The Department of Civil and Structural Engineering

The Hong Kong Polytechnic University

Study the Effect of Wax on Bitumen and Bituminous Mixes

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A thesis submitted in partial fulfilment

of the requirements for the Degree of Master of Philosophy

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CERTRIFICATE OF ORIGINALITY

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Abstract of thesis entitled :

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submitted by LEE Hong-nin for the degree of Master of Philosophy

at The Hong Kong Polytechnic University

Wax naturally exists in crude oil from which bitumen is produced, and it crystallizes on cooling and melts on heating. Wax in bitumen affects the performance of bituminous materials on roads. Bituminous mixes with high wax content tend to become soft leading to rutting problem on pavement under hot weather and brittle in cold seasons.

The road length in Hong Kong is about 2,000 km and about 75% of the road network is of flexible construction consisting of multi-layers of bituminous materials. Bitumen is one of the main constituents used in the bituminous layers giving the performance to sustain design traffic loading. The use of Penetration-grade 60-70 bitumen has been set as a standard requirement in the local specifications. Though basic tests on bitumen are required to verify its physical properties, no test for determining the wax content is specified and hence it is unable to assess the effect of wax content on the quality of the bitumen.

The study aims at investigating the effect of the wax content on bitumen and bituminous mixtures by means of performance-related tests with a view to reviewing the local specifications of bitumen. It also provides basic information and paves the way for developing performance specifications for bitumen and further research on bitumen and bituminous materials.

This study investigates the physical and rheological properties of seven sources of bitumen of similar Penetration-grades but of various wax content levels. Two typical bitumens of different wax contents were then selected for preparing bituminous mixes according to the local mix design for further tests on their mechanical properties. The evaluations were twofold. Firstly, a comparative study on the physical properties, wax content and rheological properties of bitumen was made. Secondly, the mechanical properties of the two bituminous mixes including stiffness, strength and resistance to performance deformation were compared for verifying and supplementing the findings of the first stage.

The results show that though all seven bitumens are of Penetration-grade 60-70 and satisfy the requirements of the local specifications, they have different levels of wax content and rheological properties. In other words, the basic tests in the local specifications fail to assess the effect of wax content on the performance of bitumen. In addition, the test results for the two bituminous mixes indicate that the mix made of bitumen with lower wax content exhibits better performance in the mechanical properties.

The local road authority should review the bitumen specifications and specify appropriate requirements on the wax content or Performance-grade with a view to ensuring that the bitumen to be selected for producing the bituminous mixes is able to provide the required mechanical properties and to prevent inferior performance and premature defects during the service life. This study also recommends a large-scale field trial by the use of accelerated pavement tester.

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Chapter 1

Introduction

1.1 Background

Wax generally refers to all waxlike solids and liquids found in nature and in organic substances that crystallize on cooling and melt on heating (Warth, 1956). It practically exists in all types of crude oil from which bitumen is generally manufactured. Chemically, crude oils may be predominantly paraffinic, naphthenic or formed by a combination of the two (Shell Bitumen U.K. 1991). Naphthenic-based crude oil often gives a large yield of bitumen that is of good quality, while paraffinic crude oil can either give bitumen of good quality or yield bitumen not suitable for road paving (Lu et al. 2006) because of its high wax content. Though the presence of wax affects the performance of bitumen in many ways, the crystalline nature and nonsticky characteristic of paraffin waxes was believed to have a negative effect on the thermal stability of bitumen and its ability to adhere to aggregates, hence the resistance to rutting and fatigue of the bituminous materials (Edwards et al. , 2003). In this regard, some European countries (EN 12591, 2000) and China (JTG F40, 2004) have specified the maximum limit of wax content in bitumen. The wax content in bitumen has been a major concern in China as the crude oil deposited in China is generally paraffinic, with relatively high wax content (Lu, 2001; Shen, 2001).

In Hong Kong, bitumen has been imported mainly from Singapore and sometimes from Thailand. The source of the crude oil is from the Middle East and is predominantly of the naphthenic type with low wax content. Since Hong Kong is now a part of the People's Republic of China and geographically adjoins the mainland, bitumen manufactured from crude oil deposited in China is being used more frequently in Hong Kong for road paving.

The use of Penetration-grade 60-70 bitumen has been set as a standard requirement in the local specification (Hong Kong Government, 1992). Though basic tests on bitumen are required to verify its physical properties, no test for determining the wax content is specified and hence it is unable to assess the effect of wax content on the quality of the bitumen. It is therefore considered necessary to investigate the effect of the wax content by means of performance-related tests and to review the local specification, if necessary.

1.2 Objectives and Scope of Works

The principle objective of this study is to study the effect of wax on bitumen and bituminous mixtures. With a view to evaluating the performance of bitumen and bituminous mixtures, the following tasks were identified:-

- Conduct a literature review of the properties of wax and findings of relevant researches, tests on bitumen and bituminous mixtures, grading system for bitumen;
- Conduct a survey on the application and practice of the use and grading system of bitumen in the local industry and overseas countries including the Mainland China, and a study on the formation of distress of bituminous pavements;
- Conduct a detailed and comprehensive testing program on seven sources of bitumens of different wax contents and two bituminous mixtures;
- Compare and evaluate the relationship of the basic properties and wax content level of bitumen;
- Evaluate the relationship of the basic properties and rheological properties of bitumen;
- Investigate and evaluate the relationship of the wax content and rheological properties of bitumen;

- Compare the mechanical properties of bituminous mixes made with bitumen of different wax contents; and
- Provide recommendation to local road authority for reviewing the specification for bitumen and pave the way for further study.

1.3 Dissertation Structure

The thesis is divided into the following six chapters.

1) Chapter 1 introduces the background and objective of the study.
2) Chapter 2 covers the literature review, which provides a review on the researches conducted on the effect of wax content on bitumen/bituminous materials, the bitumen grading and test, and types and formation of road distresses.
3) Chapter 3 briefly describes the source of materials and methods for preparing samples for testing.
4) Chapter 4 describes the bitumen tests and presents the evaluation of the test results.
5) Chapter 5 focuses on the tests for bituminous mixtures and presents the analysis of the test results.
6) Chapter 6 presents the summary of the conclusions and recommendations, and outlines the way forward

Chapter 2

Literature Review

The literature review of this study is presented in three parts covering the presence of wax in bitumen, standards in classifying bitumen and road defects arising from poor pavement materials. The first part focuses on the nature of wax, its classification and effects of wax on bitumen revealed from recent researches. Wax exists in the crude oil and affects the properties of this valuable natural resource and hence the production, delivery and manufacturing process for the crude oil. In the past decades, researches on wax and its effect on various types of petroleum products and manufacturing process have been carried out by researchers around the world, particularly in the North America (US and Canada), Northern Europe, Middle East (Saudi Arabia) and China where there are abundant deposit of crude oil and mega-scale petroleum refinery industry. Though these researches cover the following topics but the literature review focuses on the findings of researches of the last topic, which is closely related to this study.

- Wax precipitation inside oil pipeline
- Paraffin deposition in the petroleum production and processing industry
- Crude oil properties

- Wax crystallization at low temperatures
- Effect of bitumen with addition of commercial wax
- Influence of wax on bitumen and bituminous mixtures

The second part of the literature review presents the background of asphalt/bitumen, conventional tests and standards for bitumen, determination of wax content, bitumen rheology testing, bitumen grading systems, and overseas and local practices. The review indicates that there are a number and different tests and standards for classifying the bitumen currently adopted in local, overseas countries and the Mainland China. Selection of appropriate tests and standards for a particular region and location depends on various factors including the scale and location of market, availability of testing apparatus and skilled testing personnel, and requirements of local authority. The selection of the appropriate bitumen is vital to ensure good quality bituminous materials, which should be able to sustain the traffic loading. In Hong Kong, bitumen selection is based on conventional standard classification system and few standards are provided, such as the penetration, softening point and ductility, which are mainly to provide quality control to bitumen but not able to give direct description to the performance of the bitumen selected. Hong Kong locates in the high temperature region of Mainland China, where the road surface temperature will exceed over 60^0C in summer under very humid weather. While the bituminous materials are very sensitive to temperature, the environment of high temperature will influence the performance of bitumen and bituminous materials significantly if the choice of bitumen is not suitable.

Bitumen is a major component in the road pavement materials providing its ability to sustain traffic load. Bituminous paving materials will fail or be damaged if it is no longer able to sustain traffic or other environmental loadings. The last part of the literature review presents various types of road defects commonly found in Hong Kong, of which formation may be attributed to various factors including the performance of road pavement materials. The review gives the readers an insight of those road defects and the possible causes.

2.1 Wax in Bitumen

2.1.1 What is Wax?

Wax was originally referred to beeswax which is a substance secreted by bees for constructing their honeycombs by themselves. Nowadays, the term wax has come to refer more generally to a class of substances with properties similar to beeswax. Waxes may be natural secretions of plants or animals, artificially produced by purification from crude oil or completely synthetic. In addition to beeswax, paraffin (a petroleum wax) is a commonly encountered wax which occur naturally. Chemically speaking, a wax is a type of lipid that may contain a wide variety of long-chain alkanes, esters, polyesters and hydroxy esters of long-chain primary alcohols and fatty acids. The chemical structure of wax is quite complex, which is no less than that of petroleum. Physically, in general, waxes are water-resistant materials and indissoluble in water, and hardly difficult to dissolve in alcohol.

Wax has been used in a lot of applications including production of wax papers, polishes, candles and impregnating materials. Most of this wax has been manufactured from crude oil, which is a by-product in the petroleum industry. Naphthenic-based crude oil often gives a large yield of bitumen that is of good quality, while paraffinic crude oil can either give bitumen of good quality or yield bitumen not suitable for road paving because of its high wax content. Effect of wax on bitumen and wax content of bitumen have been of great interest in petroleum refinery and road construction industry. Views of effect of wax on bitumen are sometimes very different and even contradictory, probably because of the different wax properties may have different effect on bitumen. The crystalline nature and nonsticky characteristic of paraffin waxes was believed to have a negative effect on the thermal stability of bitumen and its ability to adhere to aggregates, hence the resistance to rutting and fatigue of the bituminous materials (Lu et al., 2006). In this connection, a maximum amount of wax content in bitumen is generally specified in relevant standards with a view to controlling the adverse effect of wax on performance of the pavement materials. Removing all wax from bitumen may not be practicable from a manufacturing viewpoint and may seriously affect the fundamental properties of bitumen.

In a study, wax was added with low-density polyethylene with a view to evaluating the thermal, mechanical and viscoelastic properties of the polymer blends (Djokovic et al., 2003). It was found that small concentrations of wax improved physical properties of the blends such as thermal stability, elastic modulus and yield stress. At higher concentrations, however, due to crystal phase separation, wax deteriorates the thermal as well as the mechanical properties. It was also shown that a formerly established two-process model for the stress relaxation in semicrystalline polymers could be used for the explanation of the viscoelastic behaviour of the blends. Though the study focus on the properties of mixtures with polyethylene, the findings could give an insight for the study on the effect of wax on bitumen, which is also a complicated structure with a lot of C-links.

2.1.2 Effect of Wax in Bitumen

Researches have been conducted to evaluate properties of bitumen with various types of wax and wax contents. Some of these studies are mentioned below.

Wax was isolated from bitumen by McKay using the IEC neutral fractions and wax precipitation in methyl ethyl ketone at -25°C (McKay, 1995). From the rheological data, the author concluded that in general paraffin waxes in bitumen appear to give higher stiffness and may result in poor low-temperature properties, and that microcrystalline waxes appear to reduce stiffness and may improve low-temperature properties of bitumens.

Wax was separated from samples of bitumen of different sources by Lu according to a European standard method (DIN 52015) and a method based on size exclusion chromatography (SEC). A variety techniques were used to characterize bitumen waxes with respect to their chemical composition and structural characteristics (Lu et al., 2007). These techniques include differential scanning calorimetry (DSC), high-temperature gas chromatography, gas chromatography-mass spectroscopy, field ionization mass spectroscopy, nuclear magnetic resonance spectroscopy and wide-angle X-ray diffraction spectrometry. Based on the test results on bitumens, it was concluded that waxes of bitumen were found to be complex mixtures of hydrocarbons, such as n-alkanes with carbon number C_{15}-C_{57} and isoalkanes, cycloalkanes, and aromatics which could be larger than C_{57}. Proportions of these different groups of compounds are strongly dependent on bitumen origins. In addition, wax compositions, as well as wax content in bitumen, is influenced by different separation methods.

Wax was isolated from bitumen by Carbognani, using clay absorption of the polar compounds followed by extraction of neutral oils and wax precipitation at -10°C. Rheology tests were performed on bitumens from 10°C to 70°C. Test results suggested that at high temperature, paraffinic waxes were found to slightly impair the rheological behaviour of bitumen (decrease in complex modulus). At low temperature, paraffinic waxes increased the dynamic shear modulus (Carbognani et al., 1998).

In another study, various types of waxes including natural bitumen waxes, slack wax and polyethylene wax (commercial waxes), and polyphosphoric acid which is not a wax product but has similar properties of those commercial waxes, were mixed in various amounts with non-waxy bitumens. From the rheological data on laboratory-made bitumen, the author concluded that magnitude and type of effect on bitumen rheology depends on the bitumen itself as well as type and amount of additive. Comparing the bituminous mixture test results to the corresponding bitumen test results, the effects on bituminous mixtures from adding commercial wax or polyphosphoric acid were less evident (Edwards, 2005).

In the Mainland China, studies have also been carried out to evaluate the effect of wax on bitumen and bituminous mixtures. In a study, wax was separated from several sources of bitumens in China before and after ageing process. Technique of differential scanning calorimetry (DSC) was also used to characterize waxes. Based on the test results, the author concluded that crystallized wax formed in the course of ageing is the main factor which adversely affects the bitumen performance, which is further proven by thermal analysis method, DSC (Yuan, 1997).

In another study carried out by Fung et al., paraffin wax was separated from bitumen manufactured from the crude oil deposited in the northwest region in the Mainland China in view of the presence of relative large amount of wax. Different amount of wax was then mixed with non-waxy bitumen with a view to evaluating the effect of wax on performance of bitumen. Based on the test results, the authors were not able to find a straight-forward relationship between the wax content and properties of bitumen owing to the complex nature of wax and bitumen, and the complicated chemical interaction between different types of wax and bitumen. The authors have taken the view that it might not be necessary to specify a maximum wax content in bitumen specification. In this regard, it was suggested that the local bitumen specification could make reference to those related to the rheological properties currently adopted in the U.S. Wax content could be specified as a secondary requirement but it should be supplemented with further detailed study on the composition of wax in various types of bitumens and its effect on these bitumens, which are manufactured in the Mainland China, particularly from the local oil fields.

The observations from the findings and conclusions of the above studies are summarized below.

- wax and bitumen are complicated structures as well as their interaction;
- there are different methods available to separate wax from bitumen and wax can be classified by techniques used in chemistry such as chromatography and spectrometry;
- there are ways to add a particular amount of wax to a non-waxy bitumen in laboratory for testing;

- rheology of bitumen is often used to evaluate the effect of wax on bitumen;
- there is no straight-forward relationship between the wax content and bitumen in view of the complex nature of the substances;
- there are different views on the need of specifying wax content in bitumen; and
- there are not many studies for evaluating the effect of wax content on the bituminous mixtures, particularly in the Mainland China

This study focuses on evaluating the effect of wax content on bitumen by conventional and rheology tests without using the techniques of chromatography and spectrometry. Various sources of bitumens of different wax contents were collected and tested under the study. In addition to tests on bitumens, bituminous mixtures were also prepared for further testing, which are described in Chapter 5. For preparing the bitumen samples for testing, the method of mixing a particular amount of wax in a non-waxy bitumen is not adopted because of the lack these materials in the local market. Besides, proper mixing of these substances requires sophisticated laboratory apparatus, appropriate skills of technicians and researchers, etc. The degree of representation of the bitumen sample of a particular wax content therefore depends on a lot of factors and it is very difficult, if not impossible, to prepare samples of bitumens of accurate wax contents in a general civil engineering material laboratory.

2.2 Bitumen Grading and Test

2.2.1 Background of Asphalt/Bitumen

Asphalt is one of the major constituents of hot asphaltic materials. Asphalt is often for pavement, waterproof, thermoplastic, viscoelastic adhesive. In other words, it acts as a glue that holds the road together (Anderson, Youtcheff and Zupanick, 2000). The term "asphalt" or "asphalt cement" are commonly used in the US whereas "bitumen" is often used in the UK, some European countries and Hong Kong for naming the binder agent. But just what are, asphalt, bitumen and how is it characterized? For engineering purposes, the definition needs to be more precise and unequivocal. ASTM D 8 provides the following definitions listed in Table 2.1.

Table 2.1 Definitions of Asphalt and Bitumen (ASTM D 8)

Asphalt	A dark brown to black cementitious material in which the predominating constituents are bitumens, which occur in nature or are obtained in petroleum processing.
Asphalt Cement	A fluxed or unfluxed asphalt specially prepared as to quality and consistency for direct use in the manufacture of bituminous pavements, and having a penetration at 25°C of between 5 and 300, under a load of 100 grams applied for 5 seconds.
Bitumen	A class of black or dark-colored (solid, semi-solid or viscous) cementitious substances, natural or manufactured, composed principally of high molecular weight hydrocarbons, of which asphalts, tars, pitches, and asphaltenes are typical.
Flux	A bituminous material, generally liquid, used for softening other bituminous materials.

This thesis uses the term, "bitumen", to represent the principal binding agent in the bituminous road surfacing materials as this term has long been used in the local construction industry and road authority. The bitumens selected under the study are all refined from crude oil without any polymer modification.

In the simplest term, bitumen is simply the residue left over from petroleum refining process by means of fractional distillation. Thus, bitumen is produced mainly by petroleum refiners and, to a lesser extent, by formulators who purchase blending stock from the refiners. The composition of base crude oil from which asphalt is refined can vary widely and thus the bitumen yield from different crude oil sources can also vary widely. Today, bitumen for pavement materials is produced almost entirely from refining of crude oil, except a few from other natural source, such as lake asphalt.

2.2.2 Conventional Tests and Standards

Conventional standards, mainly developed for a grading system, are traditionally used in many countries to set the acceptance criteria for bitumen to be used in road pavements. In these standards, the following major tests have generally been carried out in order to provide data for verifying the quality control of particular batches of bitumen. Additional tests may also be required according to the local practices.

2.2.2.1 Penetration Test

Penetration test is the oldest bitumen test. In 1888, H.C. Bowen of the Barber Asphalt Paving Company invented the forerunner to the penetration test, the Bowen Penetration Machine. The basic principle of the penetration test, was to determine the depth to which a truncated sewing needle penetrated a bitumen sample under specified conditions of load, time and temperature. In 1915, ASTM even went as far as specifying the brand of needle (Halstead and Welborn, 1974).

Figure 2.1 Penetration Tester

The current penetration tester (Figure 2.1), first published in 1959, follows the basic procedure below:

- Melt and cool the asphalt binder sample under controlled conditions.
- Measure the penetration of a standard needle into the asphalt binder sample under the following conditions:

  Load = 100 grams

  Temperature = 25^0C

  Time = 5 seconds

The depth of penetration is measured in units of 0.1 mm and reported in penetration units (e.g., if the needle penetrates 6 mm, the asphalt penetration number is 60).

2.2.2.2 Softening Point

Softening point is one of the common consistency indicators of bitumen. Bitumen is a mixture of many carbohydrates, so it does not have definite melting point. The softening point is the temperature at which different bitumen will get to the same determined viscosity. Therefore, the softening point may provide indication of the high temperature performance of binders. Because of the simplicity of the test procedures and apparatus, the method is also used for examining and controlling binder quality in many countries.

The softening point is defined as the temperature at which a bitumen sample can no longer support the weight of a 3.5 g steel ball. Basically, two horizontal disks of bitumen, cast in shouldered brass rings (Figure 2.2), are heated at a controlled rate in a liquid bath while each supports a steel ball. The softening point is reported as the mean of the temperatures at which the bitumen at the two disks soften enough to allow each ball, enveloped in bitumen, to fall a distance of 25 mm.

Figure 2.2 Softening Point Sample

2.2.2.3 Bitumen Viscosity

Viscosity is the ratio between the applied shear stress and rate of shear and it is also called the coefficient of viscosity. It is described by the following equation (1):

$$\mu = \frac{\tau}{\gamma} \quad \text{...(1)}$$

where: μ = viscosity (in cgs units of poise). poise = dyne·sec/cm^2 = g/cm·sec
(the SI unit of viscosity is the Pa·sec = N·sec/m^2 = 10 poise)

τ = shear stress

γ = shear rate

The test, used in the current study, is described in ASTM D 2171 “Standard Test Method for Viscosity of Asphalts by Vacuum Capillary Viscometer”, which measures the viscosity of bitumen by vacuum capillary viscometers at 60^0C (140^0F). It is applicable to materials having viscosities in the range from 0.0036Pa·s to over 20000Pa·s. Bitumen is drawn up through a capillary tube (Figure 2.3) by means of vacuum, under the closely controlled conditions of vacuum and temperature in a vacuum apparatus (Figure 2.4). The rate of shear decreases as the bitumen moved up the tube. This coefficient is thus a measure of the resistance to flow of the bitumen. The tests can also be carried out at 100°C and 135°C.

Figure 2.3 Capillary Tube

Figure 2.4 Vacuum Apparatus

2.2.2.4 Ductility

The ductility test (Figure 2.5) measures bitumen ductility by stretching a standard-sized briquette of bitumen (Figure 2.6) to its breaking point under a standard pulling speed. The elongated distance in centimeters at breaking is reported as the ductility. This test method provides a measure of tensile properties of bitumens. Similar to the penetration test, this test is conducted at a single and generally medium temperature, and therefore has its limitation.

Figure 2.5 Ductility Test

Figure 2.6 Ductility Test Specimen

2.2.3 Determination of Wax Content

To address the potential adverse effect of wax on bitumen, European countries limit the wax content to 2.2% according to BS EN 12606-1. In Mainland China, bitumens are classified into 3 grades, Grades A, B and C according to GBJ 50092 and there are limitations on the use of Grades B and C bitumens in road construction, which have relative high wax contents.

The test is generally carried out using a distilling system, an electric heater, a thermo-regulator and compressor refrigeration. DIN 52015 (German standard), T66-015 (French standard) and GB T 0615 (Chinese standard) describe the detailed procedures of the wax content determination, which are similar in procedure.

There were two major processes during the determination of wax content in bitumen:-

1) Extraction of bitumen oil from bitumen by distillation, which involved the use of a purposed made distillation flask (Figures 2.7 and 2.8).

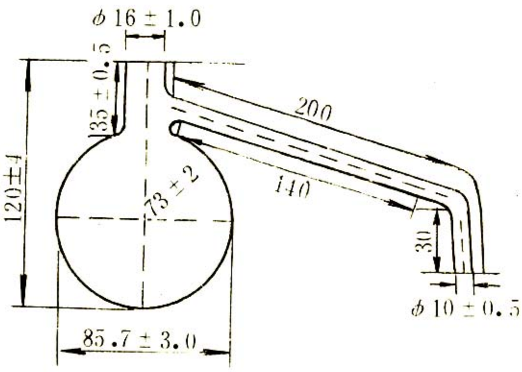

Figure 2.7 Purposed Made Distillation Flask (GB T 0615)

Figure 2.8 Distillation Flask and Associated Apparatus

2) Extraction of wax from bitumen oil, which involved the use of a cooling filter apparatus (Figures 2.9 and 2.10) to crystallize the wax at a very low temperature of -20^{0}C and to separate the crystallized wax (Figure 2.11) by filtration within a refrigerating chamber (Figure 2.12).

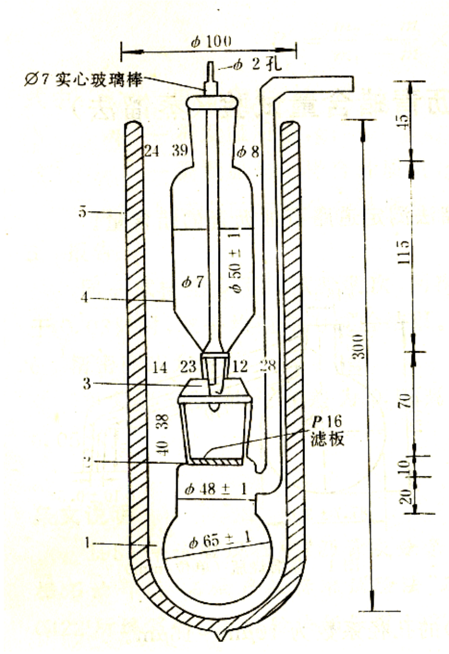

Figure 2.9 Purposed Made Cooling Filter Apparatus (GB T 0615)

Figure 2.10 Cooling Filter Apparatus

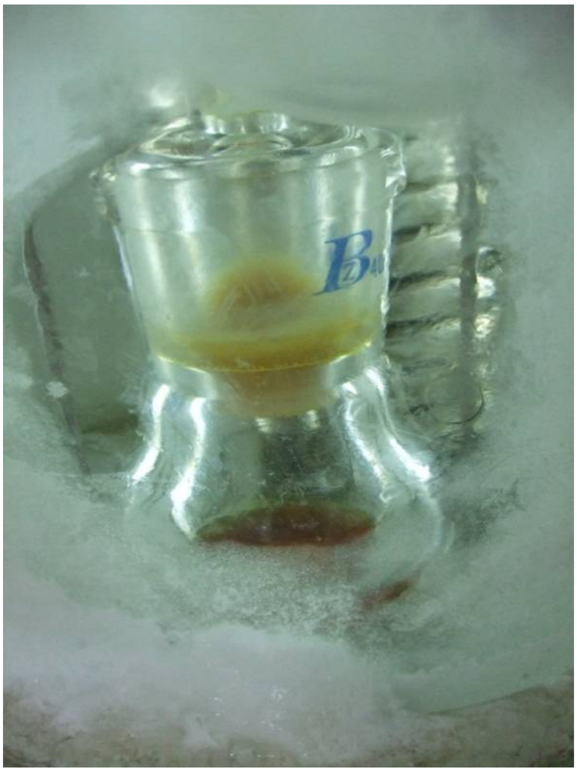

Figure 2.11 Wax Crystallized under Low Temperature

Figure 2.12 Refrigerating Chamber

Calculation of the wax content was based on the following equation (2).

$$P = \frac{m_1 \times m_w}{m_b \times m_2} \times 100 \qquad (2)$$

where: P = Wax content (%)

m_b = Mass of specimen (g)

m_1 = Total mass of distillated oil (g)

m_2 = Mass of distillated oil for wax extraction (g)

m_w = Mass of wax extracted (g)

2.2.4 Bitumen Rheology Testing

In the U.S., Performance-grade (PG) was developed under the Strategic Highway Research Program (SHRP) for assessing the rheological properties of bitumen (National Research Council, 1994). Rheology is a study of deformation and flow of substance. In view of the visco-elastic behaviour of bitumen, the deformation and flow of bitumen in bituminous road surfacing materials is one of the major factors which affect the performance of the surfacing materials. Bitumen that deforms and flows too much may cause thermal and fatigue cracking of bituminous materials. Deformation of bituminous pavement is closely related to the rheological properties of bitumen.

The Dynamic Shear Rheometer (DSR) (Figure 2.13) for assessing the rheological properties of bitumen from medium to high temperature viscosities (the test is conducted between 46^{0}C and 82^{0}C) was developed as part of the Superpave bitumen specifications. The DSR is able to compare the rheological properties of different bitumens at various reference temperatures over a range of temperatures that the bitumen may encounter during its service life.

Figure 2.13 Dynamic Shear Rheometer

The basic DSR test uses a thin asphalt binder sample sandwiched between two parallel circular plates (8 or 25 mm in diameter). A 1 to 2mm thick sample of asphalt is placed between two. The actual thickness depends on the stiffness of the binder. The lower base plate is fixed while the upper plate oscillates back and forth across the sample at 1.59 Hz to create a shearing action (Figure 2.14). These oscillations at 1.59 Hz (10 radians/sec) are meant to simulate the shearing action corresponding to a traffic speed of about 90 to 100 km/hr.

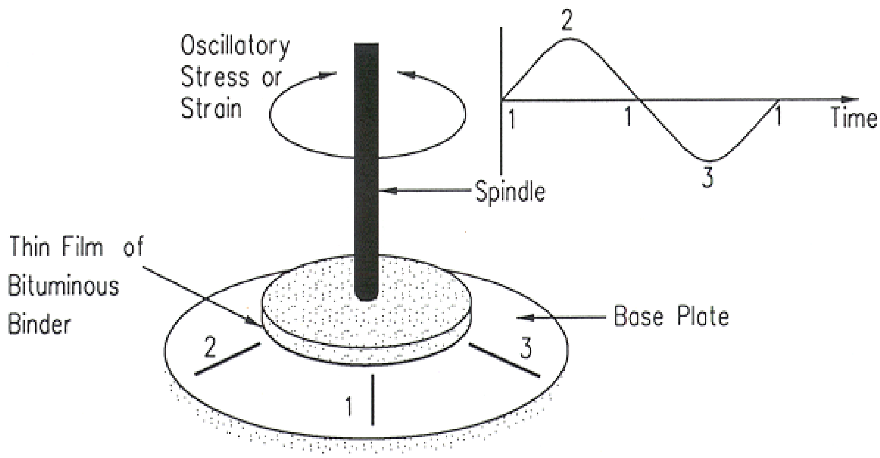

Figure 2.14 Oscillation in Dynamic Shear Rheometer

The complex modulus G* and phase angle δ of the bitumen within a range of temperatures under each condition were determined from the DSR test according to the following equations (3).

$$\tau_{\max} = \frac{2T}{\pi r^3} \qquad \gamma_{\max} = \frac{\theta\, r}{h} \qquad G^* = \frac{\tau_{\max}}{\gamma_{\max}} \qquad \delta = time\ lag \quad \ldots\ldots\ldots\ldots(3)$$

where: τ_{max} = maximum applied shear stress

T = maximum applied torque

r = radius of binder specimen (either 12.5 or 4 mm)

γ_{max} = maximum resulting shear strain

θ = deflection (rotation) angle

h = specimen height (either 1 or 2 mm)

G^* = complex shear modulus

δ = phase angle (time lag (expressed in radians) between the maximum applied shear stress and the maximum resulting shear strain)

Bitumen in the medium to high temperature range behave partly like an elastic solid (deformation due to loading is recoverable – it is able to return to its original shape after a load is removed) and a viscous liquid (deformation due to loading is non-recoverable – it cannot return to its original shape after a load is removed). By measuring G* and δ, it is able to determine the total complex shear modulus as well as its elastic (G') and viscous (G") components (Figure 2.15).

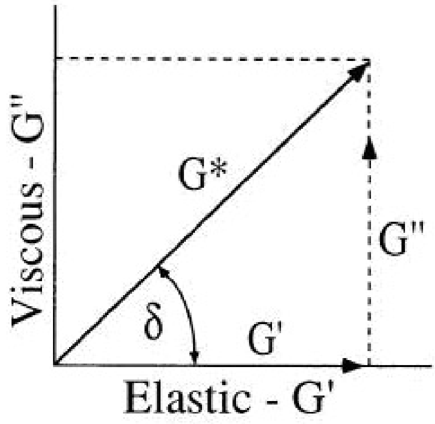

Figure 2.15 Complex Shear Modulus Components (SHRP-A-410)

Rheological properties of bitumen are determined by the DSR under three different conditions including the original, the aging that occurs during the mixing, laying and compaction process, and finally the long-term aging condition. For the preparation of aged bitumen, the rolling thin film oven (RTFO) is used to achieve the aging that occurs during the mixing and laying process. Long-term aging, which simulates field aging during the first five to ten years of service, is achieved by further aging of the bitumen using the Pressurized Aging Vessel (PAV). Arrangement of the aging process and tests for bitumen in this study is described in more details in Chapter 3.

