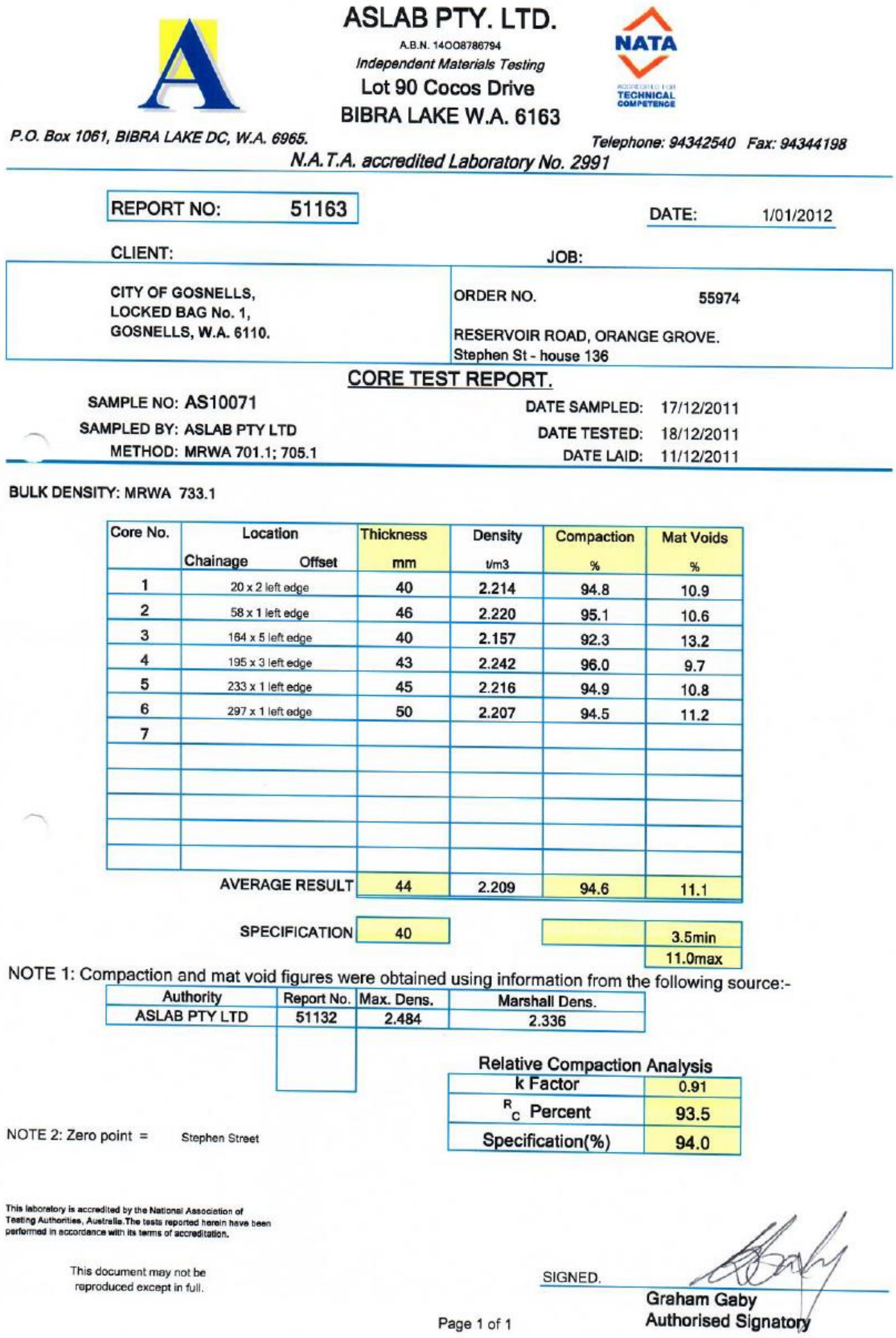

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Independent Materials Testing
Lot 90 Cocos Drive
BIBRA LAKE W.A. 6163

P.O. Box 1061, BIBRA LAKE DC, W.A. 6965.
Telephone: 94342540 Fax: 94344198
N.A.T.A. accredited Laboratory No. 2991

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REPORT NO: 51163

DATE: 1/01/2012

CLIENT:

CITY OF GOSNELLS,
LOCKED BAG No. 1,
GOSNELLS, W.A. 6110.

JOB:

ORDER NO. 55974

RESERVOIR ROAD, ORANGE GROVE.
Stephen St - house 136

CORE TEST REPORT.

SAMPLE NO: AS10071
SAMPLED BY: ASLAB PTY LTD
METHOD: MRWA 701.1; 705.1

DATE SAMPLED: 17/12/2011
DATE TESTED: 18/12/2011
DATE LAID: 11/12/2011

BULK DENSITY: MRWA 733.1

Core No.	Location	Thickness	Density	Compaction	Mat Voids
	Chainage Offset	mm	t/m3	%	%
1	20 x 2 left edge	40	2.214	94.8	10.9
2	58 x 1 left edge	46	2.220	95.1	10.6
3	164 x 5 left edge	40	2.157	92.3	13.2
4	195 x 3 left edge	43	2.242	96.0	9.7
5	233 x 1 left edge	45	2.216	94.9	10.8
6	297 x 1 left edge	50	2.207	94.5	11.2
7					
	AVERAGE RESULT	44	2.209	94.6	11.1
	SPECIFICATION	40			3.5min 11.0max

NOTE 1: Compaction and mat void figures were obtained using information from the following source:-

Authority	Report No.	Max. Dens.	Marshall Dens.
ASLAB PTY LTD	51132	2.484	2.336

Relative Compaction Analysis

k Factor	0.91
$^{R}{}_{C}$ Percent	93.5
Specification(%)	94.0

NOTE 2: Zero point = Stephen Street

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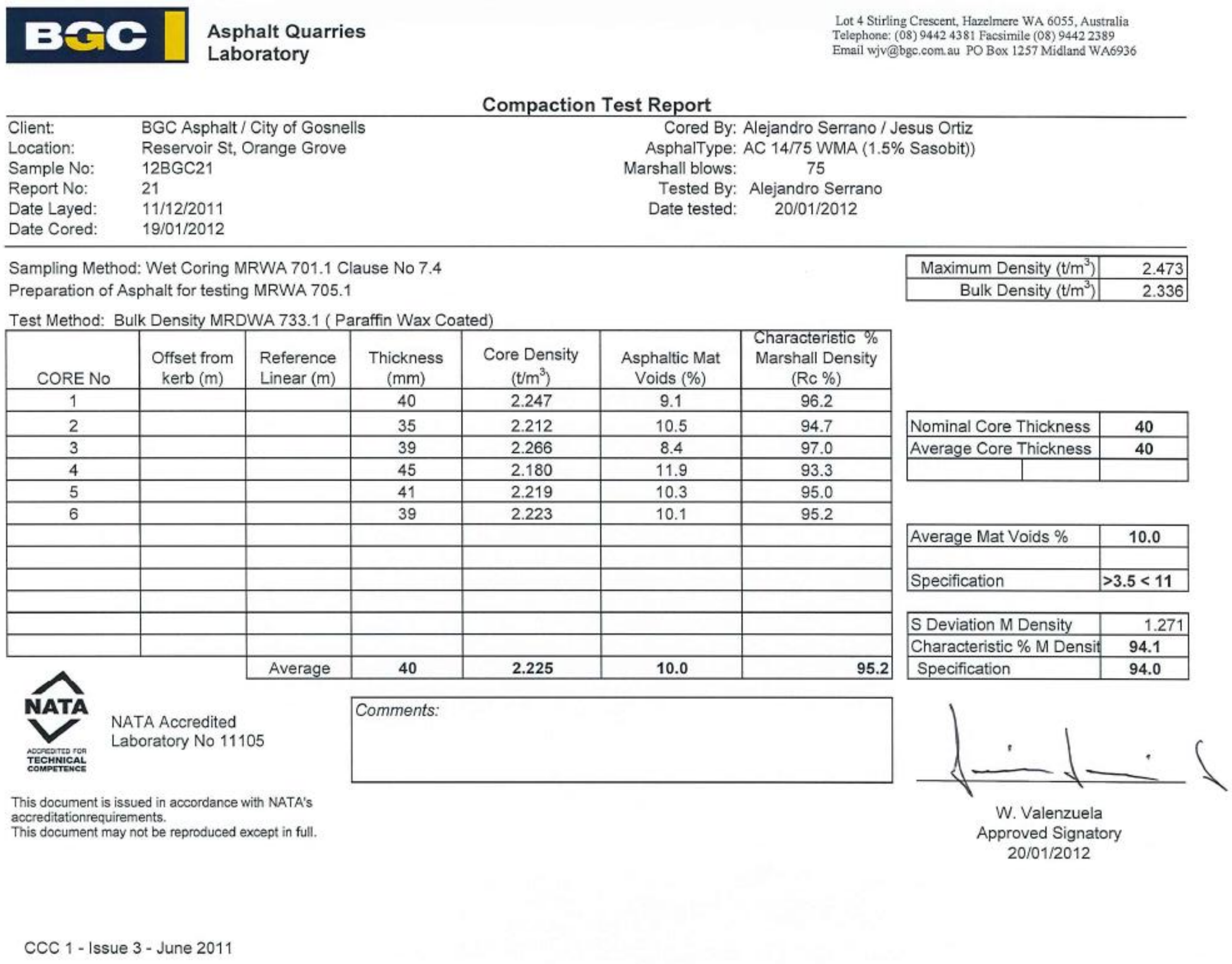

BGC Asphalt Quarries Laboratory

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Compaction Test Report

Client: BGC Asphalt / City of Gosnells
Location: Reservoir St, Orange Grove
Sample No: 12BGC21
Report No: 21
Date Layed: 11/12/2011
Date Cored: 19/01/2012

Cored By: Alejandro Serrano / Jesus Ortiz
AsphalType: AC 14/75 WMA (1.5% Sasobit))
Marshall blows: 75
Tested By: Alejandro Serrano
Date tested: 20/01/2012

Sampling Method: Wet Coring MRWA 701.1 Clause No 7.4
Preparation of Asphalt for testing MRWA 705.1

Maximum Density (t/m^3)	2.473
Bulk Density (t/m^3)	2.336

Test Method: Bulk Density MRDWA 733.1 (Paraffin Wax Coated)

CORE No	Offset from kerb (m)	Reference Linear (m)	Thickness (mm)	Core Density (t/m^3)	Asphaltic Mat Voids (%)	Characteristic % Marshall Density (Rc %)
1			40	2.247	9.1	96.2
2			35	2.212	10.5	94.7
3			39	2.266	8.4	97.0
4			45	2.180	11.9	93.3
5			41	2.219	10.3	95.0
6			39	2.223	10.1	95.2
		Average	**40**	**2.225**	**10.0**	**95.2**

Nominal Core Thickness	**40**
Average Core Thickness	**40**

Average Mat Voids %	**10.0**
Specification	**>3.5 < 11**

S Deviation M Density	1.271
Characteristic % M Densit	**94.1**
Specification	**94.0**

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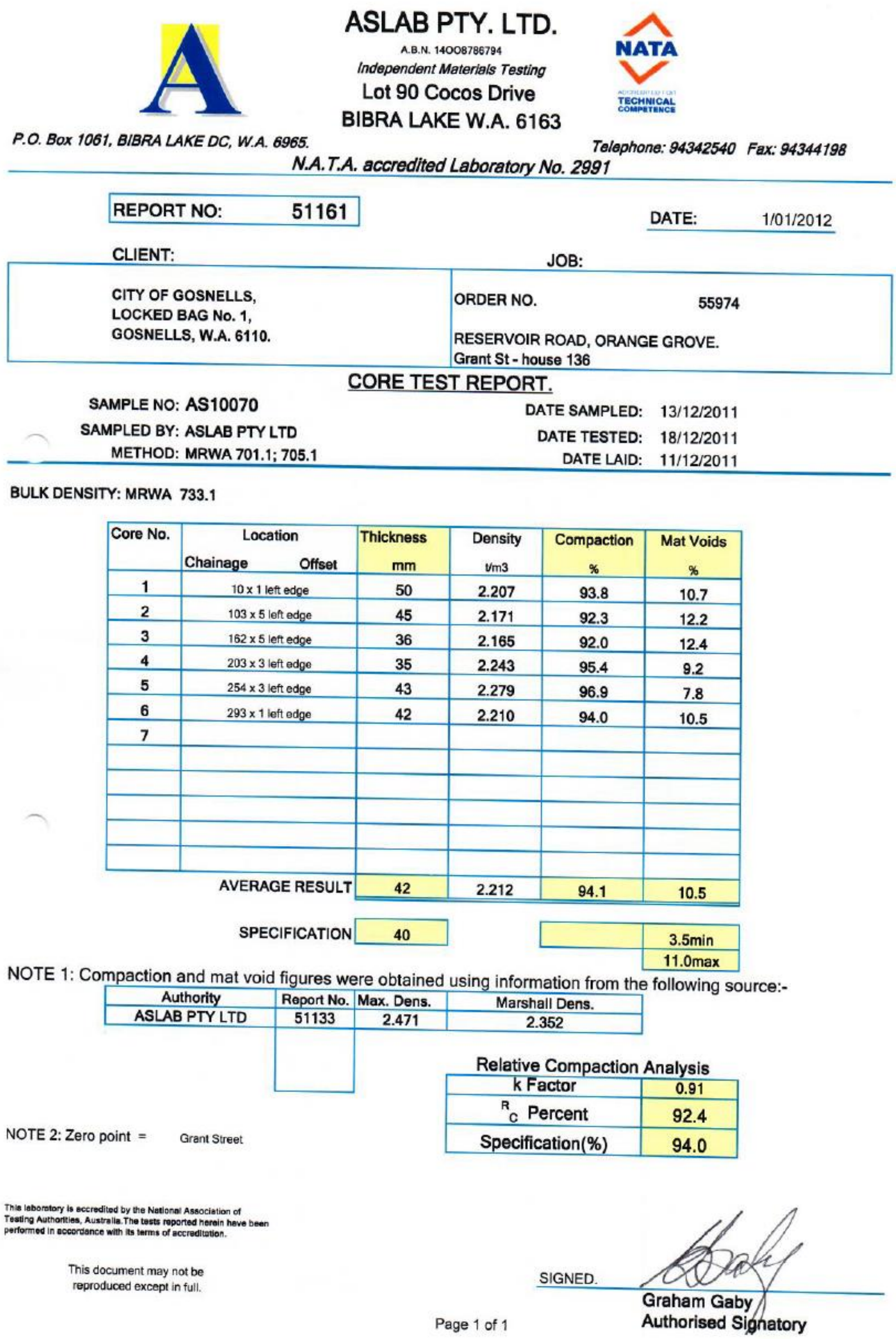

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BIBRA LAKE W.A. 6163

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P.O. Box 1061, BIBRA LAKE DC, W.A. 6965.
Telephone: 94342540 Fax: 94344198
N.A.T.A. accredited Laboratory No. 2991

REPORT NO: 51161

DATE: 1/01/2012

CLIENT:

CITY OF GOSNELLS,
LOCKED BAG No. 1,
GOSNELLS, W.A. 6110.

JOB:

ORDER NO. 55974

RESERVOIR ROAD, ORANGE GROVE.
Grant St - house 136

CORE TEST REPORT.

SAMPLE NO: AS10070
SAMPLED BY: ASLAB PTY LTD
METHOD: MRWA 701.1; 705.1

DATE SAMPLED: 13/12/2011
DATE TESTED: 18/12/2011
DATE LAID: 11/12/2011

BULK DENSITY: MRWA 733.1

Core No.	Location		Thickness	Density	Compaction	Mat Voids
	Chainage	Offset	mm	t/m3	%	%
1	10 x 1 left edge		50	2.207	93.8	10.7
2	103 x 5 left edge		45	2.171	92.3	12.2
3	162 x 5 left edge		36	2.165	92.0	12.4
4	203 x 3 left edge		35	2.243	95.4	9.2
5	254 x 3 left edge		43	2.279	96.9	7.8
6	293 x 1 left edge		42	2.210	94.0	10.5
7						
	AVERAGE RESULT		42	2.212	94.1	10.5
	SPECIFICATION		40			3.5min 11.0max

NOTE 1: Compaction and mat void figures were obtained using information from the following source:-

Authority	Report No.	Max. Dens.	Marshall Dens.
ASLAB PTY LTD	51133	2.471	2.352

Relative Compaction Analysis

k Factor	0.91
$^{R}_{c}$ Percent	92.4
Specification(%)	94.0

NOTE 2: Zero point = Grant Street

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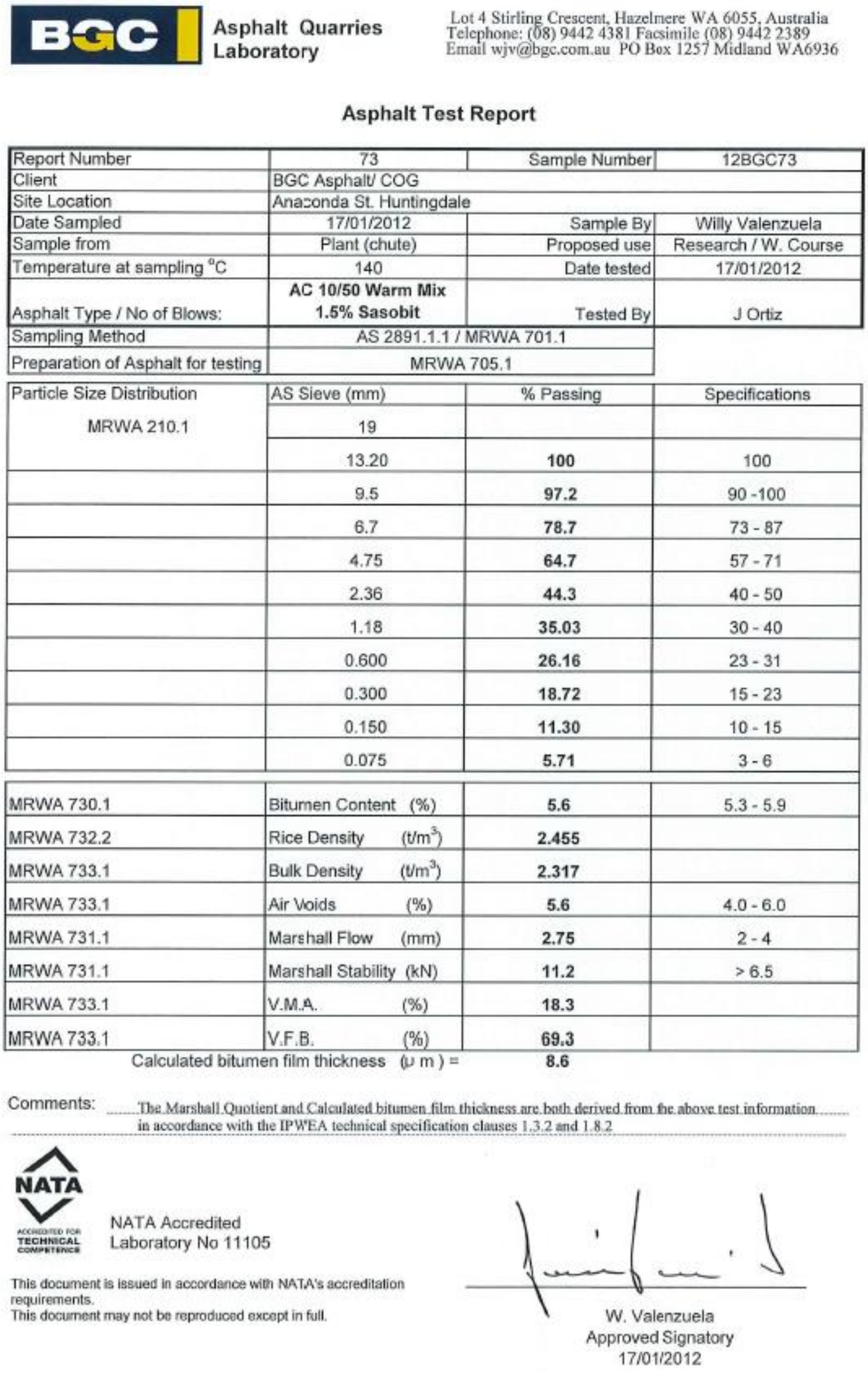
Appendix H Production Asphalt Report (trial 2)



