The Effects of Compaction Effort On the Lifespan Of Bituminous Pavements

by

Amir Mu'az Bin Ahmad Zulkifli

Dissertation submitted in partial fulfilment of
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Bandar Seri Iskandar
31750 Tronoh
Perak Darul Ridzuan

CERTIFICATION OF APPROVAL

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Approved by,

(AP Dr. Madzlan Bin Napiah)

UNIVERSITI TEKNOLOGI PETRONAS

TRONOH, PERAK

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CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

AMIR MU'AZ BIN AHMAD ZULKIFLI
UTP STUDENT I.D. NUMBER : 1671

ABSTRACT

More often than not, in Malaysia, millions of ringgit is spent each year remedying failures due to fatigue cracking and permanent deformation. Chief among the causes of these failures is the inability to ensure maximum desired compaction, especially on the bituminous surfacing layer. The materials used for our road construction projects are of the highest quality. It is suspected then, that a lack of supervision during the construction and compaction phase of a project results in the lack of compaction effort, which leads to failure.

The objectives of this Final Year Project are to firstly establish the relationship between compaction effort and the performance and lifespan of bituminous pavements. This relationship could be expressed in the form of graphs, equations, charts and so on. Secondly, once a relationship is established, the second objective of this Final Year Project would be a comparative analysis on the life-cost cycle of any project, to show potential savings from an increased investment in compaction effort.

This Final Year Project starts with a review on past works and research regarding bituminous materials, compaction and life-cycle costing. This is followed by a series of laboratory tests, namely the static creep test and the wheel-tracking test. From this, a relationship between the level of compaction with respect to the lifespan of pavements could be obtained and a comparative analysis could be done on potential cost savings.

From the laboratory tests that were conducted, a trend/pattern was established relating to the increase in pavement performance proportional to the increase in compaction. However, due to the inability to obtain maximum compaction, a definite relationship between compaction effort and lifespan of pavements could not be obtained. After making some assumptions, a comparative analysis was done and it was found that for every kilometer of road, a savings of $200,000 could be obtained for the entire project cycle. The assumptions are exaggerated and would have led to even greater cost savings if the exact relationship between compaction effort and the lifespan of pavements.

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CHAPTER 1

INTRODUCTION

1.1 Background of Study

Hot Mixed Asphalt (HMA) consists of two basic ingredients, which are aggregate and asphalt binder. The two ingredients, its respective type and amount, represent the basis of all mix designs used for pavement construction. A good grasp of the knowledge of a mix design will enable a better understanding as to how a mix will perform in the field during construction and under subsequent traffic loading.

Roads in Malaysia consist mainly of asphaltic roads, which are made using HMA. Asphaltic pavements take precedence over concrete pavements due to its ease of construction, material availability, and most importantly, low costs. *"The components of a flexible pavement are the subgrade or prepared roadbed, the subbase, the base and the wearing surface."* [Garber, 2002]

One of the many ways to ascertain the performance capabilities of the HMA is by conducting tests on the samples either cored from existing roads or mixed in the lab. The two types of tests that can be conducted are destructive tests and non-destructive tests. Non-destructive tests are uncommon in pavement tests. So, this project will concentrate on two destructive tests, which are the creep test and the wheel-tracking test.

Costing in general is perceived by many to be the single most important factor in determining the success of a project. While many may not understand rut depth or standard axial load cycles, when it comes to money and how much extra cost is expected, the public and contractors will pay more attention. Hence, there is a need to relate the lifespan of pavements, as derived from the various tests, to the extra incurred costs in the event of insufficient compaction.

1.2 Problem Statement

1.2.1 Problem Identification

"Every year, government spends millions of Ringgit on road maintenance. Most of our roads did not last to their design life due to premature failures. The two most common type of failure are permanent deformation and fatigue cracking. These failures occur as a consequence of insufficient compaction, especially on the bituminous surfacing layer. Materials used to build our roads are of superior quality. However, lack of proper supervision during construction was suspected for under-compaction of pavement layers." [Napiah, 2004]

1.2.2 Significance of the Project

Since much research has been conducted with regards to compaction and its effects on pavement performance, new findings with regard to compaction and its relationship to pavement lifespan are not expected. However, there is hope that a definite quantifiable relationship can be established between pavement lifespan and the cost cycle associated with road construction. With this cost cycle established, the importance of proper compaction can be brought into light using the single most common and important denominator in the world, which is money.