2.2.5 Grading Systems

In many places, bitumen is generally classified according to either three grading systems namely penetration grading, viscosity grading and Superpave performance grading. This subsection briefly describes these major grading systems and how the bitumen is graded.

2.2.5.1 Penetration Grading

The penetration grading system was developed at the beginning of the last century and was the oldest one among the three systems. Penetration grading system generally requires the following properties of bitumen:

- Penetration depth of a 100 g needle applied for 5 seconds at 25^0C
- Softening Point
- Viscosity
- Ductility
- Flash point temperature
- Solubility in trichloroethylene
- Retained penetration after short-term aging
- **Wax content (required in some countries)**

The basic assumption of penetration grading is that the less viscous the bitumen, the deeper the needle will penetrate. This penetration depth is empirically correlated with the performance of bitumen. Therefore, bitumen of low penetration value is used for warm or hot climates whereas that of high penetration value is used for cold climate. In the Mainland China and some European countries, requirements of allowable wax content are also specified to supplement the penetration grading system. Typical Penetration-grades are 40-50, 60-70, 85-100 and over 100.

2.2.5.2 Viscosity Grading

In the early 1960s an improved bitumen viscosity grading system was developed that incorporated a more rational scientific approach. This scientific test replaced the empirical penetration test as the key bitumen characterization. Viscosity grading system generally takes into account the following bitumen characteristics:

- Viscosity at 60^0C
- Viscosity at 135^0C
- Penetration depth of a 100 g needle applied for 5 seconds at 25^0C
- Flash point temperature
- Ductility at 25^0C
- Solubility in trichloroethylene
- Viscosity and ductility after short-term aging

In the U.S., viscosity grading can be conducted on original bitumen samples (AC grading) or aged samples (AR grading). The AR viscosity test is based on the viscosity of aged bitumen from the rolling thin film oven test. The AR grading system attempts to simulate bitumen properties after the bitumen undergoes a typical manufacturing process for hot bituminous material. The AR grading system should therefore be more representative to demonstrate how bitumen behaves in bituminous pavements.

Under the viscosity grading system, viscosity is measured in poise. The higher the poise number, the higher the viscosity and thus the more difficult a substance flows. Thus, AC-30 (viscosity of 3000 poise at 60^0C) is more viscous that AC-2.5 (viscosity of 250 poise at 60^0C). Table 2.2 shows standard viscosity grades for the AC and AR grading systems according to AASHTO M 226 and ASTM D 3381. In the U.S., typical viscosity-grades used for bituminous road paving materials are AC-10, AC-20, AC-30, AR-4000 and AR 8000 according to ASTM D 3381.

Table 2.2 Viscosity Grades (AASHTO M 226 and ASTM D 3381)

Standard	Grading based on Original Bitumen (AC)						Grading based on Aged Bitumen (AR)				
ASTM D 3381	AC-2.5	AC-5	AC-10	AC-20	AC-30	AC-40	AR-1000	AR-2000	AR-4000	AR-8000	AR-16000
AASHTO M 226	AC-2.5	AC-5	AC-10	AC-20	AC-30	AC-40	AR-10	AR-20	AR-40	AR-80	AR-160

2.2.5.3 Superpave Performance Grading (PG)

In 1990s Superpave performance grading was developed in the U.S. under the Strategic Highway Research Program (SHRP) for assessing the rheological properties of bitumen. It was derived based on the idea that the properties of a bitumen should be closely related to the conditions at where it is used. As most of the bituminous pavements are paved outdoor, the grading system takes into account the expected climatic conditions and different aging considerations and therefore the system is named as “performance grading”. Though the selection of penetration or viscosity graded bitumen follows the same rule, the relationships between bitumen properties and conditions of use are more relevant and more precise with the Superpave PG system.

Bitumen is classified by a set of two numbers in Superpave PG system. The first number is the average seven-day maximum pavement temperature and the second number is the minimum pavement design temperature likely to be experienced. Thus, a PG 64-16 is intended for use where the average seven-day maximum pavement temperature is 64^0C and the expected minimum pavement temperature is -16^0C. The first number ranges from 46 to 82 at intervals of 6 whereas the full range of the second number is from 10 to 46 also at intervals of 6. The range of the second number under particular first number is not identical. It should be noted that these numbers are pavement temperatures and not air temperatures and thus, an algorithm contained in the LTPP Bind program has been developed to estimate the pavement temperatures from air temperatures.

2.2.6 Overseas and Local Practices

2.2.6.1 Bitumen Application in the U.S.

About 32 million tonnes of bitumen is used annually in the U.S. It is anticipated that the bitumen usage will grow substantially in the next ten years despite that there is now a temporary hiccup in the demand arising from the economic tsunami. Not only used in road construction, bitumen is also used in roofing materials, batteries, adhesives and coatings. Over 90 percent of the paved roads in the U.S. are surfaced with bituminous materials produced by the conventional hot-mix method. Generally, hot-mix bituminous pavements comprise several compacted layers, which contain mainly mineral or recycled aggregate, bitumen and air voids. The latter two components are comparatively small in proportion as bitumen content and air void content are both about five percent. Despite the small quantity of bitumen in the materials, the type of bitumen plays a critical role in the performance of the bituminous materials.

Prior to 1987, bitumen was tested and graded by two primary methods, viz. the penetration grading and viscosity grading. The American Association of State Highway Officials (AASHO) published the standard specifications for penetration graded asphalt cements in 1931. The penetration grading system was created to establish different asphalt grades for varying climates and applications. The primary test for penetration grading is the penetration test. Additional tests are conducted to determine the retained penetration, and to evaluate the asphalt binder's flash point, ductility and solubility. **No wax content test** is required in the penetration grading system.

The Federal Highway Association (FHWA), American Society for Testing and Materials (ASTM), American Association of State and Highway Transportation Officials (AASHTO), several state highway departments and bitumen industry jointly sought to replace the empirical tests of the penetration grading system with scientifically-based viscosity tests. The bitumen viscosity grading system was initiated in the early 1960's and soon became the most widely used grading system in the U.S. The bitumen viscosity grading system, also known as the AC viscosity grading system, characterizes bitumen's performance based on the viscosity at 60°C. Bitumen's performance at near mixing/compacting temperatures is evaluated by conducting viscosity tests at 135^0C. Despite the fact that the objective of developing the viscosity grading system is to replace the empirical tests of the penetration grading system, the viscosity grading still require the performance of tests for penetration, flash point, ductility, and solubility, and some on aged bitumen samples. **No wax content test** is required in the viscosity grading system.

From 1987 to 1993, the Strategic Highway Research Program (SHRP) conducted a 50 million dollars research programme to develop performance-based tests and specifications for both binders and mixtures. The research led to the development of the Performance Graded (PG) binder tests and specifications for evaluating bitumen binder properties and performance. The new SHRP binder specifications were developed to address the shortcomings of the penetration and viscosity grading systems. The PG binder tests comprise four physical tests and two conditioning processes. The four physical tests are the Dynamic Shear Rheometer (DSR), Rotational Viscometer (RV), Direct Tension Tester (DTT) and the Bending Beam Rheometer (BBR). The two conditioning processes are the Rolling Thin Film Oven (RTFO) and the Pressurized Aging Vessel (PAV), which are described in more details in Chapter 3.

Though more tests on bitumen have been developed in the past decades in the U.S, the penetration, viscosity and performance grading systems are still currently used in the U.S. and the selection of the grading system depends upon the geographical and administrative locations of the highways, availability of the testing equipment and local practice. In summary, in addition to the tests in the penetration grading system, more tests are required in the viscosity grading system. Traditional tests including penetration, ductility and solubility are no longer required in the PG grading system whereas sophisticated tests have been developed for evaluating bitumen binder properties and performance. **No wax content test** is specified in these three grading systems.

2.2.6.2 Bitumen Application in the United Kingdom (UK) and European Countries

About 2 million tonnes of bitumen was used in the UK in 2002. Similar to the U.S. over 90 percent of the paved roads in the UK are surfaced with bituminous materials produced by the hot-mix method. Penetration grading system has been generally used in the UK to characterize the performance of bitumen. In addition to the primary penetration test, tests for retained penetration, softening point, flash point and solubility, and some tests on aged samples are required in the grading system.

Harmonization of European Standards for petroleum products was set as a target by the 'Committee European of Normalization' (CEN) during the mid 1980s to eliminate trade barriers within the member states of the European Union. One of the first steps in achieving this aim was the publication of the 'Construction Products Directive' (CPD). The CPD requires that construction products used in member states must be fit for their intended use, satisfying the following essential requirements:

- Mechanical resistance and stability
- Fire safety
- Safety in use

- Hygiene, health and environmental concerns
- Energy, economy and heat retention

Taking on board the above requirements, the CEN working groups (WGs) dealing with paving grade bitumens proposed a pan-European specification that has finally led to the publication of BS EN 12591. In addition to the traditional tests that are used for characterizing bitumens in the UK, an optional test for determining **wax content** is specified with a maximum allowable wax content in the bitumen.

2.2.6.3 Development in Mainland China

Application of bitumen in road construction in a place has a close relationship with the development of highways or motorways of that particular region. In China, the development of motorway was constrained from 1949 to the end of 1980s. Before 1987, the total length of highway is about 1 million km but there was not a single motorway that was constructed up to an international standard. Resulting from the economic reform that happened in the end of 1980s, the motorway network has increased sharply in the subsequent three decades. Figure 2.16 shows the total length of motorway in China since 1988 to 2002. The total length has dramatically increased from 20 km in 1988 to 25,130 km in 2002. According to the implementation plan of the road authority in China, the total length of motorway in 2010 will reach 55,000 km, while the ultimate target in medium term is 85,000 km. There is no relevant data for the total road length of other primary and secondary road networks in China but there is no reason not to believe that it should follow the same development trend of motorway.

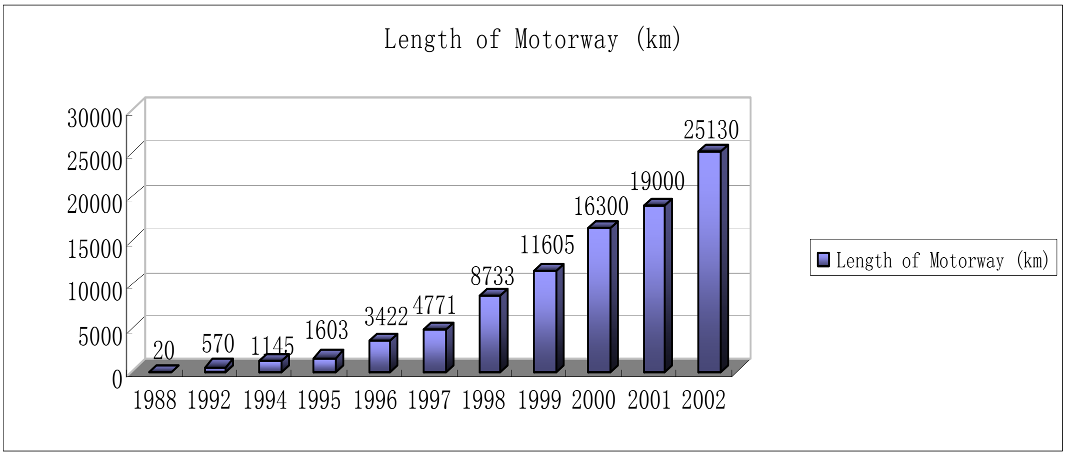

Figure 2.16 Length of Motorway in China (Source from Tongji University)

Most of the motorways in China are semi-flexible pavements in which bituminous surfacing materials of thickness ranging from 100 mm to 200 mm have been laid on bound roadbase layers, which are made of aggregates and cement, pulverized fuel ash or lime as the binding agent. Though the thickness bituminous material is about a half to one third of the thickness of full flexible pavements commonly adopted in overseas, the quantity of bituminous materials required for road construction is tremendous owing to the rapid development of motorway and road networks. The length of motorway in China is the second largest among all countries; just less than the U.S., and is expected to increase at a rapid rate owing to the economic growth. Thus, there is a strong demand on bitumen for producing bituminous paving material in China. In China, known crude oil fields are located at Liaoling, Heilongjiang, Xinjiang, etc. but the quantity of crude oil deposited is not very large as compared to other oil-producing areas.

Today, the four main oil-producing areas in the world are the U.S., the Middle East, Russia and the countries around the Caribbean. Crude oils differ in their physical and chemical properties. Physically, they vary from viscous black liquids to free-flowing straw coloured liquids. Chemically, crude oils may be predominantly paraffinic, naphthenic with combinations of the first two being most common. There are nearly 1500 different crudes produced but only a few of these are considered suitable for the manufacture of bitumen. The wax content in bitumen has been a major concern in China as the crude oil deposited in China is generally paraffinic, with a relatively high wax content. Thus, the grading system for bitumen adopted in China covers the requirements on wax content.

The Chinese standard JTG F40-2004 characterizes bitumens primarily according to the penetration grading of the materials. Similar to the EN standards, the target values of penetration, softening point, dynamic viscosity, flashing point and solubility, and mass loss after RTFOT, retained penetration and change in softening point, are specified. Requirements on ductility at 10^0C and 15^0C are stated. In addition, the standard also sub-divides bitumens into A, B and C grades according to **wax content** and puts forward different technical targets for penetration index, softening point, dynamic viscosity and ductility. Only Grade A, with wax content below 2.2% is allowed for motorway pavement construction. Grades B and C, with wax content limits of 3.0% and 4.5% respectively, can only be used on roads with relatively lower traffic or underlying layers of motorways. The standard also considers regional environmental effects on the behaviour of bitumen and divides the country into eight climatic regions for bituminous road design and construction. Figure 2.17 presents the distribution of the climatic regions and Hong Kong is located in the Climatic Region “1-4”. According to the standard, bitumens of penetration values between 40 and 80 might be used in Hong Kong.

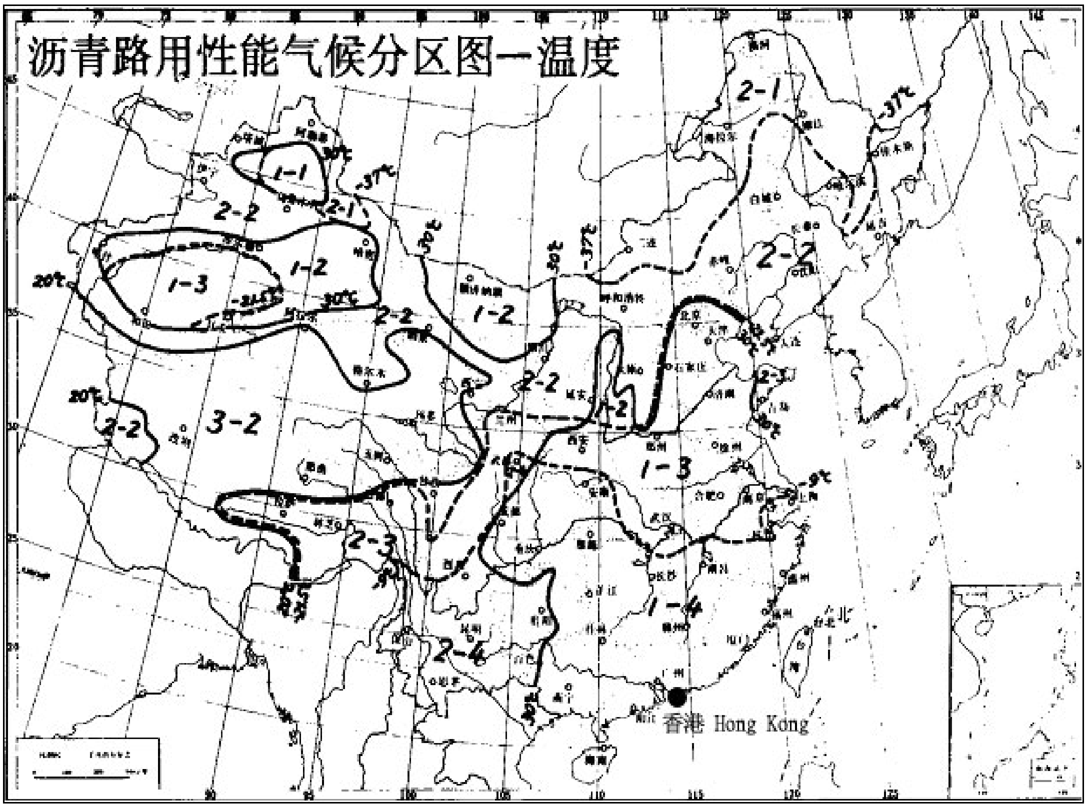

Figure 2.17 Distribution of Climatic Region for Bituminous Road Pavement in Mainland China (Shen, 1994)

2.2.6.4 Development in Hong Kong

The total road length including motorway in Hong Kong is only about 2,000 km and about 75% of the road network is of full flexible construction consisting of multi-layers of bituminous materials. The local road authority has adopted the penetration grading system to characterize the bitumen for road paving construction. The use of Penetration-grade 60-70 bitumen has been set as a standard requirement. In addition to the penetration test, tests for determining the softening point, ductility, solubility, loss on heating, viscosity and retained penetration after aging are required to be performed under the system. Requirements of the tests are summarized in Table 2.3.

Table 2.3 Requirements for Bitumen in Hong Kong (Hong Kong Government, 1992)

Test	Requirement
Penetration at 25^0C	60 - 70
Softening Point (^{0}C)	44 - 55
Ductility at 25^0C (cm)	Greater than 100
Solubility (%)	Greater than 99
Retained Penetration after Rolling Thin Film Oven (%)	Greater than 52

In Hong Kong, bitumen has been imported mainly from Singapore and sometimes from Thailand. The source of the crude oil is from the Middle East and is predominantly of the naphthenic type with a low wax content. Since Hong Kong is now a part of the People's Republic of China and geographically adjoins the mainland, bitumen manufactured from crude oil deposited in China is being used more frequently in Hong Kong for road paving.

Though basic tests on bitumen are required to verify its physical properties, no test for determining the wax content is specified. Therefore it is unable to grade the bitumen according to the wax content, and hence not able to evaluate the effect of wax content on the quality of the bitumen. It is considered necessary investigating the effect of the wax content on bitumen and bituminous mixes made with local materials by means of performance-related tests and to review the local specification, if necessary. Prior to the investigation on the effect of wax content on bitumen, it is essential to understand the road distresses that may be formed owing to the use of inferior materials and the reasons of the formation of the distresses.

2.3 Distress of Bituminous Pavemens

Bitumen with high wax contents are not recommended in the production of bituminous pavement materials according to the national specifications in the Mainland China and some European countries including the UK, France and German. Bitumen of high wax content is generally not allowed to be used in the surfacing layer or underlying layers of heavily trafficked roads, where the stress on bituminous materials induced by traffic is high. It is believed that bitumen of high wax content will affect the stability of the bituminous materials and hence causing pre-mature distress and defect of bituminous road pavements. In order to understand the effect of wax on bituminous pavement materials, it is essential to realise different types of bituminous pavement distress or defects. Local road maintenance authority in Hong Kong has grouped the common mode of distresses/defects in bituminous road pavements into four categories namely cracks, deformations, surface texture deficiencies and potholes (Highways Department, 2009). Details of these road distresses and their possible causes are summarized and discussed in the following sub-sections.

2.3.1 Cracks

Cracks are fissures resulting from partial or complete fractures of the pavement surface and underlying layers. They can range from isolated single cracks to a series of interconnected cracks spreading over the entire pavement surface. Detailed descriptions of the cracks and the possible causes are presented in Table 2.4.

Table 2.4 Cracks

Cracks	Detailed Description	Possible Causes	Figure No.
Block	Interconnected cracks forming a series of large polygon.	• Hardening and shrinkage of bituminous mixture • Fatigue cracking in embrittled bituminous wearing course	2.18
Crocodile	Interconnected or interlaced cracks	• Saturated base • Rupture of surface course	2.19

Cracks	Detailed Description	Possible Causes	Figure No.
	forming a series of small polygons resembling a crocodile hide.	• Inadequate thickness • Developing from a surface showing block cracking underneath	
Diagonal	An unconnected crack which generally takes a diagonal line across a pavement	• Reflection of a shrinkage crack or joint in and underlying cemented material • Differential settlements between embankments, cuts or structures • Service installation	2.20
Longitudinal	Crack running longitudinal along the pavement	• Poor workmanship • Differential movement in case of pavement widening • Bitumen hardening	2.21
Slippage	Half moon or crescent shaped crack in the direction of traffic	• Inadequate bonding layers • Slippage of wearing course at road locations with high shear stresses • Low modulus base course	2.22

Cracks	Detailed Description	Possible Causes	Figure No.
Transverse	Transverse rupture across the pavement for bituminous surfacing	• Construction joint or shrinkage crack • Reflective crack • Movement of underlying layers	2.23

Figure 2.18 Block Crack

Figure 2.19 Crocodile Crack

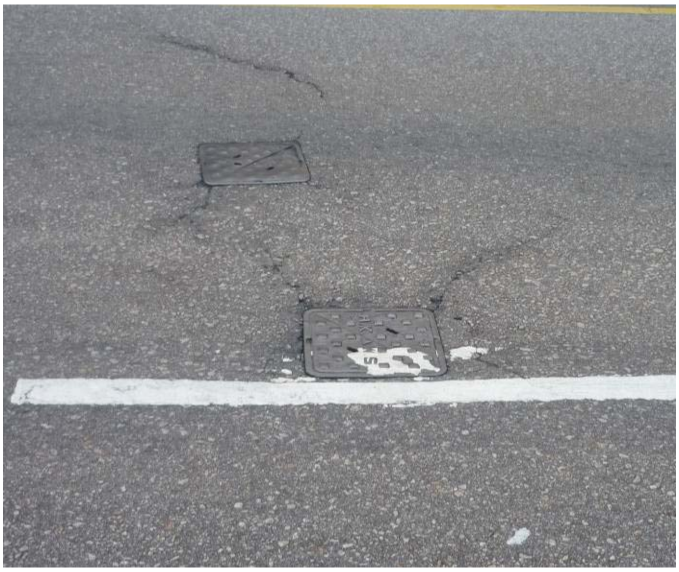

Figure 2.20 Diagonal Crack

Figure 2.21 Longitudinal Crack

Figure 2.22 Slippage Crack

Figure 2.23 Transverse Crack

2.3.2 Deformations

Deformation can be conceived as any change of the road surface, which leaves the road surface in a shape different from the one intended. It may be due to load associated or non-load associated influences. Deformation affects serviceability and may reflect structural inadequacies. Detailed descriptions of the distresses and the possible causes are presented in Table 2.5.

Table 2.5 Deformations

Deformation	Detailed Description	Possible Causes	Figure No.
Corrugation	Transverse undulations, closely and regularly spaced (ripples)	• Low stability of bituminous mix • Low air voids of mix • Road locations under high tangential traffic stresses	2.24

Deformation	Detailed Description	Possible Causes	Figure No.
Depression	Localised area within a pavement with elevations lower than the surrounding area	• Settlement of utility trenches • Consolidation of isolated areas of soft or poorly compacted subgrade • Settlement due to the instability of embankment	2.25
Rutting	Longitudinal deformation in a wheelpath (channelling)	• Inadequate compaction in surfacing or base • Plastic deformation of bituminous materials (flow) • Settlement of underlying layers and subgrade under traffic	2.26
Shoving	Bulging of the road surface generally parallel to the direction of traffic; and/or horizontal displacement of surfacing materials mainly in the	• Inadequate strength of surfacing or base • Poor bond between pavement layers • Stop and start of vehicles at intersection • Low air void content in bituminous layers	2.27

Deformation	Detailed Description	Possible Causes	Figure No.
	direction of traffic where braking or acceleration movement occur		

Figure 2.24 Corrugation (Source from Website)

Figure 2.25 Depression

Figure 2.26 Rutting

Figure 2.27 Shoving

2.3.3 Surface Texture Deficiencies

Though surface texture deficiencies may not affect pavement structural inadequacy, they have a significant effect on its serviceability. Various types of surface texture deficiencies and their possible causes are presented in Table 2.6.

Table 2.6 Surface Texture Deficiencies

Deficiencies	Detailed Description	Possible Causes	Figure No.
Flushing	Immersion, partially or completely, of the aggregates into the bituminous binder resulting in a black and brilliant aspect	• Excessive binder content of wearing course with low voids • Penetration of aggregate into base (low strength base course)	2.28
Polishing	Smooth and rounding of the upper surface of the roadstone, usually occurs in the wheeltracks.	• Inadequate resistance to polishing of surface aggregates	2.29
Ravelling	Progressive disintegration of the pavement surface by loss of both bitumen and aggregates	• Separation of bituminous film from aggregates (stripping) • Disintegration of aggregates; poor construction	2.30

Figure 2.28 Flushing

Figure 2.29 Polishing

Figure 2.30 Ravelling

2.3.4 Potholes

Potholes are bowl-shaped depressions in the pavement surface developing from another defect (cracking, delamination etc.), and resulting in allowing the entry of water and disintegration with removal of material by traffic over weakened spots on the surface. Typical pothole and delamination are shown in Figure 2.31 and 2.32 respectively. This type of distress is usually caused by inadequate cleaning or inadequate tack coat before placement of upper layers; seepage of water through cracks to break bond between surface and lower layers; insufficient thickness or stability of wearing course; full damage of surface layer and patching over failed pavement.

Figure 2.31 Pothole

Figure 2.32 Delamination

The defects presented in this section are common in Hong Kong. The local road maintenance authority suggests that the major causes of these distresses are attributed to poor construction, heavy traffic volume and loading, movement of underlying layers, high ambient temperature, etc. In addition, few causes are related to the bituminous material itself including ageing of material, faulty mix design and poor quality aggregates. However, there is yet no evidence or concern over the effect of the use of inferior bitumen in the road pavement material. It is probably because the source and type of bitumen currently used in Hong Kong is consistent and hence the property of bitumen is stable.

Since Hong Kong is now a part of the People's Republic of China and geographically adjoins the mainland, bitumen manufactured from crude oil deposited in China with high wax content may be used more frequently for road paving. Hence, it is necessary to investigate and understand the performance of bitumen with various wax contents and bituminous materials made with local ingredients. The use of appropriate type of bitumen and bituminous materials should be able to prevent early occurrence of road distresses and ensure a long-lasting road pavement.

Chapter 3

Materials and Preparation of Test Samples

3.1 Source of Materials

3.1.1 Bitumen

The materials used in this study are aggregates, mineral filler and bitumen. Seven sources of bitumen of similar Penetration-grades were collected for the study, which included six types from China and the conventional type of Penetration-grade 60-70 imported from Singapore, which has been used in Hong Kong. These are all virgin bitumens without undergoing any modification with polymers or other additives. Details of the supplier and brand of bitumen are listed in Table 3.1.

Table 3.1 Bitumen Brands and Suppliers

Bitumen No.	Source Location	Supplier/Brand	Crude Oil Source
1	Singapore	Shell(Pen 60/70)	Middle East
2	China	CNOOC(AH-70)	China
3	China	Supplier (AH-70, Class B)	China
4	China	Maoming (No.1 bitumen)	Mixed Sources
5	China	Maoming (No.2 bitumen)	Mixed Sources
6	China	Sinopec (Zhonghua bitumen)	Middle East
7	China	Taizhou (Zhonghai bitumen)	China

Among the six sources from China, one type (No. 6) was manufactured from crude oil imported from the Middle East as China has imported crude oil from overseas countries to meet the local demand on petrol and other oil refinery products. Three types (No. 2, 3 and 7) were manufactured from crude oil deposited in China. The remaining two sources of bitumen (No. 4 and 5) were produced by the blending of crude oil from various sources by a manufacturer but they are categorized into two different grades according to the wax content claimed by the manufacturer.

3.1.2 Aggregates

Crushed granite aggregates and filler used in this study and were supplied by a single local bituminous material supplier. Tests for hardness (10% fines value), water absorption, density and shape (flakiness index) were carried out to characterize the properties of coarse and fine aggregates. Test results are given in Table 3.2, which comply with the local specification for aggregates.

Table 3.2 Properties of Aggregates

Item	Aggregate Size (mm)	Test Result
10% Fines Value (kN)		180
Water Absorption Value (%)	37.5 – 28	0.40
	28 – 20	0.40
	20 – 14	0.50
	14 – 10	0.60
	10 – 5	0.70
	5 – 0.075	0.40
Apparent Density	37.5 – 28	2.64
	28 – 20	2.65
	20 – 14	2.65
	14 – 10	2.65
	10 – 5	2.64
	5 – 0.075	2.62
Flakiness Index (%)	37.5	12
	20	15
	10	10

3.2 Preparation of Test Samples

3.2.1 Bitumen

Specimens of bitumens were prepared according to the Chinese standard T0602-1993 for testing for the penetration, softening point, ductility, viscosity, loss on heating, solubility and relative density, which are specified in the local specification. In addition to these conventional tests, tests for wax content and rheological properties were conducted.

Rheological properties of bitumen were determined by the Dynamic Shear Rheometer (DSR) under three different conditions including the original (virgin), the aging that occurs during the mixing, laying and compaction process, and finally the long-term aging condition. For the preparation of aged bitumen, the rolling thin film oven (RTFO) (ASTM D 2872) (Figure 3.1) was used to achieve the aging that occurs during the mixing and laying process. In this test, a specified amount of bitumen was poured into a specially designed glass bottle. The bottle was placed horizontally in a rack that rotates around a horizontal axis. Heated air was blown into the bottle to purge vapours from the bottle once each rotation. The rotating bottle enables the fresh film of bitumen to be continuously exposed. The bitumen in a rolling glass bottle was heated in an oven for 85 minutes at 163^0C. The

RTFOT can accommodate more samples than thin film oven test (TFOT) in which only a single pan poured with bitumen is place and hence the time required for simulating the aging condition is shorter.

Figure 3.1 Rolling Thin Film Oven

Long-term aging, which simulates field aging during the first five to ten years of service, was achieved by further aging of the bitumen using the Pressurized Aging Vessel (PAV) (ASTM D 6521). The bitumen aged after the RTFOT was placed in pans which were placed into the PAV (Figure 3.2). The depth of the bitumen in pan was 3.2mm±0.1mm (approximately 50g). The bitumen was aged for 20 hours under an air pressure of 2,100 kPa and an aging temperature at 100^0C. The aging temperature at 100^0C was adopted taking into account the moderately high air temperature in Hong Kong.

Aging the bitumen samples under pressure is advantageous because:

- There is a limited loss of volatiles; and
- The oxidation process can be accelerated without resorting to extremely high temperatures.

Figure 3.2 Pressurized Aging Vessel

3.2.2 Bituminous Mixtures

In view of the huge amount of laboratory works required for preparing the bituminous mixtures and performing the subsequent tests, and the limited quantity of bitumen available for the tests, two typical bitumens of different wax content levels among the seven bitumens tested were selected for preparing bituminous mixtures to verify and supplement the findings in the evaluation of bitumens under this study. These two bitumens are Bitumen No. 1 (conventional Penetration-grade 60-70 bitumen supplied by Shell) and Bitumen No. 5 (supplied by Maoming). For comparing the properties of the two bituminous materials, the mix design of both materials follows a local mix design for the 20 mm size wearing course material, which is shown in Table 3.3.

Table 3.3 Mix Design of Bituminous Material

BS Test Sieve (mm)	20mm Wearing Course Percentage by Mass Passing		
	Lower Bound	Upper Bound	Target Mix Design
50	-	-	-
37.5	-	-	-
28	100	-	100
20	91	100	97
14	78	90	88
10	68	84	80
5	54	72	67
2.36	42	58	48
1.18	34	48	35
0.6	24	38	26
0.3	16	28	18
0.15	8	18	12
0.075	4	8	7.9
Bitumen content (%)	5.0-5.5	5.0-5.5	5.0
Air void	3.0-5.0	3.0-5.0	4.0

3.2.2.1 Preparation of Aggregates

Aggregates were washed over a 75 μm sieve and dried to a constant weight at 105^{o}C±5^{o}C in an oven. Dried aggregates were then separated into the desired coarse and fine fractions by dry sieving, using the same sieve sizes as those given in the grading specification. The aggregate blends were weighed separately for each test specimen in accordance with the mix design and the size of samples.