Asphalt Quarries Laboratory

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Telephone: (08) 9442 4381 Facsimile (08) 9442 2389
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Asphalt Test Report

Report Number	73	Sample Number	12BGC73
Client	BGC Asphalt/ COG		
Site Location	Anaconda St. Huntingdale		
Date Sampled	17/01/2012	Sample By	Willy Valenzuela
Sample from	Plant (chute)	Proposed use	Research / W. Course
Temperature at sampling °C	140	Date tested	17/01/2012
Asphalt Type / No of Blows:	**AC 10/50 Warm Mix 1.5% Sasobit**	Tested By	J Ortiz
Sampling Method	AS 2891.1.1 / MRWA 701.1		
Preparation of Asphalt for testing	MRWA 705.1		

Particle Size Distribution	AS Sieve (mm)	% Passing	Specifications
MRWA 210.1	19		
	13.20	**100**	100
	9.5	**97.2**	90 -100
	6.7	**78.7**	73 - 87
	4.75	**64.7**	57 - 71
	2.36	**44.3**	40 - 50
	1.18	**35.03**	30 - 40
	0.600	**26.16**	23 - 31
	0.300	**18.72**	15 - 23
	0.150	**11.30**	10 - 15
	0.075	**5.71**	3 - 6

MRWA 730.1	Bitumen Content (%)	**5.6**	5.3 - 5.9
MRWA 732.2	Rice Density (t/m^3)	**2.455**	
MRWA 733.1	Bulk Density (t/m^3)	**2.317**	
MRWA 733.1	Air Voids (%)	**5.6**	4.0 - 6.0
MRWA 731.1	Marshall Flow (mm)	**2.75**	2 - 4
MRWA 731.1	Marshall Stability (kN)	**11.2**	> 6.5
MRWA 733.1	V.M.A. (%)	**18.3**	
MRWA 733.1	V.F.B. (%)	**69.3**	

Calculated bitumen film thickness (μ m) = **8.6**

Comments: The Marshall Quotient and Calculated bitumen film thickness are both derived from the above test information in accordance with the IPWEA technical specification clauses 1.3.2 and 1.8.2

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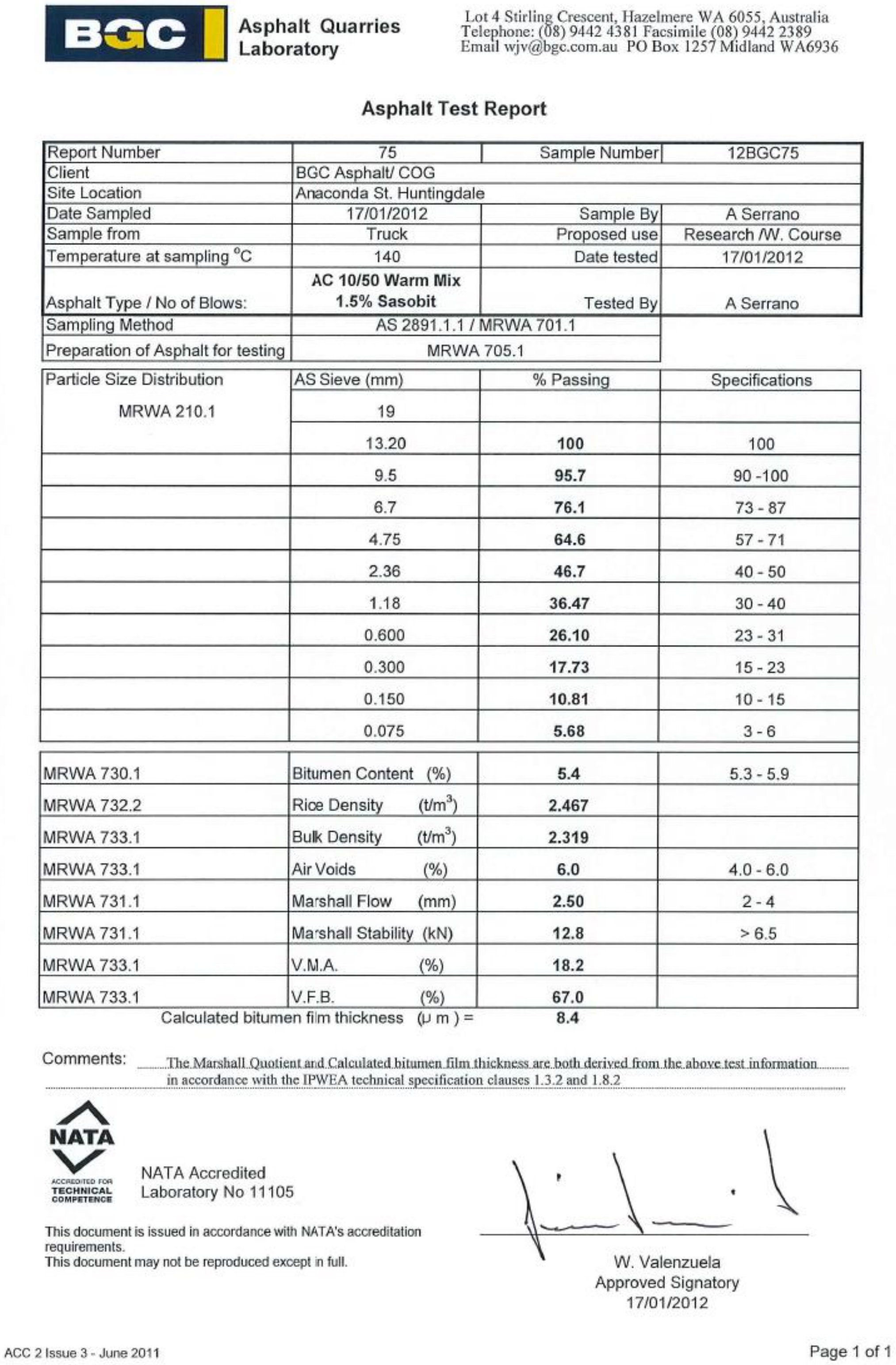

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Email wjv@bgc.com.au PO Box 1257 Midland WA6936

Asphalt Test Report

Report Number	75	Sample Number	12BGC75
Client	BGC Asphalt/ COG		
Site Location	Anaconda St. Huntingdale		
Date Sampled	17/01/2012	Sample By	A Serrano
Sample from	Truck	Proposed use	Research /W. Course
Temperature at sampling °C	140	Date tested	17/01/2012
Asphalt Type / No of Blows:	**AC 10/50 Warm Mix 1.5% Sasobit**	Tested By	A Serrano
Sampling Method	AS 2891.1.1 / MRWA 701.1		
Preparation of Asphalt for testing	MRWA 705.1		

Particle Size Distribution	AS Sieve (mm)	% Passing	Specifications
MRWA 210.1	19		
	13.20	**100**	100
	9.5	**95.7**	90 -100
	6.7	**76.1**	73 - 87
	4.75	**64.6**	57 - 71
	2.36	**46.7**	40 - 50
	1.18	**36.47**	30 - 40
	0.600	**26.10**	23 - 31
	0.300	**17.73**	15 - 23
	0.150	**10.81**	10 - 15
	0.075	**5.68**	3 - 6

MRWA 730.1	Bitumen Content (%)	**5.4**	5.3 - 5.9
MRWA 732.2	Rice Density (t/m^3)	**2.467**	
MRWA 733.1	Bulk Density (t/m^3)	**2.319**	
MRWA 733.1	Air Voids (%)	**6.0**	4.0 - 6.0
MRWA 731.1	Marshall Flow (mm)	**2.50**	2 - 4
MRWA 731.1	Marshall Stability (kN)	**12.8**	> 6.5
MRWA 733.1	V.M.A. (%)	**18.2**	
MRWA 733.1	V.F.B. (%)	**67.0**	

Calculated bitumen film thickness (μ m) = **8.4**

Comments: The Marshall Quotient and Calculated bitumen film thickness are both derived from the above test information in accordance with the IPWEA technical specification clauses 1.3.2 and 1.8.2

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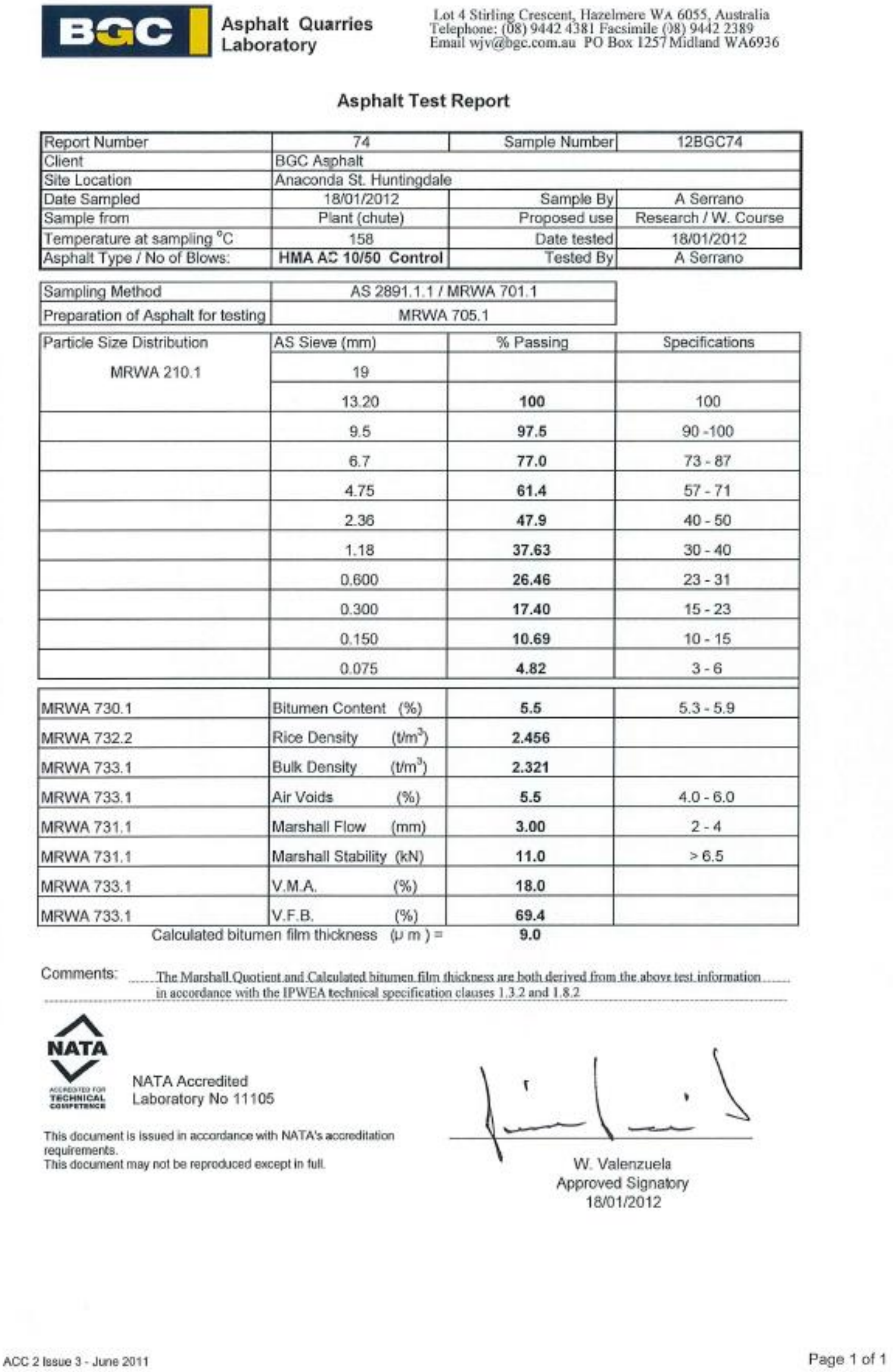

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Asphalt Test Report

Report Number	74	Sample Number	12BGC74
Client	BGC Asphalt		
Site Location	Anaconda St. Huntingdale		
Date Sampled	18/01/2012	Sample By	A Serrano
Sample from	Plant (chute)	Proposed use	Research / W. Course
Temperature at sampling °C	158	Date tested	18/01/2012
Asphalt Type / No of Blows:	**HMA AC 10/50 Control**	Tested By	A Serrano

Sampling Method	AS 2891.1.1 / MRWA 701.1
Preparation of Asphalt for testing	MRWA 705.1

Particle Size Distribution	AS Sieve (mm)	% Passing	Specifications
MRWA 210.1	19		
	13.20	**100**	100
	9.5	**97.5**	90 -100
	6.7	**77.0**	73 - 87
	4.75	**61.4**	57 - 71
	2.36	**47.9**	40 - 50
	1.18	**37.63**	30 - 40
	0.600	**26.46**	23 - 31
	0.300	**17.40**	15 - 23
	0.150	**10.69**	10 - 15
	0.075	**4.82**	3 - 6

MRWA 730.1	Bitumen Content (%)	**5.5**	5.3 - 5.9
MRWA 732.2	Rice Density (t/m^3)	**2.456**	
MRWA 733.1	Bulk Density (t/m^3)	**2.321**	
MRWA 733.1	Air Voids (%)	**5.5**	4.0 - 6.0
MRWA 731.1	Marshall Flow (mm)	**3.00**	2 - 4
MRWA 731.1	Marshall Stability (kN)	**11.0**	> 6.5
MRWA 733.1	V.M.A. (%)	**18.0**	
MRWA 733.1	V.F.B. (%)	**69.4**	

Calculated bitumen film thickness (μ m) = **9.0**

Comments: The Marshall Quotient and Calculated bitumen film thickness are both derived from the above test information in accordance with the IPWEA technical specification clauses 1.3.2 and 1.8.2

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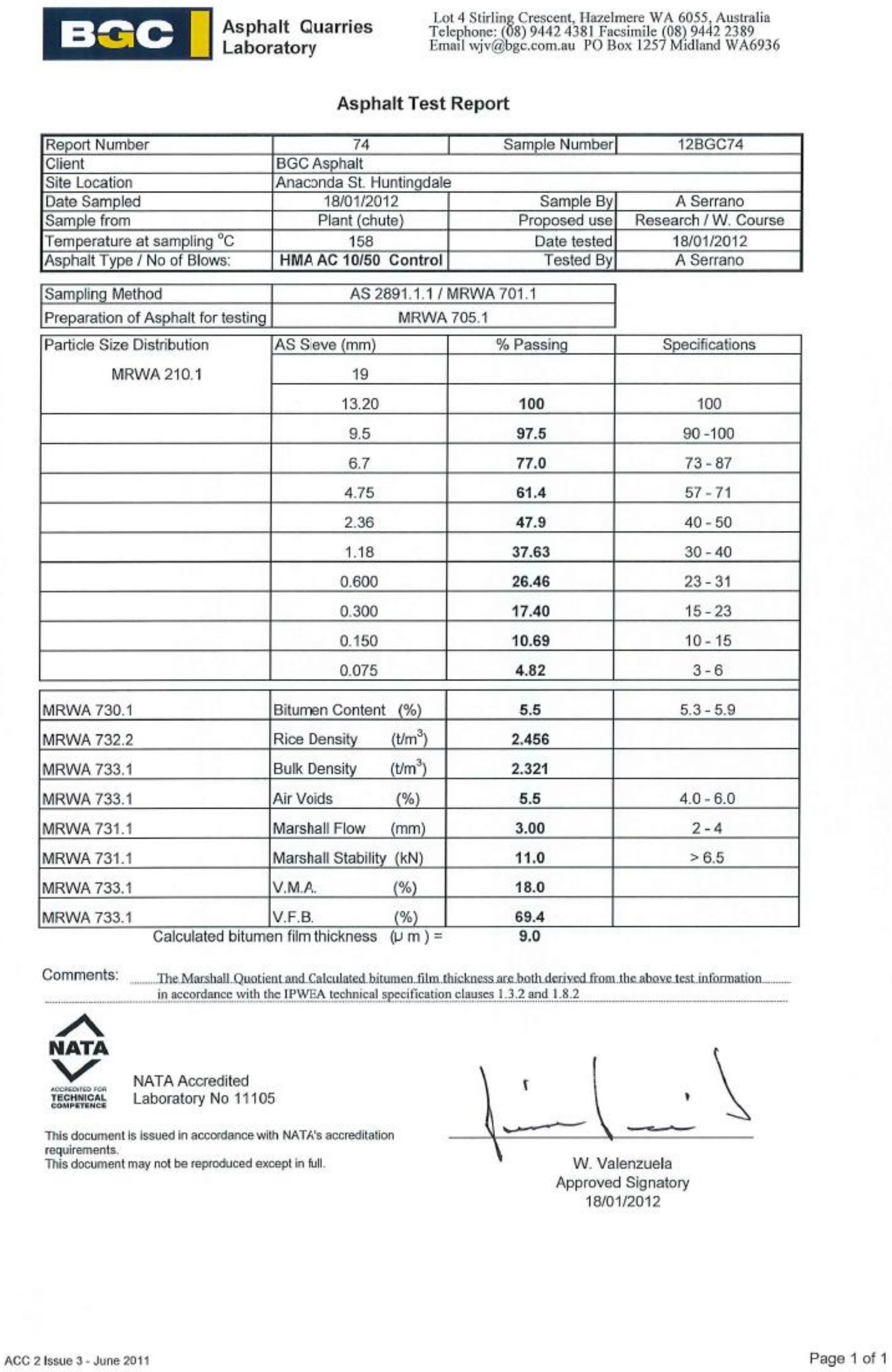