1.3 Objectives and Scope of Study

1.3.1 Feasibility of the project within the Scope and Timeframe

The objectives of this Final Year Project are as follows:

(i) To establish a relationship between level of compaction and estimated pavement life. This relationship can be in the form of graphs, empirical formula, combination of previous research, or all of the above.

(ii) To develop a life cycle cost model on compaction supervision during construction. The life cycle cost model will be conceived with the intention of showing the potential savings from added compaction efforts as compared to the current maintenance programs.

1.4 Assumptions

The HMA that will be researched however will only vary in terms of degree of compaction. The mix design is used to determine an optimum binder/aggregate content to be used for testing purposes. All other factors, including mix temperature, material, binder and aggregate type and rollers used will be disregarded in order to make this research project more focused.

The focus of this research project is the effect of compaction effort on the life of pavements. For purposes of narrowing down the scope, the research will be confined to the asphalt layer (top layer) of a pavement, with total disregard to the base and subbase layers of a pavement.

The life cycle cost model currently used, will be based on the life cycle cost model used by Jabatan Kerja Raya (JKR). All cost assumptions too, will be based on the JKR guidelines.

CHAPTER 2

LITERATURE REVIEW

In this chapter the general concept of hot mixed asphalts is discussed, starting with its composition, which are aggregates, binder and filler, along with a review of previous research on compaction. This is then followed by a review of the present road construction project life cost cycle which will be important in determining the effects of proper compaction on the life cycle costs of particular stretch of asphalt pavement.

2.1 Aggregates

"Aggregates are granular mineral particles used either in combination with various types of cementing material to form concretes or alone as road bases, backfill, etc." [Atkins, 2003]

"An aggregate is an assemblage of mineral grains, 0-80mm in size, specially intended for making mortars and concretes, as well as the wearing course, base course and subbase of roads and railway tracks" [Ruban, 2002][1]

The statements above refer to the general description of aggregates used in flexible pavement construction. There are two main sources of aggregates, which are natural sand and gravel deposits and crushed rock. The samples of aggregates that are obtained from natural sand and gravel deposits are naturally sifted to segregate finer particles of silt and clay that are not desired. These samples are then crushed in the crusher to provide the desired sizes of aggregates.

Crushed gravel, which is the product of a crusher run, can be made of many different types of mineral particles; limestone, sandstone and granite, of which granite is the preferred choice for construction purposes due to its durability, strength and hydro-phobic characteristics. Some of the common characteristics

[Hunter, 2000][2] that should be present in all suitable pavement aggregates are as follows:

(i) Hardness, toughness and ability to withstand disintegration from atmospheric and chemical action.

(ii) Absence of mud or dust, and particularly very adhesive mud.

(iii) A good foothold under all weather conditions.

(iv) Sufficient binding properties to prevent raveling or breaking up in dry weather.

(v) A tendency to break into a cubical shape when being converted into road metal.

(vi) A uniformed product which contained no weathered aggregate which is likely to wear away quickly.

Though the listed criteria are deemed to be rather vague and ambiguous, further studies conducted since that paper was published in 1910 have yielded a more accurate guide on the properties of aggregates needed for use in flexible pavement construction. Table 1[3] in the appendix clearly states the required characteristics, based on British Standard Tests.

Aggregates can be further separated into coarse aggregates and fine aggregates. Coarse aggregates function to provide stability due to its interlocking behavior and acts to withstand most of the traffic loads. The shape and textures affect the stability of any mix. Therefore, good aggregates are generally aggregates that are hard, round shaped with an overall angular shaped and rough surface texture.

Fine aggregates act to further enhance the stability of the mix by filling up the voids left out by the composition of coarse aggregates. Fine aggregates should be of good gradation between the 2.36mm to 0.075mm sieve sizes.

Textures are also an important criterion in determining the stability of the mix, as an increase in surface roughness reflects an increment of stability of a particular mix. Particles with bigger sizes provide the adequate surface roughness needed to provide the frictional surface for a pavement.

Finer fine aggregates with smaller sizes act to increase the surface area of the aggregates. This will then enable the aggregate mix to contain a high content of bitumen and therefore directly enhancing the binding force of the mix. It can therefore be concluded that a balanced mixture of properly graded aggregates is needed to provide the necessary frictional effects and stability of a mix design.