3.2.2.2 Mixing of Aggregates and Bitumen

The mixing process adopted in this study aims at simulating the mixing of materials in a batching plant during production. The procedure of the mixing process is as follow:

- Aggregates and bitumen were preheated at the temperatures recommended by the supplier;
  - The aggregate blend was placed in an oven and heat to a temperature of 187^0C, approximately 28^0C above the mixing temperature of 159^0C, in accordance with MS-2 of Asphalt Institute for 8 hours
  - The bitumen was preheated in an oven to the mixing temperature for at least two hours
- The moulds, cylinders, extension collars, roller head and compaction pedestal to a temperature of 93^0C-149^0C were preheated;
- The mass of the bitumen to the nearest 0.1g to be added to each aggregate blend was calculated;
- The aggregate blend was taken out from the oven to the mixer bowl;
- The bitumen in its container was stirred and weighed the required amount of bitumen into the mix. The aggregates and bitumen were mixed in a

temperature-controlled mechanical mixer (Figure 3.3) rapidly until the aggregates were coated uniformly with bitumen; and

- The cylindrical mould was taken out from the oven for assembly. The plain paper was placed in the bottom of the mould and all the mixed material in the mechanical mixer was transferred into the mould. The top of the mixture was evened with a heated spatula.

Figure 3.3 Mechanical Mixer and Cylindrical Moulds

3.2.2.3 Preparation of Cylindrical Samples

For fabricating test samples for Indirect Tensile Stiffness Modulus (ITSM), Indirect Tensile Strength (ITS) test and Dynamic Creep Test, the bituminous mixtures were compacted using a Superpave gyratory compactor (Figure 3.4) in this study. Compaction is the process of compressing a given volume of mix into a small volume and is achieved by pushing the aggregates coated with bitumen closer to a target air void content. During the compaction process, density and air void were controlled by the volume of the sample. The dimensions of samples for particular tests are shown in Table 3.4.

Table 3.4 Dimension of Cylindrical Samples

Test	Diameter of Sample (mm)	Height of Sample (mm)
Indirect Tensile Stiffness Modulus (ITSM)	150	60
Indirect Tensile Strength (ITS)	100	63.5
Cyclic Compression Test	150	60

The Superpave gyratory compaction is a laboratory method for compacting test specimens which is intended to simulate the compaction on road paving materials in field. Instead of the typical axial compression method, the Superpave gyratory compactor adopts a kneading compaction method, which compacts the materials at an angle of gyration of 1.25±0.02^{0}C with a rate of 30 gyrations per minute. During the compaction, a constant vertical pressure of 600 kPa was maintained.

Figure 3.4 Superpave Gyratory Compactor

3.2.2.4 Compaction by Gyratory Compactor

Compaction was carried out using the Gyratory Compactor according to ASTM D 3387 and the compaction procedure is summarized as follow:

- When the temperature of the bituminous mixture fell within the compaction temperature ±2^{0}C, another plain paper was placed on the top of the material.

The mould assembly was transferred to the compaction pedestal and was located in the mould holder.

- The mixture was compacted to the target bulk specific density (Gmb) of the mix design, which was calculated from Equation (4).

$$Gmb = Gmm \times (1-VIM) \quad \ldots\ldots (4)$$

where: Gmb = Bulk specific density of mixture

Gmm = Theoretical maximum specific density of mixture

VIM = Air void content (%)

(Air void content refer to the mix design)

- The mould was removed from the compactor and 10 minutes (as recommended in ASSHTO T312-4) was allowed before removing the specimen from the mould. The specimen was extruded from the mould with great care in order not to distort the specimen. The pieces of paper were removed from both ends of the specimen while the specimen was still warm to avoid excessive sticking.

Chapter 4

Testing on Bitumen

4.1 Test Methods on Bitumen

4.1.1 Conventional Tests

A series of conventional standard laboratory tests (including the determination of density, softening point, penetration, ductility, solubility, viscosity and loss on heating) was performed on each of seven bitumens according to the local specification. Details of the test methods are as follow:

- Penetration testing - The penetration is the commonest consistency indicator of bitumen. Whether the bitumen classification standard is in accordance with penetration or viscosity grading systems, penetration testing is included. Tests were conducted in accordance with ASTM D 5. In addition to the test on virgin bitumen, tests on aged bitumen after thin film oven test (TFOT) (ASTM D 1754) were performed for determining the retained penetration.

- Softening point test - Softening point is one of the common consistency indicators of bitumen. It is the equi-viscous temperature, at which different bitumens will get to the same consistency. Softening points of different bitumens are not the same. Therefore, the softening point may indicate the high temperature performance of bitumen. Tests were conducted in accordance with BS 2000.

- Viscosity test - The test was conducted at 60^0C to characterize the flow behaviour, which is close to the high pavement temperature. Thus, the viscosity at this temperature partially reflects the ability to resist the deformation of the bituminous mixture in high temperature. Tests were performed in accordance with ASTM D 2171.
- Ductility test - This test method provides a measure of tensile properties of bitumen. Tests were performed at 25^0C in accordance with ASTM D 113.
- Loss of heating test - This test method is useful in characterizing certain petroleum products by the determination of their loss of mass upon heating under standardized conditions. The test can be used to monitor the volatile composition that is easily evaporated at high temperature. Tests were conducted in accordance with BS 2000.
- Solubility test - This test is a measure of the solubility of bitumen in solvent. The test is used to control the content of impurities that are introduced into bitumen during the refinery process. The samples were dissolved in solvent (trichloroethylene) and filtered through a glass-fibre

pad. The insoluble material was washed, dried, and weighed. The portion that is soluble in solvent represents the active cementing constituents. Tests were performed in accordance with BS 2000.

- Tests for relative density were carried out in accordance with ASTM D 3289.

4.1.2 Test for Wax Content

The distillation method according to the Chinese standard GB T0615 was adopted in this study to determine the wax content of bitumen as most of the bitumens in this study were sourced from Chinese manufacturers (See Table 3.1). For each type of the bitumens, two specimens were prepared for testing. The tests were carried out using the bitumen wax content analyzer, Model SYD-0615, which consisted of a distilling system, a thermo-regulator and a compressor-refrigerator.

4.1.3 Test for Rheological Properties

The tests for determining the basic properties and wax content of bitumen are not directly related to its performance in pavement materials. These tests may not able to provide information related to the rheological properties of bitumen under different loading, loading time and thermal conditions.

Rheological properties of bitumen were determined by the DSR under three different conditions including the original, the aging that occurs during the mixing, laying and compaction process, and finally the long-term aging condition. The complex modulus G* and phase angle δ of the bitumen within a range of temperatures under each condition were determined from the DSR test. Rutting factor ($G^*/\sin\delta$), and fatigue factor ($G^*\sin\delta$), were then calculated.

For the preparation of aged bitumen, the rolling thin film oven (RTFO) (ASTM D 2872) was used to achieve the aging that occurs during the mixing and laying process. The bitumen in a rolling glass bottle was heated in an oven for 85 minutes at 163^0C. It is believed that such method is able to simulate the aging of bitumen during the production and laying of bituminous materials. Long-term aging, which simulates field aging during the first five to ten years of service, was achieved by further aging of the bitumen using the Pressurized Aging Vessel (PAV) (ASTM D 6521). Residue from the rolling thin film oven test (RTFOT) was placed in the PAV chamber and aged for 20 hours under an air pressure of 2,100 kPa and an aging temperature at 100^0C. The aging temperature at 100^0C was adopted taking into account the moderately high air temperature in Hong Kong.

To minimize the rutting and to control the fatigue of bituminous mixtures, the rheological properties of the bitumen of a particular Performance-grade (PG) should comply with the following three conditions.

Original (as-supplied)

DSR modulus for quality control Stiffness value : $G^*/\sin\delta \geq 1.0$ kPa

RTFO (simulates aging that occurs during the mixing and laying process)

Rutting at high temperature Stiffness value : $G^*/\sin\delta \geq 2.2$ kPa

RTFO+PAV (simulates long-term aging in service)

Fatigue cracking at intermediate temperature Stiffness value : $G^*\sin\delta \leq 5{,}000$ kPa

4.2 Analysis of Test Results

4.2.1 Penetration Test Result

The penetration test results of the seven bitumens at 25°C are shown in Table 4.1.

Table 4.1 Results of Penetration Test

Penetration at 25^{0}C (0.1mm)	Bitumen No.							Requirements in Hong Kong
	1	2	3	4	5	6	7	
Reading 1	61	65	61	65	65	68	68	
Reading 2	61	66	62	66	64	67	70	
Reading 3	61	65	60	65	64	67	66	
Average	61	65	61	65	64	67	68	60 - 70
Retained Penetration after TFOT (%)	69	71	66	68	70	61	63	>52

From the test results, it can be concluded that the penetration values of each of the seven bitumens are consistent. Bitumens No. 1 and No. 3 have the lowest penetration value of 61 whereas Bitumens No. 6 and 7 have the highest penetration values. The penetration values of Bitumens No. 2, 4 and 5 fall within the middle range. Nevertheless, the averages of all bitumens comply with the local specification. They are classified as Penetration-grades 60-70 bitumens.

From the test results on retained penetration after aging, penetration values of all the seven bitumens at aged condition are smaller than those at virgin condition. It indicates that the bitumens have hardened during the aging process. The retained penetration values of all bitumens comply with local specification. Bitumens No. 6 and 7 have the lowest retained penetration values among all the bitumens. The results suggest that the penetration values of Bitumens No. 6 and 7 may be susceptible to the aging process by TFOT as the penetration values drop relatively large as compared to others. Another factor is that the penetration values of Bitumens No. 6 and 7 are already high in the unaged condition.

4.2.2 Softening Point Test Result

The softening point test results of the seven bitumens are presented in Table 4.2. The softening point was reported as the mean of the temperatures at which the bitumen at the two disks softened enough to allow each ball, enveloped in bitumen, to fall a distance of 25 mm. The softening points of the seven bitumens are very similar and the largest difference is only 1.2^{0}C. The softening points of the seven bitumens all comply with the local specification.

Table 4.2 Results of Softening Point

Softening Point (^0C)	Bitumen No.							Requirements in Hong Kong
	1	2	3	4	5	6	7	
Left Ball	49.6	49.6	49.6	48.3	49.4	48.6	48.6	
Right Ball	50.0	49.4	49.8	48.8	49.0	48.6	48.7	
Average	49.8	49.6	49.8	48.6	49.2	48.6	48.6	44 - 55

4.2.3 Summary of Conventional Test Results

For ease of reference and comparison, all the conventional test results conducted under the study for the basic properties of all the seven bitumens are presented in Table 4.3.

Table 4.3 Results of Conventional Tests

Test	Bitumen No.							Require-ments in Hong Kong
	1	2	3	4	5	6	7	
Penetration at 25^0C (0.1mm)	61	65	61	65	64	67	68	60 - 70
Softening Point (^{0}C)	49.8	49.6	49.8	48.6	49.2	48.6	48.6	44 - 55
Ductility at 25^0C (cm)	>100	>100	>100	>100	>100	>100	>100	>100
Viscosity (Pa·s) at 60^0C	270	228	249	217	231	187	263	-
Retained penetration after TFOT (%)	69	71	66	68	70	61	63	>52
Loss on heating (%)	0.00	0.00	0.05	0.00	0.00	0.05	0.10	-
Solubility (%)	99.90	99.95	99.95	99.80	99.80	99.60	99.75	>99
Density at 25^0C (kg/m^3)	1030	1010	1030	1030	1030	1020	1010	-

From the test results above, major findings can be drawn as follows:

1) From the penetration test results, the penetration values of the seven bitumens are similar and they all lie between 60-70.

2) There are no significant differences in the softening points of the bitumens and

the largest difference is only 1.2^{0}C.

3) The ductility test results indicate that all bitumens were able to elongate over the minimum requirement of 100 cm at the temperature of 25^{0}C.

4) Bitumens No. 1 (currently used in Hong Kong) and 7 have similar viscosity at the temperature of 60^{0}C, which are greater than other bitumens, and thus have lower temperature susceptibility. Bitumen No. 6 has the lowest viscosity, which is the least viscous at the testing temperature.

5) Bitumens No. 6 and 7 have the lowest retained penetration values among all the bitumens. The results suggest that the penetration values of Bitumens No. 6 and 7 may be susceptible to the aging process by TFOT as the penetration values drop relatively large as compared to others. Another factor is that the penetration values of Bitumens No. 6 and 7 are already high in the unaged condition.

6) All seven bitumens have similar properties in loss of heating, solubility and density. The highest loss on heating is only 0.1% that indicated the bitumens selected have only trace of volatile components. The lowest solubility is only 99.6%, which indicate that all seven bitumens achieve a very high level of solubility.

7) All seven bitumens comply with the local requirements and they are classified

as Penetration-grades 60-70 in the local specification. The local specification is not able to tell more than the above.

4.2.4 Wax Content Test Result

Two specimens of each bitumen were tested for determining the wax content and the results are tabled in Table 4.4.

Table 4.4 Wax Content Test Results

Bitumen No.	Specimen No.	Wax Content (%)			Classification (Grade)
		Individual	Difference	Average	
1	1	2.20	0.08	2.2	A
	2	2.12			
2	1	2.06	0.30	1.9	A
	2	1.76			
3	1	2.55	0.06	2.5	B
	2	2.49			
4	1	2.21	0.10	2.2	A
	2	2.11			
5	1	2.68	0.47	2.9	B
	2	3.15			
6	1	1.98	0.06	2.0	A
	2	1.93			
7	1	2.66	0.02	2.7	B
	2	2.68			

The differences between the two specimens of the same bitumen comply with the requirements of 0.3% and 0.5% for low and high wax content respectively, as specified in GB T0615. In China, bitumen is classified according to the Penetration-grade and is further divided into three sub-grades (A, B and C), according to the wax content. The maximum allowable wax content for Grade A, B and C are 2.2%, 3.0% and 4.5% respectively. The results indicate that the Bitumens No. 1 (currently used in Hong Kong), 2, 4 and 6 are Grade A whereas the Bitumens No. 3, 5 and 7 are Grade B because of their high wax contents. There is no Grade C bitumen in this study.

4.2.5 Effect of Wax Content on Basic Properties

In order to assess the relationship between the wax content and basic properties, the data of three major properties including penetration and softening point, and viscosity of the bitumens were plotted against wax contents as shown in Figure 4.1 and 4.2 respectively.

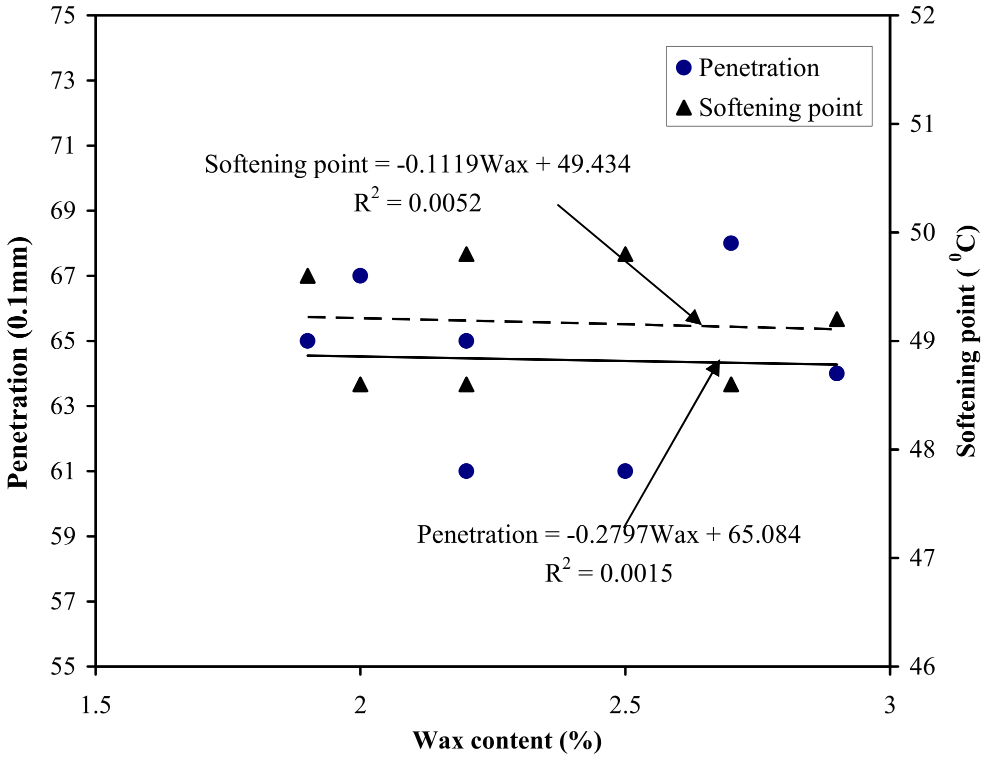

Figure 4.1 Effect of Wax Content on Penetration and Softening Point

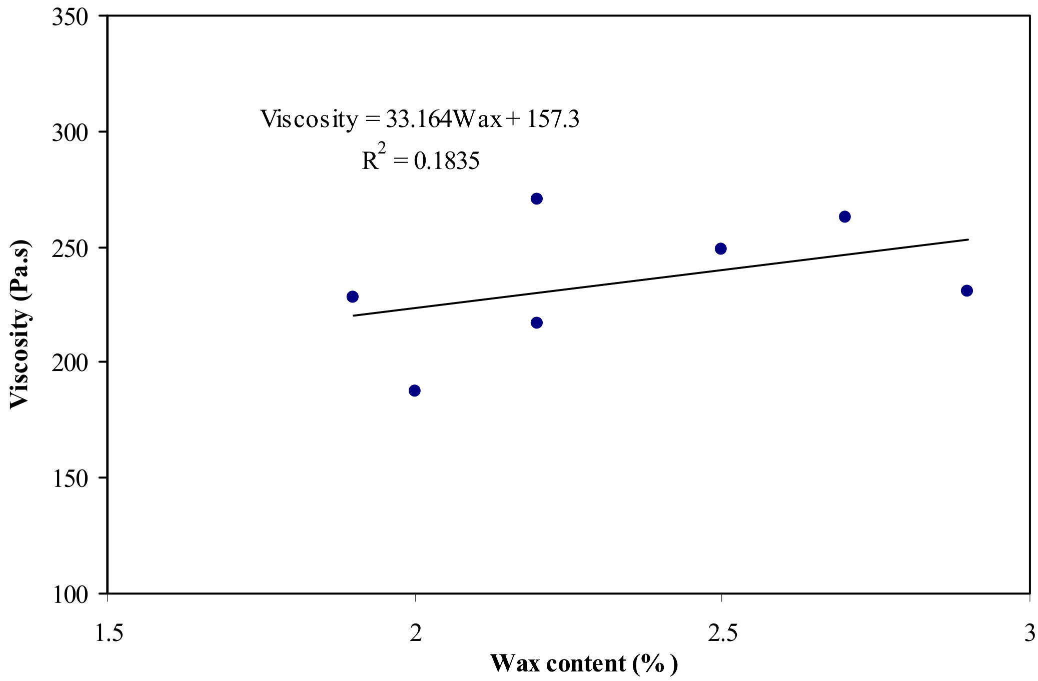

Figure 4.2 Effect of Wax Content on Viscosity

The R^2 of the correlation line of penetration, softening point and viscosity against wax content are 0.0015, 0.0052 and 0.1835 respectively, which indicates that there is hardly any correlation between the wax content and the above basic properties. Theoretically, high wax content in the bitumen should adversely affect the high temperature stability and the test results on viscosity at 60^0C may be able to indicate such effect. However, from the viscosity test results shown in Figure 4.2, the gradient of the correlation line is positive, indicating that bitumen of higher wax content may also give high viscosity. This contradicts the above assumption. This result may be attributed to the unsuitability of these conventional testing methods for determining the rheological properties of the bitumen and the selection of bitumen samples of a narrow range of wax content under similar Penetration-grades.

4.2.6 Dynamic Shear Rheometer (DSR) Test Result

Three specimens of each of the seven bitumens were tested by the DSR and a typical set of test results under the original, aging conditions after RTFO and PAV conditions are presented in Table 4.5, 4.6 and 4.7 respectively.

Table 4.5 DSR Test Results of Original Bitumens

Bitumen No.	Temperature (^oC)	G*/sin(δ) (kPa)	Phase angle (δ) (Degree)	Complex modulus (G*) (kPa)
1	52.1	15.92	82.0	15.8
	58.0	6.58	84.5	6.55
	64.2	3.03	86.2	3.02
	70.2	1.43	87.5	1.43
	76.1	0.70	88.5	0.70
2	52.0	13.44	85.0	13.39
	57.9	5.70	86.2	5.69
	64.0	2.53	87.2	2.53
	69.9	1.24	87.9	1.24
	75.9	0.64	88.4	0.63
3	52.1	6.70	86.5	6.69
	57.9	2.81	87.7	2.81
	63.9	1.23	88.6	1.23
	69.9	0.56	89.1	0.56
4	52.1	13.21	85.9	13.18
	58.0	5.31	87.2	5.31
	63.9	2.38	88.0	2.38
	70.1	1.15	88.7	1.15
	76.0	0.57	89.0	0.57
5	52.2	9.50	82.0	9.41
	57.9	4.17	84.3	4.15
	64.6	1.73	86.3	1.73
	70.1	0.86	87.4	0.86
6	52.1	13.21	86.4	13.19
	58.1	5.62	87.7	5.61
	64.0	2.29	88.7	2.29
	70.1	1.08	89.2	1.08
	75.9	0.58	89.7	0.58
7	52.1	9.98	84.2	9.93
	57.9	4.39	86.0	4.38
	63.9	2.00	87.4	2.00
	70.0	0.95	88.5	0.95

Table 4.6 DSR Test Results of RTFO Conditioned Bitumens

Bitumen No.	Temperature (^oC)	G*/sin(δ) (kPa)	Phase angle (δ) (Degree)	Complex modulus (G*) (kPa)
1	51.0	41.10	76.2	39.92
	58.1	15.28	80.3	15.06
	64.3	6.71	83.2	6.66
	70.2	3.04	85.3	3.03
	76.2	1.54	86.8	1.53
2	52.0	26.77	79.4	26.31
	58.0	11.30	82.2	11.19
	64.0	4.87	84.5	4.85
	70.0	2.30	86.3	2.30
	76.1	1.05	87.6	1.05
3	52.0	22.39	82.9	22.22
	58.0	9.28	85.0	9.24
	64.0	3.92	86.6	3.91
	70.0	1.74	87.7	1.74
4	52.2	29.24	79.8	28.78
	58.1	12.49	82.6	12.39
	64.2	5.18	84.7	5.16
	70.3	2.21	86.5	2.21
	76.1	1.53	87.2	1.53
5	52.0	17.03	81.6	16.85
	58.0	7.16	83.6	7.11
	63.9	3.03	85.1	3.02
	69.9	1.50	86.5	1.49
6	52.1	31.90	79.8	31.40
	58.0	13.63	82.6	13.51
	64.0	5.90	84.9	5.87
	70.1	2.70	86.6	2.69
	76.2	1.30	88.0	1.30
7	52.0	21.29	82.8	21.12
	57.9	9.04	84.9	9.01
	63.9	3.97	86.5	3.96
	69.9	1.84	87.7	1.84

Table 4.7 DSR Test Results of PAV Conditioned Bitumens

Bitumen No.	Temperature (°C)	G* sin(δ) (kPa)	Phase angle (δ) (Degree)	Complex modulus (G*) (kPa)
1	31.0	1904.99	59.1	2220.1
	28.0	3005.12	55.1	3664.1
	25.0	4636.15	51.3	5940.5
	22.0	7020.20	47.3	9552.4
2	31.0	1946.53	60.1	2245.4
	28.0	2992.52	56.8	3576.3
	25.0	4629.29	53.3	5773.8
	22.1	6843.80	49.7	8973.5
3	31.3	2541.25	56.0	3065.3
	28.2	3777.04	52.9	4735.6
	25.3	5593.71	49.7	7334.4
4	31.2	2095.83	62.5	2362.8
	28.2	3225.57	59.2	3755.2
	25.3	5044.82	55.7	6106.8
5	31.1	2598.90	50.9	3348.9
	28.6	3680.57	47.9	4960.5
	25.4	5339.87	45.2	7525.5
6	31.1	2128.94	58.9	2486.3
	28.3	3214.42	55.5	3900.4
	25.3	4967.60	51.6	6338.7
	22.2	7603.15	47.4	10329.0
7	31.1	2369.34	55.8	2864.7
	28.1	3571.50	52.9	4477.9
	25.3	5181.90	49.8	6784.4

4.2.7 Effect of Wax Content on Rheological Properties

Comparison between the dynamic shear rheology and result obtained from the conventional tests has been conducted. Similar to the relationship between the index values of the basic tests and wax content, no sound correlation can be found between these index values and the rheological properties of bitumens.

The effect of wax content on the rheological properties of bitumens under different conditions is discussed in the following sections:

4.2.7.1 Original Bitumen

The rheology results obtained from the original bitumens prior to any conditioning are illustrated in Figure 4.3. In accordance with the AASHTO, the value of high temperature stiffness value (G*/sinδ) was determined at 6^0C intervals, increasing from 52^0C until the stiffness value was below l.0 kPa. The high temperature PG grade of the bitumen was the value of the temperature obtained just before l.00 kPa was reached. It is evident that all the seven bitumens belong to either PG64 or PG70. All Grade A bitumens No. 1, 2, 4 and 6 (with wax content not greater than 2.2%) can be classified as PG70, whereas the other three Grade B bitumens No. 3, 5 and 7 (with wax content greater than 2.2% but smaller than 3.0%) belong to PG64.

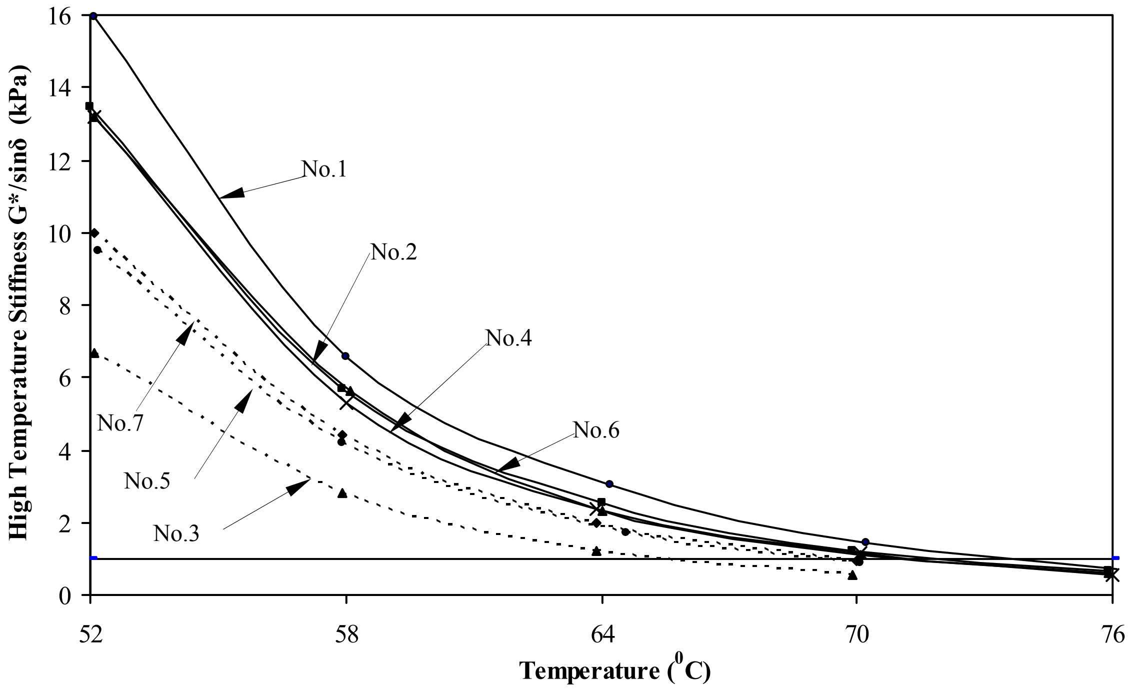

Figure 4.3 High Temperature Stiffness of Original Bitumens

As seen in Figure 4.3, Bitumen No. 1 generally has greater stiffness value than others under the range of testing temperature and thus it is relatively less susceptible to deformation. The rheological properties of original Bitumen No. 2, 4 and 6 are very similar. Though Bitumen No. 5 and 7 are similar in rheological properties, they are generally more susceptible to deformation under high temperature range. Bitumen No. 3 has the lowest resistance to permanent deformation among all bitumens under high temperatures.

4.2.7.2 RTFO Conditioned Bitumen

Fourteen specimens, i.e. two specimens for each bitumen, were prepared for DSR test and further aging under the PAV. The change in sample mass after RTFOT was measured and presented in Table 4.8. The value of mass loss was measured to the nearest 0.001%. The result indicates that the changes in mass of all the specimens are not significant and satisfy the requirement of not exceeding ± 1.0%.

Table 4.8 Change of Mass of Specimens after RTFOT

Bitumen No.	Specimen No.	Specimen Mass (g)	Loss of Mass (%)
1	1	35.30	-0.026
	2	34.88	-0.016
2	1	35.51	0.026
	2	35.22	0.009
3	1	35.27	-0.110
	2	34.65	-0.050
4	1	35.14	-0.530
	2	35.01	0.089
5	1	34.83	0.080
	2	35.34	0.070
6	1	35.33	-0.100
	2	35.32	-0.050
7	1	35.24	0.042
	2	35.34	0.008

The rheology results obtained from the bitumens after RTFOT is presented in Figure 4.4. In accordance with the AASHTO, the value of high temperature stiffness (G*/sinδ) was also determined at 6^0C intervals, increasing from 52^0C but until the stiffness value was below 2.2 kPa. The PG grade of the bitumen was the value of the temperature obtained just before 2.2 kPa was reached. The test results indicate that the seven bitumens after RTFOT belong to either PG64 or PG70. It is also noted that for each bitumen, there is no difference in PG between the original and the RTFO conditions.

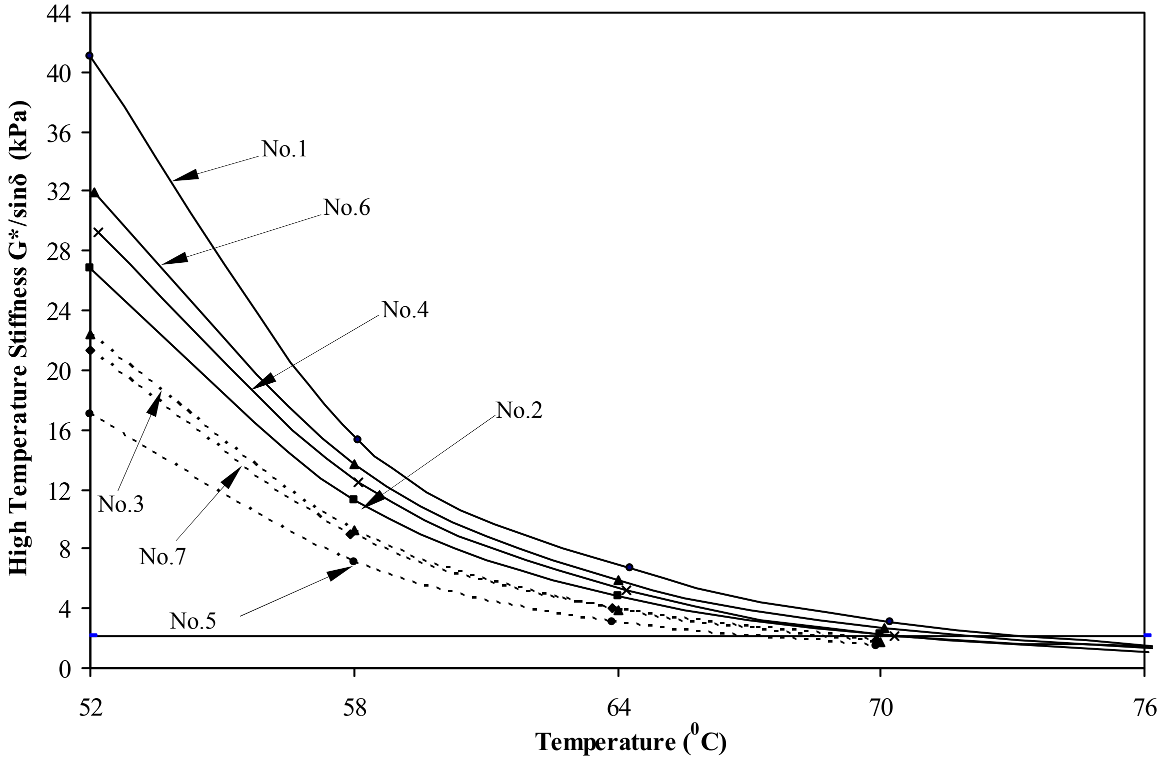

Figure 4.4 High Temperature Stiffness of RTFO Conditioned Bitumens

As shown in Figure 4.3 and 4.4, the general trend of G*/sinδ value changes over temperature is similar for the seven bitumens. G*/sinδ value drops with the increase in temperature. Generally, when the temperature at the lower range, G*/sinδ value drops more rapidly but the reduction rate decreases with the temperature increase. The difference of G*/sinδ value is narrowed down with increasing temperature. Under the original and RTFO conditions, Bitumen No. 1 generally has greater G*/sinδ value than others.