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Telephone: (08) 9442 4381 Facsimile (08) 9442 2389
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Asphalt Test Report

Report Number	74	Sample Number	12BGC74
Client	BGC Asphalt		
Site Location	Anaconda St. Huntingdale		
Date Sampled	18/01/2012	Sample By	A Serrano
Sample from	Plant (chute)	Proposed use	Research / W. Course
Temperature at sampling °C	158	Date tested	18/01/2012
Asphalt Type / No of Blows:	**HMA AC 10/50 Control**	Tested By	A Serrano

Sampling Method	AS 2891.1.1 / MRWA 701.1
Preparation of Asphalt for testing	MRWA 705.1

Particle Size Distribution	AS Sieve (mm)	% Passing	Specifications
MRWA 210.1	19		
	13.20	**100**	100
	9.5	**97.5**	90 -100
	6.7	**77.0**	73 - 87
	4.75	**61.4**	57 - 71
	2.36	**47.9**	40 - 50
	1.18	**37.63**	30 - 40
	0.600	**26.46**	23 - 31
	0.300	**17.40**	15 - 23
	0.150	**10.69**	10 - 15
	0.075	**4.82**	3 - 6

MRWA 730.1	Bitumen Content (%)	**5.5**	5.3 - 5.9
MRWA 732.2	Rice Density (t/m^3)	**2.456**	
MRWA 733.1	Bulk Density (t/m^3)	**2.321**	
MRWA 733.1	Air Voids (%)	**5.5**	4.0 - 6.0
MRWA 731.1	Marshall Flow (mm)	**3.00**	2 - 4
MRWA 731.1	Marshall Stability (kN)	**11.0**	> 6.5
MRWA 733.1	V.M.A. (%)	**18.0**	
MRWA 733.1	V.F.B. (%)	**69.4**	

Calculated bitumen film thickness (μ m) = **9.0**

Comments: The Marshall Quotient and Calculated bitumen film thickness are both derived from the above test information in accordance with the IPWEA technical specification clauses 1.3.2 and 1.8.2

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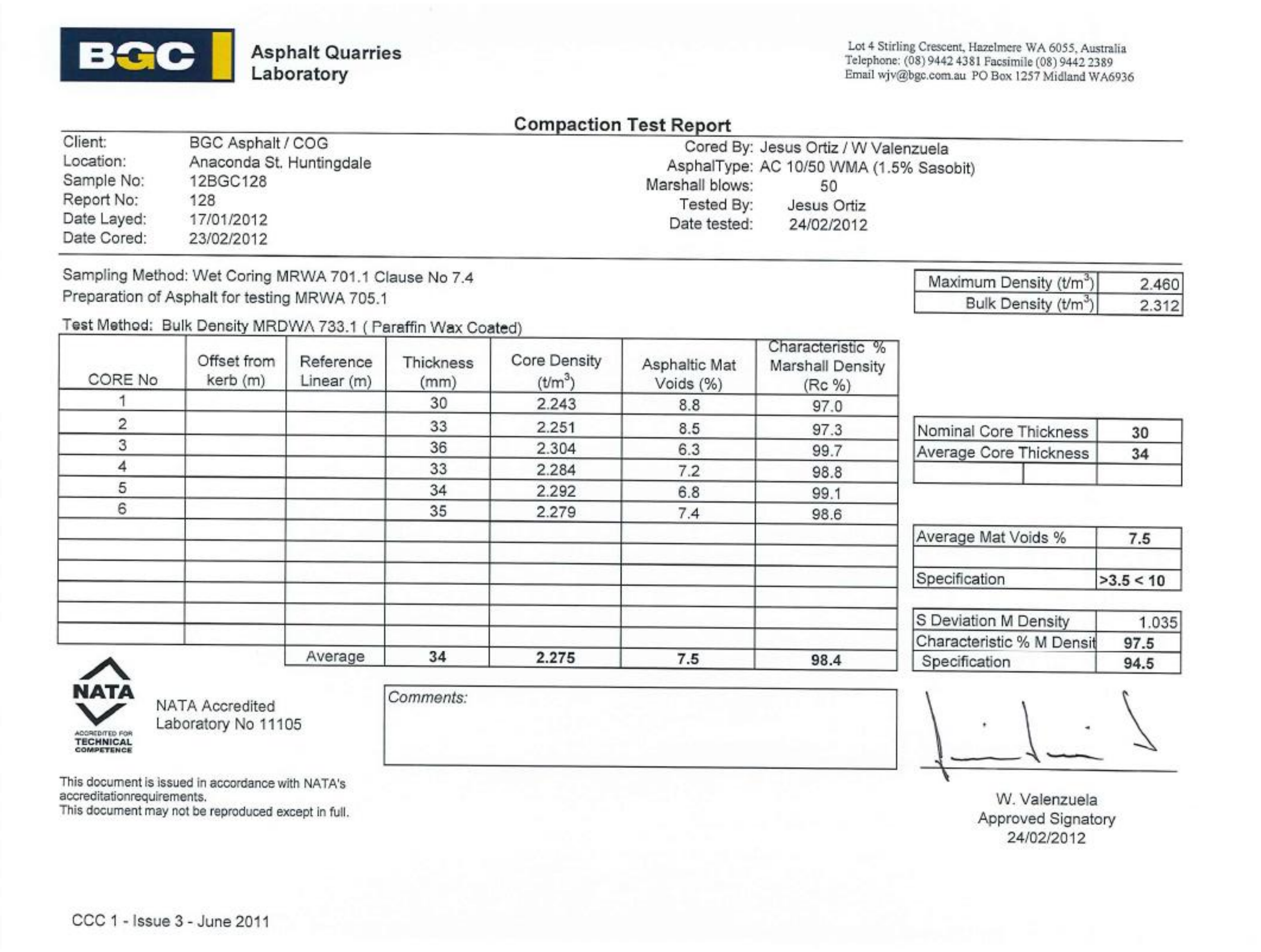
Appendix I Compaction Reports (trial 2)



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Telephone: (08) 9442 4381 Facsimile (08) 9442 2389
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Compaction Test Report

Client: BGC Asphalt / COG
Location: Anaconda St. Huntingdale
Sample No: 12BGC128
Report No: 128
Date Layed: 17/01/2012
Date Cored: 23/02/2012

Cored By: Jesus Ortiz / W Valenzuela
AsphalType: AC 10/50 WMA (1.5% Sasobit)
Marshall blows: 50
Tested By: Jesus Ortiz
Date tested: 24/02/2012

Sampling Method: Wet Coring MRWA 701.1 Clause No 7.4
Preparation of Asphalt for testing MRWA 705.1
Test Method: Bulk Density MRDWA 733.1 (Paraffin Wax Coated)

Maximum Density (t/m^3)	2.460
Bulk Density (t/m^3)	2.312

CORE No	Offset from kerb (m)	Reference Linear (m)	Thickness (mm)	Core Density (t/m^3)	Asphaltic Mat Voids (%)	Characteristic % Marshall Density (Rc %)
1			30	2.243	8.8	97.0
2			33	2.251	8.5	97.3
3			36	2.304	6.3	99.7
4			33	2.284	7.2	98.8
5			34	2.292	6.8	99.1
6			35	2.279	7.4	98.6
		Average	**34**	**2.275**	**7.5**	**98.4**

Nominal Core Thickness	**30**
Average Core Thickness	**34**

Average Mat Voids %	**7.5**
Specification	**>3.5 < 10**

S Deviation M Density	1.035
Characteristic % M Densit	**97.5**
Specification	**94.5**

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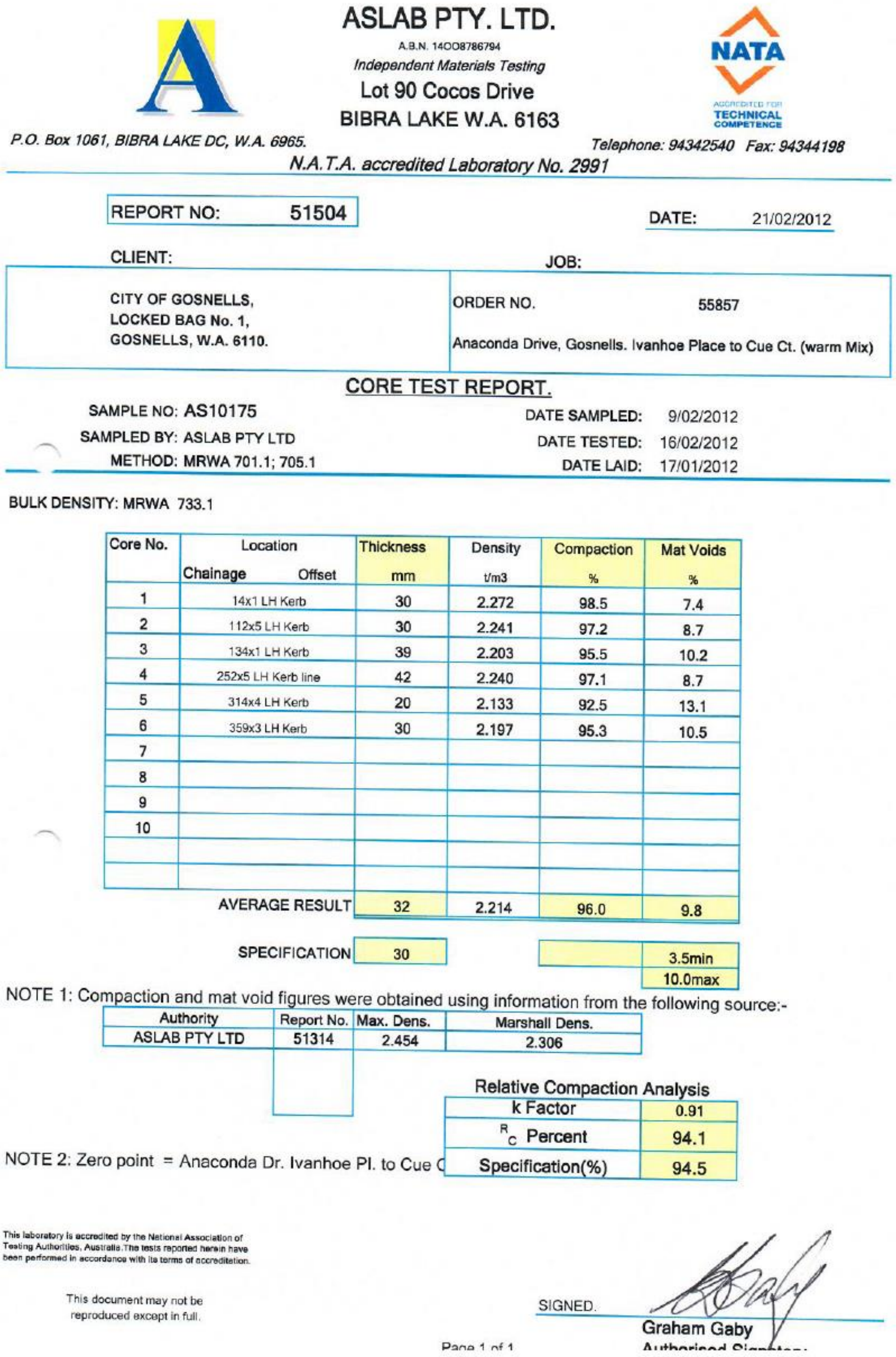

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Lot 90 Cocos Drive
BIBRA LAKE W.A. 6163

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P.O. Box 1061, BIBRA LAKE DC, W.A. 6965.
Telephone: 94342540 Fax: 94344198
N.A.T.A. accredited Laboratory No. 2991

REPORT NO: 51504

DATE: 21/02/2012

CLIENT:

CITY OF GOSNELLS,
LOCKED BAG No. 1,
GOSNELLS, W.A. 6110.

JOB:

ORDER NO. 55857

Anaconda Drive, Gosnells. Ivanhoe Place to Cue Ct. (warm Mix)

CORE TEST REPORT.

SAMPLE NO: AS10175
SAMPLED BY: ASLAB PTY LTD
METHOD: MRWA 701.1; 705.1

DATE SAMPLED: 9/02/2012
DATE TESTED: 16/02/2012
DATE LAID: 17/01/2012

BULK DENSITY: MRWA 733.1

Core No.	Location	Thickness	Density	Compaction	Mat Voids
	Chainage Offset	mm	t/m3	%	%
1	14x1 LH Kerb	30	2.272	98.5	7.4
2	112x5 LH Kerb	30	2.241	97.2	8.7
3	134x1 LH Kerb	39	2.203	95.5	10.2
4	252x5 LH Kerb line	42	2.240	97.1	8.7
5	314x4 LH Kerb	20	2.133	92.5	13.1
6	359x3 LH Kerb	30	2.197	95.3	10.5
7					
8					
9					
10					
	AVERAGE RESULT	32	2.214	96.0	9.8
	SPECIFICATION	30			3.5min 10.0max

NOTE 1: Compaction and mat void figures were obtained using information from the following source:-

Authority	Report No.	Max. Dens.	Marshall Dens.
ASLAB PTY LTD	51314	2.454	2.306

Relative Compaction Analysis

k Factor	0.91
$^{R}_{C}$ Percent	94.1
Specification(%)	94.5

NOTE 2: Zero point = Anaconda Dr. Ivanhoe Pl. to Cue C

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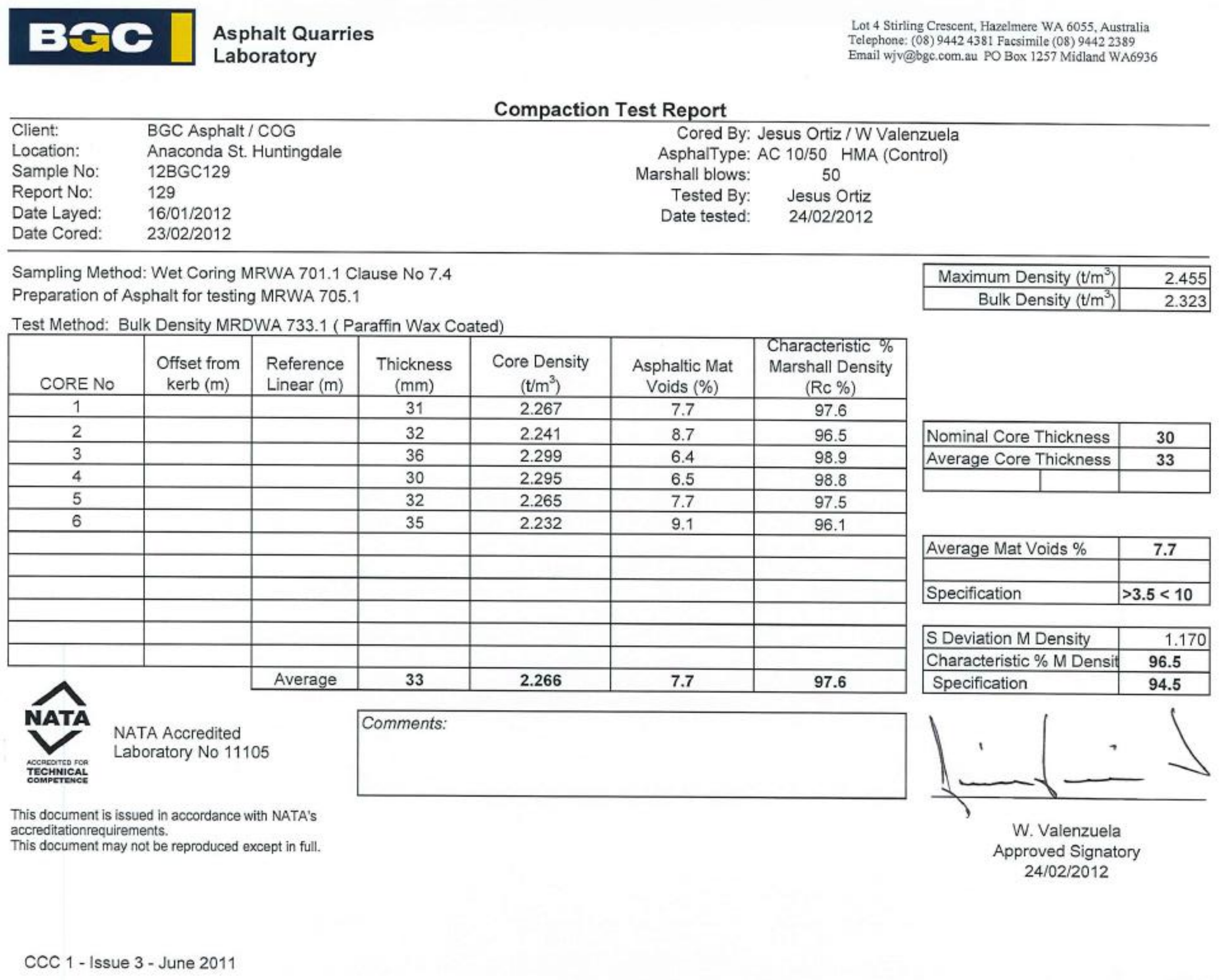
Authorised Signatory

Page 1 of 1



Asphalt Quarries Laboratory

Lot 4 Stirling Crescent, Hazelmere WA 6055, Australia
Telephone: (08) 9442 4381 Facsimile (08) 9442 2389
Email wjv@bgc.com.au PO Box 1257 Midland WA6936

Compaction Test Report

Client: BGC Asphalt / COG
Location: Anaconda St. Huntingdale
Sample No: 12BGC129
Report No: 129
Date Layed: 16/01/2012
Date Cored: 23/02/2012

Cored By: Jesus Ortiz / W Valenzuela
AsphalType: AC 10/50 HMA (Control)
Marshall blows: 50
Tested By: Jesus Ortiz
Date tested: 24/02/2012

Sampling Method: Wet Coring MRWA 701.1 Clause No 7.4
Preparation of Asphalt for testing MRWA 705.1

Maximum Density (t/m^3)	2.455
Bulk Density (t/m^3)	2.323

Test Method: Bulk Density MRDWA 733.1 (Paraffin Wax Coated)