2.2 Binder

The main choice of binder for this Final Year Project is Bitumen. *"Bituminous materials (bitumen) are described as hydrocarbons that are soluble in carbon disulphate"* [Atkins, 2003]. At normal temperatures, bitumen is generally hard in nature. However, when heated to temperatures of above 130°C bitumen will liquidize. When mixed with aggregate and mineral filler in this fluid state and allowed to cool to room temperature, the mixture will solidify and bind the material together, to form what is known as the pavement surface.

There are generally 4 types of bitumen that are commonly used for paving work, which are native asphalts[4], rock asphalts[5], tars[6] and petroleum asphalts[7]. For this project, bitumen with a penetration range of 80-100 will be used as binder. Decision on which particular sub-range of penetration to be used depends on climate and traffic loading on the particular pavement in question. Bitumen with an 80/100 penetration would be used for this project.

2.3 Filler

Filler, as the name suggests, refers to fine material that is added in small quantities to any mix design in order to fill in the voids that are too minute to be filled by fine aggregates. This is to further ensure that a high surface area is available for the binder to fully mix with the aggregates and avoidance of air voids that will lead to a stronger mix. Common filler material include limestone dust, Ordinary Portland Cement (OPC), hydrated chalk or dust from other fine materials with more than 85% passing on the 0.063mm sieve size.

For this project, the filler used was Ordinary Portland Cement. This is due to its ease of availability, and its uniform size and readiness of use. No prior crushing and sieving were required.

2.4 Compaction

"Compaction is the process by which the volume of air in an HMA mixture is reduced by using external forces to reorient the constituent aggregate particles into a more closely spaced arrangement."[Ruban, 2002]. This reduction in air volume translates to an increase in HMA unit weight or its density. Therefore, a major factor to be focused on in this project is the percentage of air voids in the HMA mixture.

As mentioned in the problem statement, "*an inadequate compaction results in a pavement with decreased stiffness, reduced fatigue life, accelerated aging/decreased durability, rutting, raveling and moisture damage.*"[Ruban, 2002]

Percent air voids is typically calculated by using AASHTO T 269, ASTM D 3203 or an equivalent procedure. The procedures mentioned above use the laboratory to determine the bulk specific gravity and maximum theoretical specific gravity using the following equations:

$$Percent\ Air\ Voids = 100\left(\frac{G_{mm} - G_{mb}}{G_{mm}}\right)$$

With,

$$G_{mb} = \frac{W_d}{W_{SSD} - W_{sub}}$$

$$G_{mm} = \frac{W_{agg} + W_b}{V_{eff} + V_b}\ or$$

$$G_{mm} = \frac{1}{\frac{1-P_b}{G_{se}} + \frac{P_b}{G_b}}$$

Where:

G_{mm}	=	Theoretical Max Specific Gravity
G_{mb}	=	Bulk Specific Gravity of HMA
W_d	=	Dry Weight
W_{SSD}	=	Saturated Surface Dry Weight
W_{sub}	=	Weight Submerged in Water
W_{agg}	=	Weight of Aggregate
W_b	=	Weight of Asphalt Binder
V_{eff}	=	Effective Volume of Aggregate
V_b	=	Volume of Asphalt Binder
P_b	=	Asphalt Content by Weight of mix
G_{se}	=	Effective Specific Gravity Aggregate
G_b	=	Specific Gravity Asphalt Binder

The equations will be useful in determining the percent air voids, which will aid in the compaction process and the generation of a suitable relationship between compaction and pavement life. There have been reports generated detailing that air voids should not be more than 8% nor fall below 3% in the case of road works, to avoid failure of the pavement.

The air voids content can also be calculated from the following equation [Hunter, 2000]:

$$V_t = 100\left(\frac{S_t - S_b}{S_t}\right)$$

Where:

V_t = Percentage air voids

S_t = Theoretical maximum density of loose mixture

S_b = Bulk density of compacted specimen

"The theoretical maximum density of the mixture may be determined from the individual densities of its constituents... calculation of air voids is sensitive to differences in specific gravity of aggregates, and so the basis of determining aggregate density is important. Selection may be made from aggregate particle densities on an over dried basis (bulk), saturated surface dry basis, or on an apparent basis, their values increasing in magnitude of the same order. A change in aggregate density of 0.02 corresponds to a change in air voids content of around 0.6%." [Hunter, 2000]

Table 2[8] in the appendix relates to the factors that commonly affect compaction efforts in road works. There have been numerous papers and research published over the decades that deals with compaction. All of these researches have come to the general conclusion that the degree of resistance to deformation rises as the degree of compaction rose.