4.2.7.3 PAV Conditioned Bitumen

The rheology results obtained from the PAV conditioned bitumens are presented in Figure 4.5. In accordance with the AASHTO, the value of intermediate temperature stiffness (G* sinδ) was determined at $3^{o}C$ intervals, decreasing from $31^{0}C$ until the stiffness value was above 5,000 kPa. With the test results, the PG grade of the bitumen related to the low temperature stiffness was read directly from the AASHTO requirements. The test results indicate that the starting low temperature grades of the three bitumens (No. 3, 5 and 7) belong to PGxx-16, one bitumen (No. 4) belongs to PGxx-22 and the remaining three bitumens (No. 1, 2 and 6) are PGxx-28. It is noted that the three bitumens of PGxx-16 are Grade B bitumen. The other four bitumens belong to Grade A bitumen.

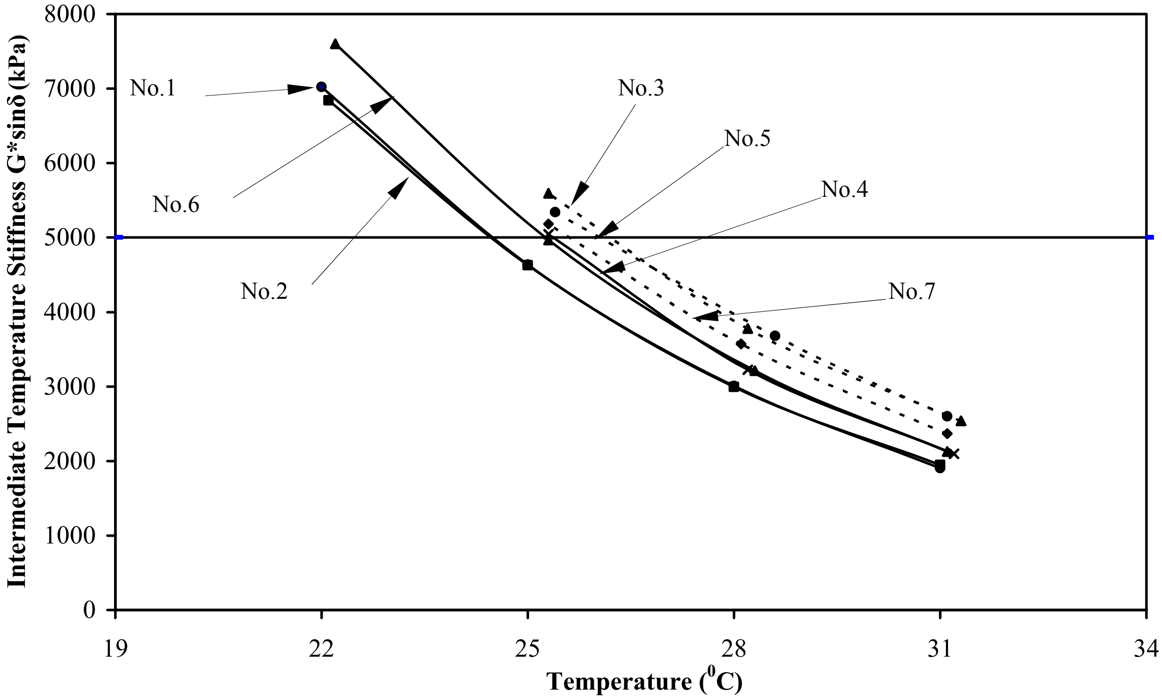

Figure 4.5 Intermediate Temperature Stiffness of PAV Conditioned Bitumens

4.2.7.4 Wax Content and DSR Data Analysis

In order to investigate the effect of wax content on the rheological properties of bitumen, the temperatures at various DSR stiffness values of each bitumen under different conditions were determined by interpolation for evaluation.

Original Bitumens

For the original bitumens, the temperature at critical DSR stiffness value (G*/ sinδ reaches 1 kPa) of each bitumen was plotted against the wax content as given in Figure 4.6. It indicates that the temperatures of bitumens of high wax content are generally lower than that for bitumens with low wax content. This suggests that the high temperature stability of the original bitumen at the time the stiffness value of G*/ sinδ reaches 1 kPa is adversely affected by the amount of wax content. The relationship of the wax content and the temperature of bitumen at the time the stiffness values of G*/ sinδ reaching 1 kPa, 2 kPa, 4 kPa and 8 kPa are shown in Figure 4.7 for comparison.

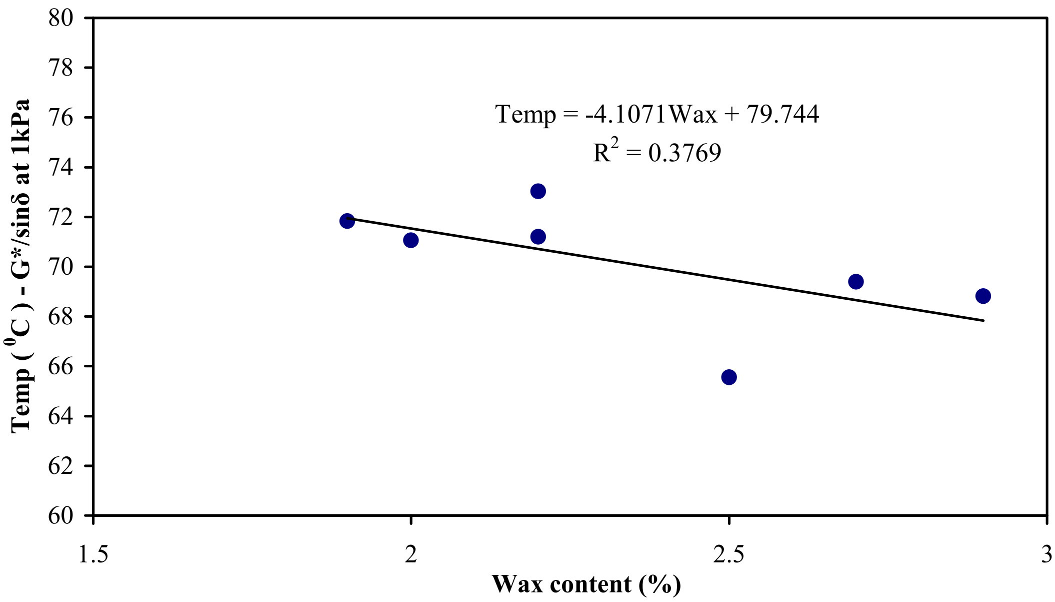

Figure 4.6 Temperature of Original Bitumen (G*/ sinδ reaches 1 kPa)

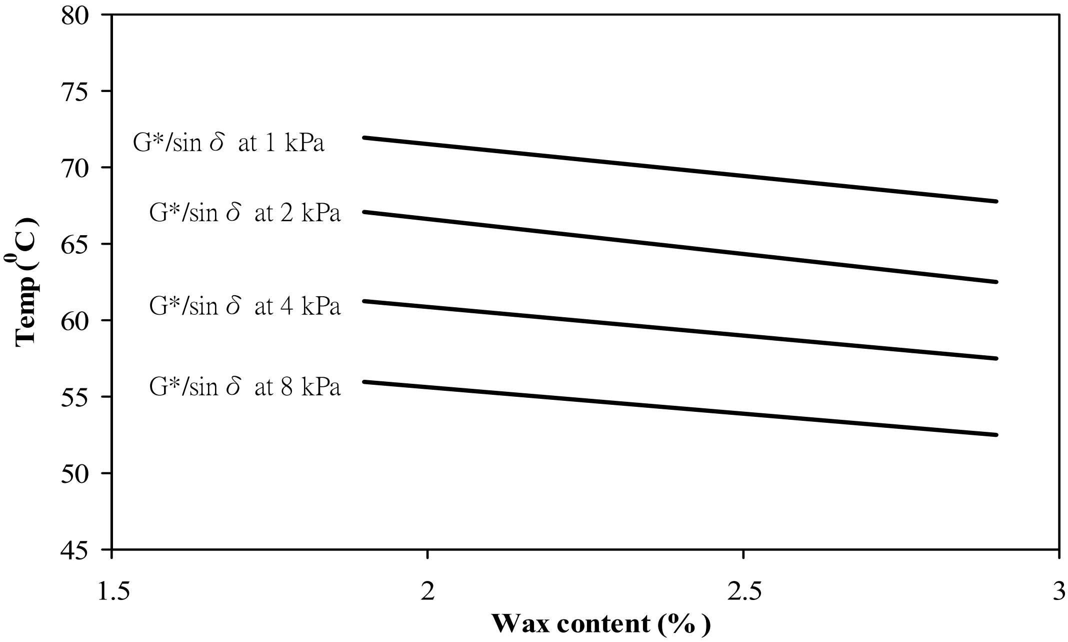

Figure 4.7 Temperature of Original Bitumen (Various G*/ sinδ Levels)

The R^2 values of the correlation line of temperature against wax content under various stiffness value of G*/ sinδ are presented in Table 4.9.

Table 4.9 R^2 of Correlation Line at Various Stiffness Value for Original Bitumen

Stiffness value, G*/ sinδ (k Pa)	R^2 of Correlation Line
1.0	0.3769
2.0	0.4541
4.0	0.3849
8.0	0.3885

RTFO Conditioned Bitumen

Under the RTFOT aging condition, the temperature at critical DSR stiffness value (G*/ sinδ reaches 2.2 kPa) of each bitumen was plotted against the wax content as given in Figure 4.8. It shows that the temperatures of bitumens of high wax content are generally lower than that for bitumen with low wax content. This suggests that the high temperature stability of the RTFO conditioned bitumen at the time the stiffness value of G*/ sinδ reaches 2.2 kPa is adversely affected by the amount of wax content, which is similar to original bitumen. The relationship between the wax content and the temperature of bitumen at the time the stiffness values of G*/ sinδ reaching 2.2 kPa, 4 kPa, 8 kPa and 16 kPa are shown in Figure 4.9 for comparison.

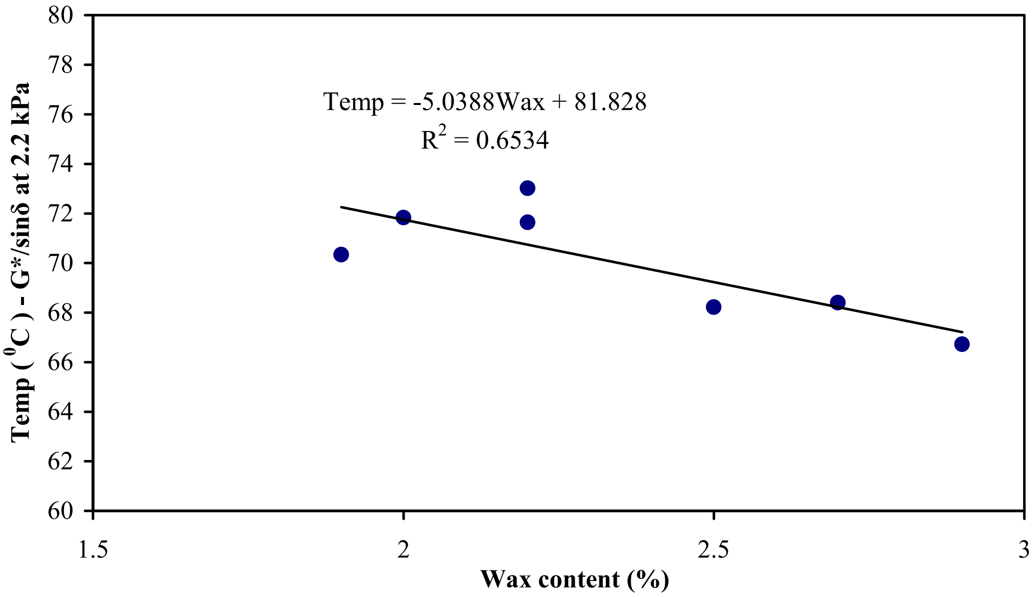

Figure 4.8 Temperature of RTFO Conditioned Bitumen

(G*/ sinδ reaches 2.2 kPa)

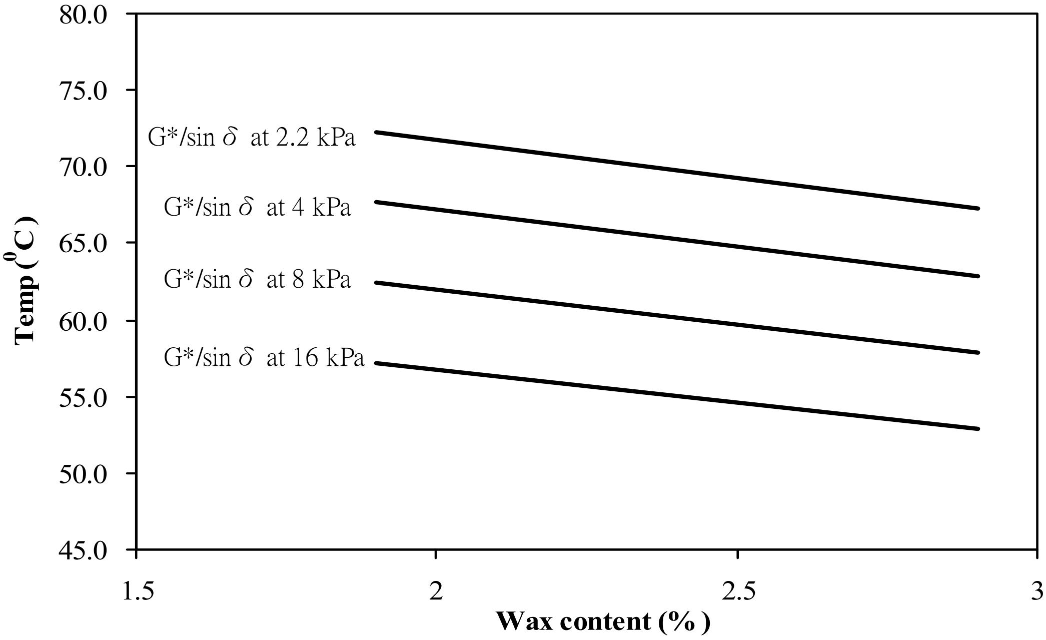

Figure 4.9 Temperature of RTFO Conditioned Bitumen

(Various G*/ sinδ Levels)

The R^2 values of the correlation line of temperature against wax content under various stiffness value of G*/ sinδ are presented in Table 4.10.

Table 4.10 R^2 of Correlation Line at Various Stiffness Value for RTFO Conditioned Bitumen

Stiffness value, G*/ sinδ (k Pa)	R^2 of Correlation Line
2.2	0.6534
4.0	0.6612
8.0	0.6684
16.0	0.6726

PAV Conditioned Bitumen

Under the PAV aging condition, the temperature at critical DSR stiffness value (G* sinδ reaches 5,000 kPa) of each bitumen was plotted against the wax content as given in Figure 4.10. It indicates that the temperatures of bitumens of high wax content are generally higher than that for bitumen with low wax content. This suggests that high wax content adversely affects the intermediate temperature stability of bitumen under the long-term aging condition. The relationship between the wax content and the temperature of bitumen at the time the stiffness values of G* sinδ reaching 5,000 kPa, 4000 kPa and 3,000 kPa are shown in Figure 4.11 for comparison.

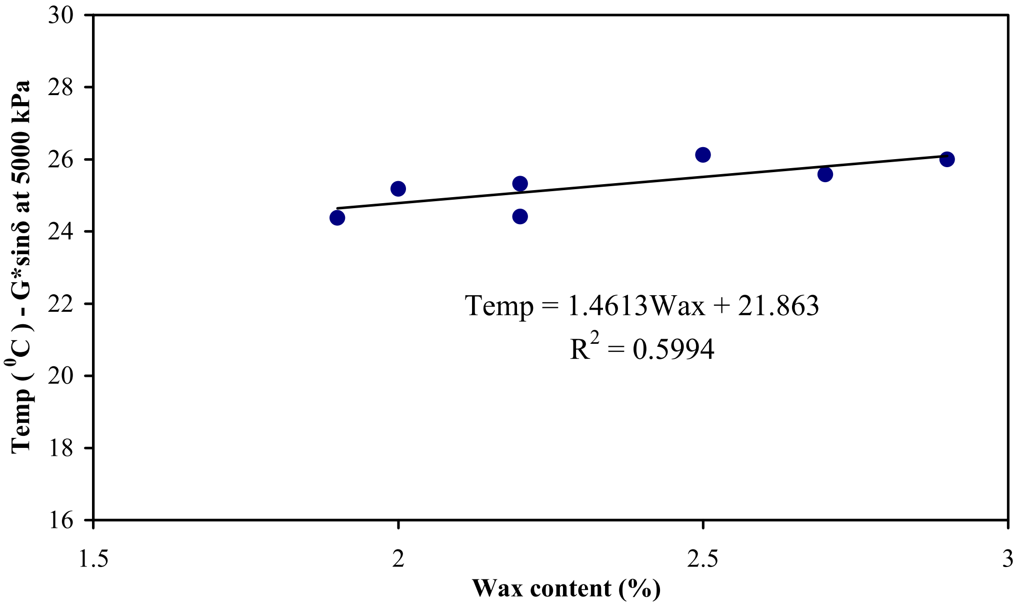

Figure 4.10 Temperature of PAV Conditioned Bitumen

(G* sinδ reaches 5,000 kPa)

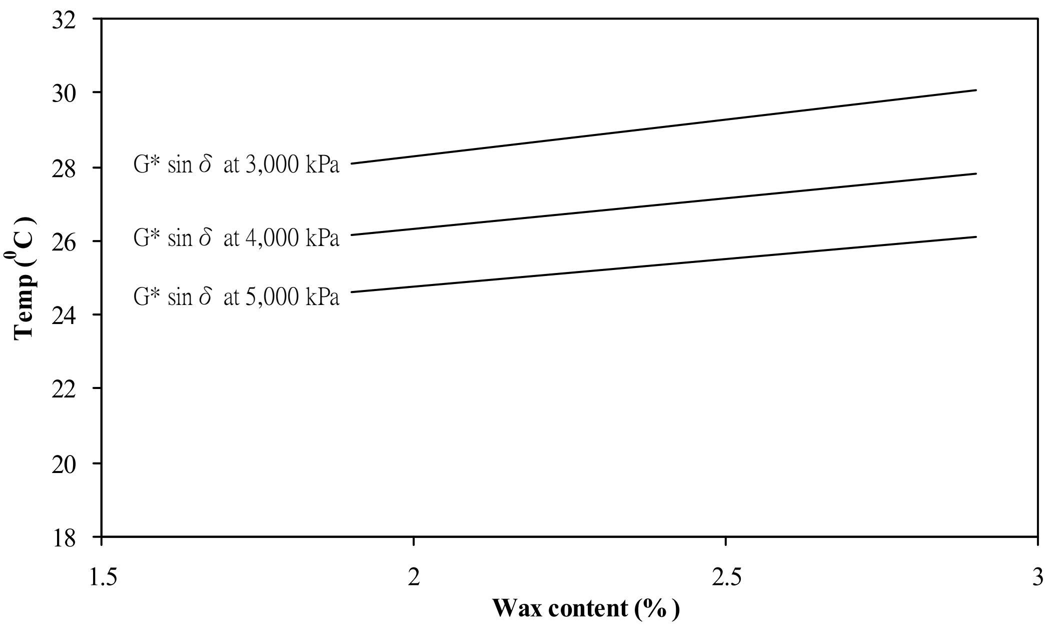

Figure 4.11 Temperature of PAV Conditioned Bitumen

(Various G* sinδ Levels)

The R^2 values of the correlation line of temperature against wax content under various stiffness value of G* sinδ are presented in Table 4.11.

Table 4.11 R^2 of Correlation Line at Various Stiffness Value for PAV Conditioned Bitumen

Stiffness value, G* sinδ (k Pa)	R^2 of Correlation Line
3000	0.6878
4000	0.6471
5000	0.5994

The R^2 of the correlation line of temperature against wax content under the original, RTFOT and PAV conditions at critical stiffness values are 0.3769 (1.0 kPa), 0.6534 (2.2 kPa) and 0.5994 (5,000 kPa) respectively. The correlations of temperature against wax content at various levels of stiffness values under original and different ageing conditions are similar and follow the same trend. Though the R^2 value under the original condition is quite low and less than 0.5, the values under the RTFOT and PAV aging conditions are higher than 0.5 and are all much higher than those of the basic test results and wax contents. It is concluded that the rheology test is more appropriate to evaluate the effect caused by the high wax content in bitumen. With more testing data, it is believed that the R^2 value can be further increased.

According to the wax content and rheology test results, Grade A bitumens are PG70, which is one grade higher than the other Grade B bitumens, indicating that bitumens of low wax content are performing better than those of high wax content with respect to the high temperature stability according to the Superpave specifications. For ease of reference, the Performance-grades and wax content gradings are presented in Table 4.12. Though the bitumens selected for this study are all Penetration-grades 60-70 and the range of wax content was not so wide because there were only Grade A and B bitumens, the relationship between the wax contents and temperatures at critical stiffness values under different aging conditions could be clearly established and demonstrated.

Table 4.12 Performance-grade and Wax Content Grading

Bitumen No.	Wax Content Level (Grading)	Performance-grade (PG)	
		High Temperature Grade	Starting Low Temperature Grade
1	A	70	28
2	A	70	28
3	B	64	16
4	A	70	22
5	B	64	16
6	A	70	28
7	B	64	16

Note : This study mainly focuses on the performance of bitumen in Hong Kong where it is of tropical climate. The low temperature grade under the PG system is therefore not a major concern and thus the other relevant tests including the Bending Beam Rheometer and Direct Tension Tester have not been carried out. The low temperature grade of PG determined in this study is the starting low temperature grade based on the rheology test results.

4.3 Major Findings in Tests of Bitumen

1) All the seven bitumens are Penetration-grade 60-70 and satisfy the requirements of the Hong Kong specification for the ordinary and unmodified bitumen.

2) Bitumens produced from crude oil deposited in the Middle East have low wax content and are classified as Grade A according to the Chinese standard. Bitumens produced from crude oil deposited in China are either Grade A or Grade B. There is no Grade C bitumen in this study.

3) No sound correlation between the wax contents and the index values obtained from the conventional tests was identified in the study. This may be attributed to the unsuitability of these conventional methods for determining the effect of wax content on the performance of bitumen and the selection of bitumen samples of a narrow range of wax content under similar Penetration-grades.

4) Under the original and RTFOT aging (short-term) conditions, the temperatures of bitumens of high wax content are generally lower than that of bitumen with low wax content at respective critical stiffness values. In other words, the higher the wax content of the bitumen is, the lesser its ability to resist permanent deformation and hence the bitumen is more susceptible to damage under high temperature.

5) Under the PAV aging (long-term) condition, the temperatures of bitumens of high wax content are generally higher than that of bitumen with low wax content at the critical stiffness value, which is contrary to the original and RTFOT aging conditions. It is thus believed that the bitumen with low wax content will perform better than that with high wax content with respect to resistance to fatigue at low temperature, though the tests were performed at intermediate temperatures. In summary, results of the DSR test indicate that high wax content adversely affects the high and intermediate temperature stability of bitumen.

6) The R^2 of the correlation line of temperature against wax content under the original, RTFOT and PAV aging conditions at respective critical stiffness values are 0.3769 (1.0 kPa), 0.6534 (2.2 kPa) and 0.5994 (5,000 kPa) respectively. Though the R^2 value under the original condition is quite low and less than 0.5, the values under the RTFOT and PAV aging conditions are higher than 0.5 and are much higher than those of the basic test results and wax contents, which varied between 0.0015 to 0.1835. The performances of bitumen at both high and intermediate temperatures have relatively good correlation with the wax contents. In addition, the correlations of temperature against wax content at various levels of stiffness values under the original and

different ageing conditions are similar and follow the same trend.

7) According to the classification based on the DSR test results, the Grade A bitumens belong to PG70, whereas Grade B bitumens are PG64. The starting low temperature grades of the Grade B bitumens belong to PGxx-16, whereas the Grade A bitumens are higher grades of either PGxx-22 or PGxx-28.

8) Bitumens of Grade A or PG70 have been proven to perform better and provide stronger resistance to deformation and flow than bitumens of PG64 or Grade B at high temperature.

9) The tests specified in Hong Kong are unable to assess the effect of wax content on the performance of bitumen.

Chapter 5

Testing on Bituminous Mixture

With a view to understanding the effect of wax content on the performance of the bituminous mixtures and to supplementing the findings of the tests on bitumens, laboratory test results, bituminous paving materials were prepared in the laboratory for further testing. In view of the huge amount of laboratory works required for preparing the bituminous mixtures and performing the subsequent tests, and the limited quantity of bitumen available for the tests, Bitumen No. 1 (currently used in Hong Kong) and Bitumen No. 5 (supplied by Maoming) of different wax content levels among the seven bitumens tested were selected for preparing bituminous mixtures. The wax contents of Bitumen No. 1 and 5 are 2.2% and 2.9% and are classified as Grade A and B respectively in accordance with Chinese standards. Under the PG grading system, Bitumen No. 1 and 5 are of PG 70 and 64 respectively. According to the test results from Chapter 4, Bitumen No. 1 is expected to perform better and provide stronger resistance to deformation and flow than Bitumen No. 5 at high temperature. For comparing the properties of the bituminous materials made of the two bitumens, the mix design of both materials follows a local mix design for the 20 mm size wearing course material. The performance of the wearing course materials are presented in the following sections.

5.1 Test Methods on Bituminous Mixture

A series of laboratory tests for assessing the fundamental mechanical properties and durability performance including volumetric properties, stiffness, strength and resistance to deformation of the two types of bituminous were conducted. The two bitumens used were Bitumen No. 1 (currently used in Hong Kong and supplied by Shell) and Bitumen No. 5 (supplied by Maoming). Cylindrical samples were prepared and compacted as described in Chapter 3 for the testing. The test methods on cylindrical samples are described as follows:

5.1.1 Volumetric Property Test

The test on volumetric properties of bituminous mixtures covered the determination of the bulk relative density, theoretical maximum specific density and percent air voids of the specimens of the two laboratory moulded bituminous mixtures. The main objective of the tests was to:

- Calculate the amount of bitumen absorbed by the aggregate;
- Calculate the percent air void of the compacted bituminous mixture;

- Provide target values for the compaction of paving mixtures; and
- Compare the volumetric properties of laboratory moulded specimens and from the mix design

In accordance with ASTM D 3203, for wearing course mixtures which are dense bituminous paving mixtures, the percent air voids in a compacted bituminous paving mixture was calculated from Equation (5).

$$\text{Percent Air Voids} = 100 \times (1 - \frac{\text{Gmb}}{\text{Gmm}}) \quad \text{.............................(5)}$$

where: Gmb = bulk specified gravity of mixture

Gmm = theoretical maximum specified gravity of mixture

Three cylindrical specimens (of size ø150mm×60mm) were prepared for each of the two bituminous mixtures for determining Gmb according to ASTM D 2726. To avoid the influence of differences in gradation and bitumen content, uncompacted comparable bituminous mixtures were prepared to determine Gmm in accordance with ASTM D 2041.

5.1.2 Indirect Tensile Stiffness Modulus Test

Indirect Tensile Stiffness Modulus (ITSM) tests were conducted to evaluate the load spreading ability of the mixtures in accordance with BS EN 12697-26. The tests were performed by using the Nottingham Asphalt Tester (NAT) NU-10 (Figure 5.1) on cylindrical specimens from the gyratory compactor. The temperatures chosen for the ITSM tests were based on temperatures appropriate to the Hong Kong environment. Thus the stiffness tests were carried out at the standard temperature of 20^0C and at higher temperatures of 30^0C and 35^0C. Stiffness values under extreme high temperature are not consistent and not recommended as the unbound condition of the specimen cannot provide a load spreading platform to determine the stiffness. Three cylindrical specimens (of size ø 150 mm × 60 mm) of each bituminous mixture were prepared for ITSM testing at three specified temperatures. The stiffness modulus of the bituminous mixtures was calculated from Equation (6).

$$S_m = \frac{L}{(D \times t)} \times (v + 0.27) \quad \text{.......................................(6)}$$

where:

	L	=	peak value of the applied vertical load (in N)
	D	=	peak horizontal diametral deformation resulting from the applied load (in mm)
	t	=	mean thickness of the test specimen (in mm)
	v	=	value of Poisson's ratio for the bituminous mixture at the temperature of test ($v = 0.35$)

Figure 5.1 Nottingham Asphalt Tester (NAT) NU-10

Tests were carried in a temperature-controlled chamber. Before tests were conducted, specimens were placed in the chamber at the testing temperature for conditioning. Load was applied by a pneumatic load actuator of which a load could be applied vertically across the diameter of the test specimen via the loading platens (Figure 5.2). Under each load application, the peak transient horizontal diametral deformation of the test specimen was measured and recorded by two linear variable differential transducers (LVDT). For each specimen, load was applied firstly at one axis for five times and the average of the stiffness value was calculated. The specimen was then rotated through (90^0) horizontal axis for the second test and load was applied for five times and the average of the stiffness modulus was again calculated. The mean of these two readings was the stiffness modulus of this specimen.