CORE No	Offset from kerb (m)	Reference Linear (m)	Thickness (mm)	Core Density (t/m^3)	Asphaltic Mat Voids (%)	Characteristic % Marshall Density (Rc %)
1			31	2.267	7.7	97.6
2			32	2.241	8.7	96.5
3			36	2.299	6.4	98.9
4			30	2.295	6.5	98.8
5			32	2.265	7.7	97.5
6			35	2.232	9.1	96.1
		Average	**33**	**2.266**	**7.7**	**97.6**

Nominal Core Thickness	**30**
Average Core Thickness	**33**

Average Mat Voids %	**7.7**
Specification	**>3.5 < 10**

S Deviation M Density	1.170
Characteristic % M Densit	**96.5**
Specification	**94.5**

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Laboratory No 11105

Comments:

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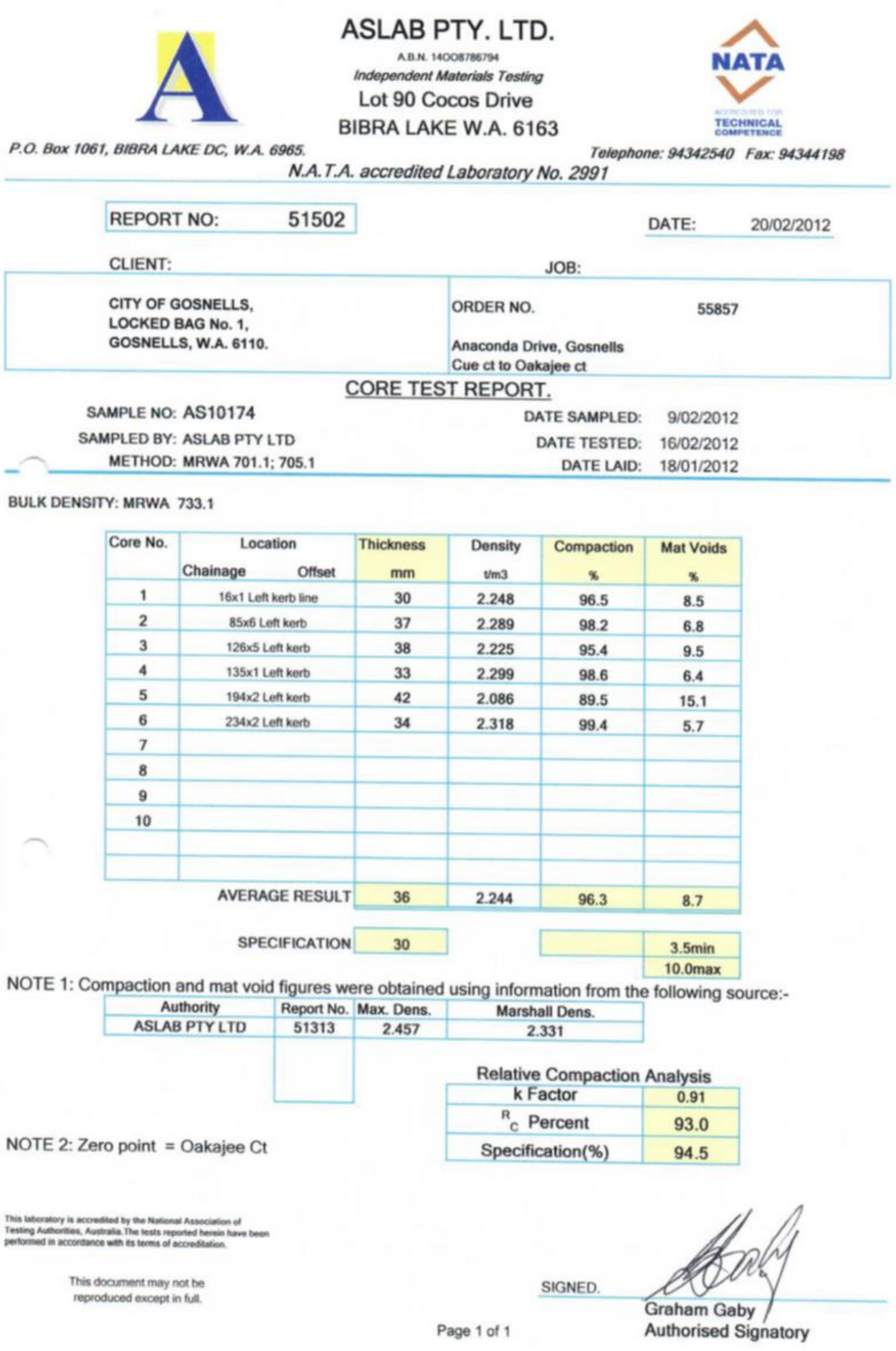
Approved Signatory
24/02/2012

CCC 1 - Issue 3 - June 2011



ASLAB PTY. LTD.
A.B.N. 14008786794
Independent Materials Testing
Lot 90 Cocos Drive
BIBRA LAKE W.A. 6163

P.O. Box 1061, BIBRA LAKE DC, W.A. 6965.
Telephone: 94342540 Fax: 94344198

N.A.T.A. accredited Laboratory No. 2991

NATA
ACCREDITED FOR
TECHNICAL COMPETENCE

REPORT NO: 51502

DATE: 20/02/2012

CLIENT:
CITY OF GOSNELLS,
LOCKED BAG No. 1,
GOSNELLS, W.A. 6110.

JOB:
ORDER NO. 55857
Anaconda Drive, Gosnells
Cue ct to Oakajee ct

CORE TEST REPORT.

SAMPLE NO: AS10174
SAMPLED BY: ASLAB PTY LTD
METHOD: MRWA 701.1; 705.1

DATE SAMPLED: 9/02/2012
DATE TESTED: 16/02/2012
DATE LAID: 18/01/2012

BULK DENSITY: MRWA 733.1

Core No.	Location	Thickness	Density	Compaction	Mat Voids
	Chainage Offset	mm	t/m3	%	%
1	16x1 Left kerb line	30	2.248	96.5	8.5
2	85x6 Left kerb	37	2.289	98.2	6.8
3	126x5 Left kerb	38	2.225	95.4	9.5
4	135x1 Left kerb	33	2.299	98.6	6.4
5	194x2 Left kerb	42	2.086	89.5	15.1
6	234x2 Left kerb	34	2.318	99.4	5.7
7					
8					
9					
10					
	AVERAGE RESULT	36	2.244	96.3	8.7
	SPECIFICATION	30			3.5min 10.0max

NOTE 1: Compaction and mat void figures were obtained using information from the following source:-

Authority	Report No.	Max. Dens.	Marshall Dens.
ASLAB PTY LTD	51313	2.457	2.331

Relative Compaction Analysis

k Factor	0.91
$^{R}_{C}$ Percent	93.0
Specification(%)	94.5

NOTE 2: Zero point = Oakajee Ct

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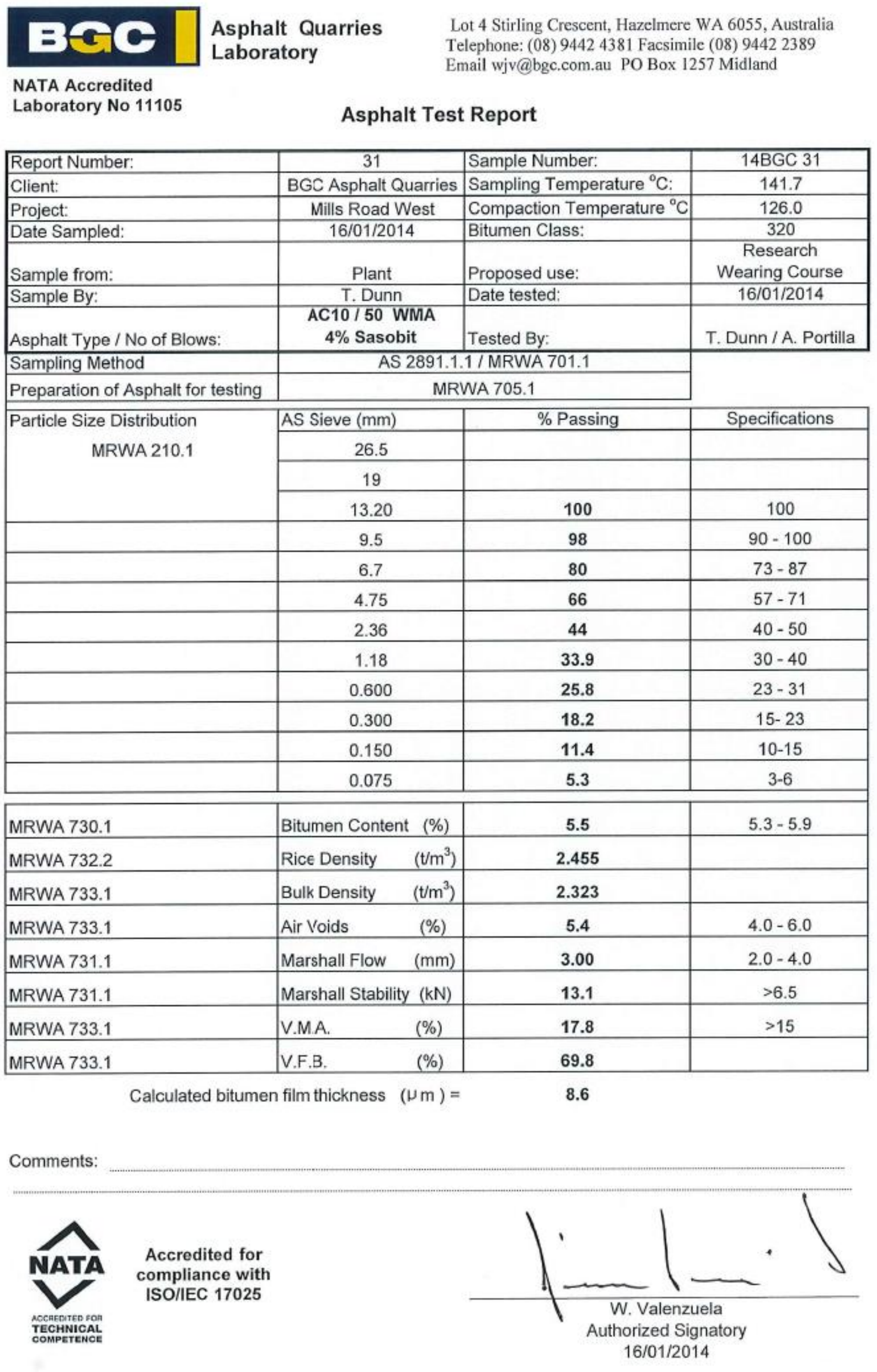
Appendix J WMA Reports with 4% Sasobit



BGC **Asphalt Quarries Laboratory**

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Email wjv@bgc.com.au PO Box 1257 Midland

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Laboratory No 11105

Asphalt Test Report

Report Number:	31	Sample Number:	14BGC 31
Client:	BGC Asphalt Quarries	Sampling Temperature °C:	141.7
Project:	Mills Road West	Compaction Temperature °C	126.0
Date Sampled:	16/01/2014	Bitumen Class:	320
Sample from:	Plant	Proposed use:	Research Wearing Course
Sample By:	T. Dunn	Date tested:	16/01/2014
Asphalt Type / No of Blows:	**AC10 / 50 WMA 4% Sasobit**	Tested By:	T. Dunn / A. Portilla
Sampling Method	AS 2891.1.1 / MRWA 701.1		
Preparation of Asphalt for testing	MRWA 705.1		

Particle Size Distribution	AS Sieve (mm)	% Passing	Specifications
MRWA 210.1	26.5		
	19		
	13.20	**100**	100
	9.5	**98**	90 - 100
	6.7	**80**	73 - 87
	4.75	**66**	57 - 71
	2.36	**44**	40 - 50
	1.18	**33.9**	30 - 40
	0.600	**25.8**	23 - 31
	0.300	**18.2**	15- 23
	0.150	**11.4**	10-15
	0.075	**5.3**	3-6

MRWA 730.1	Bitumen Content (%)	**5.5**	5.3 - 5.9
MRWA 732.2	Rice Density (t/m^3)	**2.455**	
MRWA 733.1	Bulk Density (t/m^3)	**2.323**	
MRWA 733.1	Air Voids (%)	**5.4**	4.0 - 6.0
MRWA 731.1	Marshall Flow (mm)	**3.00**	2.0 - 4.0
MRWA 731.1	Marshall Stability (kN)	**13.1**	>6.5
MRWA 733.1	V.M.A. (%)	**17.8**	>15
MRWA 733.1	V.F.B. (%)	**69.8**	

Calculated bitumen film thickness (μm) = **8.6**

Comments: ....

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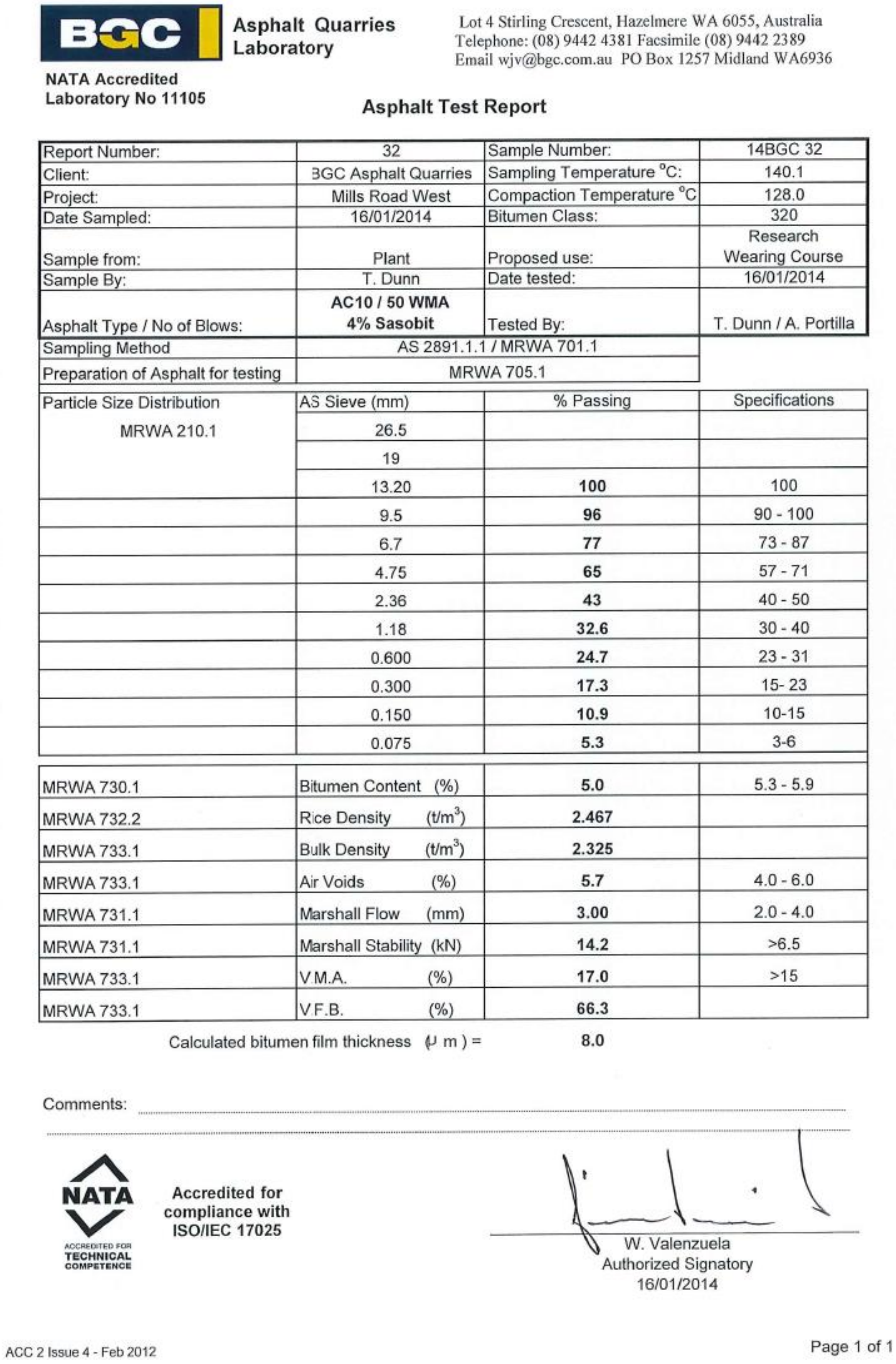
Authorized Signatory
16/01/2014



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Asphalt Test Report

Report Number:	32	Sample Number:	14BGC 32
Client:	BGC Asphalt Quarries	Sampling Temperature °C:	140.1
Project:	Mills Road West	Compaction Temperature °C	128.0
Date Sampled:	16/01/2014	Bitumen Class:	320
Sample from:	Plant	Proposed use:	Research Wearing Course
Sample By:	T. Dunn	Date tested:	16/01/2014
Asphalt Type / No of Blows:	**AC10 / 50 WMA** **4% Sasobit**	Tested By:	T. Dunn / A. Portilla
Sampling Method	AS 2891.1.1 / MRWA 701.1		
Preparation of Asphalt for testing	MRWA 705.1		

Particle Size Distribution	AS Sieve (mm)	% Passing	Specifications
MRWA 210.1	26.5		
	19		
	13.20	**100**	100
	9.5	**96**	90 - 100
	6.7	**77**	73 - 87
	4.75	**65**	57 - 71
	2.36	**43**	40 - 50
	1.18	**32.6**	30 - 40
	0.600	**24.7**	23 - 31
	0.300	**17.3**	15- 23
	0.150	**10.9**	10-15
	0.075	**5.3**	3-6

MRWA 730.1	Bitumen Content (%)	**5.0**	5.3 - 5.9
MRWA 732.2	Rice Density (t/m^3)	**2.467**	
MRWA 733.1	Bulk Density (t/m^3)	**2.325**	
MRWA 733.1	Air Voids (%)	**5.7**	4.0 - 6.0
MRWA 731.1	Marshall Flow (mm)	**3.00**	2.0 - 4.0
MRWA 731.1	Marshall Stability (kN)	**14.2**	>6.5
MRWA 733.1	V.M.A. (%)	**17.0**	>15
MRWA 733.1	V.F.B. (%)	**66.3**	

Calculated bitumen film thickness (μ m) = **8.0**

Comments: ....