There have also been studies conducted that relate to the relationship of percentage air voids in relation to deflection. From figure 1 and 2 in the appendix, it can be clearly seen in the figure 1[9] that the rate of tracking decreases as the number of roller passes increases, while in figure 2, it can be seen that as the air voids rises from 3.5% to 13%, there is also a substantial rise in pavement deformation.

Table 3[10] in the appendix relates to the differences between field conditions and laboratory conditions. This table is important because it highlights the differences in compaction between lab conditions and field conditions.

The effects of proper compaction are great, with the aggregate interlocking better with one another, and internal friction increased and volume of intergranular voids reduced. The following are several other effects of compaction [Ruban, 2002]:

(i) Risks of subsequent deformations are minimized or eliminated.

(ii) Penetrations and movements of water and water vapor inside the body are slowed down or halted.

(iii)Intergranular distances being shorter, binder efficiency is increased.

For this project, the Gyratory Compactor is used. The software used to control the gyratory compactor stops the gyratory compactor under 3 conditions, which can be set. These three conditions are total gyrations, density (kg/m^3), and height (mm) of specimen. The compactor stops once any one of these requirements is met. The operator can choose to stop the gyratory compactor for either one of the conditions, or can choose to stop once the first of the three are met.

The maximum height of the specimen, or the density of the specimen, or the total gyrations, is adjusted in order to produce sample specimens of 100%, 98%, 96% compaction e tc. Calculation on degree of compaction is done by taking volume at 100% bulk density[11] of 2274 kg/m^3 and to find the ratio of volume for subsequent degrees of compaction.

The height of each sample can be determined based on the volume of the sample. The gyratory compactor can then be set to stop once a particular sample height is reached, and would then theoretically yield the desire degree of compaction.

2.5 Finance and Budgeting

"It should be emphasized that money spent on maintenance should be treated as an investment in the same way as for that spent on new construction... cost-benefit analysis is an appropriate tool for making decisions about maintenance expenditure... particularly important for maintenance activities to consider impact on the life of the works and the resulting future cost streams... application of cost-benefit principles to decisions about maintenance investment implies consideration of the concepts of life cycle costing." [Robinson, 1998]

The second objective of this project requires a life-cycle cost analysis regarding current road maintenance practice, and that of improved investment into compaction activities during the road construction phase of the life-cycle cost. Based on the literature available, the higher the engineering and maintenance level adopted, higher the overall investment cost into a project. Though the increase in investment will be substantial, *"it may result in lower costs of road administration in terms of future costs of maintenance and renewal."* [Robinson, 1998].

The importance of life cycle c osting is that without it, investment decisions become subjective and dependant upon the application of standards and intervention levels.

While this might prove to be an acceptable standard, it is often mentioned that the application standards themselves are more dependant on historical precedent rather than objective analysis. Besides this, life cycle costing aims to result in maintenance friendly measures being taken. What this basically means is that life cycle costing aims to reduce the amount spent on maintenance and frequency of the maintenance.

Some of the common contributors to road administration and maintenance costs are pavements, footways and footpaths, cycle tracks, drainage features, structures and signage. Some of these are fixed costs while others are variables, depending on the following variables [Robinson, 1998]:

(i) Standard of road concerned
(ii) Geographic location within a country
(iii)Geotechnical environment through which the road passes
(iv)Degree of urbanization surrounding the road.
(v) Sensitivity of the physical and socio-environment through which the road passes.

From the contributing factors above and the contributors listed, this project will focus on the life cycle costs of pavements, and will deal exclusively with the standard of the road concerned.

Figures 3 & 4[12] in the appendix are that of an example of an annual Cycle of Costs and Road Deterioration Model and the Typical Structure of a Life Cycle Cost Model. From these two figures, it can be concluded that the relationship between each phase of the life cycle cost model is indeed complicated, as costs and the relationship between costs change over time. For instance, road deterioration increases over time, which would lead to an increase in maintenance costs over time, which would lead to an increase in vehicle operating costs, which might also increase accident and travel time costs. *"The road standards, environment, vehicles and level of maintenance all have an effect on costs and the changes in costs experienced by the road users."* [Robinson, 1998]

CHAPTER 3

METHODOLOGY/PROJECT WORK

3.1 Procedure Identification

A special procedure was devised in order to ensure that the entire laboratory section of this project runs smoothly. The following are the stages of the methodology involved in conducting the two experiments to be mentioned later in this chapter.