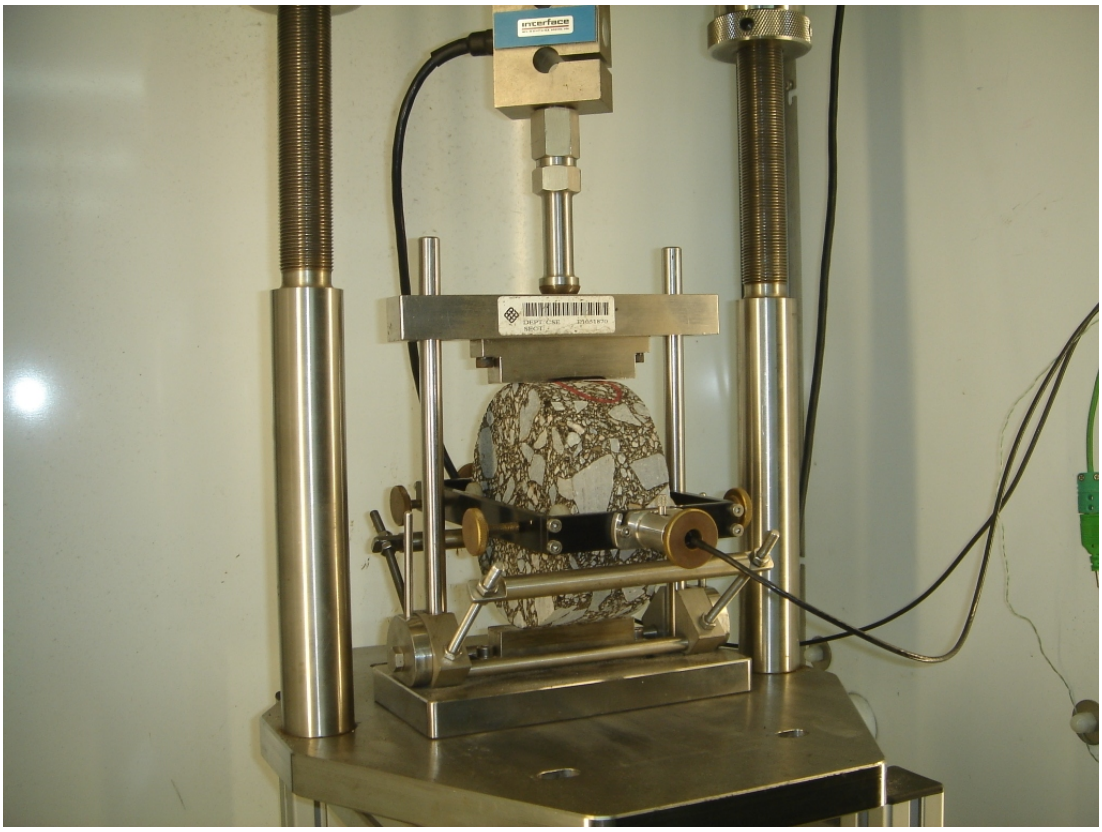

Figure 5.2 Loading Platens and LVDT in NAT

5.1.3 Indirect Tensile Strength Test

Hong Kong has tropical climate and the rainfall intensity and frequency is relatively great. Thus, the effect of water on the performance of the bituminous paving materials should be one of the major concerns on its durability during the service life. There are two main mechanisms by which moisture can impair the integrity and durability of bituminous mixture:

- Loss of the cohesion of bitumen film; and
- Failure of the adhesion between aggregates and bitumen

When the aggregate tends to have a preference for absorbing water, the bitumen would be susceptible to be stripped away. Thus, requirements for allowable water absorption of aggregates have been specified in the local specification. Bitumen stripping leads to premature distress of pavement that reduces the ultimate service life of the pavement.

In order to assess the water sensitivity of the two bituminous mixtures, the tests for Indirect Tensile Strengths (ITS) on the specimens before and after water conditioning were carried out in accordance with AASHTO T283. ITS was defined as the maximum stress from a diametrical vertical force that a sample could withstand.

The test involved the application of the vertical force at a loading rate of 50 mm per minute until the maximum load was reached under a testing temperature of 25^0C.

Six cylindrical specimens (of size ø 100 mm × 63.5 mm) of each bituminous mixture were prepared for testing. Three unconditioned specimens were tested for ITS (Figure 5.3) whereas the other three specimens were soaked into the water for conditioning according to AASHTO T283 prior to testing.

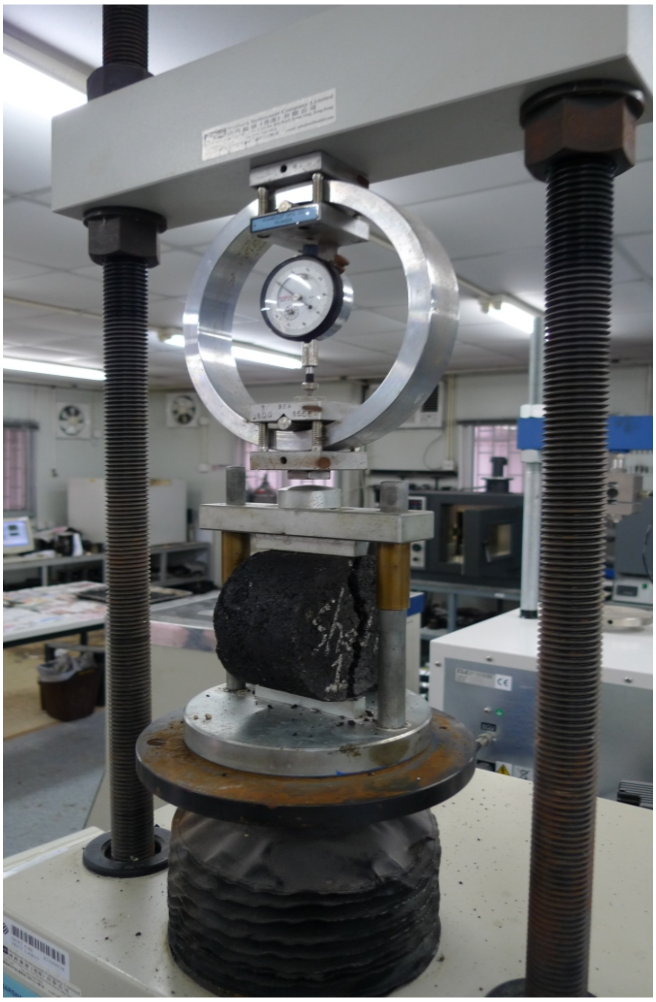

Figure 5.3 Set up for ITS Test

The value of ITS was determined according to Equation (7).

$$S_t = \frac{2000 \times P}{\pi \times t \times D} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (7)$$

where: S_t = indirect tensile strength (kPa)

P = maximum load (N)

t = specimen height (mm)

D = specimen diameter (mm)

From the measured indirect tensile strengths, the indirect tensile strength ratio (ITSR) was calculated for each sample according to Equation (8).

$$ITSR = \frac{S_{tm}}{S_{td}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (8)$$

where: S_{tm} = average tensile strength of the moisture-conditioned subset

S_{td} = average tensile strength of the unconditioned subset

5.1.4 Cyclic Compression Test (with Confinement)

The resistance to permanent deformation of bituminous materials can be determined by the creep characteristics of the mixtures by means of cyclic compression. In this study, Method A of BS EN 12697-25 by using an uniaxial cyclic compression with some confinement on the test specimens was adopted. It is believed that the confinement can better simulate the actual condition in which the material is supported by surrounding material. In the test, a cylindrical specimen was subjected to cyclic axial stress by a load actuator inside a temperature-controlled chamber (Figure 5.4). The diameter of the upper loading platen was taken smaller than that of the sample to achieve a certain confinement given by the edge of the material (Figure 5.5).

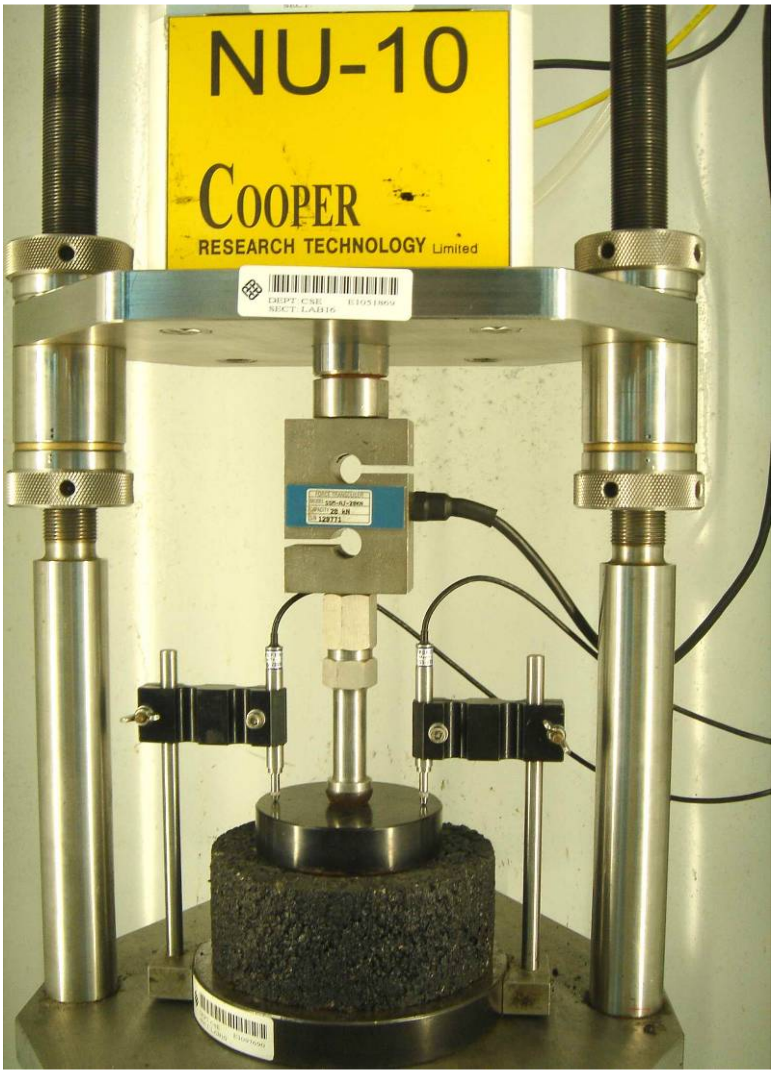

Figure 5.4 Application of Load in Cyclic Compression Test

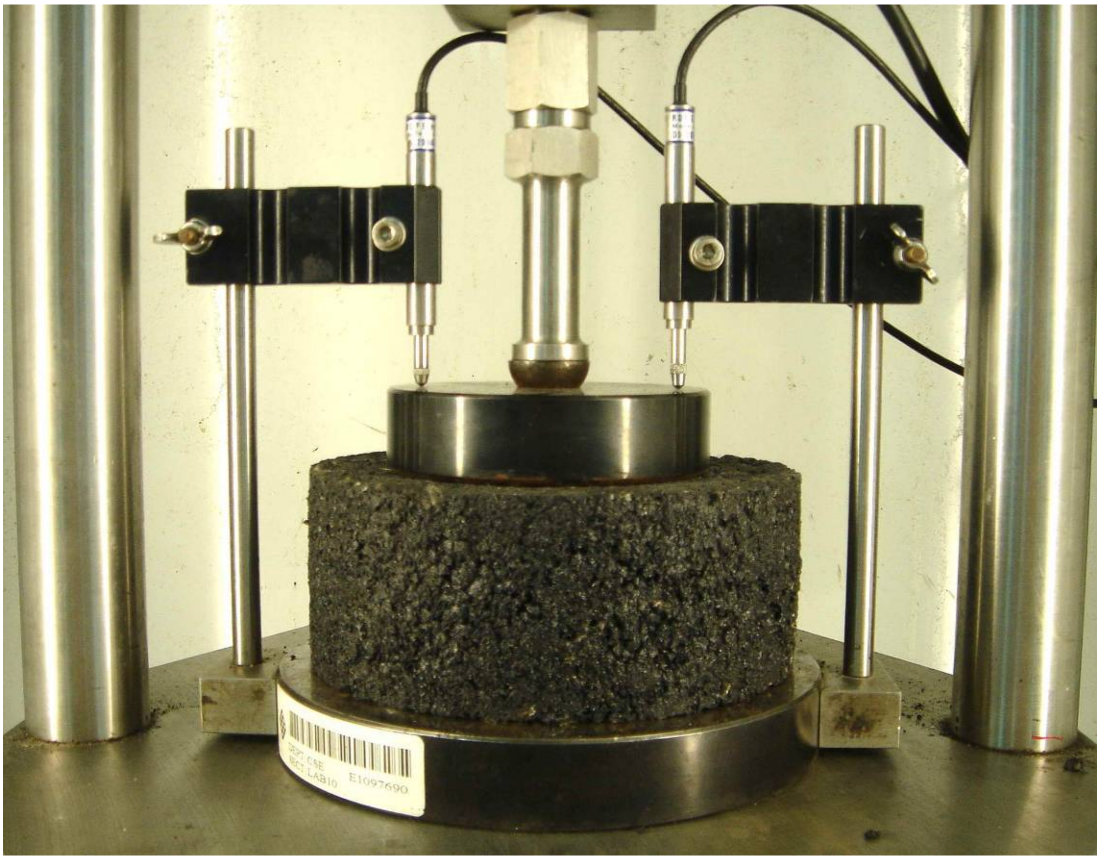

Figure 5.5 Test Apparatus for Cyclic Compression Test

Three cylindrical specimens (of size ø 150 mm × 60 mm) of each bituminous mixture were prepared for testing under an elevated conditioning temperature of 40^0C. The testing conditions of the cyclic compression test are presented in Table 5.1. Test results would be useful to study the performance of resistance to permanent deformation.

Table 5.1 Testing Conditions of Cyclic Compression Test

Item	Conditions
Testing Temperature (^{0}C)	40 ± 0.5
Axial Stress (kPa)	100
Load Application Period (s)	1
Rest Period (s)	1
Test Duration (s)	3,600
Upper Loading Diameter (mm)	100
Condition Stress (kPa)	10

Figure 5.6 shows the cumulative axial strain, expressed in %, of a specimen as a function of the number of load applications. Generally the following stages can be distinguished:

- Stage 1: the (initial) part of the deformation curve, where the slope of the curve decreases with increasing number of loading cycles;
- Stage 2: the (middle) part of the deformation curve, where the slope of the curve is quasi constant and with a turning point on the deformation curve; and
- Stage 3: the (last) part of the deformation curve, where the slope increases with increasing number of loading cycles.

Depending on the testing conditions and on the mix, one or more stages may be absent.

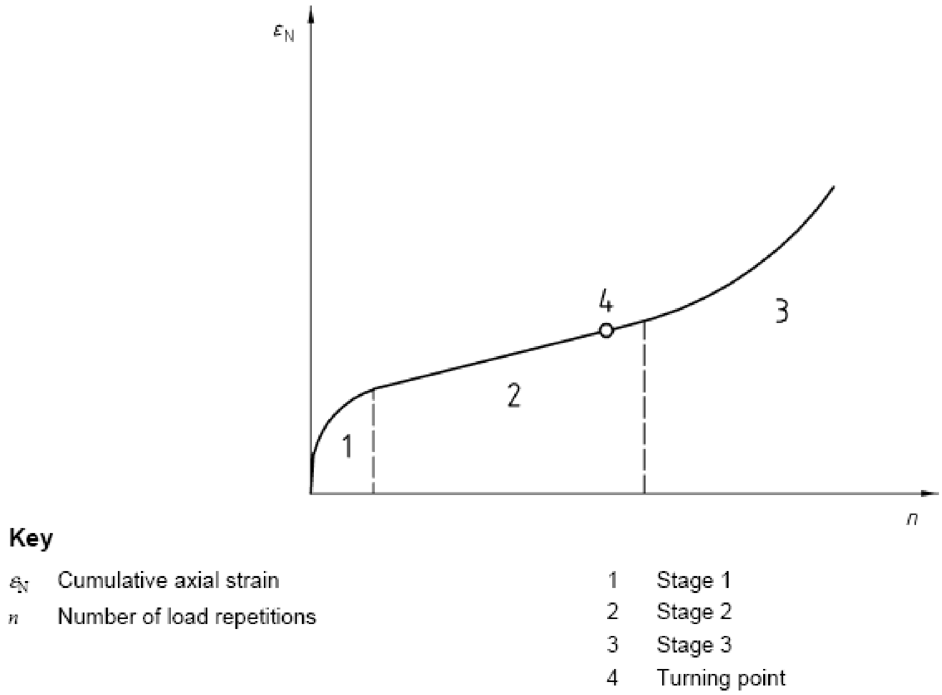

Figure 5.6 Typical Creep Curve (EN 12697-25)

5.2 Analysis of Test Results

5.2.1 Volumetric Property

The results of bulk relative density, theoretical maximum specific density and percent air voids of the two types of bituminous mixtures are presented in Table 5.2. Table 5.3 presents, together with the target volumetric requirements, a summary of the results obtained from the volumetric property test in the current study. There is little difference between the measured densities and the required densities, indicating that the materials have been compacted to meet the air voids and density requirements of the local mix design.

Table 5.2 Density and Air Void of Bituminous Mixtures

Mixture Type	Specimen No.	Gmb (g/cm^3)	Specimen No.	Gmm (g/cm^3)	Air Void (%)
Bitumen No. 1	1	2.346	4	2.440	3.84
	2	2.339	5	2.437	4.02
	3	2.341	6	2.435	3.87
	Average	2.342	Average	2.437	3.91
Bitumen No. 5	1	2.350	4	2.452	4.17
	2	2.345	5	2.441	3.92
	3	2.339	6	2.438	4.05
	Average	2.345	Average	2.444	4.05

Note : Gmb and Gmm denote bulk relative density and theoretical maximum specific density respectively.

Table 5.3 Comparison of Density and Air Voids with Target Volumetric Requirements

Mixture Type	Average Results		Target Volumetric Requirements	
	Gmm (g/cm^3)	Air Void (%)	Gmm (g/cm^3)	Air Void (%)
Bitumen No. 1	2.437	3.91	2.435	4.0
Bitumen No. 5	2.444	4.05	2.435	4.0

5.2.2 Indirect Tensile Stiffness Modulus

The Indirect Tensile Stiffness Modulus (ITSM) test results of the two bituminous mixtures at testing temperatures of 20^0C, 30^0C and 35^0C are summarized in Table 5.4, 5.5 and 5.6 respectively. Stiffness modulus of a mix is related to its load spreading ability and thus to be related to its rutting resistance. A bituminous mixture with low stiffness modulus normally would result in larger rutting during the service life. Detailed data from the ITSM test is presented in **Appendix A**.

Table 5.4 ITSM Test Result at 20^{0}C

Mixture Type	Specimen No.	Indirect tensile stiffness modulus			
		1st reading (MPa)	2nd reading (MPa)	Mean (MPa)	Overall average (MPa)
Bitumen No. 1	1	3912	3802	3857	3887
	2	3890	3874	3882	
	3	4015	3826	3921	
Bitumen No. 5	1	2564	2468	2516	2543
	2	2576	2524	2550	
	3	2618	2510	2564	

Table 5.5 ITSM Test Result at 30^{0}C

Mixture Type	Specimen No.	Indirect tensile stiffness modulus			
		1st reading (MPa)	2nd reading (MPa)	Mean (MPa)	Overall average (MPa)
Bitumen No. 1	1	1293	1315	1304	1279
	2	1278	1259	1269	
	3	1295	1231	1263	
Bitumen No. 5	1	791	766	779	788
	2	813	800	807	
	3	781	779	780	

Table 5.6 ITSM Test Result at 35^{0}C

Mixture Type	Specimen No.	Indirect tensile stiffness modulus			
		1st reading (MPa)	2nd reading (MPa)	Mean (MPa)	Overall average (MPa)
Bitumen No. 1	1	761	739	750	756
	2	749	757	753	
	3	771	760	766	
Bitumen No. 5	1	506	547	527	522
	2	545	504	525	
	3	518	513	516	

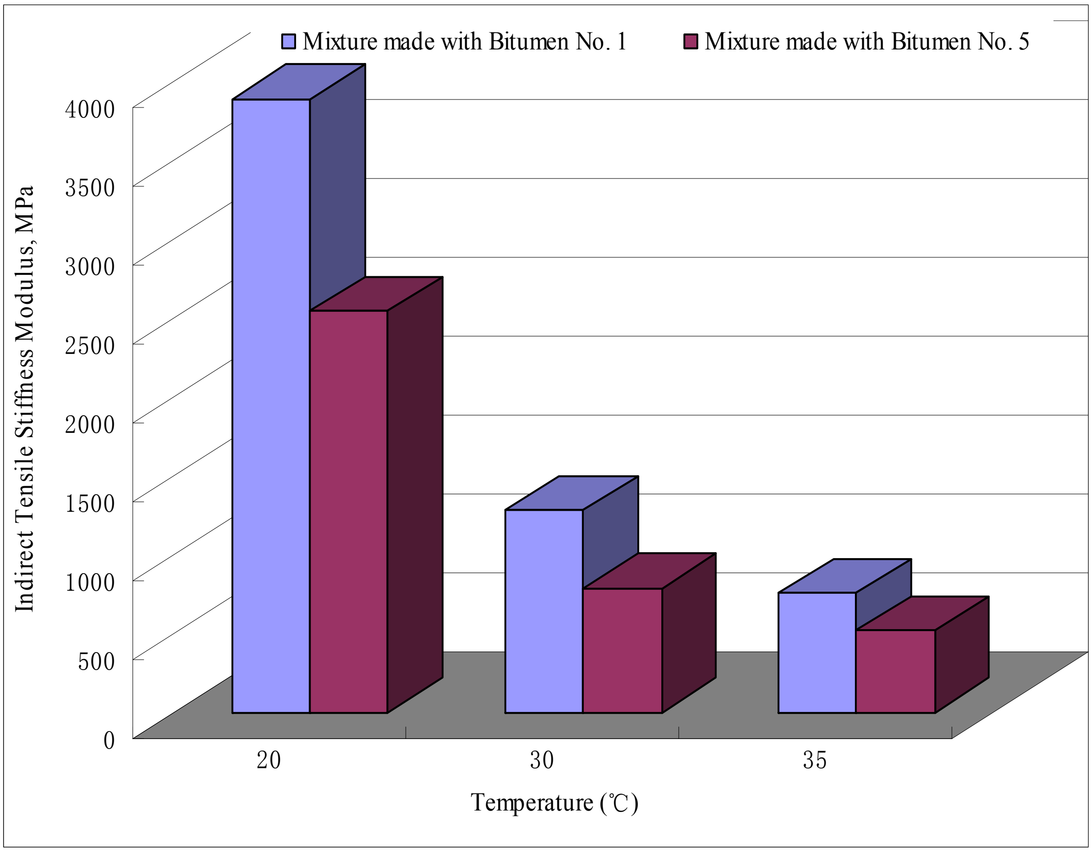

Figure 5.7 Summary of ITSM Test

Stiffness moduli of the two mixtures are illustrated in a bar chart as shown in Figure 5.7 for comparison. The results indicate that the stiffness modulus of bituminous mixtures decrease with increasing temperature. The stiffness values are reduced substantially by about two thirds when the testing temperature is increased from 20^0C to 30^0C followed by a further reduction of another one third when the testing temperature is increased by 5^0C. The stiffness moduli of mixtures made with Bitumen No.5 are about 31% to 38% lower than those of Bitumen No. 1 (Table 5.7). A difference in ITSM value of 10% or less would normally be considered as of little significant; for example, a variation in the test temperature of 1^oC may result in a change of the measured stiffness by 10%. The large difference of ITSM of the two bituminous mixtures is believed to be attributed to the presence of higher wax content in Bitumen No. 5, which may affect the load transferring capacity of the bituminous material.

Table 5.7 Comparison of ITSM of Bituminous Mixtures

Mixture Type	**ITSM (MPa) at Various Temperatures**		
	20^0C	**30^0C**	**35^0C**
Bitumen No. 1	3887	1279	756
Bitumen No. 5	2543	788	522
Difference (%)	-35	-38	-31

5.2.3 Water Sensitivity

The test results for Indirect Tensile Strength (ITS) before and after water conditioning are given in Table 5.8 and 5.9 respectively, and are presented in Figure 5.8. The results of the Indirect Tensile Strength Ratio (ITSR) are presented in Table 5.10 for comparison. Bituminous materials of ITSR over 0.7 are believed to be able to resist water damage. The ITSR of both mixtures exceed 0.8 indicating that these materials have satisfactory performance in resisting water damage. However, the average ITS under the two water conditioning of the mixtures made with Bitumen No. 1 are higher than those of Bitumen No. 5 by 8.9% and 7.3% respectively, suggesting that the high wax content in Bitumen No. 5 may reduce the strength of the material.

Table 5.8 ITS Test Results before Water Conditioning

Mixture Type	Specimen No.	Load (kN)	Indirect Tensile Strength	
			Individual Result (kPa)	Average (kPa)
Bitumen No. 1	1	11.8	1179.5	1120.8
	2	11.2	1121.6	
	3	10.6	1061.2	
Bitumen No. 5	1	10.2	1026.6	1021.3
	2	9.9	988.9	
	3	10.5	1048.4	

Table 5.9 ITS Test Results after Water Conditioning

Mixture Type	Specimen No.	Load (kN)	Indirect Tensile Strength	
			Individual Result (kPa)	Average (kPa)
Bitumen No. 1	1	9.6	963.1	938.0
	2	9.1	908.2	
	3	9.4	942.6	
Bitumen No. 5	1	8.1	814.5	869.9
	2	8.9	891.2	
	3	9.0	904.0	

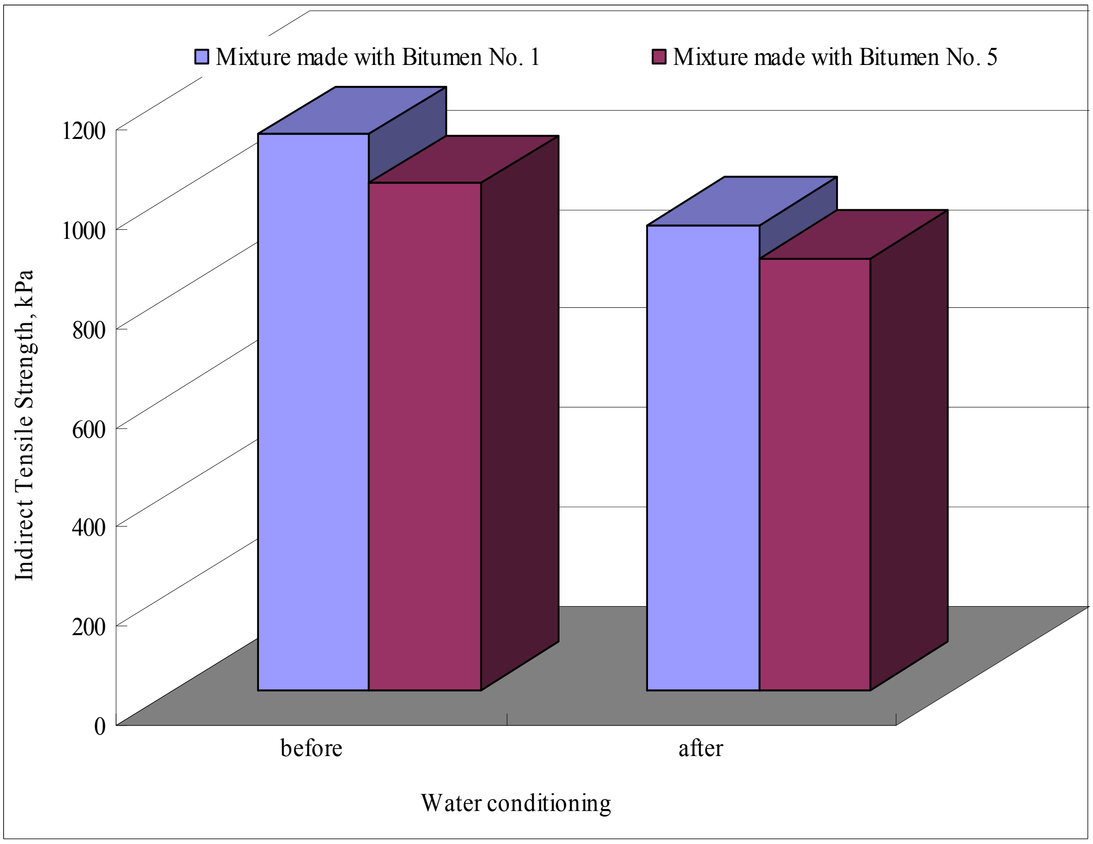

Figure 5.8 Summary of ITS Test Results

Table 5.10 ITS Ratio

Mixture Type	ITS before Water Conditioning (kPa)	ITS after Water Conditioning (kPa)	ITSR
Bitumen No. 1	1120.8	938.0	0.84
Bitumen No. 5	1021.3	869.9	0.85
Difference (%)	-8.9	-7.3	1.8

5.2.4 Resistance to Permanent Deformation

The cyclic compression test results of the permanent axial deformation of Bitumen No. 1 and 5 are plotted in Figure 5.9 and 5.10 respectively. The deformation results of specimens in each bituminous mixture are similar and consistent. A summary of the test results is plotted in Figure 5.11, which shows the average permanent deformation curve of each mixture. Table 5.11 tabulates the end results obtained from each specimen and Figure 5.12 presents a bar chart showing the final permanent deformation after the test. Detailed data from the cyclic compression test is given in **Appendix B**. Though the performance in the resistance to permanent deformation of the two materials are typical and similar, the average axial strain of the mixture made with Bitumen No. 5 at 3600 load cycles is greater than Bitumen No. 1 by 7.8%. The compression tests were stopped at 3600 load cycles according to the standard testing method but Bitumen No. 5 mixture has a tendency of achieving higher strain rate afterwards as shown in Figure 5.11.