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16/01/2014

ACC 2 Issue 4 - Feb 2012

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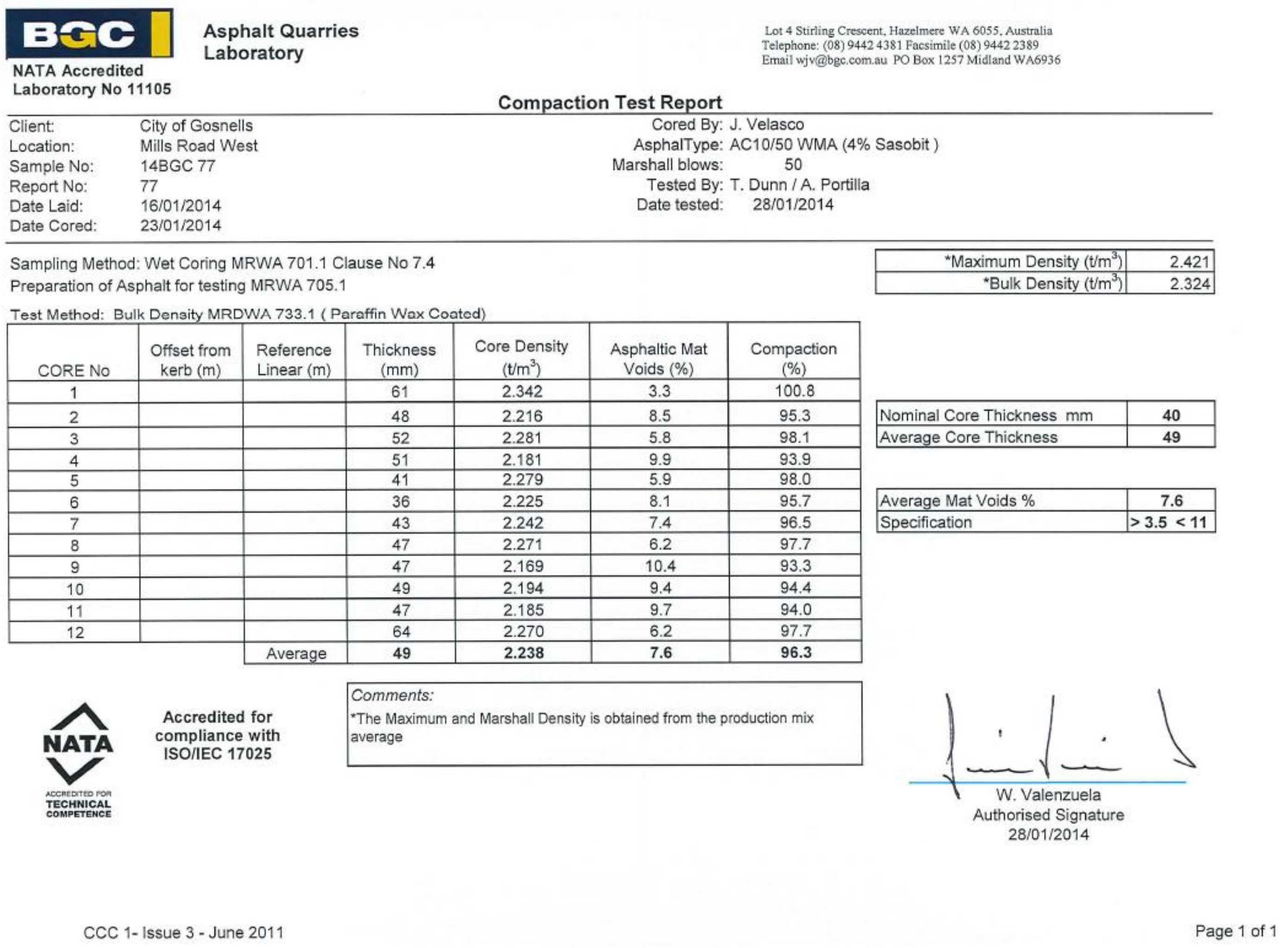
Appendix K WMA Compaction Reports with 4% Sasobit



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Asphalt Quarries
Laboratory

Lot 4 Stirling Crescent, Hazelmere WA 6055, Australia
Telephone: (08) 9442 4381 Facsimile (08) 9442 2389
Email wjv@bgc.com.au PO Box 1257 Midland WA6936

Compaction Test Report

Client:	City of Gosnells
Location:	Mills Road West
Sample No:	14BGC 77
Report No:	77
Date Laid:	16/01/2014
Date Cored:	23/01/2014

Cored By:	J. Velasco
AsphalType:	AC10/50 WMA (4% Sasobit)
Marshall blows:	50
Tested By:	T. Dunn / A. Portilla
Date tested:	28/01/2014

Sampling Method: Wet Coring MRWA 701.1 Clause No 7.4

Preparation of Asphalt for testing MRWA 705.1

*Maximum Density (t/m^3)	2.421
*Bulk Density (t/m^3)	2.324

Test Method: Bulk Density MRDWA 733.1 (Paraffin Wax Coated)

CORE No	Offset from kerb (m)	Reference Linear (m)	Thickness (mm)	Core Density (t/m^3)	Asphaltic Mat Voids (%)	Compaction (%)
1			61	2.342	3.3	100.8
2			48	2.216	8.5	95.3
3			52	2.281	5.8	98.1
4			51	2.181	9.9	93.9
5			41	2.279	5.9	98.0
6			36	2.225	8.1	95.7
7			43	2.242	7.4	96.5
8			47	2.271	6.2	97.7
9			47	2.169	10.4	93.3
10			49	2.194	9.4	94.4
11			47	2.185	9.7	94.0
12			64	2.270	6.2	97.7
		Average	**49**	**2.238**	**7.6**	**96.3**

Nominal Core Thickness mm	**40**
Average Core Thickness	**49**

Average Mat Voids %	**7.6**
Specification	**> 3.5 < 11**

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Comments:
*The Maximum and Marshall Density is obtained from the production mix average

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28/01/2014

CCC 1- Issue 3 - June 2011

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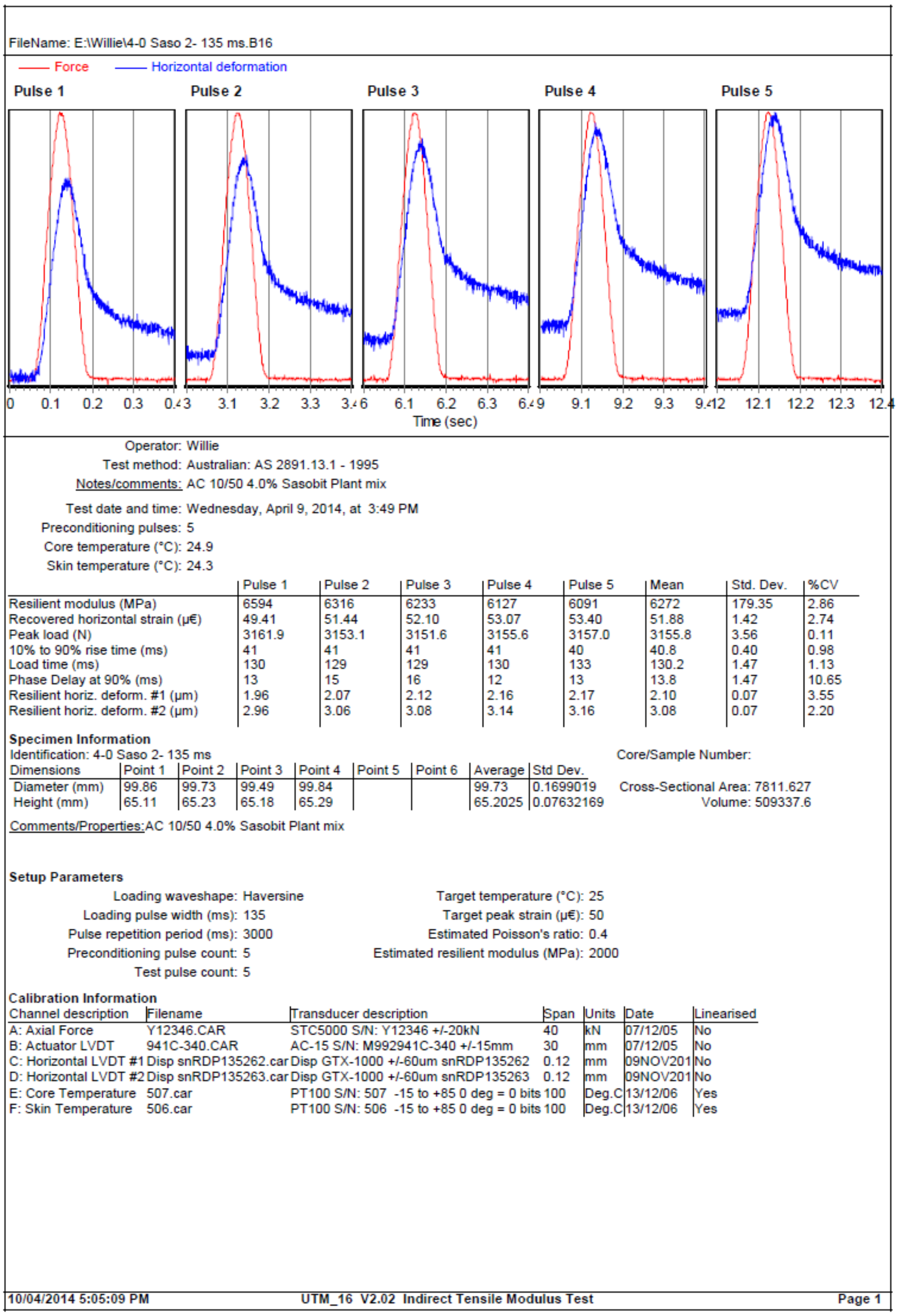
Appendix L Sample Production Performance test results

Resisilien Modulus (4% Sasobit)



FileName: E:\Willie\4-0 Saso 2- 135 ms.B16

Operator: Willie
Test method: Australian: AS 2891.13.1 - 1995
Notes/comments: AC 10/50 4.0% Sasobit Plant mix

Test date and time: Wednesday, April 9, 2014, at 3:49 PM
Preconditioning pulses: 5
Core temperature (°C): 24.9
Skin temperature (°C): 24.3

	Pulse 1	Pulse 2	Pulse 3	Pulse 4	Pulse 5	Mean	Std. Dev.	%CV
Resilient modulus (MPa)	6594	6316	6233	6127	6091	6272	179.35	2.86
Recovered horizontal strain (µ€)	49.41	51.44	52.10	53.07	53.40	51.88	1.42	2.74
Peak load (N)	3161.9	3153.1	3151.6	3155.6	3157.0	3155.8	3.56	0.11
10% to 90% rise time (ms)	41	41	41	41	40	40.8	0.40	0.98
Load time (ms)	130	129	129	130	133	130.2	1.47	1.13
Phase Delay at 90% (ms)	13	15	16	12	13	13.8	1.47	10.65
Resilient horiz. deform. #1 (µm)	1.96	2.07	2.12	2.16	2.17	2.10	0.07	3.55
Resilient horiz. deform. #2 (µm)	2.96	3.06	3.08	3.14	3.16	3.08	0.07	2.20

Specimen Information

Identification: 4-0 Saso 2- 135 ms

Core/Sample Number:

Dimensions	Point 1	Point 2	Point 3	Point 4	Point 5	Point 6	Average	Std Dev.
Diameter (mm)	99.86	99.73	99.49	99.84			99.73	0.1699019
Height (mm)	65.11	65.23	65.18	65.29			65.2025	0.07632169

Cross-Sectional Area: 7811.627
Volume: 509337.6

Comments/Properties: AC 10/50 4.0% Sasobit Plant mix

Setup Parameters

Loading waveshape: Haversine
Loading pulse width (ms): 135
Pulse repetition period (ms): 3000
Preconditioning pulse count: 5
Test pulse count: 5

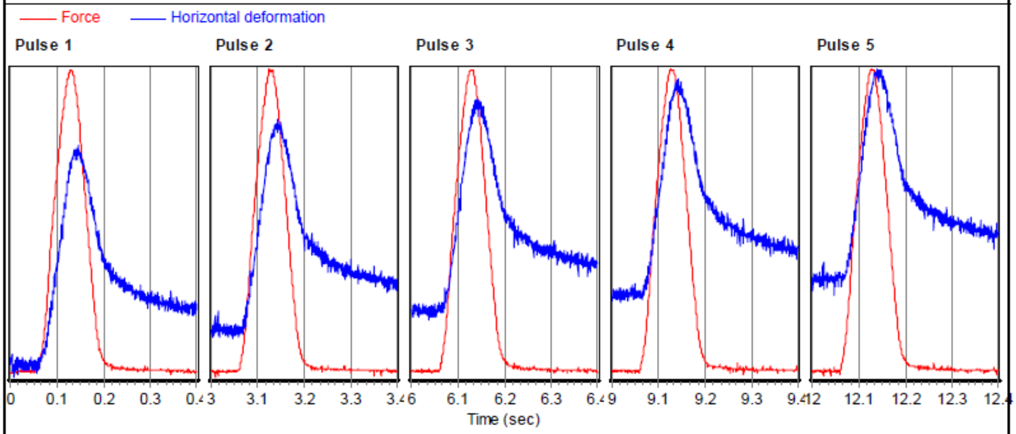
Target temperature (°C): 25
Target peak strain (µ€): 50
Estimated Poisson's ratio: 0.4
Estimated resilient modulus (MPa): 2000

Calibration Information

Channel description	Filename	Transducer description	Span	Units	Date	Linearised
A: Axial Force	Y12346.CAR	STC5000 S/N: Y12346 +/-20kN	40	kN	07/12/05	No
B: Actuator LVDT	941C-340.CAR	AC-15 S/N: M992941C-340 +/-15mm	30	mm	07/12/05	No
C: Horizontal LVDT #1	Disp snRDP135262.car	Disp GTX-1000 +/-60um snRDP135262	0.12	mm	09NOV201	No
D: Horizontal LVDT #2	Disp snRDP135263.car	Disp GTX-1000 +/-60um snRDP135263	0.12	mm	09NOV201	No
E: Core Temperature	507.car	PT100 S/N: 507 -15 to +85 0 deg = 0 bits	100	Deg.C	13/12/06	Yes
F: Skin Temperature	506.car	PT100 S/N: 506 -15 to +85 0 deg = 0 bits	100	Deg.C	13/12/06	Yes

10/04/2014 5:05:09 PM **UTM_16 V2.02 Indirect Tensile Modulus Test** **Page 1**

FileName: E:\Willie\4-0 Saso 3- 135 ms.B16



Operator: Willie
Test method: Australian: AS 2891.13.1 - 1995
Notes/comments: AC 10/50 4.0% Sasobit Plant mix

Test date and time: Wednesday, April 9, 2014, at 4:02 PM
Preconditioning pulses: 5
Core temperature (°C): 25.2
Skin temperature (°C): 24.8

	Pulse 1	Pulse 2	Pulse 3	Pulse 4	Pulse 5	Mean	Std. Dev.	%CV
Resilient modulus (MPa)	7382	7157	6922	6796	6870	7025	215.58	3.07
Recovered horizontal strain (µ€)	41.33	42.85	44.07	45.04	44.55	43.57	1.33	3.06
Peak load (N)	2974.4	2990.0	2973.9	2983.6	2983.6	2981.1	6.16	0.21
10% to 90% rise time (ms)	45	44	44	43	44	44.0	0.63	1.44
Load time (ms)	144	142	144	140	140	142.0	1.79	1.26
Phase Delay at 90% (ms)	15	11	12	14	10	12.4	1.85	14.96
Resilient horiz. deform. #1 (µm)	2.33	2.35	2.43	2.48	2.49	2.42	0.07	2.77
Resilient horiz. deform. #2 (µm)	1.81	1.93	1.98	2.02	1.97	1.94	0.07	3.71

Specimen Information

Identification: 4-0 Saso 3- 135 ms

Core/Sample Number:

Dimensions	Point 1	Point 2	Point 3	Point 4	Point 5	Point 6	Average	Std Dev.
Diameter (mm)	99.98	99.96	100.1	100			100.01	0.06218253
Height (mm)	65.22	65.38	65.49	65.15			65.31	0.1538397

Cross-Sectional Area: 7855.553
Volume: 513046.1

Comments/Properties: AC 10/50 4.0% Sasobit Plant mix

Setup Parameters

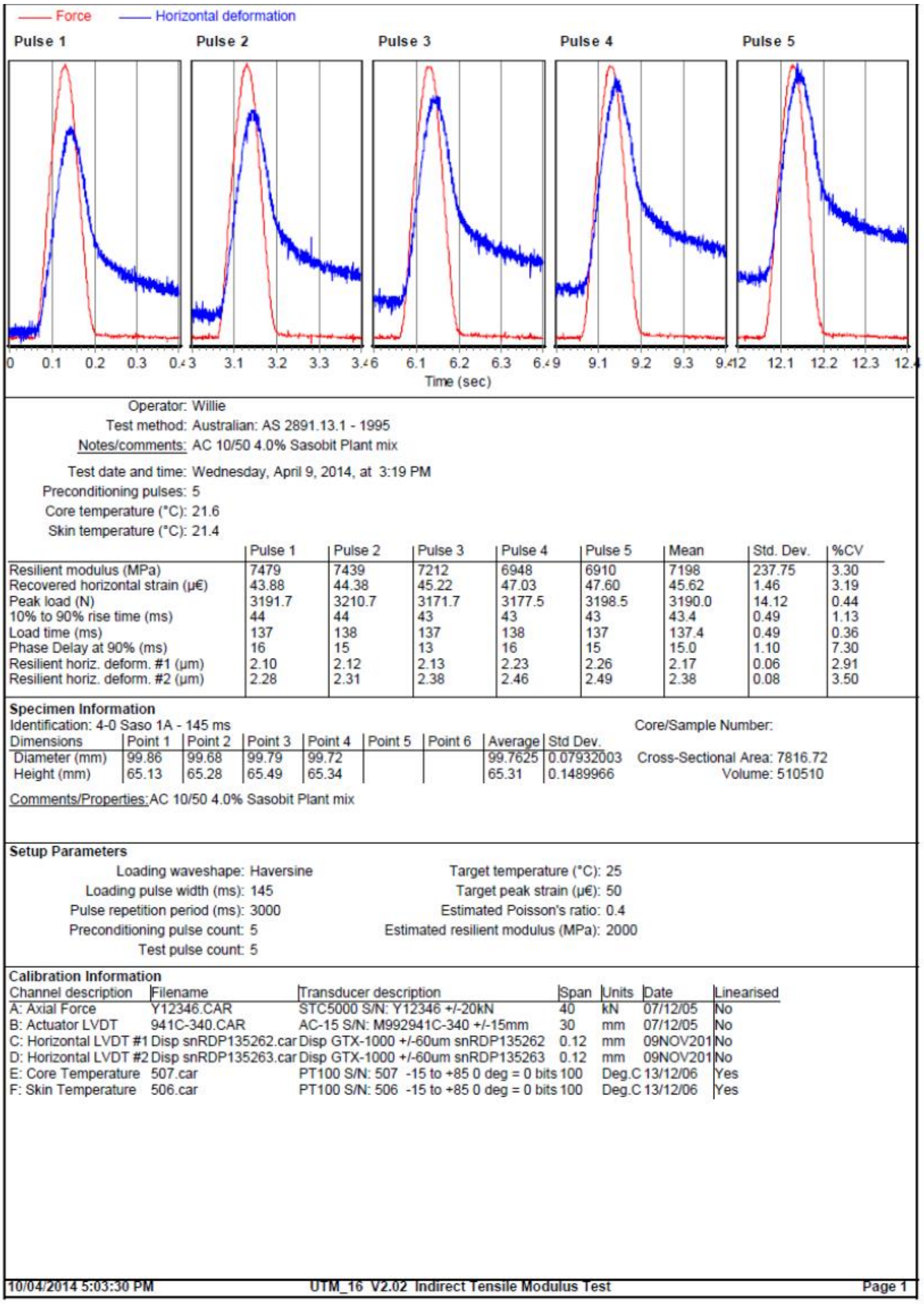
Loading waveshape: Haversine
Loading pulse width (ms): 135
Pulse repetition period (ms): 3000
Preconditioning pulse count: 5
Test pulse count: 5