3.1.1 Research

This step included an in-depth research on the various literature review topics, as well as a review on the methods for the tests to be conducted. This was then followed by thorough planning and execution of the laboratory work needed.

3.1.2 Pre-Laboratory Work

To ensure that the experiments to be conducted ran as smoothly as possible, a series of pre-laboratory preparation was conducted. The pre-laboratory work included aggregate, binder and filler preparation, sieve analysis test, Marshall Mix design and particle density and water absorption test. The material was washed and oven dried where needed, while the 3 pre-laboratory tests were conducted to obtain the optimum binder content of the mix to be used, as well as the theoretical maximum density of a particular sample.

3.1.3 Sample Preparation

At the early stages of the sample preparation stage, there was a need to produce about 25 samples for the purpose of testing. This was done over a course of about 3 days, varying the degrees of porosity for each sample, thus ensuring different compaction efforts for each sample.

Due to some complications with regard to the inability to obtain maximum compaction, a total of 28 100mm diameter cylindrical samples were fabricated, with an additional 5 150mm cylindrical samples fabricated for the wheel-tracking test.

After the tests were conducted, it was realized that only about 12 100mm samples were used. There are plans to hand over the remaining samples to the laboratory technicians to be used by the civil engineering students for future experiments.

3.1.4 Laboratory Experiments

There were a total 2 laboratory experiments that were conducted. The 2 experiments were the static creep test and the wheel-tracking test. A total of 7 samples for the creep test and 5 samples for the wheel-tracking test were tested. Further detail on each test will be elaborated in Section 3.2 and 3.3.

3.1.5 Data Collection and Analysis

Data from the two laboratory experiments were conducted and analyzed. For the creep test, the samples were first divided into 4 different density ranges and an average mean reading was obtained for each range. For the wheel-tracking test, the samples were tested and a straight-forward analysis was done on the performance of the samples with regard to compaction.

3.2 Static Creep Test

3.2.1 Introduction

This test is used to determine the permanent deformation due to temperatures and loads similar to those experienced by the asphalt pavement. The measured parameters are the stiffness and permanent deformation of the samples.

3.2.2 Tools and Equipment

The tools that are required for the static creep test are the loading press, temperature control system with confined environment to carry out the test, static creep test jig complete with Linear Variable Differential Transducers (LVDT) and suitable software for the control of the equipment and recording of the data. The tools are then set up as shown in figure 3.1.