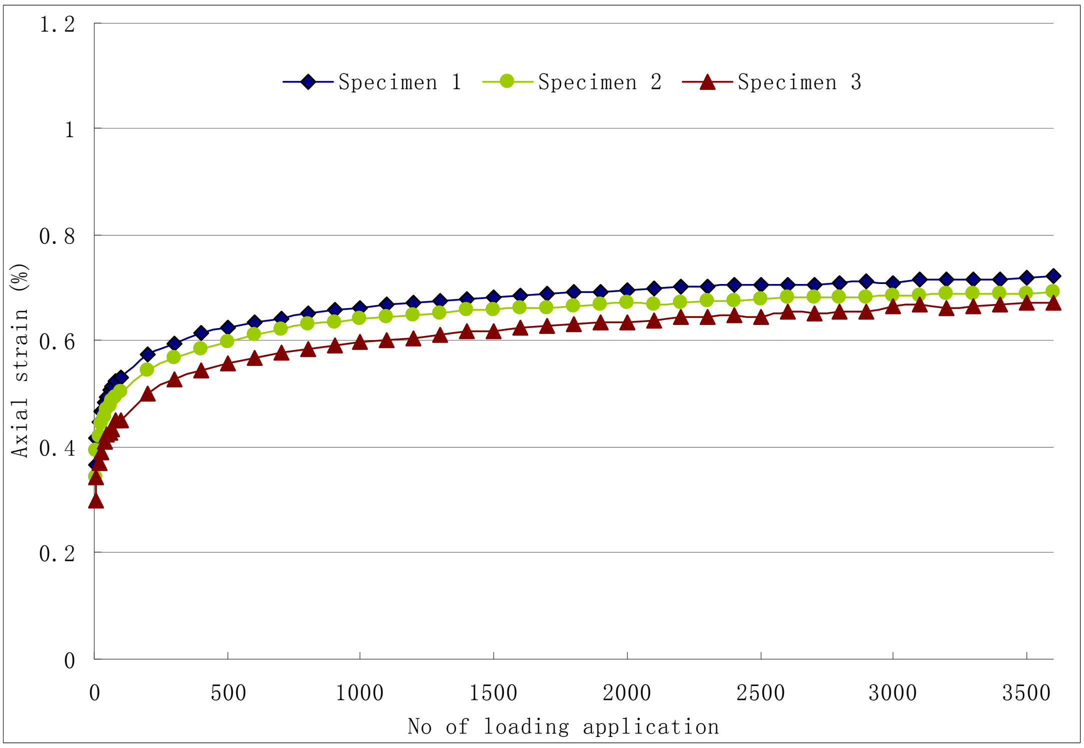

Figure 5.9 Permanent Deformation Results of Bitumen No. 1 Mixture

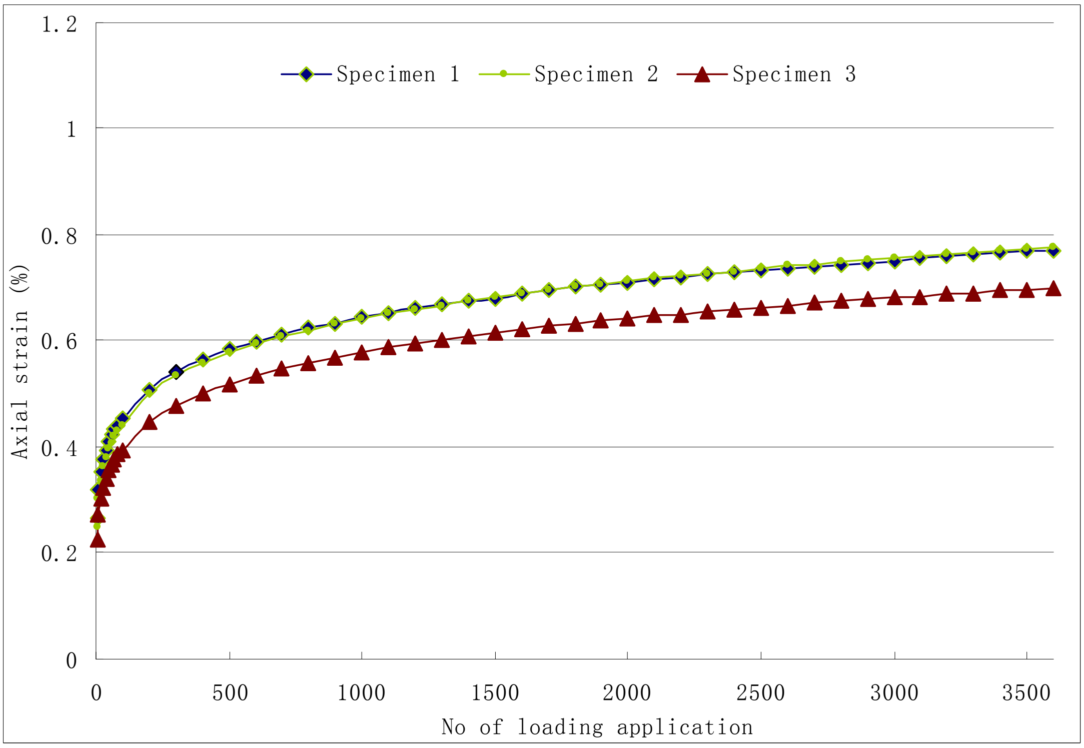

Figure 5.10 Permanent Deformation Results of Bitumen No. 5 Mixture

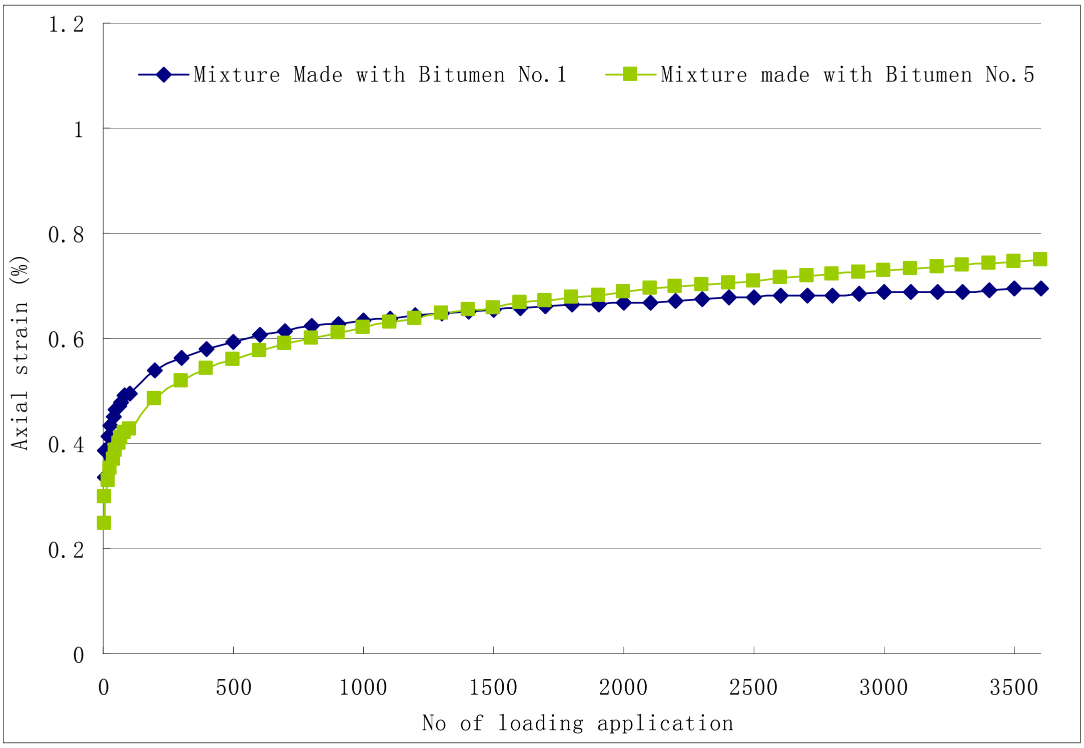

Figure 5.11 Summary of Creep Curves (Average Values)

Table 5.11 Summary of Cyclic Compression Test Results

Mixture Type	Specimen No.	Number of Cycler	Axial Strain (%)	Average Axial Strain (%)
Bitumen No. 1	1	3600	0.7223	0.6950
	2	3600	0.6909	
	3	3600	0.6717	
Bitumen No. 5	1	3600	0.7701	0.7493
	2	3600	0.7776	
	3	3600	0.7003	

5.3 Major Findings in Tests of Bituminous Mixtures

1) There is little difference between the measured densities and percent air voids, and the target values, indicating that the materials have been compacted to meet the air voids and density requirements of the local mix design. The consistency and conformation of volumetric properties are vital to the level of confidence on results of subsequent tests on the laboratory-made mixtures.

2) The stiffness moduli of mixtures made with Bitumen No.5 are about 31% to 38% lower than those of Bitumen No. 1 at different testing temperatures. The large difference of ITSM of the two bituminous mixtures is believed to be attributed to the presence of higher wax content in Bitumen No. 5, which may affect the load transferring capacity of the bituminous material.

3) Bituminous materials of ITSR over 0.7 are believed to be able to resist water damage. The ITSR of both mixtures exceed 0.8 indicating that these materials have satisfactory performance in resisting water damage. However, the average ITS under the two water conditioning of the mixtures made with Bitumen No. 1 are higher than those of Bitumen No. 5 by 8.9% and 7.3% respectively, suggesting that the high wax content in Bitumen No. 5 may reduce the strength of the material.

4) Though the performance in the resistance to permanent deformation of the two

materials are typical and similar, the average axial strain of the mixture made with Bitumen No. 5 at 3600 load cycles is greater than Bitumen No. 1 by 7.8%. The Bitumen No. 5 mixture has a tendency of achieving higher strain rate after 3600 load cycles because of its higher wax content.

Chapter 6

Conclusion and Recommendation

6.1 Conclusion

The conclusions of the study are summarized as follow:

1) All the seven bitumens are Penetration-grade 60-70 and satisfy the requirements of the Hong Kong specification for the ordinary and unmodified bitumen.

2) Bitumens (Bitumen No. 1 and 6) produced from crude oil deposited in the Middle East have low wax content and are classified as Grade A according to the Chinese standard. Bitumens produced from crude oil deposited in China are either Grade A (Bitumen No. 2 and 4) or Grade B (Bitumen No. 3, 5 and 7).

3) No sound correlation between the wax contents and the index values obtained from the conventional tests was identified in the study.

4) Results of the DSR test indicate that high wax content adversely affects the high and intermediate temperature stability of bitumen. The performances of bitumen at both high and intermediate temperatures have relatively good correlation with the wax contents. Grade A bitumens belong to PG70, whereas Grade B bitumens are PG64.

5) Bitumens of Grade A or PG70 (classified by the Chinese. and U.S standards

respectively) have been proven to perform better and provide stronger resistance to deformation and flow than bitumens of PG64 or Grade B at high temperature.

6) The tests specified in Hong Kong are unable to assess the effect of wax content on the performance of bitumen.

7) For the two bituminous materials (made with Bitumen No. 1 and 5) compacted by the gyratory compactor, there are little differences between the measured densities and percent air voids, and the target values, indicating that the materials have been compacted to meet the air voids and density requirements of the local mix design. The consistency and conformation of volumetric properties are vital to the level of confidence on results of subsequent tests on the laboratory-made mixtures.

8) The Indirect Tensile Stiffness Modulus (ITSM) of mixtures made with Bitumen No.5 are about 31% to 38% lower than those of Bitumen No. 1 (currently used in Hong Kong) at different testing temperatures. The large difference of ITSM of the two bituminous mixtures is believed to be attributed to the presence of higher wax content in Bitumen No. 5 (Grade B), which may affect the load transferring capacity of the bituminous material.

9) The Indirect Tensile Strength Ratio (ITSR) of both mixtures exceed 0.8

indicating that these materials have satisfactory performance in resisting water damage. However, the average ITS under the two water conditioning of the mixtures made with Bitumen No. 1 are higher than those of Bitumen No. 5 by 8.9% and 7.3% respectively, suggesting that the high wax content in Bitumen No. 5 may reduce the strength of the material.

10) Though the performance in the resistance to permanent deformation of the two mixtures are typical and similar, the average axial strain of the mixture made with Bitumen No. 5 at 3600 load cycles is greater than Bitumen No. 1 by 7.8%. The Bitumen No. 5 mixture has a tendency of achieving higher strain rate after 3600 load cycles because of its higher wax content.

11) The load spreading ability (stiffness modulus) and the ability to resist the permanent deformation of the bituminous mixture made with Bitumen No. 1 of lower wax content (Grade A) are superior than the mixture of Bitumen No. 5 (Grade B). These findings are in line with those of the analysis of bitumen test results in Chapter 4.

6.2 Recommendation

It is evident that wax in bitumen affects the performance of bitumen and bituminous materials. However, the tests specified in Hong Kong are unable to assess the effect of wax content on the performance of bitumen or the bituminous material. In view of the heavy trafficked conditions of the road network in Hong Kong and to ensure the quality and the performance of bitumen to be used in Hong Kong, the local road authority should review the bitumen specifications and specify requirements on the allowable wax content in the bitumen.

Selection of bitumen for a particular place should be based on the performance of the bitumen under the local environmental and traffic conditions. Hong Kong is now using Penetration-grade 60-70 bitumen. According to the Chinese standard, Hong Kong is located in the 1-4 Climatic Region, where bitumens of penetration values between 40 and 80 might be used. Furthermore, it is worth investigating the Performance-grade that is suitable for Hong Kong. The U.S. standards also recommend that bitumen of one or two grade higher might be used owing to the traffic conditions (e.g. stationary, slow moving or severe traffic).

In this connection, further study to investigate the Performance-grade that is suitable for Hong Kong and to evaluate the suitability and effectiveness of adopting the PG system or other appropriate performance-related grading system is recommended. The test results and findings of this study provide necessary and fundamental data for the further laboratory study.

6.3 Proposed Field Trial

Apart from the laboratory study of bitumen and bituminous materials, a further study is recommended for evaluating the performance of bituminous materials made of different types of bitumens with various wax content levels. The test results for bituminous materials in this study only give an initial assessment on the performance of materials tested under laboratory controlled and simulated conditions. For evaluating the performance of bituminous materials, it is advisable and essential to arrange trial laying of materials on field followed by monitoring and evaluation. However, a number of factors including site constraints in Hong Kong, difficulty in identify suitable trial site, long monitoring period and hence escalated cost for subsequent monitoring impose constraints the implementation of field trials.

6.3.1 Accelerated Pavement Tester (APT)

With a view to addressing the above concerns on field trial, accelerated pavement testers (APT) have been developed and deployed in many countries to evaluate the performance road pavement materials on field. Repeated and fixed loads, normally through tyres, are applied on the pavement materials to shorten the monitoring period. No real traffic is running on the trial pavement, except the applied loads. Some of these APT have been constructed indoor under a temperature-controlled environment with a view to controlling the testing temperature and to avoiding the influence on materials arising from the change of ambient temperature, humidity and climate. Figure 6.1 shows an APT located at Southeast University at Nanjing in China.

Figure 6.1 APT in Southeast University at Nanjing

It is an indoor APT with loads applied by two sets of dual-tyre running on the bituminous pavements along a circular track. The tyres are loaded with weights and connected by steel arms to the motor unit located at the centre of the APT. Heating device has been installed under the pavement to increase and control the temperature of the pavement structure for testing. Appropriate sensors for collecting the temperature, loading and deformation data have also been installed in the pavement. During testing, loaded tyres are running on the pavement surface at fixed speed and data will be collected by the sensors installed regularly. The test may last from a couple of days to weeks depending on the objective and scope of the test.

Similar outdoor APT can be found in France. Figure 6.2 show a bird's eye view of an APT in France. The scale of the APT is larger than the one in Nanjing but it is located outdoor. Loads are applied by four sets of tyres running along a circular track. Various loading configurations for dual-tyre and triple-tyre loading systems are shown in Figure 6.3 and 6.4 respectively. The flexibility of the tyre configuration allows the set up of loading system of that for trucks or even airplanes

Figure 6.2 Bird's Eye View of APT at France (Source from Website)

Figure 6.3 Dual-tyre Loading System (Source from Website)

Figure 6.4 Triple-tyre Loading System (Source from Website)

Loaded tyres in APT are not always travelling in a circular path but sometimes longitudinally in a back-and-forth movement. Figure 6.5 shows a new APT being constructed indoor in Tongji University at Shanghai in China. The research institute was constructing the foundation of the pavement using different types of subgrade followed by overlaying with pavement layers including bituminous material layers. The loading frame and tyres are yet to be installed. Upon completion of the installation works, the APT is believed to be the largest APT in China.

Figure 6.5 APT in Tongji University at Shanghai (Under Construction)

The Hong Kong Road Research laboratory of The Hong Kong Polytechnic University has planned to construct an APT locally for the research of road pavement materials. Figure 6.6 gives the proposed site layout plan of the APT and the associated facilities. Typical cross-section of the APT is shown in Figure 6.7. It is an outdoor APT with loads applied by 4 sets of dual-tyres running on the bituminous pavements along a circular track. The tyres are loaded with weights and connected by steel arms to the motor unit located at the centre of the APT. The construction works for the APT are now in progress and are expected to be completed for commissioning in 2011. Upon completion, large-scale field trial and testing of bituminous materials can be conducted.

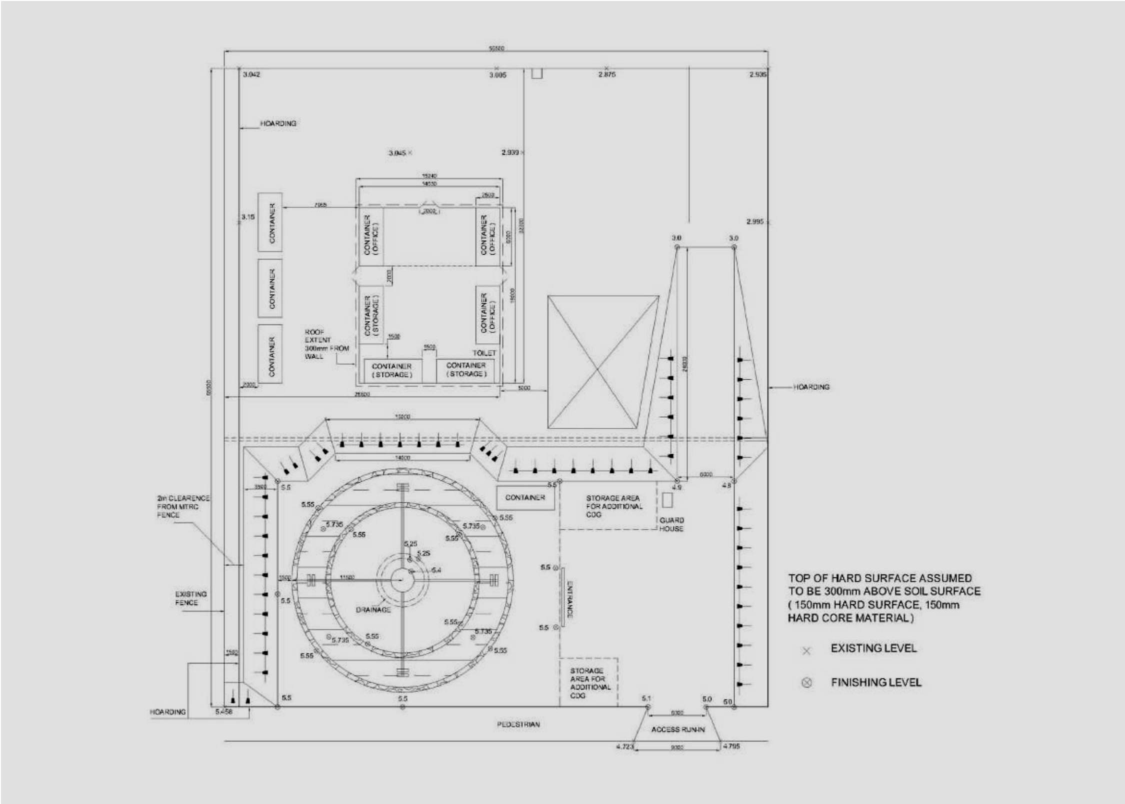

Figure 6.6 Proposed Layout of APT at Shatin (Source from Hong Kong Road Research Laboratory)

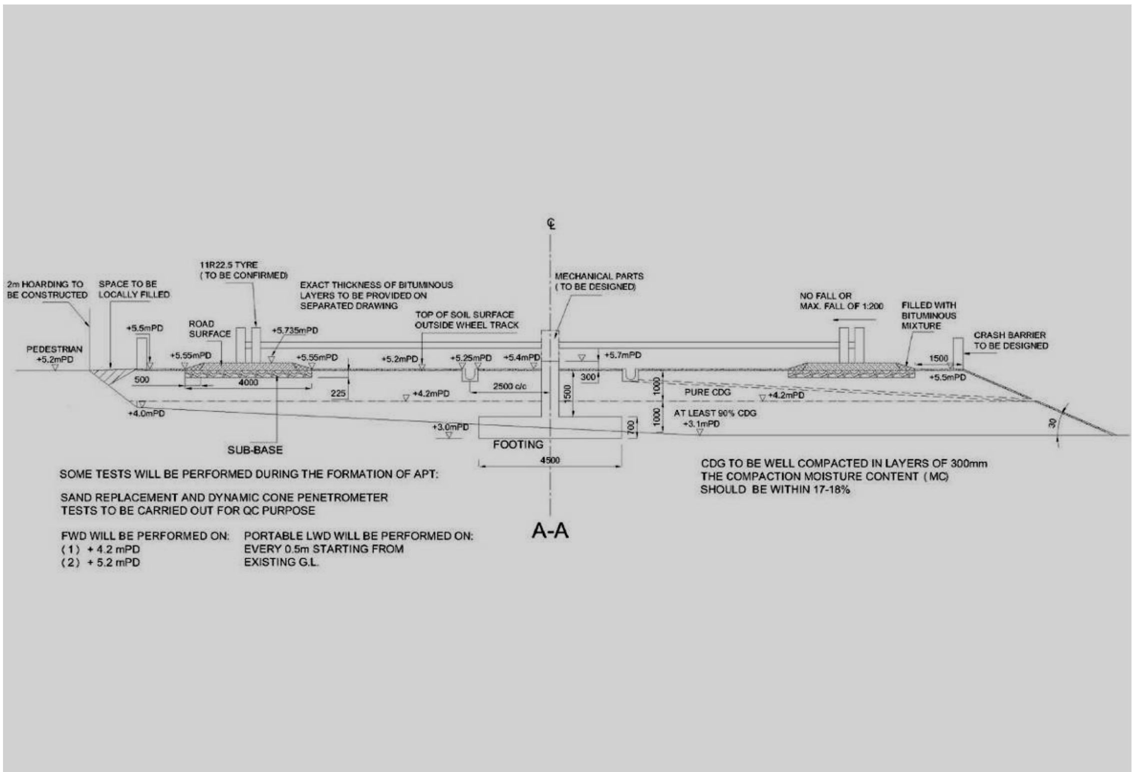

Figure 6.7 Cross-section of APT (Source from Hong Kong Road Research Laboratory)

6.3.2 Research Framework

The main objective of the proposed research is to evaluate on the performance and service life of typical wearing course material (WC) made with different types of bitumen of various wax contents. In addition to the tests on laboratory-made samples, materials produced from the batching plant will be laid on site, which are to be tested under the APT. The research shall also investigate the relationship of the field and laboratory data, which may provide fundamental correlation and prediction model for future studies under different contexts.

The proposed scope of the large-scale field trial for evaluating the performance of bituminous materials made of bitumen with different wax content levels may include the following:-

- to carry out a literature review on different pavement deterioration mechanisms such as rutting, cracking, deflection and etc. for bituminous pavement of different structures
- to construct a full-scale pavement test bed including subgrade, granular sub-base and four types of wearing course materials made with different wax content levels;

- to install instrumentations at the pavement structures to collect data including traffic loads, environmental data including temperature, moisture and pore water pressure, and other associated induced pavement response including vertical strain, horizontal strain and vertical load;
- to prepare specimens and carry out tests on various types of laboratory-made bituminous materials, which are similar to those adopted in this study, and to evaluate the correlation of the laboratory and field data; and
- to benchmark the performance of materials based on laboratory and field data

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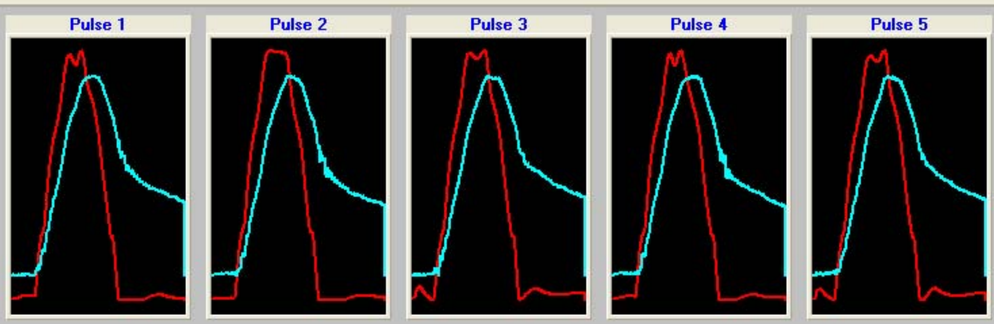
Stiffness of Bitumen No. 1 Mixture at 20^{0}C

Specimen 1 – 1st Reading

itsm7



Pulse No.	Vertical force (kN)	Horizontal stress (kPa)	Risetime (ms)	Horizontal defm (microns)	Pulse shape factor (%)	Stiffness modulus (MPa)	
						Measured	Adjusted
1	2.56	181.0	133	6.9	0.666	3835	3978
2	2.47	174.4	99	6.8	0.577	3728	3680
3	2.55	180.6	146	7.1	0.676	3732	3893
4	2.55	180.5	129	6.7	0.657	3953	4081
5	2.57	181.8	144	7.0	0.671	3774	3926
Mean	2.54	179.7	130	6.9	0.649	3804	3912

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Specimen 1 – 2nd Reading

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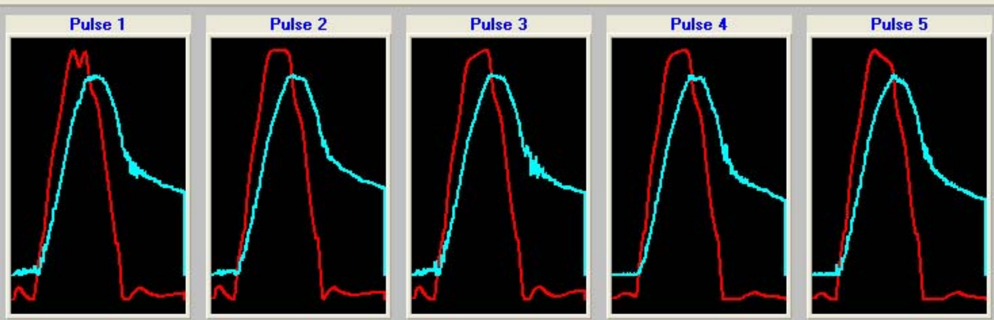

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						Measured	Adjusted
1	2.61	184.5	112	7.1	0.560	3772	3687
2	2.52	178.3	113	7.0	0.586	3729	3699
3	2.55	180.5	145	6.9	0.671	3828	3982
4	2.51	177.2	138	6.9	0.676	3753	3913
5	2.53	178.8	111	6.9	0.583	3764	3727
Mean	2.54	179.8	124	7.0	0.615	3769	3802

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Stiffness of Bitumen No. 1 Mixture at 20^{0}C

Specimen 2 – 1st Reading

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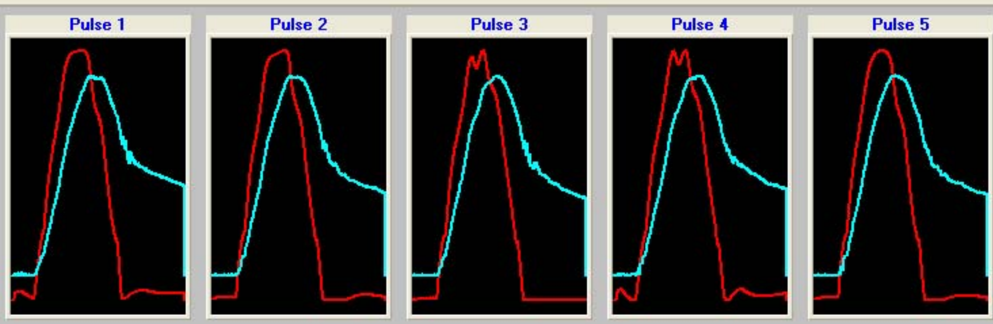

Pulse No.	Vertical force (kN)	Horizontal stress (kPa)	Risetime (ms)	Horizontal defm (microns)	Pulse shape factor (%)	Stiffness modulus (MPa) Measured	Stiffness modulus (MPa) Adjusted
1	2.55	180.4	135	7.2	0.656	3658	3772
2	2.50	177.0	138	6.9	0.677	3761	3925
3	2.58	182.6	133	6.9	0.650	3861	3972
4	2.61	184.5	144	7.1	0.652	3783	3893
5	2.52	178.4	125	6.9	0.645	3793	3889
Mean	2.55	180.6	135	7.0	0.656	3771	3890

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Specimen 2 – 2nd Reading

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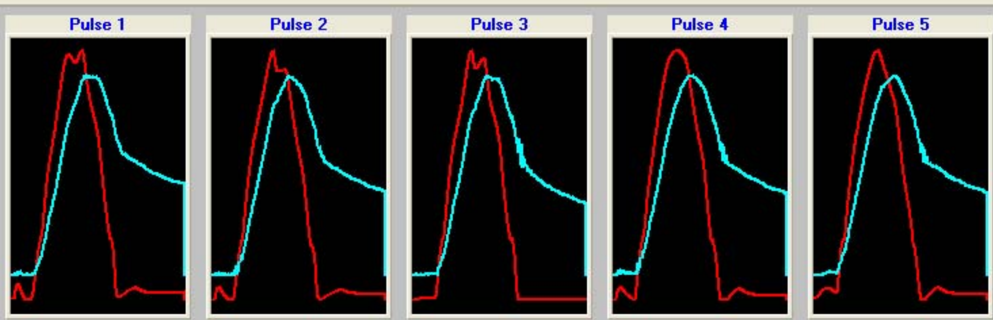

Pulse No.	Vertical force (kN)	Horizontal stress (kPa)	Risetime (ms)	Horizontal defm (microns)	Pulse shape factor (%)	Stiffness modulus (MPa) Measured	Stiffness modulus (MPa) Adjusted
1	2.65	187.5	143	7.2	0.660	3778	3906
2	2.72	192.5	114	7.1	0.570	3958	3889
3	2.64	186.4	102	6.8	0.565	3981	3901
4	2.63	186.0	118	7.2	0.614	3776	3806
5	2.68	189.7	114	7.2	0.610	3847	3869
Mean	2.66	188.4	118	7.1	0.604	3868	3874

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Stiffness of Bitumen No. 1 Mixture at 20^{0}C

Specimen 3 – 1st Reading

Pulse No.	Vertical force (kN)	Horizontal stress (kPa)	Risetime (ms)	Horizontal defm (microns)	Pulse shape factor (%)	Stiffness modulus (MPa)	
						Measured	Adjusted
1	2.53	179.1	112	6.6	0.575	3978	3922
2	2.54	179.9	144	6.5	0.658	4020	4154
3	2.59	183.2	123	6.7	0.596	4011	4001
4	2.56	180.7	122	6.5	0.606	4085	4099
5	2.58	182.6	117	6.8	0.590	3921	3898
Mean	2.56	181.1	124	6.6	0.605	4003	4015

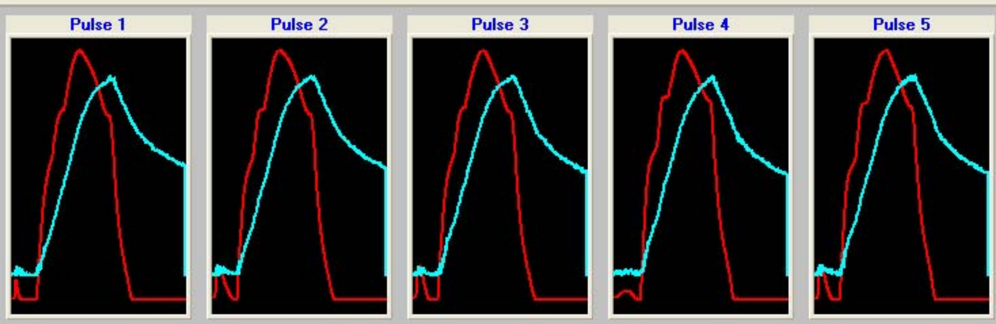
Specimen 3 –2nd Reading

Pulse No.	Vertical force (kN)	Horizontal stress (kPa)	Risetime (ms)	Horizontal defm (microns)	Pulse shape factor (%)	Stiffness modulus (MPa)	
						Measured	Adjusted
1	2.60	183.6	126	7.2	0.660	3741	3869
2	2.59	183.5	98	6.9	0.561	3864	3778
3	2.64	186.6	100	7.3	0.552	3756	3653
4	2.64	186.6	126	7.2	0.633	3811	3882
5	2.55	180.4	128	6.9	0.660	3821	3952
Mean	2.60	184.1	116	7.1	0.613	3799	3826

Stiffness of Bitumen No. 1 Mixture at 30^{0}C

Specimen 1 – 1st Reading

itsm7



Pulse No.	Vertical force (kN)	Horizontal stress (kPa)	Risetime (ms)	Horizontal defm (microns)	Pulse shape factor (%)	Stiffness modulus (MPa) Measured	Stiffness modulus (MPa) Adjusted
1	0.86	60.6	121	7.3	0.657	1217	1246
2	0.87	61.7	124	7.2	0.669	1243	1278
3	0.88	62.3	129	7.1	0.682	1277	1320
4	0.84	59.3	119	6.9	0.693	1251	1299
5	0.87	61.5	131	7.1	0.706	1268	1324
Mean	0.86	61.1	125	7.1	0.681	1251	1293

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Specimen 1 –2nd Reading

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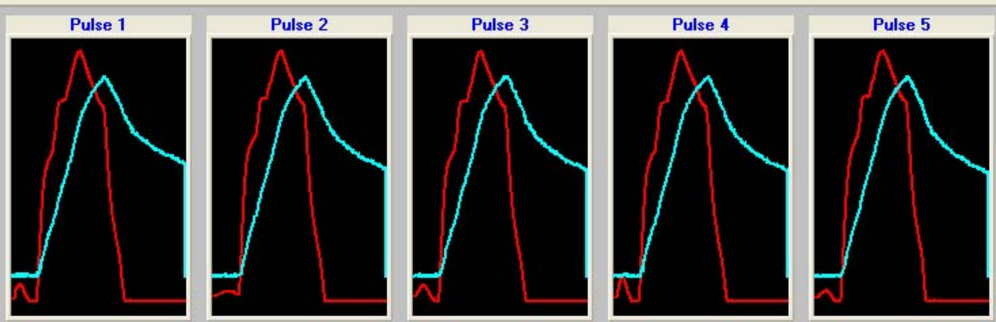