Target temperature (°C): 25
Target peak strain (µ€): 50
Estimated Poisson's ratio: 0.4
Estimated resilient modulus (MPa): 2000

Calibration Information

Channel description	Filename	Transducer description	Span	Units	Date	Linearised
A: Axial Force	Y12346.CAR	STC5000 S/N: Y12346 +/-20kN	40	kN	07/12/05	No
B: Actuator LVDT	941C-340.CAR	AC-15 S/N: M992941C-340 +/-15mm	30	mm	07/12/05	No
C: Horizontal LVDT #1	Disp snRDP135262.car	Disp GTX-1000 +/-60um snRDP135262	0.12	mm	09NOV201	No
D: Horizontal LVDT #2	Disp snRDP135263.car	Disp GTX-1000 +/-60um snRDP135263	0.12	mm	09NOV201	No
E: Core Temperature	507.car	PT100 S/N: 507 -15 to +85 0 deg = 0 bits	100	Deg.C	13/12/06	Yes
F: Skin Temperature	506.car	PT100 S/N: 506 -15 to +85 0 deg = 0 bits	100	Deg.C	13/12/06	Yes

10/04/2014 5:06:57 PM **UTM_16 V2.02 Indirect Tensile Modulus Test** **Page 1**



Operator: Willie
Test method: Australian: AS 2891.13.1 - 1995
Notes/comments: AC 10/50 4.0% Sasobit Plant mix

Test date and time: Wednesday, April 9, 2014, at 3:19 PM
Preconditioning pulses: 5
Core temperature (°C): 21.6
Skin temperature (°C): 21.4

	Pulse 1	Pulse 2	Pulse 3	Pulse 4	Pulse 5	Mean	Std. Dev.	%CV
Resilient modulus (MPa)	7479	7439	7212	6948	6910	7198	237.75	3.30
Recovered horizontal strain (µ€)	43.88	44.38	45.22	47.03	47.60	45.62	1.46	3.19
Peak load (N)	3191.7	3210.7	3171.7	3177.5	3198.5	3190.0	14.12	0.44
10% to 90% rise time (ms)	44	44	43	43	43	43.4	0.49	1.13
Load time (ms)	137	138	137	138	137	137.4	0.49	0.36
Phase Delay at 90% (ms)	16	15	13	16	15	15.0	1.10	7.30
Resilient horiz. deform. #1 (µm)	2.10	2.12	2.13	2.23	2.26	2.17	0.06	2.91
Resilient horiz. deform. #2 (µm)	2.28	2.31	2.38	2.46	2.49	2.38	0.08	3.50

Specimen Information

Identification: 4-0 Saso 1A - 145 ms

Core/Sample Number:

Dimensions	Point 1	Point 2	Point 3	Point 4	Point 5	Point 6	Average	Std Dev.
Diameter (mm)	99.86	99.68	99.79	99.72			99.7625	0.07932003
Height (mm)	65.13	65.28	65.49	65.34			65.31	0.1489966

Cross-Sectional Area: 7816.72
Volume: 510510

Comments/Properties: AC 10/50 4.0% Sasobit Plant mix

Setup Parameters

Loading waveshape: Haversine
Loading pulse width (ms): 145
Pulse repetition period (ms): 3000
Preconditioning pulse count: 5
Test pulse count: 5

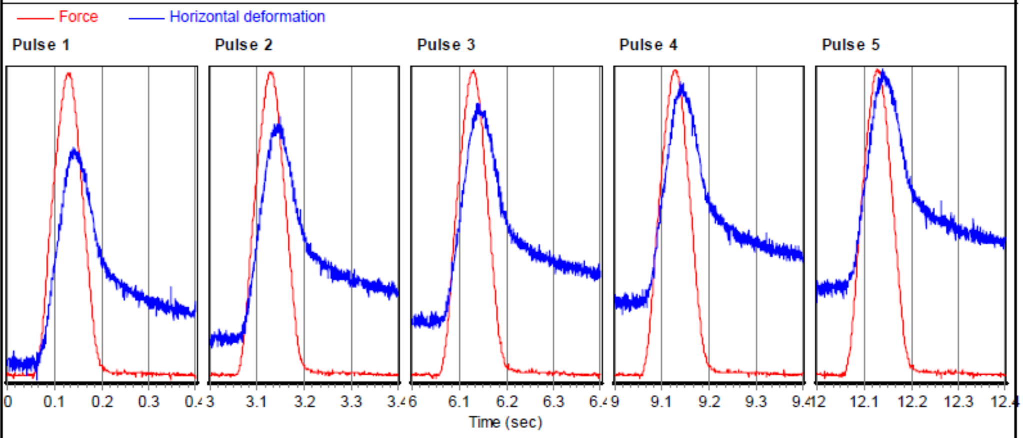
Target temperature (°C): 25
Target peak strain (µ€): 50
Estimated Poisson's ratio: 0.4
Estimated resilient modulus (MPa): 2000

Calibration Information

Channel description	Filename	Transducer description	Span	Units	Date	Linearised
A: Axial Force	Y12346.CAR	STC5000 S/N: Y12346 +/-20kN	40	kN	07/12/05	No
B: Actuator LVDT	941C-340.CAR	AC-15 S/N: M992941C-340 +/-15mm	30	mm	07/12/05	No
C: Horizontal LVDT #1	Disp snRDP135262.car	Disp GTX-1000 +/-60um snRDP135262	0.12	mm	09NOV201	No
D: Horizontal LVDT #2	Disp snRDP135263.car	Disp GTX-1000 +/-60um snRDP135263	0.12	mm	09NOV201	No
E: Core Temperature	507.car	PT100 S/N: 507 -15 to +85 0 deg = 0 bits	100	Deg.C	13/12/06	Yes
F: Skin Temperature	506.car	PT100 S/N: 506 -15 to +85 0 deg = 0 bits	100	Deg.C	13/12/06	Yes

10/04/2014 5:03:30 PM **UTM_16 V2.02 Indirect Tensile Modulus Test** **Page 1**

FileName: E:\Willie\4-0 Saso 2A- 135 ms.B16



Operator: Willie
Test method: Australian: AS 2891.13.1 - 1995
Notes/comments: AC 10/50 4.0% Sasobit Plant mix

Test date and time: Wednesday, April 9, 2014, at 5:35 PM
Preconditioning pulses: 5
Core temperature (°C): 24.2
Skin temperature (°C): 24.1

	Pulse 1	Pulse 2	Pulse 3	Pulse 4	Pulse 5	Mean	Std. Dev.	%CV
Resilient modulus (MPa)	7321	6912	7104	6826	6891	7011	180.93	2.58
Recovered horizontal strain (µ€)	41.89	44.49	43.40	45.16	45.00	43.99	1.22	2.77
Peak load (N)	2976.3	2984.1	2992.4	2991.9	3009.5	2990.9	11.04	0.37
10% to 90% rise time (ms)	45	44	44	43	43	43.8	0.75	1.71
Load time (ms)	141	140	143	141	141	141.2	0.98	0.69
Phase Delay at 90% (ms)	13	15	11	13	11	12.6	1.50	11.88
Resilient horiz. deform. #1 (µm)	1.77	1.90	1.84	1.93	1.91	1.87	0.06	3.08
Resilient horiz. deform. #2 (µm)	2.41	2.54	2.49	2.58	2.58	2.52	0.06	2.56

Specimen Information

Identification: 4-0 Saso 2- 135 ms

Core/Sample Number:

Dimensions	Point 1	Point 2	Point 3	Point 4	Point 5	Point 6	Average	Std Dev.
Diameter (mm)	99.86	99.73	99.49	99.84			99.73	0.1699019
Height (mm)	65.11	65.23	65.18	65.29			65.2025	0.07632169

Cross-Sectional Area: 7811.627
Volume: 509337.6

Comments/Properties: AC 10/50 4.0% Sasobit Plant mix

Setup Parameters

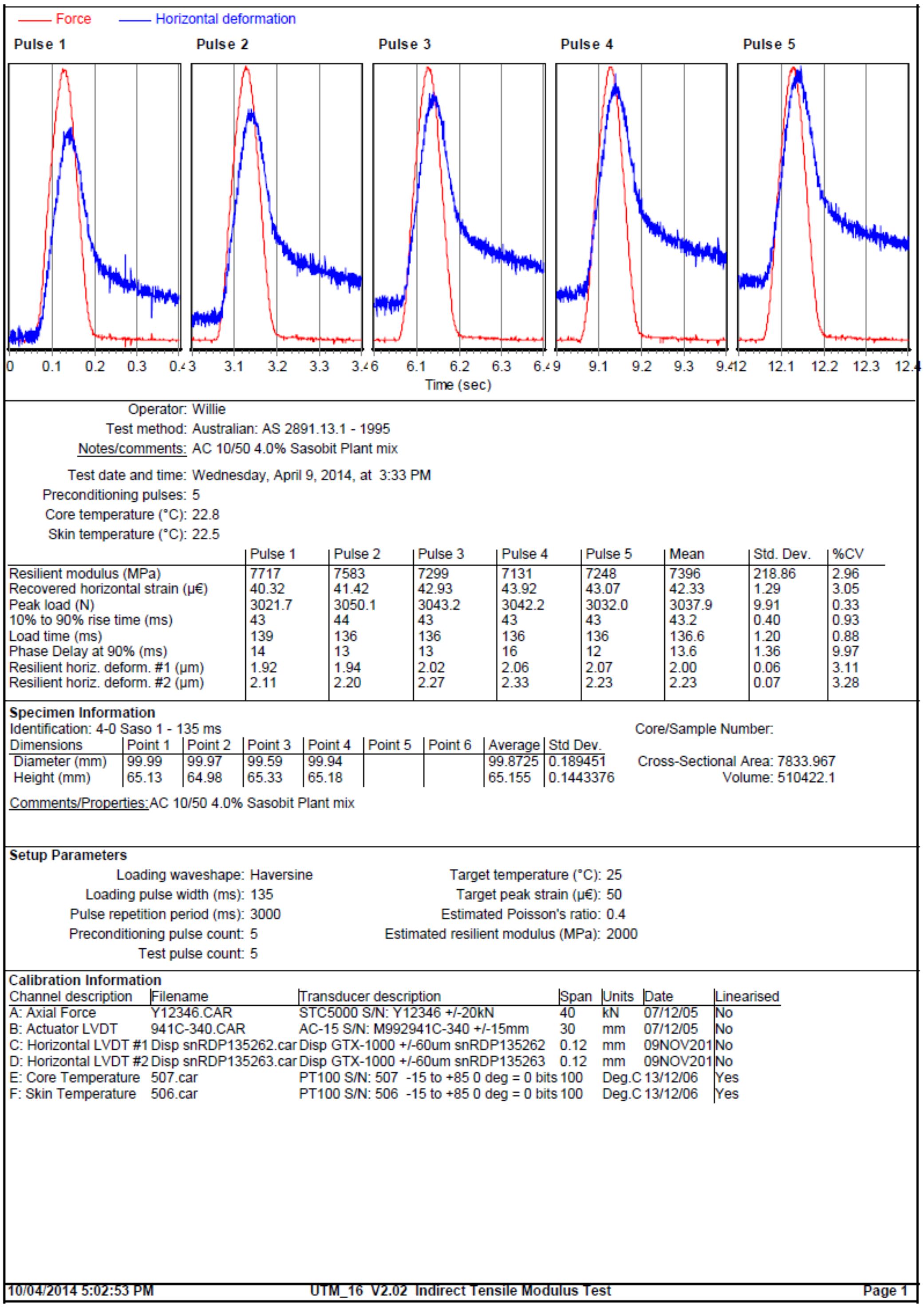
Loading waveshape: Haversine
Loading pulse width (ms): 135
Pulse repetition period (ms): 3000
Preconditioning pulse count: 5
Test pulse count: 5

Target temperature (°C): 25
Target peak strain (µ€): 50
Estimated Poisson's ratio: 0.4
Estimated resilient modulus (MPa): 2000

Calibration Information

Channel description	Filename	Transducer description	Span	Units	Date	Linearised
A: Axial Force	Y12346.CAR	STC5000 S/N: Y12346 +/-20kN	40	kN	07/12/05	No
B: Actuator LVDT	941C-340.CAR	AC-15 S/N: M992941C-340 +/-15mm	30	mm	07/12/05	No
C: Horizontal LVDT #1	Disp snRDP135262.car	Disp GTX-1000 +/-60um snRDP135262	0.12	mm	09NOV201	No
D: Horizontal LVDT #2	Disp snRDP135263.car	Disp GTX-1000 +/-60um snRDP135263	0.12	mm	09NOV201	No
E: Core Temperature	507.car	PT100 S/N: 507 -15 to +85 0 deg = 0 bits	100	Deg.C	13/12/06	Yes
F: Skin Temperature	506.car	PT100 S/N: 506 -15 to +85 0 deg = 0 bits	100	Deg.C	13/12/06	Yes

10/04/2014 5:05:39 PM **UTM_16 V2.02 Indirect Tensile Modulus Test**



Operator: Willie
Test method: Australian: AS 2891.13.1 - 1995
Notes/comments: AC 10/50 4.0% Sasobit Plant mix

Test date and time: Wednesday, April 9, 2014, at 3:33 PM
Preconditioning pulses: 5
Core temperature (°C): 22.8
Skin temperature (°C): 22.5

	Pulse 1	Pulse 2	Pulse 3	Pulse 4	Pulse 5	Mean	Std. Dev.	%CV
Resilient modulus (MPa)	7717	7583	7299	7131	7248	7396	218.86	2.96
Recovered horizontal strain (µ€)	40.32	41.42	42.93	43.92	43.07	42.33	1.29	3.05
Peak load (N)	3021.7	3050.1	3043.2	3042.2	3032.0	3037.9	9.91	0.33
10% to 90% rise time (ms)	43	44	43	43	43	43.2	0.40	0.93
Load time (ms)	139	136	136	136	136	136.6	1.20	0.88
Phase Delay at 90% (ms)	14	13	13	16	12	13.6	1.36	9.97
Resilient horiz. deform. #1 (µm)	1.92	1.94	2.02	2.06	2.07	2.00	0.06	3.11
Resilient horiz. deform. #2 (µm)	2.11	2.20	2.27	2.33	2.23	2.23	0.07	3.28

Specimen Information
Identification: 4-0 Saso 1 - 135 ms
Core/Sample Number:

Dimensions	Point 1	Point 2	Point 3	Point 4	Point 5	Point 6	Average	Std Dev.
Diameter (mm)	99.99	99.97	99.59	99.94			99.8725	0.189451
Height (mm)	65.13	64.98	65.33	65.18			65.155	0.1443376

Cross-Sectional Area: 7833.967
Volume: 510422.1

Comments/Properties: AC 10/50 4.0% Sasobit Plant mix

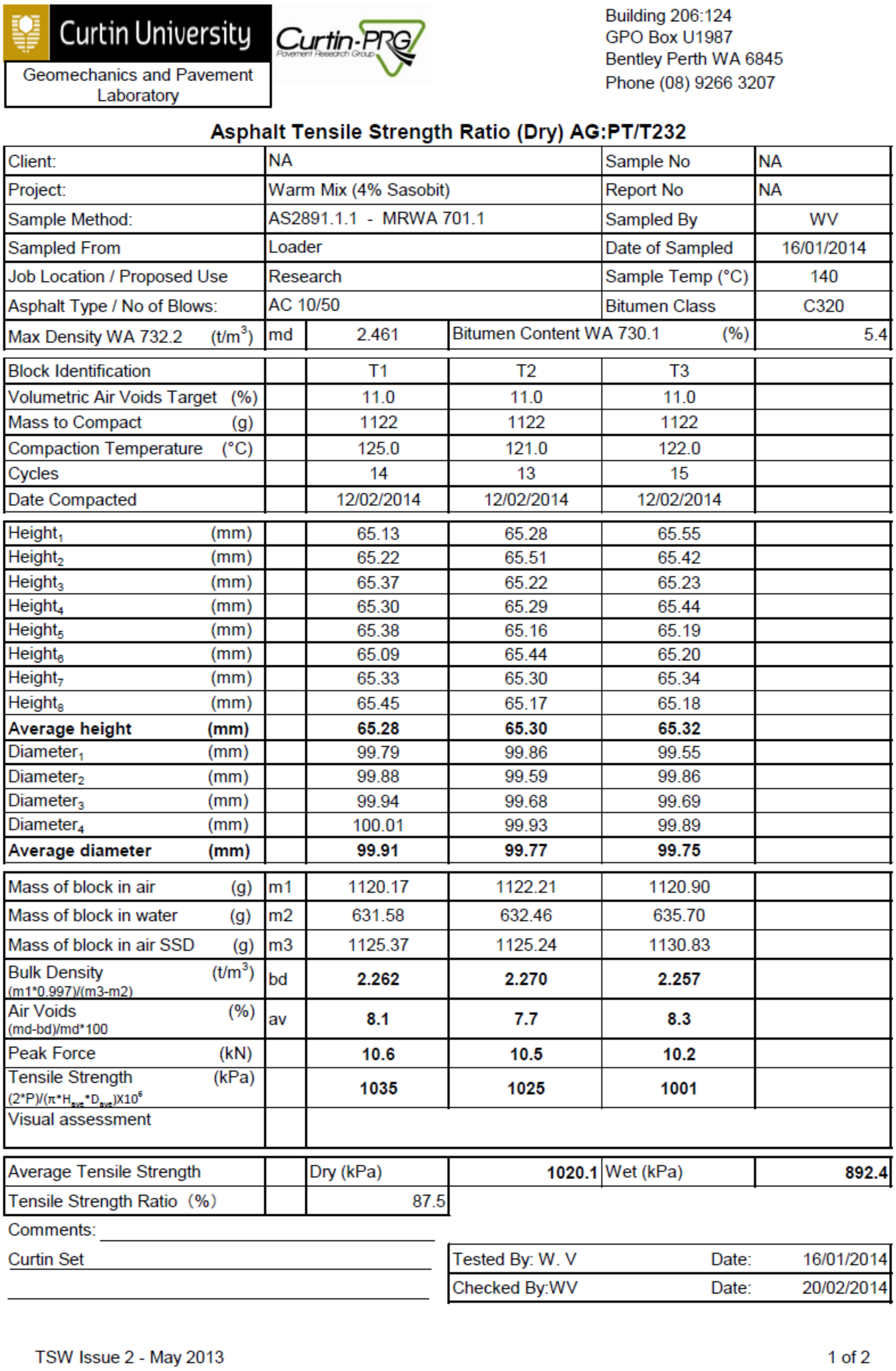
Setup Parameters
Loading waveshape: Haversine
Loading pulse width (ms): 135
Pulse repetition period (ms): 3000
Preconditioning pulse count: 5
Test pulse count: 5
Target temperature (°C): 25
Target peak strain (µ€): 50
Estimated Poisson's ratio: 0.4
Estimated resilient modulus (MPa): 2000

Calibration Information

Channel description	Filename	Transducer description	Span	Units	Date	Linearised
A: Axial Force	Y12346.CAR	STC5000 S/N: Y12346 +/-20kN	40	kN	07/12/05	No
B: Actuator LVDT	941C-340.CAR	AC-15 S/N: M992941C-340 +/-15mm	30	mm	07/12/05	No
C: Horizontal LVDT #1	Disp snRDP135262.car	Disp GTX-1000 +/-60um snRDP135262	0.12	mm	09NOV201	No
D: Horizontal LVDT #2	Disp snRDP135263.car	Disp GTX-1000 +/-60um snRDP135263	0.12	mm	09NOV201	No
E: Core Temperature	507.car	PT100 S/N: 507 -15 to +85 0 deg = 0 bits	100	Deg.C	13/12/06	Yes
F: Skin Temperature	506.car	PT100 S/N: 506 -15 to +85 0 deg = 0 bits	100	Deg.C	13/12/06	Yes

10/04/2014 5:02:53 PM **UTM_16 V2.02 Indirect Tensile Modulus Test** **Page 1**

Moisture Sensitivity



Curtin University
Geomechanics and Pavement Laboratory
Curtin-PRG Pavement Research Group

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Bentley Perth WA 6845
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Asphalt Tensile Strength Ratio (Dry) AG:PT/T232

Client:	NA	Sample No	NA
Project:	Warm Mix (4% Sasobit)	Report No	NA
Sample Method:	AS2891.1.1 - MRWA 701.1	Sampled By	WV
Sampled From	Loader	Date of Sampled	16/01/2014
Job Location / Proposed Use	Research	Sample Temp (°C)	140
Asphalt Type / No of Blows:	AC 10/50	Bitumen Class	C320

Max Density WA 732.2 (t/m^3)	md	2.461	Bitumen Content WA 730.1 (%)	5.4

Block Identification		T1	T2	T3	
Volumetric Air Voids Target (%)		11.0	11.0	11.0	
Mass to Compact (g)		1122	1122	1122	
Compaction Temperature (°C)		125.0	121.0	122.0	
Cycles		14	13	15	
Date Compacted		12/02/2014	12/02/2014	12/02/2014	
Height$_1$ (mm)		65.13	65.28	65.55	
Height$_2$ (mm)		65.22	65.51	65.42	
Height$_3$ (mm)		65.37	65.22	65.23	
Height$_4$ (mm)		65.30	65.29	65.44	
Height$_5$ (mm)		65.38	65.16	65.19	
Height$_6$ (mm)		65.09	65.44	65.20	
Height$_7$ (mm)		65.33	65.30	65.34	
Height$_8$ (mm)		65.45	65.17	65.18	
Average height (mm)		**65.28**	**65.30**	**65.32**	
Diameter$_1$ (mm)		99.79	99.86	99.55	
Diameter$_2$ (mm)		99.88	99.59	99.86	
Diameter$_3$ (mm)		99.94	99.68	99.69	
Diameter$_4$ (mm)		100.01	99.93	99.89	
Average diameter (mm)		**99.91**	**99.77**	**99.75**	
Mass of block in air (g)	m1	1120.17	1122.21	1120.90	
Mass of block in water (g)	m2	631.58	632.46	635.70	
Mass of block in air SSD (g)	m3	1125.37	1125.24	1130.83	
Bulk Density (t/m^3) (m1*0.997)/(m3-m2)	bd	**2.262**	**2.270**	**2.257**	
Air Voids (%) (md-bd)/md*100	av	**8.1**	**7.7**	**8.3**	
Peak Force (kN)		**10.6**	**10.5**	**10.2**	
Tensile Strength (kPa) (2*P)/(π*H$_{ave}$*D$_{ave}$)X10^6		**1035**	**1025**	**1001**	
Visual assessment					

Average Tensile Strength		Dry (kPa)	**1020.1**	Wet (kPa)	**892.4**
Tensile Strength Ratio (%)		87.5			

Comments:

Curtin Set

Tested By: W. V	Date: 16/01/2014
Checked By:WV	Date: 20/02/2014

TSW Issue 2 - May 2013 1 of 2

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Asphalt Tensile Strength Ratio (Wet) AG:PT/T232

Client:	NA	Sample No	NA
Project:	Warm Mix (4% Sasobit)	Report No	NA
Sample Method:	AS 2891.1.1 - MRWA 701.1	Sampled By	WV
Sampled From	Loader	Date Sampled	16/01/2014
Job Location / Proposed use:	Research	Sample Temp (°C)	140
Asphalt Type / No of Blows:	AC 10/50	Bitumen Class:	C320

Max Density WA 732.2 (t/m^3)	md	2.461	Bitumen Content WA 730.1 (%)	5.4

Block Identification		T4	T5	T6	
Volumetric Air Voids Target (%)		11.0	11.0	11.0	
Mass to Compact (g)		1122	1122	1122	
Compaction Temperature (°C)		124.0	122.0	126.0	
Cycles		15	14	16	
Date Compacted		12/02/2014	12/02/2014	12/02/2014	

Conditioning	**Measurements**		Before	After	Before	After	Before	After		
Freeze/Thaw	Height$_1$ (mm)		65.28	64.99	64.87	65.44	65.23	64.81		
Start:	Height$_2$ (mm)		65.71	64.87	64.98	64.86	65.14	64.71		
End:	Height$_3$ (mm)		65.40	64.93	65.09	64.77	65.29	64.73		
60°C Moisture	Height$_4$ (mm)		65.23	65.15	65.10	64.79	65.21	64.84		
Start:	Height$_5$ (mm)		65.18	64.66	64.82	65.14	65.55	64.68		
End:	Height$_6$ (mm)		65.33	65.05	64.98	65.56	65.09	64.35		
25°C Moisture	Height$_7$ (mm)		65.12	64.76	64.72	65.04	65.18	65.01		
End:	Height$_8$ (mm)		65.24	64.61	65.02	65.10	65.03	64.99		
Average height	**(mm)**		**65.31**	**64.88**	**64.95**	**65.09**	**65.22**	**64.77**		
Diameter$_1$	(mm)		99.81	99.97	99.76	100.03	99.51	99.75		
Diameter$_2$	(mm)		99.75	100.02	99.48	99.84	99.82	99.79		
Diameter$_3$	(mm)		99.86	100.01	99.83	100.21	99.67	100.20		
Diameter$_4$	(mm)		99.94	99.88	99.64	99.62	99.28	99.85		
Average diameter	**(mm)**		**99.84**	**99.97**	**99.68**	**99.93**	**99.57**	**99.90**		
Volume π*H*D^2/4000			511.31	509.24	506.81	510.43	507.80	507.62		

Mass of block in air (g)	m1	1121.74	1120.93	1120.11	
Mass of block in water (g)	m2	634.02	635.70	632.63	
Mass of block in air SSD (g)	m3	1126.67	1131.53	1125.84	
Volume Dry (m3-m2)/0.997	Vd	494.13	497.32	494.69	
Bulk density (m1/vd) (t/m3)	Bd	2.270	2.254	2.264	
% Air Voids (Md-Bd)/Md*100	AV	7.8	8.4	8.0	
Volume Air (AV*Vd)/100 (cc)	Va	38.33	41.84	39.55	
Mass after saturation (g)	Mps	1147.76	1146.17	1145.63	
% Saturation (Mps-M1)/Va*100	Sp	67.9	60.3	64.5	
Swell ((Vmc-Vdm)/Vdm)*100		-0.405271959	0.71384859	-0.035661441	
Peak Force (kN)	P	9.22	8.72	9.38	
Tensile Strength (kPa) $(2*P)/(\pi*H_{after}*D_{after})*10^6$		900	858	920	
Visual assessment					

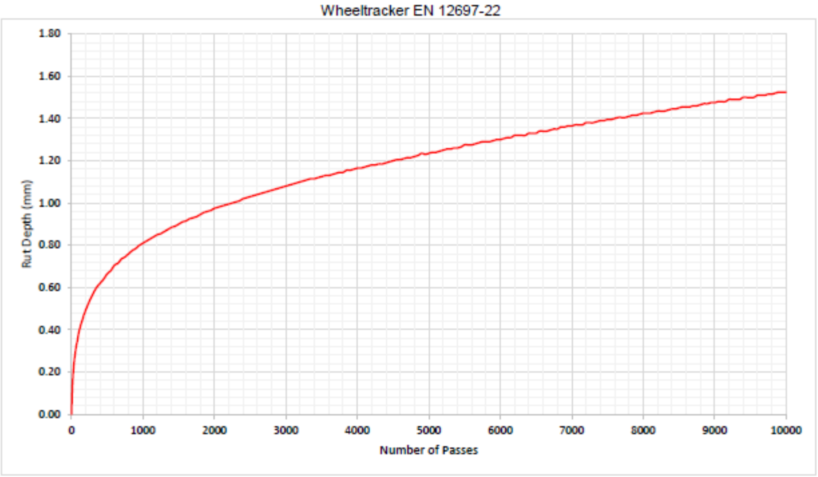
Comments:

Curtin Set

Tested By: W. V		Date:	16/01/2014
Checked By: WV		Date:	20/02/2014

Wheel Tracking

Wheeltracking Test
Specimen Name: 4.0% Sasobit AC10/50 Sample 2
Date: 18/02/2014
Test Temperature: 60 °C
Specimen Thickness: 50mm
Final Rut Depth: 1.54 mm



Wheeltracking Test
Specimen Name: 4.0% Sasobit AC10/50 Sample 1
Date: 18/02/2014
Test Temperature: 60
Specimen Thickness: 50
Final Rut Depth: 1.84 mm

Fatigue Resistance

FileName: C:\IPCglobal UTS\015 Beam Fatigue Test\Data\Willie Sasobit\Sasobit 4-0 Beam 1A.D015

Test Method: AUSTROADS Asphalt Test AST 03:2000 Fatigue life of compacted bituminous mixes subjected to repeated flexural bending
Project: Warm Mix with Sasobit
Operator: Willie
Comments:

Test Data

Start Date and Time: Friday, March 28, 2014, at 4:27:15 PM
Loading time (hh:mm:ss): 05:47:53

Cycle count: 208730 of 1000000

	Initial	Current		Initial	Current		Initial	Current
Applied load (kN):	1.0579	0.5269	Tensile stress (kPa):	2463	1227	Core temperature (°C):	20.2	20.2
Maximum load (kN):	0.4980	0.2563	Tensile strain (µ€):	399	401	Surface temperature (°C):	20.2	20.2
Minimum load (kN):	-0.5598	-0.2705	Phase angle (deg):	27.3	34.0			
Beam deflection (mm):	0.2171	0.2180	Flexural stiffness (MPa):	6177	3063	Termination flexural stiffness (MPa):		3088
Maximum LVDT (mm):	0.1086	0.1089	Modulus of elasticity (MPa):	6569	3258	Normalized modulus x Cycles (Pa/Pa):		2070.1
Minimum LVDT (mm):	0.0000	-0.0001	Dissipated energy (kPa):	2.170	1.132	Cumulative dissipated energy (MPa):		

Print date: 1/04/2014 4:50:07 PM UTS015 2.08 (Beta Release 30MAY2013) Beam Fatigue Test

FileName: C:\IPCglobal UTS\015 Beam Fatigue Test\Data\Willie Sasobit\Sasobit 4-0 Beam 1B.D015

Test Method: AUSTROADS Asphalt Test AST 03:2000 Fatigue life of compacted bituminous mixes subjected to repeated flexural bending
Project: Warm Mix with Sasobit
Operator: Willie
Comments:

Test Data

Start Date and Time: Saturday, March 29, 2014, at 7:28:11 AM
Loading time (hh:mm:ss): 06:01:10
Cycle count: 216700 of 1000000

	Initial	Current
Applied load (kN):	1.1659	0.5782
Maximum load (kN):	0.5424	0.2792
Minimum load (kN):	-0.6235	-0.2989
Beam deflection (mm):	0.2185	0.2187
Maximum LVDT (mm):	0.0906	0.0906
Minimum LVDT (mm):	-0.0186	-0.0187

	Initial	Current
Tensile stress (kPa):	2729	1353
Tensile strain (µ€):	400	400
Phase angle (deg):	26.4	33.0
Flexural stiffness (MPa):	6824	3381
Modulus of elasticity (MPa):	7255	3594
Dissipated energy (kPa):	2.445	1.233

	Initial	Current
Core temperature (°C):	20.1	20.0
Surface temperature (°C):	20.1	20.0

Termination flexural stiffness (MPa): 3412
Normalized modulus x Cycles (Pa/Pa): 2147.0
Cumulative dissipated energy (MPa):

Print date: 1/04/2014 4:50:42 PM UTS015 2.08 (Beta Release 30MAY2013) Beam Fatigue Test

FileName: C:\IPCglobal UTS\015 Beam Fatigue Test\Data\Willie Sasobit\Sasobit 4-0 Beam 1C.D015

Test Method: AUSTROADS Asphalt Test AST 03:2000 Fatigue life of compacted bituminous mixes subjected to repeated flexural bending
Project: Warm Mix with Sasobit
Operator: Willie
Comments:

Test Data

Start Date and Time: Saturday, March 29, 2014, at 2:45:10 PM
Loading time (hh:mm:ss): 03:59:05

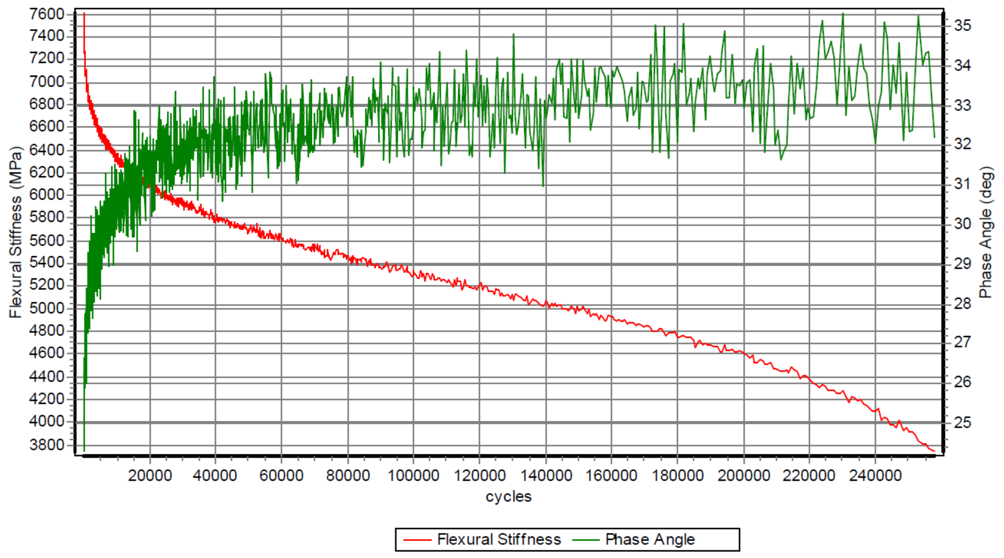
Cycle count: 143450 of 1000000

	Initial	Current		Initial	Current		Initial	Current
Applied load (kN):	1.1412	0.5685	Tensile stress (kPa):	2697	1344	Core temperature (°C):	20.3	20.1
Maximum load (kN):	0.5397	0.2769	Tensile strain (με):	400	402	Surface temperature (°C):	20.3	20.1
Minimum load (kN):	-0.6015	-0.2916	Phase angle (deg):	27.3	35.0			
Beam deflection (mm):	0.2190	0.2201	Flexural stiffness (MPa):	6746	3344	Termination flexural stiffness (MPa):	3373	
Maximum LVDT (mm):	0.0793	0.0796	Modulus of elasticity (MPa):	7169	3554	Normalized modulus x Cycles (Pa/Pa):	1422.1	
Minimum LVDT (mm):	-0.0302	-0.0304	Dissipated energy (kPa):	2.404	1.274	Cumulative dissipated energy (MPa):		

Print date: 1/04/2014 4:51:13 PM UTS015 2.08 (Beta Release 30MAY2013) Beam Fatigue Test

FileName: C:\IPCglobal UTS\015 Beam Fatigue Test\Data\Willie Sasobit\Sasobit 4-0 Beam 2A.D015

Test Method: AUSTROADS Asphalt Test AST 03:2000 Fatigue life of compacted bituminous mixes subjected to repeated flexural bending
Project: Warm Mix with Sasobit
Operator: Willie
Comments:



Test Data

Start Date and Time: Saturday, March 29, 2014, at 9:24:29 PM
Loading time (hh:mm:ss): 07:09:49

Cycle count: 257890 of 1000000

	Initial	Current
Applied load (kN):	1.2776	0.6377
Maximum load (kN):	0.5914	0.3168
Minimum load (kN):	-0.6862	-0.3209
Beam deflection (mm):	0.2180	0.2178
Maximum LVDT (mm):	0.0851	0.0848
Minimum LVDT (mm):	-0.0239	-0.0241