Pulse No.	Vertical force (kN)	Horizontal stress (kPa)	Risetime (ms)	Horizontal defm (microns)	Pulse shape factor (%)	Stiffness modulus (MPa) Measured	Stiffness modulus (MPa) Adjusted
1	0.77	54.4	120	6.3	0.685	1255	1299
2	0.76	53.5	119	6.2	0.699	1259	1310
3	0.76	53.7	118	6.1	0.688	1276	1322
4	0.77	54.1	116	6.2	0.688	1270	1316
5	0.74	52.4	118	6.0	0.700	1278	1330
Mean	0.76	53.6	118	6.2	0.692	1267	1315

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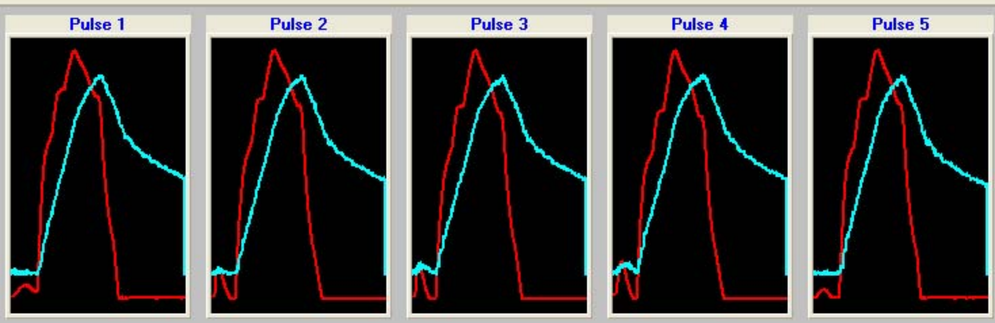
Stiffness of Bitumen No. 1 Mixture at 30^{0}C

Specimen 2 – 1st Reading

itsm7



Pulse No.	Vertical force (kN)	Horizontal stress (kPa)	Risetime (ms)	Horizontal defm (microns)	Pulse shape factor (%)	Stiffness modulus (MPa) Measured	Stiffness modulus (MPa) Adjusted
1	0.79	55.7	106	6.7	0.702	1215	1266
2	0.82	58.2	111	6.8	0.673	1247	1285
3	0.85	60.0	114	7.2	0.660	1224	1254
4	0.85	60.3	109	7.1	0.645	1240	1263
5	0.80	56.8	111	6.5	0.687	1276	1322
Mean	0.82	58.2	110	6.9	0.674	1240	1278

11:00: :26:11:2008

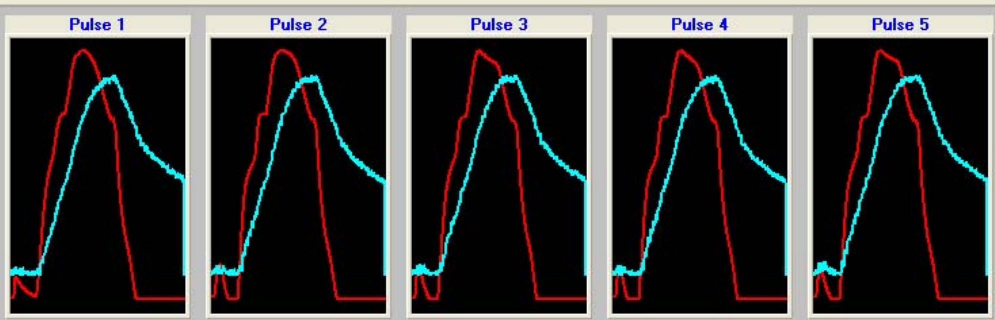
Cooper Research Technology Limited

Command

Exit | Previous | Continue

Specimen 2 –2nd Reading

itsm7



Pulse No.	Vertical force (kN)	Horizontal stress (kPa)	Risetime (ms)	Horizontal defm (microns)	Pulse shape factor (%)	Stiffness modulus (MPa) Measured	Stiffness modulus (MPa) Adjusted
1	0.85	60.3	132	7.2	0.656	1219	1247
2	0.85	60.0	124	7.0	0.674	1251	1289
3	0.85	60.4	117	7.1	0.626	1242	1255
4	0.85	60.2	119	7.1	0.651	1243	1269
5	0.84	59.7	115	7.2	0.635	1219	1236
Mean	0.85	60.1	121	7.1	0.648	1235	1259

11:00: :26:11:2008

Cooper Research Technology Limited

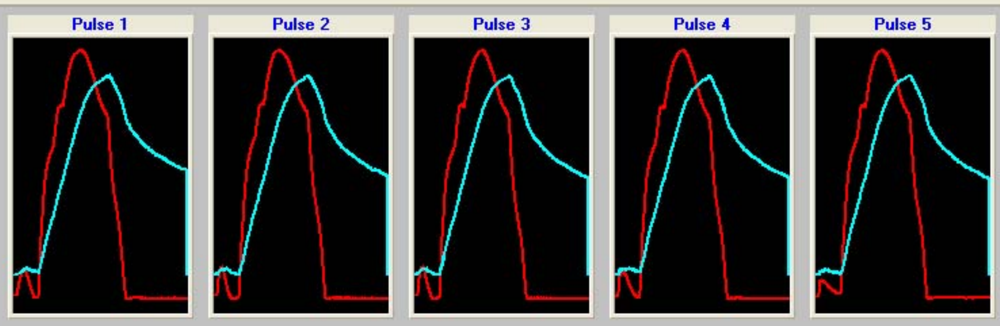
Command

Exit | Previous | Continue

Stiffness of Bitumen No. 1 Mixture at 30^{0}C

Specimen 3 – 1st Reading

itsm7



Pulse No.	Vertical force (kN)	Horizontal stress (kPa)	Risetime (ms)	Horizontal defm (microns)	Pulse shape factor (%)	Stiffness modulus (MPa) Measured	Stiffness modulus (MPa) Adjusted
1	0.81	57.4	119	7.0	0.706	1203	1254
2	0.81	57.1	113	6.7	0.693	1242	1290
3	0.81	57.3	124	6.6	0.715	1261	1320
4	0.82	57.8	122	6.8	0.697	1242	1291
5	0.80	56.9	118	6.6	0.694	1269	1318
Mean	0.81	57.3	119	6.7	0.701	1243	1295

11:01: :26:11:2008

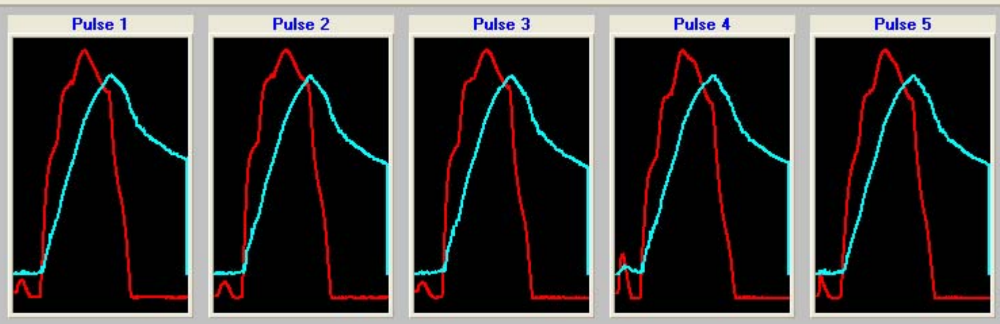
Cooper Research Technology Limited

Command

Exit Previous Continue

Specimen 3 –2nd Reading

itsm7



Pulse No.	Vertical force (kN)	Horizontal stress (kPa)	Risetime (ms)	Horizontal defm (microns)	Pulse shape factor (%)	Stiffness modulus (MPa) Measured	Stiffness modulus (MPa) Adjusted
1	0.71	50.1	126	6.4	0.712	1143	1194
2	0.71	50.0	126	6.2	0.741	1175	1242
3	0.70	49.7	126	6.1	0.734	1192	1256
4	0.76	53.7	119	6.6	0.675	1180	1216
5	0.74	52.6	126	6.3	0.675	1211	1248
Mean	0.72	51.2	125	6.3	0.707	1180	1231

11:01: :26:11:2008

Cooper Research Technology Limited

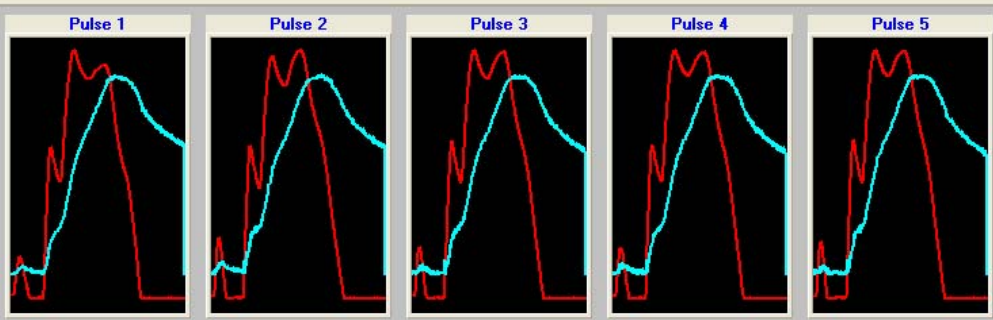
Command

Exit Previous Continue

Stiffness of Bitumen No. 1 Mixture at 35^{0}C

Specimen 1 – 1st Reading

itsm7



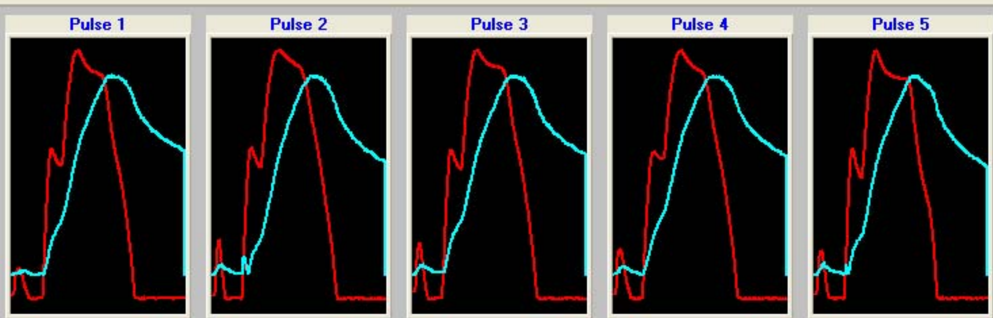
Pulse No.	Vertical force (kN)	Horizontal stress (kPa)	Risetime (ms)	Horizontal defm (microns)	Pulse shape factor (%)	Stiffness modulus (MPa) Measured	Stiffness modulus (MPa) Adjusted
1	0.49	34.3	90	6.9	0.614	730	733
2	0.50	35.5	163	7.0	0.754	740	779
3	0.49	34.5	84	6.6	0.600	760	760
4	0.48	33.9	83	6.6	0.614	755	758
5	0.48	34.2	81	6.4	0.607	775	777
Mean	0.49	34.5	100	6.7	0.638	752	761

11:16: :26:11:2008 Command Exit Previous Continue

Cooper Research Technology Limited

Specimen 1 –2nd Reading

itsm7



Pulse No.	Vertical force (kN)	Horizontal stress (kPa)	Risetime (ms)	Horizontal defm (microns)	Pulse shape factor (%)	Stiffness modulus (MPa) Measured	Stiffness modulus (MPa) Adjusted
1	0.43	30.3	98	6.3	0.628	701	707
2	0.44	31.1	106	5.8	0.659	777	793
3	0.43	30.6	101	6.5	0.636	684	692
4	0.45	31.7	110	6.5	0.633	711	719
5	0.44	30.9	89	5.8	0.621	780	786
Mean	0.44	30.9	101	6.2	0.635	731	739

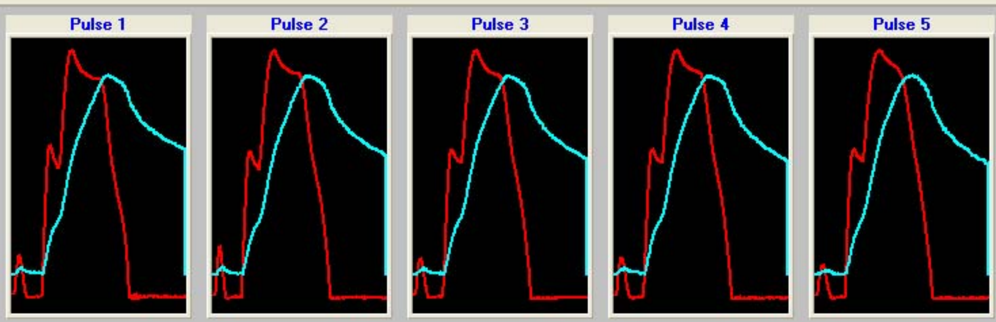
11:16: :26:11:2008 Command Exit Previous Continue

Cooper Research Technology Limited

Stiffness of Bitumen No. 1 Mixture at 35^{0}C

Specimen 2 – 1st Reading

itsm7



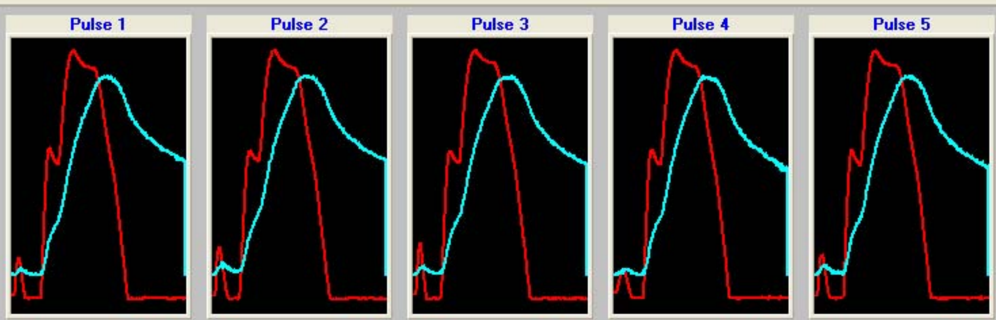
Pulse No.	Vertical force (kN)	Horizontal stress (kPa)	Risetime (ms)	Horizontal defm (microns)	Pulse shape factor (%)	Stiffness modulus (MPa) Measured	Stiffness modulus (MPa) Adjusted
1	0.45	32.0	86	6.6	0.619	703	708
2	0.46	32.8	91	6.6	0.629	729	737
3	0.46	32.3	93	6.3	0.625	752	758
4	0.46	32.4	93	6.3	0.623	752	758
5	0.44	31.4	97	5.9	0.648	773	786
Mean	0.45	32.2	92	6.3	0.629	742	749

11:17: :26:11:2008 Command Exit Previous Continue

Cooper Research Technology Limited

Specimen 2 –2nd Reading

itsm7



Pulse No.	Vertical force (kN)	Horizontal stress (kPa)	Risetime (ms)	Horizontal defm (microns)	Pulse shape factor (%)	Stiffness modulus (MPa) Measured	Stiffness modulus (MPa) Adjusted
1	0.48	34.0	92	6.6	0.638	749	759
2	0.50	35.2	99	6.9	0.631	741	748
3	0.49	34.6	95	6.8	0.629	738	745
4	0.47	33.1	91	6.4	0.634	758	767
5	0.48	34.1	90	6.6	0.630	757	765
Mean	0.48	34.2	93	6.7	0.632	749	757

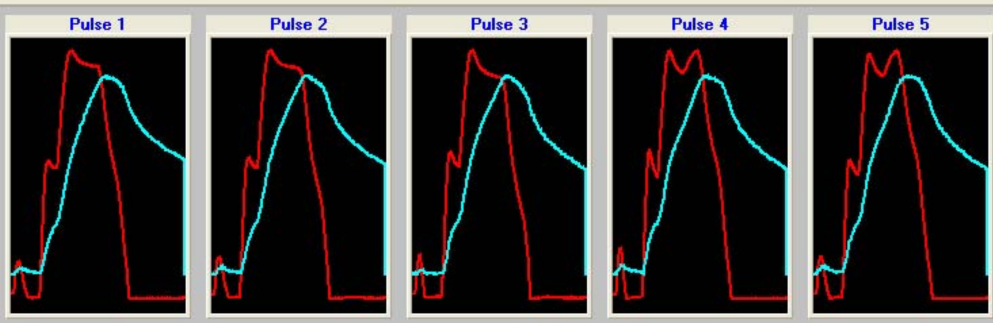
11:17: :26:11:2008 Command Exit Previous Continue

Cooper Research Technology Limited

Stiffness of Bitumen No. 1 Mixture at 35^{0}C

Specimen 3 – 1st Reading

itsm7



Pulse No.	Vertical force (kN)	Horizontal stress (kPa)	Risetime (ms)	Horizontal defm (microns)	Pulse shape factor (%)	Stiffness modulus (MPa) Measured	Stiffness modulus (MPa) Adjusted
1	0.49	34.9	91	7.1	0.615	720	724
2	0.50	35.3	86	7.0	0.613	742	745
3	0.50	35.7	86	6.7	0.623	783	789
4	0.50	35.3	158	6.9	0.780	751	797
5	0.50	35.3	158	6.8	0.758	759	799
Mean	0.50	35.3	116	6.9	0.678	751	771

11:17: :26:11:2008

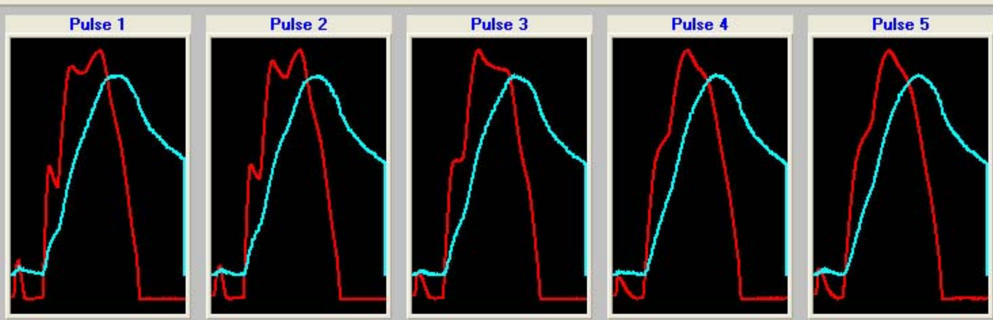
Cooper Research Technology Limited

Command

Exit | Previous | Continue

Specimen 3 –2nd Reading

itsm7



Pulse No.	Vertical force (kN)	Horizontal stress (kPa)	Risetime (ms)	Horizontal defm (microns)	Pulse shape factor (%)	Stiffness modulus (MPa) Measured	Stiffness modulus (MPa) Adjusted
1	0.49	34.8	164	7.1	0.756	717	754
2	0.49	34.5	165	6.8	0.756	737	776
3	0.49	34.3	101	6.8	0.600	738	738
4	0.50	35.6	128	6.8	0.642	761	772
5	0.51	35.8	133	7.0	0.633	751	759
Mean	0.50	35.0	138	6.9	0.678	741	760

11:18: :26:11:2008

Cooper Research Technology Limited

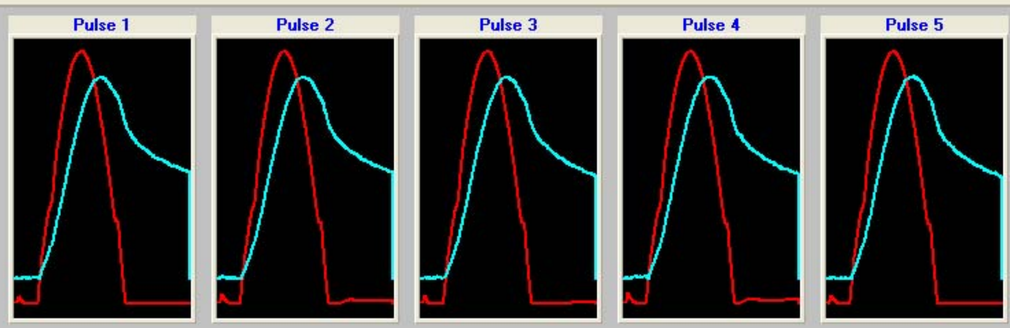
Command

Exit | Previous | Continue

Stiffness of Bitumen No. 5 Mixture at 20^{0}C

Specimen 1 – 1st Reading

itsm7



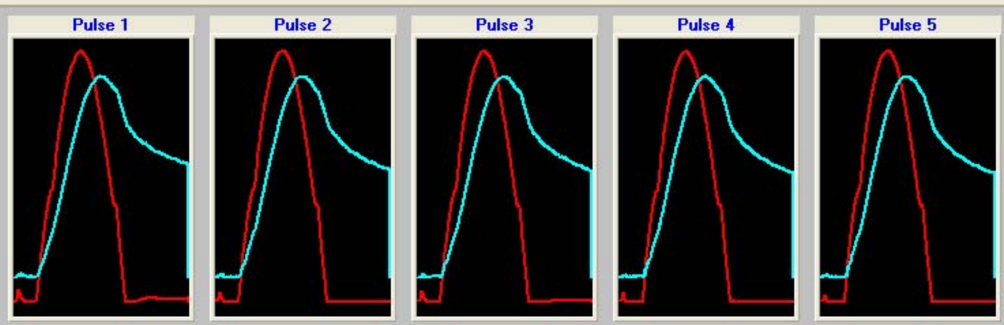
Pulse No.	Vertical force (kN)	Horizontal stress (kPa)	Risetime (ms)	Horizontal defm (microns)	Pulse shape factor (%)	Stiffness modulus (MPa) Measured	Stiffness modulus (MPa) Adjusted
1	1.76	124.2	124	7.2	0.624	2506	2537
2	1.77	125.0	128	7.3	0.622	2513	2542
3	1.76	124.5	125	7.1	0.621	2552	2580
4	1.77	125.5	122	7.2	0.602	2555	2558
5	1.76	124.5	123	7.0	0.619	2580	2606
Mean	1.76	124.7	124	7.2	0.618	2541	2564

03:20: :16:03:2009 Command Exit Previous Continue

Cooper Research Technology Limited

Specimen 1 –2nd Reading

itsm7



Pulse No.	Vertical force (kN)	Horizontal stress (kPa)	Risetime (ms)	Horizontal defm (microns)	Pulse shape factor (%)	Stiffness modulus (MPa) Measured	Stiffness modulus (MPa) Adjusted
1	1.62	114.3	122	7.0	0.607	2387	2395
2	1.59	112.4	126	6.8	0.631	2417	2455
3	1.60	112.9	121	6.8	0.607	2424	2432
4	1.58	111.8	123	6.6	0.645	2474	2530
5	1.57	111.0	122	6.6	0.642	2475	2528
Mean	1.59	112.5	123	6.7	0.626	2435	2468

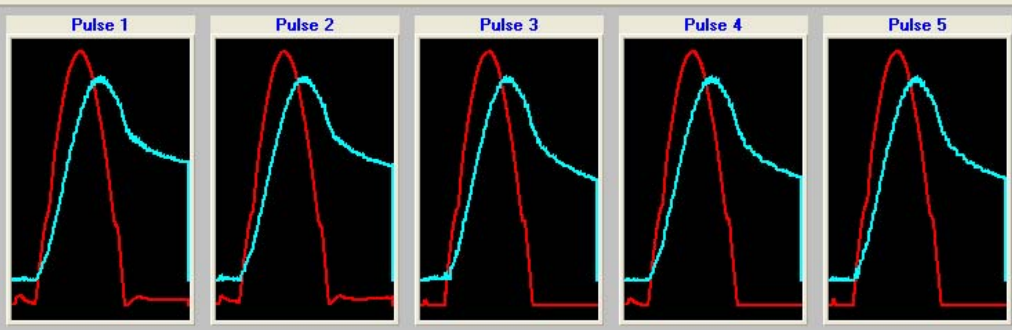
03:20: :16:03:2009 Command Exit Previous Continue

Cooper Research Technology Limited

Stiffness of Bitumen No. 5 Mixture at 20^{0}C

Specimen 2 – 1st Reading

itsm7



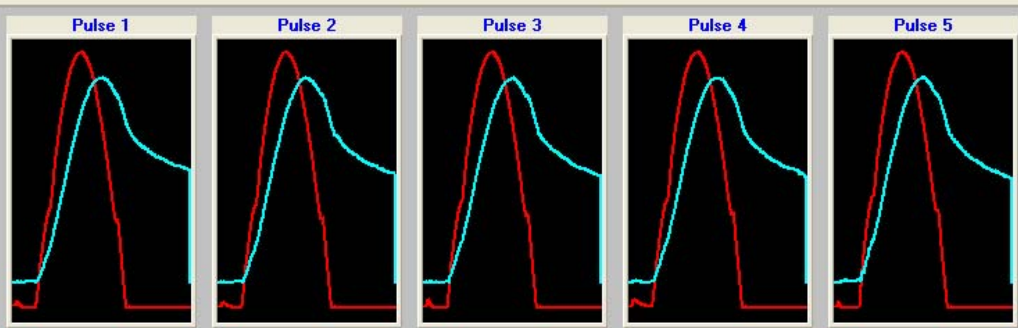
Pulse No.	Vertical force (kN)	Horizontal stress (kPa)	Risetime (ms)	Horizontal defm (microns)	Pulse shape factor (%)	Stiffness modulus (MPa) Measured	Stiffness modulus (MPa) Adjusted
1	1.80	127.4	125	7.5	0.615	2488	2507
2	1.81	127.9	126	7.4	0.615	2516	2534
3	1.77	125.2	123	6.9	0.636	2643	2692
4	1.78	125.7	124	7.3	0.617	2525	2547
5	1.77	125.5	123	7.2	0.646	2541	2601
Mean	1.79	126.3	124	7.3	0.626	2543	2576

03:20: :16:03:2009 Command Exit Previous Continue

Cooper Research Technology Limited

Specimen 2 –2nd Reading

itsm7



Pulse No.	Vertical force (kN)	Horizontal stress (kPa)	Risetime (ms)	Horizontal defm (microns)	Pulse shape factor (%)	Stiffness modulus (MPa) Measured	Stiffness modulus (MPa) Adjusted
1	1.63	115.6	126	6.8	0.618	2467	2489
2	1.62	114.6	123	6.7	0.610	2489	2502
3	1.63	115.1	126	6.7	0.637	2504	2551
4	1.63	115.6	123	6.8	0.613	2496	2513
5	1.62	114.3	116	6.6	0.631	2524	2563
Mean	1.63	115.0	123	6.7	0.622	2496	2524

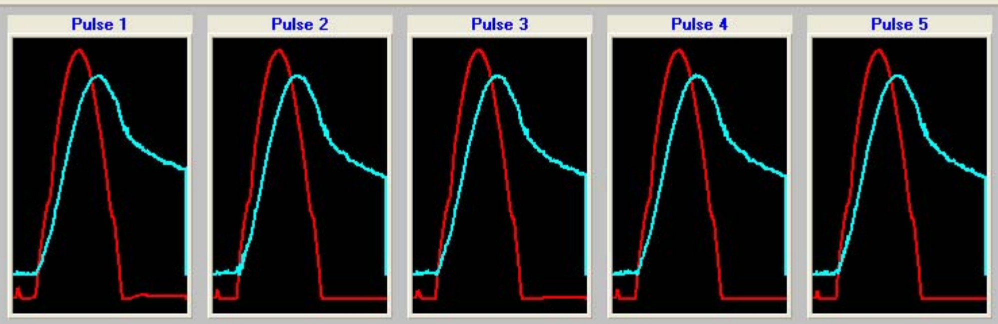
03:20: :16:03:2009 Command Exit Previous Continue

Cooper Research Technology Limited

Stiffness of Bitumen No. 5 Mixture at 20^0C

Specimen 3 – 1st Reading

itsm7



Pulse No.	Vertical force (kN)	Horizontal stress (kPa)	Risetime (ms)	Horizontal defm (microns)	Pulse shape factor (%)	Stiffness modulus (MPa) Measured	Stiffness modulus (MPa) Adjusted
1	1.77	125.0	124	7.2	0.610	2533	2546
2	1.75	123.5	119	6.8	0.630	2638	2680
3	1.75	124.0	121	7.0	0.608	2587	2598
4	1.75	123.8	120	6.9	0.610	2612	2626
5	1.75	123.6	121	6.9	0.628	2601	2638
Mean	1.75	124.0	121	7.0	0.617	2594	2618

03:20: :16:03:2009

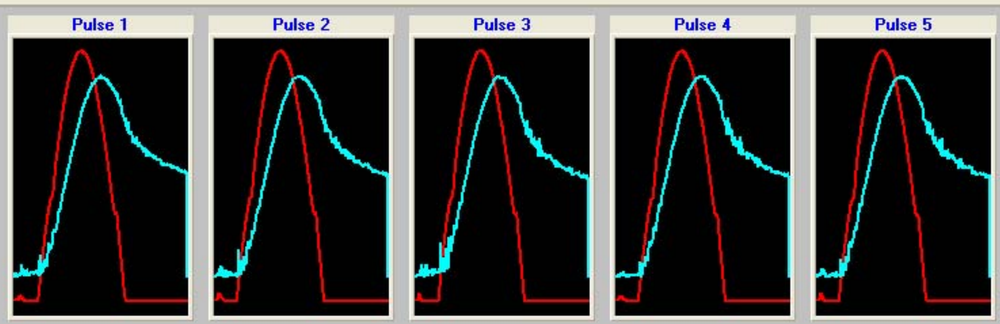
Cooper Research Technology Limited

Command

Exit | Previous | Continue

Specimen 3 –2nd Reading

itsm7



Pulse No.	Vertical force (kN)	Horizontal stress (kPa)	Risetime (ms)	Horizontal defm (microns)	Pulse shape factor (%)	Stiffness modulus (MPa) Measured	Stiffness modulus (MPa) Adjusted
1	1.70	120.0	122	7.0	0.616	2504	2524
2	1.70	120.5	121	7.1	0.607	2487	2495
3	1.69	119.5	120	6.9	0.630	2513	2552
4	1.69	119.8	125	7.1	0.624	2466	2496
5	1.70	120.2	124	7.1	0.615	2463	2482
Mean	1.70	120.0	122	7.0	0.618	2487	2510

03:20: :16:03:2009

Cooper Research Technology Limited

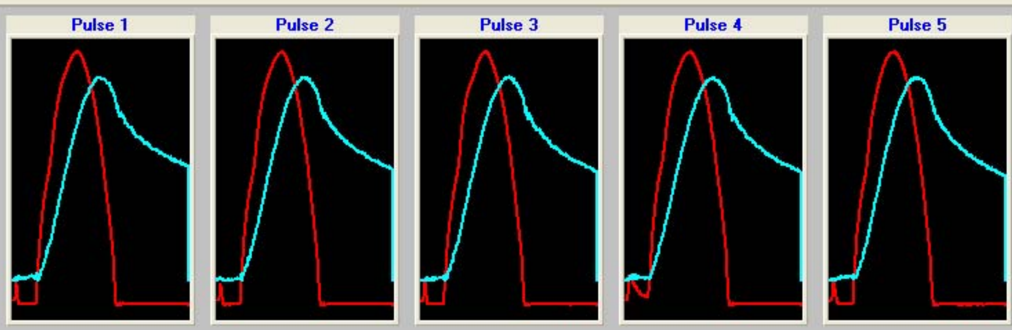
Command

Exit | Previous | Continue

Stiffness of Bitumen No. 5 Mixture at 30^{0}C

Specimen 1 – 1st Reading

itsm7



Pulse No.	Vertical force (kN)	Horizontal stress (kPa)	Risetime (ms)	Horizontal defm (microns)	Pulse shape factor (%)	Stiffness modulus (MPa) Measured	Stiffness modulus (MPa) Adjusted
1	0.49	34.4	114	6.6	0.685	762	784
2	0.49	34.5	116	6.6	0.682	762	784
3	0.49	34.8	118	6.6	0.683	775	797
4	0.50	35.2	117	6.8	0.673	760	779
5	0.48	34.2	113	6.3	0.680	789	810
Mean	0.49	34.6	116	6.6	0.681	769	791