	Initial	Current
Tensile stress (kPa):	2991	1493
Tensile strain (μ€):	399	399
Phase angle (deg):	24.7	32.2
Flexural stiffness (MPa):	7491	3742
Modulus of elasticity (MPa):	7964	3979
Dissipated energy (kPa):	2.653	1.354

	Initial	Current
Core temperature (°C):	20.1	20.1
Surface temperature (°C):	20.1	20.1

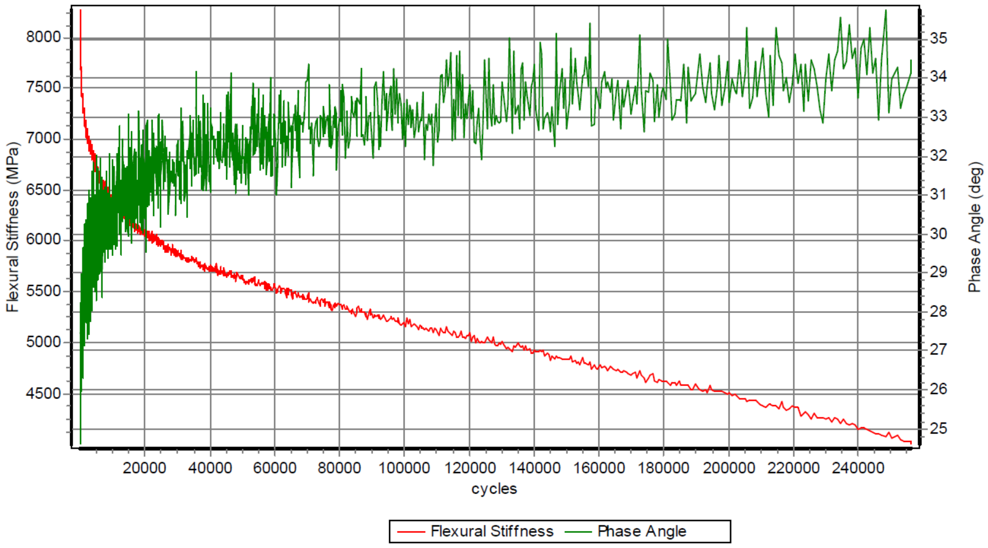
Termination flexural stiffness (MPa): 3745
Normalized modulus x Cycles (Pa/Pa): 2576.8
Cumulative dissipated energy (MPa):

Print date: 1/04/2014 4:51:40 PM

UTS015 2.08 (Beta Release 30MAY2013) Beam Fatigue Test

FileName: C:\IPCglobal UTS\015 Beam Fatigue Test\Data\Willie Sasobit\Sasobit 4-0 Beam 2B.D015

Test Method: AUSTROADS Asphalt Test AST 03:2000 Fatigue life of compacted bituminous mixes subjected to repeated flexural bending
Project: Warm Mix with Sasobit
Operator: Willie
Comments:



Test Data

Start Date and Time: Sunday, March 30, 2014, at 8:11:21 AM
Loading time (hh:mm:ss): 07:07:01
Cycle count: 256210 of 1000000

	Initial	Current
Applied load (kN):	1.3715	0.6830
Maximum load (kN):	0.6454	0.3360
Minimum load (kN):	-0.7260	-0.3470
Beam deflection (mm):	0.2188	0.2189
Maximum LVDT (mm):	0.0992	0.1001
Minimum LVDT (mm):	-0.0102	-0.0094

	Initial	Current
Tensile stress (kPa):	3221	1604
Tensile strain (µ€):	400	400
Phase angle (deg):	25.8	34.5
Flexural stiffness (MPa):	8051	4006
Modulus of elasticity (MPa):	8558	4259
Dissipated energy (kPa):	2.870	1.480

	Initial	Current
Core temperature (°C):	20.3	20.1
Surface temperature (°C):	20.3	20.1

Termination flexural stiffness (MPa): 4025
Normalized modulus x Cycles (Pa/Pa): 2550.0
Cumulative dissipated energy (MPa):

Print date: 1/04/2014 4:52:00 PM

UTS015 2.08 (Beta Release 30MAY2013) Beam Fatigue Test

FileName: C:\IPCglobal UTS\015 Beam Fatigue Test\Data\Willie Sasobit\Sasobit 4-0 Beam 2C.D015

Test Method: AUSTROADS Asphalt Test AST 03:2000 Fatigue life of compacted bituminous mixes subjected to repeated flexural bending
Project: Warm Mix with Sasobit
Operator: Willie
Comments:

Test Data

Start Date and Time: Sunday, March 30, 2014, at 5:15:01 PM

Cycle count: 261510 of 1000000

Loading time (hh:mm:ss): 07:15:51

	Initial	Current
Applied load (kN):	1.3779	0.6834
Maximum load (kN):	0.6569	0.3374
Minimum load (kN):	-0.7210	-0.3461
Beam deflection (mm):	0.2180	0.2177
Maximum LVDT (mm):	0.0824	0.0824
Minimum LVDT (mm):	-0.0265	-0.0264

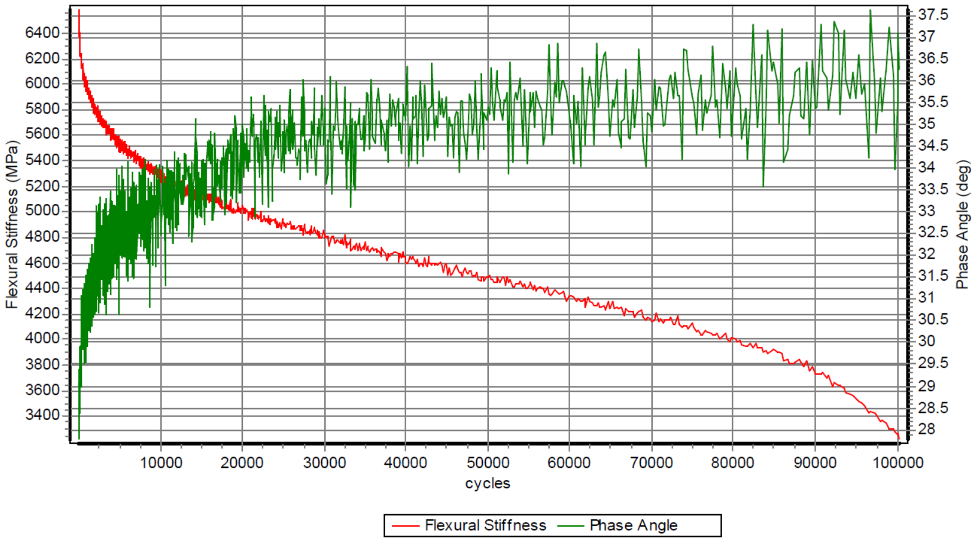
	Initial	Current
Tensile stress (kPa):	3230	1602
Tensile strain (μ€):	399	399
Phase angle (deg):	26.7	33.1
Flexural stiffness (MPa):	8090	4017
Modulus of elasticity (MPa):	8601	4271
Dissipated energy (kPa):	2.839	1.454

	Initial	Current
Core temperature (°C):	20.4	20.2
Surface temperature (°C):	20.4	20.2

Termination flexural stiffness (MPa): 4045
Normalized modulus x Cycles (Pa/Pa): 2597.1
Cumulative dissipated energy (MPa):

FileName: C:\IPCglobal UTS\015 Beam Fatigue Test\Data\Willie Sasobit\Sasobit 4-0 Beam 3A.D015

Test Method: AUSTROADS Asphalt Test AST 03:2000 Fatigue life of compacted bituminous mixes subjected to repeated flexural bending
Project: Warm Mix with Sasobit
Operator: Willie
Comments:



Test Data

Start Date and Time: Monday, March 31, 2014, at 1:06:42 AM

Cycle count: 100260 of 1000000

Loading time (hh:mm:ss): 02:47:06

	Initial	Current
Applied load (kN):	1.1032	0.5498
Maximum load (kN):	0.5305	0.2696
Minimum load (kN):	-0.5727	-0.2802
Beam deflection (mm):	0.2175	0.2185
Maximum LVDT (mm):	0.1019	0.1026
Minimum LVDT (mm):	-0.0068	-0.0067

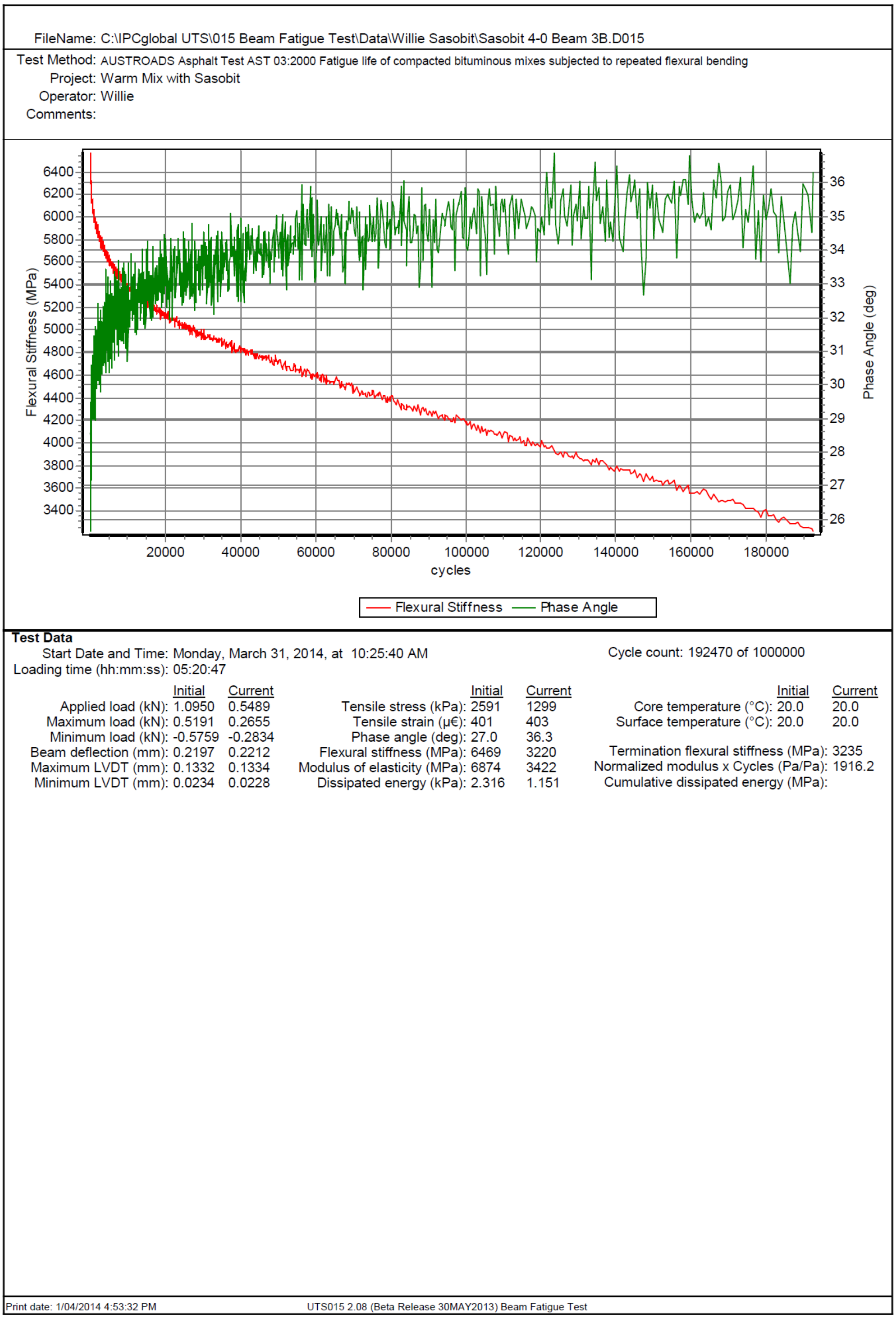
	Initial	Current
Tensile stress (kPa):	2590	1291
Tensile strain (µє):	399	401
Phase angle (deg):	28.6	36.3
Flexural stiffness (MPa):	6495	3222
Modulus of elasticity (MPa):	6906	3426
Dissipated energy (kPa):	2.298	1.185

	Initial	Current
Core temperature (°C):	20.2	20.1
Surface temperature (°C):	20.2	20.1

Termination flexural stiffness (MPa): 3247
Normalized modulus x Cycles (Pa/Pa): 994.806
Cumulative dissipated energy (MPa): 163.833

Print date: 1/04/2014 4:53:08 PM

UTS015 2.08 (Beta Release 30MAY2013) Beam Fatigue Test



FileName: C:\IPCglobal UTS\015 Beam Fatigue Test\Data\Willie Sasobit\Sasobit 4-0 Beam 3B.D015

Test Method: AUSTROADS Asphalt Test AST 03:2000 Fatigue life of compacted bituminous mixes subjected to repeated flexural bending
Project: Warm Mix with Sasobit
Operator: Willie
Comments:

Test Data

Start Date and Time: Monday, March 31, 2014, at 10:25:40 AM

Cycle count: 192470 of 1000000

Loading time (hh:mm:ss): 05:20:47

	Initial	Current
Applied load (kN):	1.0950	0.5489
Maximum load (kN):	0.5191	0.2655
Minimum load (kN):	-0.5759	-0.2834
Beam deflection (mm):	0.2197	0.2212
Maximum LVDT (mm):	0.1332	0.1334
Minimum LVDT (mm):	0.0234	0.0228

	Initial	Current
Tensile stress (kPa):	2591	1299
Tensile strain (με):	401	403
Phase angle (deg):	27.0	36.3
Flexural stiffness (MPa):	6469	3220
Modulus of elasticity (MPa):	6874	3422
Dissipated energy (kPa):	2.316	1.151

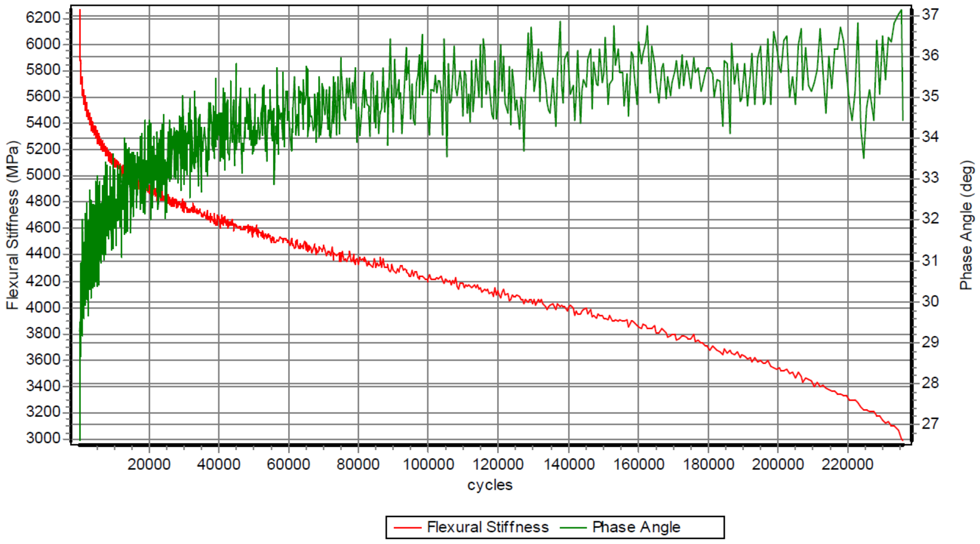
	Initial	Current
Core temperature (°C):	20.0	20.0
Surface temperature (°C):	20.0	20.0
Termination flexural stiffness (MPa):	3235	
Normalized modulus x Cycles (Pa/Pa):	1916.2	
Cumulative dissipated energy (MPa):		

Print date: 1/04/2014 4:53:32 PM

UTS015 2.08 (Beta Release 30MAY2013) Beam Fatigue Test

FileName: C:\IPCglobal UTS\015 Beam Fatigue Test\Data\Willie Sasobit\Sasobit 4-0 Beam 3C.D015

Test Method: AUSTROADS Asphalt Test AST 03:2000 Fatigue life of compacted bituminous mixes subjected to repeated flexural bending
Project: Warm Mix with Sasobit
Operator: Willie
Comments:



Test Data

Start Date and Time: Monday, March 31, 2014, at 5:46:55 PM

Cycle count: 235840 of 1000000

Loading time (hh:mm:ss): 06:33:04

	Initial	Current		Initial	Current		Initial	Current
Applied load (kN):	1.0249	0.5104	Tensile stress (kPa):	2411	1200	Core temperature (°C):	20.3	20.3
Maximum load (kN):	0.4820	0.2481	Tensile strain (µ€):	399	402	Surface temperature (°C):	20.3	20.3
Minimum load (kN):	-0.5429	-0.2623	Phase angle (deg):	27.0	34.4			
Beam deflection (mm):	0.2180	0.2196	Flexural stiffness (MPa):	6044	2988	Termination flexural stiffness (MPa):	3022	
Maximum LVDT (mm):	0.0887	0.0893	Modulus of elasticity (MPa):	6425	3177	Normalized modulus x Cycles (Pa/Pa):	2332.2	
Minimum LVDT (mm):	-0.0203	-0.0205	Dissipated energy (kPa):	2.103	1.117	Cumulative dissipated energy (MPa):		

Print date: 1/04/2014 4:54:02 PM UTS015 2.08 (Beta Release 30MAY2013) Beam Fatigue Test

Appendix M Chronological trial photos.

Trial 1

2012

Appendix M 1 HMA control section

Appendix M 2 MWA section

Trial 1

2014

Appendix M 3 HMA control section

Appendix M 4 WMA section

Trial 1

2016

Appendix M 5 HMA Control section

Appendix M 6 WMA section

Trial 1

2017

Appendix M 7 HMA control section

Appendix M 8 WMA section

Trial 2

2012

Appendix M 9 HMA control section

Appendix M 10 WMA section

Trial 2

2014

Appendix M 11 HMA control section

Appendix M 12 WMA section

Trial 2

2016

Appendix M 13 HMA control section

Appendix M 14 WMA section

Trial 2

2017

Appendix M 15 HMA control section

Appendix M 16 WMA WMA section

Trial 3 WMA 4% Saobit

2014

Appendix M 17 WMA wearing course

Appendix M 18 WMA both lanes

Appendix M 19 Expose to heavy traffic

Appendix M 20 WMA pen to traffic

Trial 3 WMA 4% Sasobit

2016

Appendix M 21 Monitoring WMA

Appendix M 22 Supervisor monitoring

Appendix M 23 3 years of trial

Appendix M 24 Surface condition

Trial 3 WMA 4% Sasobit

2017

Actual Surface Condition

Appendix M 25 WMA

Appendix M 26 WMA

Appendix M 27 WMA

Appendix M 28 WMA