03:10: :17:03:2009

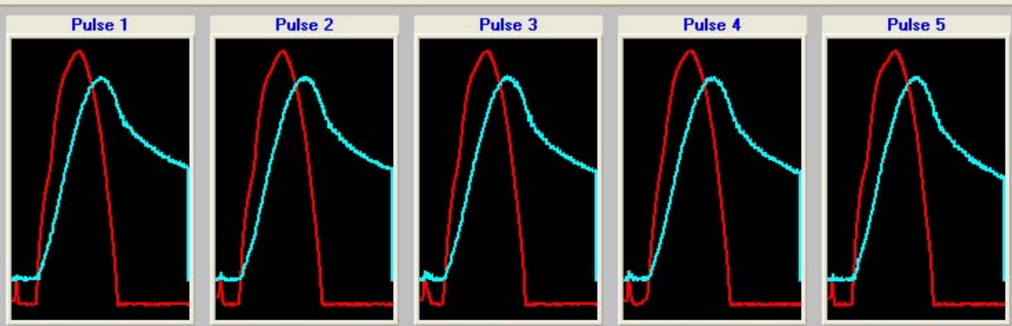
Cooper Research Technology Limited

Command

Exit | Previous | Continue

Specimen 1 –2nd Reading

itsm7



Pulse No.	Vertical force (kN)	Horizontal stress (kPa)	Risetime (ms)	Horizontal defm (microns)	Pulse shape factor (%)	Stiffness modulus (MPa) Measured	Stiffness modulus (MPa) Adjusted
1	0.47	33.4	118	6.6	0.685	738	759
2	0.48	33.7	121	6.7	0.688	735	757
3	0.48	33.7	123	6.6	0.682	745	766
4	0.48	34.0	120	6.6	0.668	747	764
5	0.47	33.0	121	6.4	0.706	756	783
Mean	0.47	33.6	121	6.6	0.686	744	766

03:10: :17:03:2009

Cooper Research Technology Limited

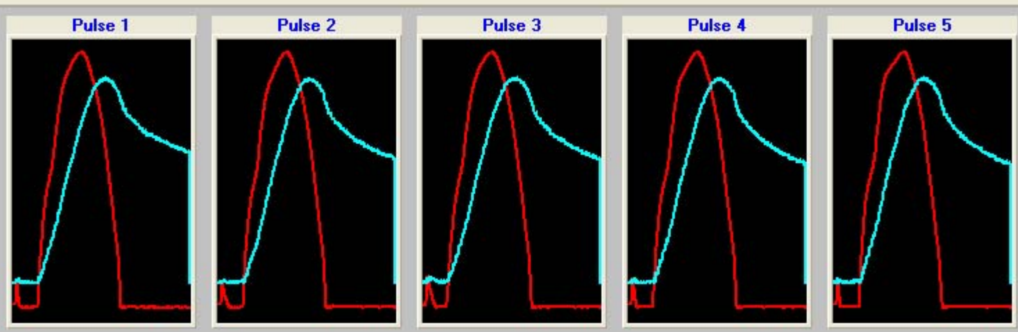
Command

Exit | Previous | Continue

Stiffness of Bitumen No. 5 Mixture at 30^{0}C

Specimen 2 – 1st Reading

itsm7



Pulse No.	Vertical force (kN)	Horizontal stress (kPa)	Risetime (ms)	Horizontal defm (microns)	Pulse shape factor (%)	Stiffness modulus (MPa) Measured	Stiffness modulus (MPa) Adjusted
1	0.48	33.6	121	6.6	0.697	749	774
2	0.48	33.9	118	6.3	0.690	785	809
3	0.49	34.4	128	6.4	0.689	785	809
4	0.49	34.5	124	6.3	0.701	800	828
5	0.49	34.3	128	6.2	0.726	809	845
Mean	0.48	34.1	124	6.4	0.701	785	813

03:11: :17:03:2009

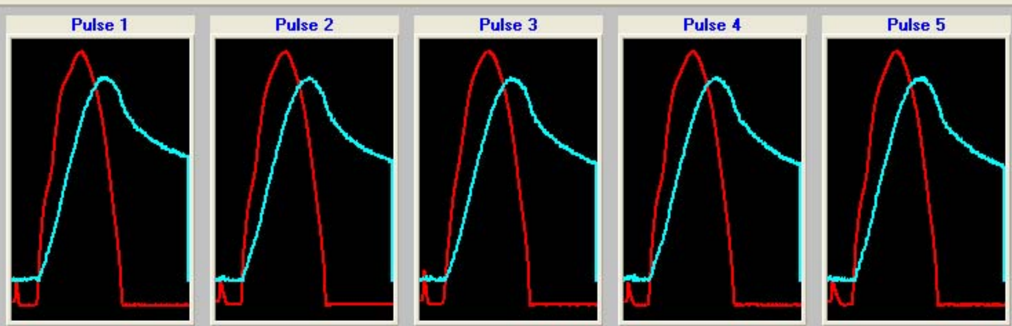
Command

Exit | Previous | Continue

Cooper Research Technology Limited

Specimen 2 –2nd Reading

itsm7



Pulse No.	Vertical force (kN)	Horizontal stress (kPa)	Risetime (ms)	Horizontal defm (microns)	Pulse shape factor (%)	Stiffness modulus (MPa) Measured	Stiffness modulus (MPa) Adjusted
1	0.52	36.7	121	6.9	0.678	774	795
2	0.52	36.6	125	6.9	0.697	777	803
3	0.52	36.9	125	7.0	0.671	772	790
4	0.52	36.5	121	6.9	0.681	773	794
5	0.52	36.4	122	6.7	0.677	795	817
Mean	0.52	36.7	123	6.9	0.681	778	800

03:11: :17:03:2009

Command

Exit | Previous | Continue

Cooper Research Technology Limited

Stiffness of Bitumen No. 5 Mixture at 30^{0}C

Specimen 3 – 1st Reading

Pulse No.	Vertical force (kN)	Horizontal stress (kPa)	Risetime (ms)	Horizontal defm (microns)	Pulse shape factor (%)	Stiffness modulus (MPa)	
						Measured	Adjusted
1	0.49	34.6	119	7.0	0.697	720	743
2	0.48	34.3	118	6.7	0.710	748	776
3	0.48	34.2	126	6.6	0.701	758	784
4	0.48	34.2	123	6.5	0.722	770	802
5	0.49	34.7	124	6.6	0.700	773	800
Mean	0.49	34.4	122	6.7	0.706	754	781

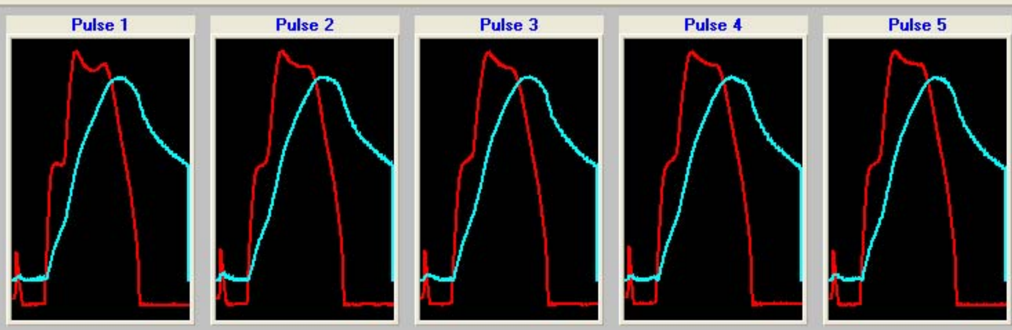
Specimen 3 –2nd Reading

Pulse No.	Vertical force (kN)	Horizontal stress (kPa)	Risetime (ms)	Horizontal defm (microns)	Pulse shape factor (%)	Stiffness modulus (MPa)	
						Measured	Adjusted
1	0.56	37.4	119	7.3	0.686	751	773
2	0.56	37.8	122	7.3	0.679	757	777
3	0.55	37.3	119	7.2	0.680	756	776
4	0.55	37.1	121	7.1	0.685	760	782
5	0.56	37.4	118	7.2	0.689	761	784
Mean	0.56	37.4	120	7.2	0.684	757	779

Stiffness of Bitumen No. 5 Mixture at 35^{0}C

Specimen 1 – 1st Reading

itsm7



Pulse No.	Vertical force (kN)	Horizontal stress (kPa)	Risetime (ms)	Horizontal defm (microns)	Pulse shape factor (%)	Stiffness modulus (MPa)	
						Measured	Adjusted
1	0.24	23.2	88	6.7	0.617	504	506
2	0.24	24.0	95	7.0	0.594	501	500
3	0.25	24.4	105	7.0	0.624	508	512
4	0.24	24.2	100	7.0	0.616	504	506
5	0.24	23.7	97	6.9	0.616	501	504
Mean	0.24	23.9	97	6.9	0.614	504	506

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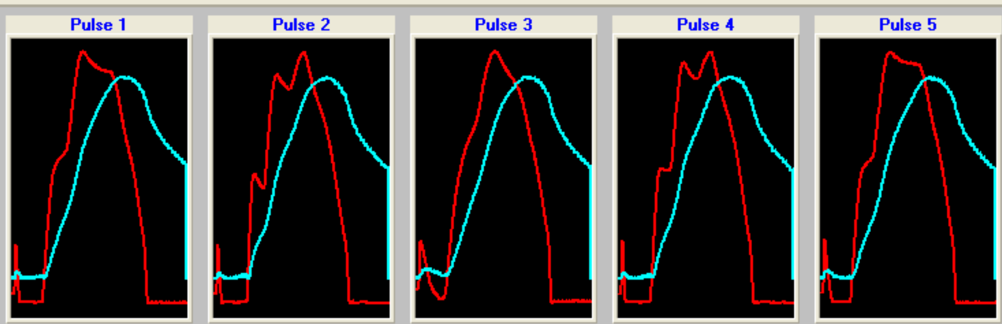
Specimen 1 – 2nd Reading

itsm7



Pulse No.	Vertical force (kN)	Horizontal stress (kPa)	Risetime (ms)	Horizontal defm (microns)	Pulse shape factor (%)	Stiffness modulus (MPa)	
						Measured	Adjusted
1	0.24	25.8	112	7.0	0.586	538	536
2	0.24	25.9	161	6.8	0.717	556	575
3	0.25	26.6	144	7.2	0.616	539	542
4	0.24	25.3	169	6.8	0.727	541	561
5	0.24	25.1	112	7.0	0.595	524	523
Mean	0.24	25.7	140	7.0	0.648	539	547

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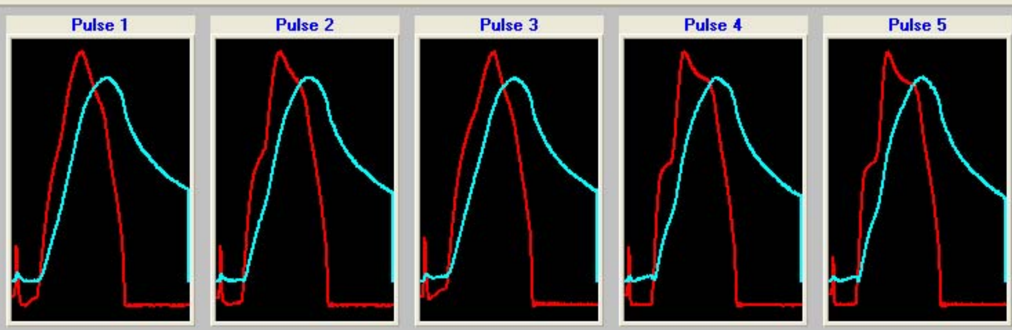
Stiffness of Bitumen No. 5 Mixture at 35^{0}C

Specimen 2 – 1st Reading

itsm7



Pulse No.	Vertical force (kN)	Horizontal stress (kPa)	Risetime (ms)	Horizontal defm (microns)	Pulse shape factor (%)	Stiffness modulus (MPa) Measured	Stiffness modulus (MPa) Adjusted
1	0.28	25.8	119	6.9	0.587	548	546
2	0.27	25.1	106	6.7	0.590	546	545
3	0.29	26.9	134	7.3	0.644	541	547
4	0.26	24.2	89	6.5	0.581	543	539
5	0.27	24.6	87	6.6	0.587	548	545
Mean	0.27	25.3	107	6.8	0.598	545	545

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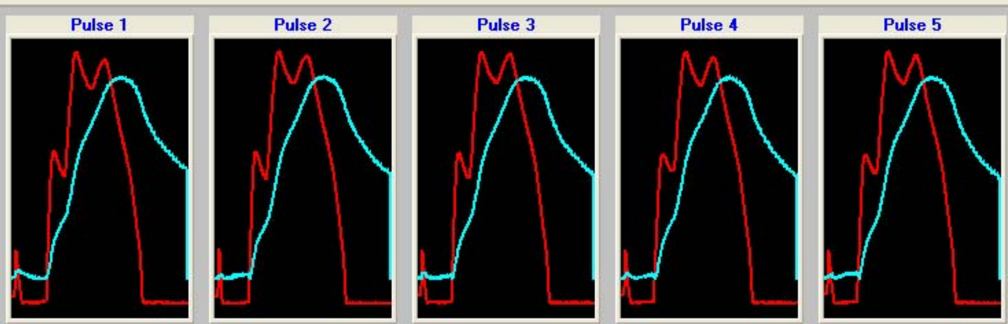
Specimen 2 – 2nd Reading

itsm7



Pulse No.	Vertical force (kN)	Horizontal stress (kPa)	Risetime (ms)	Horizontal defm (microns)	Pulse shape factor (%)	Stiffness modulus (MPa) Measured	Stiffness modulus (MPa) Adjusted
1	0.24	23.4	86	6.8	0.613	503	505
2	0.24	23.4	85	6.8	0.600	505	505
3	0.24	23.4	85	6.8	0.596	502	502
4	0.24	23.8	90	6.9	0.594	505	504
5	0.24	23.3	88	6.7	0.598	506	506
Mean	0.24	23.5	87	6.8	0.600	504	504

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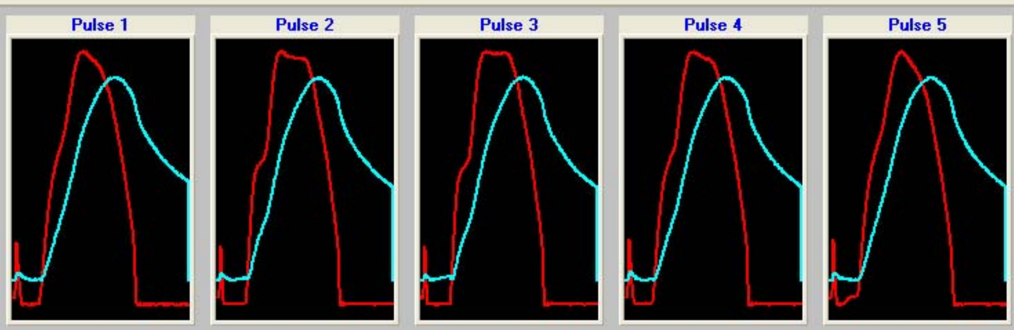
Stiffness of Bitumen No. 5 Mixture at 35^{0}C

Specimen 3 – 1st Reading

itsm7



Pulse No.	Vertical force (kN)	Horizontal stress (kPa)	Risetime (ms)	Horizontal defm (microns)	Pulse shape factor (%)	Stiffness modulus (MPa) Measured	Stiffness modulus (MPa) Adjusted
1	0.26	25.5	123	7.3	0.618	512	515
2	0.25	24.2	95	7.0	0.599	507	507
3	0.24	23.9	101	6.9	0.634	509	514
4	0.25	25.1	112	7.1	0.609	518	520
5	0.26	25.9	120	7.1	0.618	532	535
Mean	0.25	24.9	110	7.1	0.616	516	518

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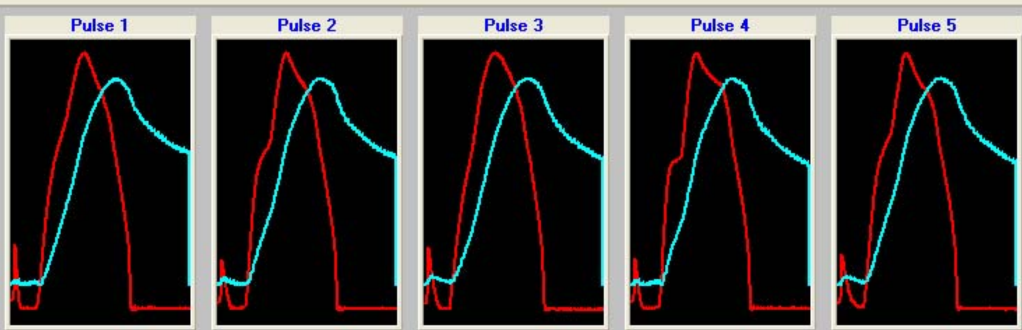
Specimen 3 –2nd Reading

itsm7



Pulse No.	Vertical force (kN)	Horizontal stress (kPa)	Risetime (ms)	Horizontal defm (microns)	Pulse shape factor (%)	Stiffness modulus (MPa) Measured	Stiffness modulus (MPa) Adjusted
1	0.24	24.2	129	7.2	0.621	491	494
2	0.24	24.1	112	6.8	0.612	517	519
3	0.25	24.2	125	7.1	0.612	501	503
4	0.24	23.7	102	6.6	0.616	523	526
5	0.26	25.5	114	7.1	0.594	525	524
Mean	0.25	24.3	116	7.0	0.611	512	513

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Bitumen No. 1 Mixture
Specimen 1
Repeated Load Axial Test

Operator	= Operator name
Specref	= Specimen name/ref
40	= Test Temperature (deg.C)
150	= Diameter (mm)
60	= Thickness (mm)
100	= Test stress (kPa)
3600	= Test period (pulses)
10	= Conditioning stress (kPa)
600	= Conditioning period (secs)
2615	= Microstrain during conditioning period

Pulse No	Ax ustrain	StresskPa	TC1_degC	TC2_degC
5	3680	99.4	39.2	37.9
10	4178	99.9	39.3	37.9
20	4461	100.2	39.2	37.9
30	4684	100.1	39.2	37.9
40	4832	99.9	39.1	37.9
50	4946	100.6	39.2	37.8
60	5065	101.0	39.2	37.8
70	5154	99.4	39.2	37.8
80	5230	99.4	39.2	37.8
100	5308	100.1	39.2	37.8
200	5734	100.4	39.1	37.7
300	5952	100.6	39.0	37.6
400	6151	99.4	39.0	37.6
500	6266	100.6	38.7	37.4
600	6357	100.9	38.9	37.5
700	6424	100.6	38.8	37.5
800	6506	100.2	38.9	37.5
900	6586	99.9	38.9	37.4
1000	6614	100.8	38.8	37.5
1100	6689	100.0	38.7	37.4
1200	6728	99.8	38.9	37.5
1300	6764	99.0	38.9	37.5
1400	6781	100.2	38.9	37.5
1500	6839	100.1	38.8	37.5
1600	6859	99.7	38.7	37.4
1700	6900	100.0	38.8	37.4
1800	6918	101.1	38.8	37.4
1900	6938	100.2	38.8	37.5
2000	6948	99.6	38.8	37.4
2100	6976	100.1	38.9	37.4
2200	7010	99.9	38.8	37.5
2300	7017	100.0	38.9	37.4
2400	7045	100.4	38.8	37.5
2500	7067	100.8	38.9	37.5
2600	7058	100.0	38.9	37.4
2700	7071	99.4	38.8	37.4
2800	7084	99.6	38.8	37.4
2900	7110	100.5	38.8	37.5
3000	7109	99.4	38.9	37.4
3100	7146	100.2	38.9	37.4
3200	7143	99.8	38.8	37.4
3300	7150	98.9	38.7	37.4
3400	7159	99.5	38.8	37.4
3500	7192	99.9	38.8	37.5
3600	7223	99.8	38.8	37.4

Bitumen No. 1 Mixture
Specimen 2
Repeated Load Axial Test

Operator = Operator name
Specref = Specimen name/ref
40 = Test Temperature (deg.C)
150 = Diameter (mm)
60 = Thickness (mm)
100 = Test stress (kPa)
3600 = Test period (pulses)
10 = Conditioning stress (kPa)
600 = Conditioning period (secs)
2967 = Microstrain during conditioning period

Pulse No	Ax ustrain	StresskPa	TC1_degC	TC2_degC
5	3440	100.5	38.5	37.5
10	3934	100.2	38.5	37.3
20	4199	99.5	38.5	37.4
30	4421	99.1	38.7	37.7
40	4570	101.1	38.5	37.5
50	4701	99.8	38.5	37.6
60	4787	99.8	38.7	37.5
70	4888	100.8	38.7	37.8
80	4957	99.4	38.7	37.7
100	5031	100.1	38.7	37.4
200	5434	101.0	38.8	37.9
300	5673	100.3	38.8	37.7
400	5845	100.5	38.8	37.5
500	5982	98.9	38.8	37.6
600	6118	100.8	38.9	38.0
700	6223	99.8	38.7	37.5
800	6317	99.7	38.8	37.6
900	6350	100.0	38.8	37.5
1000	6429	99.8	38.8	37.7
1100	6458	99.7	38.8	37.8
1200	6501	101.0	38.9	38.1
1300	6527	100.0	38.9	38.0
1400	6585	99.5	38.8	37.7
1500	6589	100.1	38.7	37.8
1600	6613	101.0	38.9	37.9
1700	6630	99.9	38.9	37.8
1800	6647	99.6	38.8	37.6
1900	6676	100.3	38.9	38.0
2000	6717	99.4	38.8	37.6
2100	6702	101.5	38.7	37.8
2200	6734	99.9	38.8	37.7
2300	6770	100.2	38.9	37.7
2400	6766	100.3	38.8	37.6
2500	6781	100.6	38.7	37.7
2600	6808	100.2	38.9	38.0
2700	6827	99.9	38.9	38.2
2800	6836	99.9	38.9	37.8
2900	6825	100.0	38.8	37.5
3000	6855	99.9	38.9	37.8
3100	6865	100.4	39.0	38.0
3200	6880	100.2	38.9	38.1
3300	6889	100.6	38.9	37.8
3400	6906	99.6	38.7	37.4
3500	6907	99.3	38.9	37.4
3600	6909	99.9	38.8	37.4

Bitumen No. 1 Mixture
Specimen 3
Repeated Load Axial Test

Operator	= Operator name
Specref	= Specimen name/ref
40	= Test Temperature (deg.C)
150	= Diameter (mm)
60	= Thickness (mm)
100	= Test stress (kPa)
3600	= Test period (pulses)
10	= Conditioning stress (kPa)
600	= Conditioning period (secs)
5304	= Microstrain during conditioning period

Pulse No	Ax ustrain	StresskPa	TC1_degC	TC2_degC
5	2979	100.3	39.6	38.9
10	3435	99.9	39.6	39.2
20	3714	100.4	39.6	38.9
30	3914	100.3	39.6	39.2
40	4089	100.4	39.4	38.2
50	4238	99.1	39.5	39.0
60	4280	102.5	39.7	39.1
70	4343	100.9	39.6	39.1
80	4509	99.9	39.5	38.9
100	4502	101.3	39.6	39.1
200	5015	99.2	39.4	38.7
300	5265	99.5	39.4	38.9
400	5430	99.2	39.4	38.7
500	5580	98.4	39.0	37.7
600	5678	98.8	39.1	38.1
700	5781	99.8	39.2	38.3
800	5848	100.6	39.2	38.1
900	5913	100.7	39.2	38.5
1000	5976	100.9	39.3	38.7
1100	6022	100.3	38.9	37.7
1200	6062	99.3	39.1	38.1
1300	6108	100.1	39.2	38.2
1400	6180	99.4	39.2	38.7
1500	6184	100.7	39.2	38.3
1600	6242	100.2	39.1	38.1
1700	6271	101.0	38.9	37.7
1800	6332	100.8	39.2	38.7
1900	6352	99.9	39.2	38.6
2000	6357	99.9	39.0	38.3
2100	6401	99.7	39.2	38.7
2200	6437	99.7	38.9	37.7
2300	6454	99.8	39.1	38.2
2400	6485	100.3	39.0	38.0
2500	6469	99.7	38.8	37.8
2600	6556	99.1	39.0	38.1
2700	6531	99.3	39.1	38.3
2800	6571	100.2	39.1	38.4
2900	6563	100.7	39.0	38.3
3000	6642	99.8	38.9	38.0
3100	6677	99.2	39.1	38.0
3200	6637	101.3	39.2	38.4
3300	6645	100.6	39.0	37.7
3400	6687	99.7	39.1	38.0
3500	6730	99.7	39.2	38.4
3600	6717	99.0	39.0	37.7

Bitumen No. 5 Mixture
Specimen 1

Repeated Load Axial Test
Operator = Operator name
Specref = Specimen name/ref
40 = Test Temperature (deg.C)
100 = Diameter (mm)
60 = Thickness (mm)
100 = Test stress (kPa)
3600 = Test period (pulses)
10 = Conditioning stress (kPa)
600 = Conditioning period (secs)
2452 = Microstrain during conditioning period

Pulse No	Ax ustrain	StresskPa	TC1_degC	TC2_degC
5	2651	99.3	26.1	25.5
10	3184	99.9	26.0	25.3
20	3513	101.4	26.0	25.0
30	3775	100.0	25.9	24.8
40	3927	99.0	25.9	24.8
50	4112	98.6	25.8	25.1
60	4232	99.3	25.7	24.9
70	4334	100.2	25.8	24.8
80	4415	100.1	25.9	24.8
100	4532	99.7	25.9	24.9
200	5069	99.0	25.8	24.7
300	5423	100.9	25.5	24.8
400	5642	100.7	25.3	24.6
500	5844	99.3	25.6	24.7
600	6000	100.4	25.7	24.8
700	6122	101.1	25.9	24.8
800	6244	98.9	26.0	25.0
900	6332	100.3	25.8	24.6
1000	6448	99.8	25.8	24.7
1100	6532	100.0	25.7	24.8
1200	6621	100.1	25.8	24.8
1300	6696	100.9	25.6	24.7
1400	6750	100.4	25.6	24.8
1500	6797	99.4	25.8	24.9
1600	6889	100.3	26.2	24.8
1700	6953	99.7	26.1	25.1
1800	7012	100.4	25.6	24.6
1900	7046	100.3	25.8	24.7
2000	7101	99.2	25.7	24.5
2100	7157	99.3	25.8	24.5
2200	7194	101.4	25.4	24.5
2300	7249	100.1	25.5	24.6
2400	7293	98.6	25.5	24.4
2500	7321	99.7	25.3	24.3
2600	7366	99.6	25.1	24.1
2700	7401	100.1	25.4	24.4
2800	7441	99.0	25.1	23.9
2900	7477	100.4	25.5	24.8
3000	7506	99.6	25.1	24.5
3100	7557	100.1	25.5	24.5
3200	7582	99.8	25.2	24.2
3300	7618	98.7	25.1	24.0
3400	7659	99.7	24.9	24.0
3500	7685	99.5	24.8	23.8
3600	7701	100.4	25.1	24.4

Bitumen No. 5 Mixture
Specimen 2

Repeated Load Axial Test
Operator = Operator name
Specref = Specimen name/ref
40 = Test Temperature (deg.C)
100 = Diameter (mm)
60 = Thickness (mm)
100 = Test stress (kPa)
3600 = Test period (pulses)
10 = Conditioning stress (kPa)
600 = Conditioning period (secs)
1691 = Microstrain during conditioning period

Pulse No	Ax ustrain	StresskPa	TC1_degC	TC2_degC
5	2501	99.4	25.6	24.8
10	3037	102.5	25.6	24.8
20	3358	101.6	26.7	25.1
30	3614	101.5	26.1	25.0
40	3792	99.5	25.5	24.8
50	3954	99.6	25.5	24.5
60	4075	100.4	25.7	24.5
70	4201	99.6	25.7	24.7
80	4315	102.3	25.7	25.0
100	4392	100.5	25.6	24.7
200	4997	99.7	25.7	24.7
300	5329	98.7	25.8	25.1
400	5576	99.6	26.2	25.2
500	5774	100.5	25.9	24.8
600	5942	100.3	26.0	25.3
700	6068	99.6	25.7	25.1
800	6191	99.4	25.1	24.4
900	6315	100.2	24.9	24.0
1000	6424	100.2	24.9	24.3
1100	6525	99.4	25.1	24.3
1200	6598	99.4	25.2	24.4
1300	6669	101.0	25.8	24.9
1400	6749	100.0	25.7	24.8
1500	6822	101.2	25.7	24.8
1600	6897	99.9	25.9	25.2
1700	6955	99.3	25.8	25.5
1800	7013	100.5	26.6	26.0
1900	7058	99.4	27.1	25.8
2000	7118	100.1	26.4	25.4
2100	7187	99.5	25.7	25.2
2200	7231	99.5	25.3	24.5
2300	7256	100.2	25.1	25.0
2400	7305	98.6	24.5	23.7
2500	7356	99.5	25.0	24.0
2600	7412	99.1	25.2	24.1
2700	7434	99.3	25.1	24.0
2800	7491	99.7	25.1	24.1
2900	7531	100.9	24.9	24.3
3000	7564	100.3	24.9	24.1
3100	7601	99.1	25.4	24.5
3200	7637	100.3	25.5	24.6
3300	7660	100.4	25.8	24.8
3400	7696	100.7	25.7	24.5
3500	7744	99.5	25.5	24.2
3600	7776	100.0	25.6	24.8

Bitumen No. 5 Mixture
Specimen 3

Repeated Load Axial Test
Operator = Operator name
Specref = Specimen name/ref
40 = Test Temperature (deg.C)
100 = Diameter (mm)
60 = Thickness (mm)
100 = Test stress (kPa)
3600 = Test period (pulses)
10 = Conditioning stress (kPa)
600 = Conditioning period (secs)
2463 = Microstrain during conditioning period

Pulse No	Ax ustrain	StresskPa	TC1_degC	TC2_degC
5	2243	99.7	25.3	25.6
10	2736	98.6	25.2	25.4
20	3012	100.6	25.6	25.5
30	3237	100.5	25.8	26.1
40	3405	99.8	25.7	26.1
50	3548	98.3	25.4	26.0
60	3673	99.4	25.3	25.7
70	3766	101.0	25.3	25.6
80	3851	98.8	25.7	25.8
100	3929	100.4	26.2	26.1
200	4478	100.6	25.7	26.3
300	4775	100.4	25.6	26.6
400	5013	99.9	26.7	27.0
500	5192	100.1	25.5	26.0
600	5331	99.5	25.8	26.1
700	5465	100.1	25.4	25.4
800	5582	99.0	26.7	26.1
900	5697	99.8	26.4	26.8
1000	5766	99.8	25.6	26.5
1100	5871	101.3	26.1	26.4
1200	5948	100.2	28.0	26.7
1300	6017	99.4	26.0	26.1
1400	6100	99.6	25.4	26.0
1500	6141	99.6	25.6	26.1
1600	6205	99.1	25.8	25.8
1700	6274	100.2	26.3	26.1
1800	6304	99.6	25.1	26.4
1900	6382	100.0	24.4	25.8
2000	6415	99.3	25.2	25.4
2100	6474	100.3	24.5	25.4
2200	6492	99.7	24.9	25.4
2300	6557	100.4	24.8	26.3
2400	6588	99.4	25.5	26.1
2500	6612	100.0	24.7	24.1
2600	6649	100.3	25.9	25.7
2700	6710	99.2	25.1	25.7
2800	6740	100.4	25.3	25.4
2900	6784	99.4	26.1	25.8
3000	6833	101.0	25.1	25.9
3100	6838	98.9	24.9	25.4
3200	6884	98.9	25.2	25.4
3300	6900	99.4	24.9	24.9
3400	6960	99.4	24.9	25.5
3500	6973	98.6	25.3	25.5
3600	7003	98.9	26.1	25.7