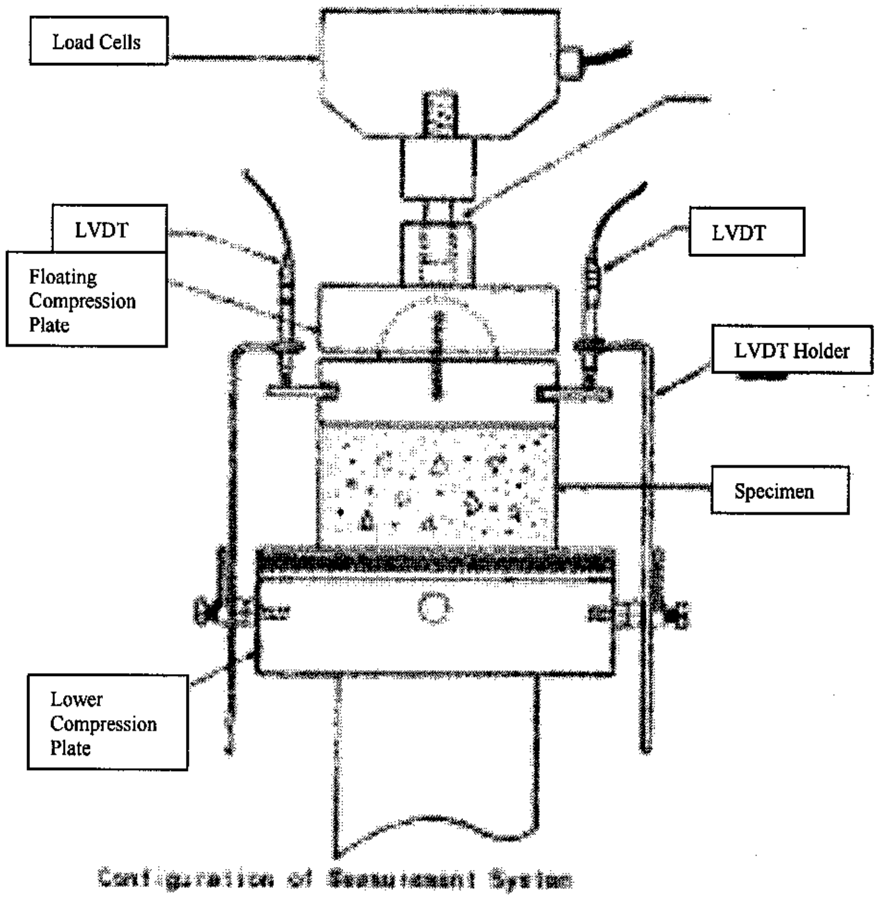

Figure 3.1: Equipment set-up for the static creep test.

3.2.3 Procedure

The static creep test was conducted according to the specifications in British Specifications (BS 598) Part III, 1995 and US NCHRP 9-19 Superpave Models Draft Test Method W1.

3.3 Wheel-Tracking Test

3.3.1 Introduction

This test is used to determine the susceptibility of a particular bituminous pavement to a continuous dynamic load similar to that of the wheel of a vehicle. The performance of the sample is based on the rut depth at a given fixed time frame and also the slope of the rut depth graph, which represents the rate of rut depth based on the loading inflicted upon the sample.

3.3.2 Tools and Equipment

The tools and equipment needed for the test are the wheel-tracking device, rut depth measurement apparatus, temperature control system, wheel pass counter and specimen mounting system.

3.3.3 Procedure

The wheel-tracking test was conducted according to the specifications mentioned in the relevant British Standards, NCHRP and ASTM Standards.

3.4 Life-Cycle Cost Analysis

3.4.1 Introduction

The life-cycle cost analysis is used to determine the overall cost of the project, with respect to the initial investment, the periodical maintenance costs and a final disposal cost, if any. Part of the scope of this analysis is a comparison of the differences between properly compacted pavements and pavements that are below the 100% compaction effort.

3.4.2 Tools and equipment

The main tool to be used is the cash flow diagram, a simple and effective tool to graphically show how cash is spent on an annual basis.

3.4.3 Procedure

Firstly, some assumptions with regard to the results of the laboratory experiments have to be conducted. The values to be assumed are based on the average roadwork projects in New Zealand[13]. The additional costs due to snow and frost maintenance are omitted, due to obvious reason of the lack of snow and frost in Malaysia.

A cash flow diagram is then produced, and the overall cost of the project for various compaction efforts is calculated. The final values are then compared and discussed.

CHAPTER 4

RESULTS AND DISCUSSIONS

The following are the results expressed in graphs, charts and tables, using data obtained from running the various tests mentioned in the previous chapter. Samples from the same batch of material were used. Comparison is made between samples of different compaction efforts and is displayed appropriately.

For ease of sample identification, table 4 & 5[14] in the appendix is provided detailing the sample l abel as well as its relevant information such as density, porosity and compaction percentage.

4.1 Pre-Laboratory Test Results and Discussion

4.1.1 Sieve Analysis Test Results and Discussion

Figure 4.1 represents the calculated percentage of each component based on the trial and error method. The total percentage (given by the aggregate gradation curve) is then plotted in a semi-logarithmic graph, and compared to the ACW 20 envelope. The graph shows that the assumption of 48% coarse aggregate, 45% fine aggregates and 7% filler is sufficient to meet the criteria set by the ACW 20 envelope, as the line that was plotted stayed within the ACW 20 envelope. Finally, ratio of 48:45:7 is used to determine the required amounts of coarse aggregates, fine aggregates and filler needed, based on a mixture mass of 1200g. The calculations have yielded that the required amount of coarse and fine aggregates and filler are listed below, in grams:

(i) Coarse Aggregates: **576 grams**
(ii) Fine Aggregates : **540 grams**
(iii)Filler : **84 grams**

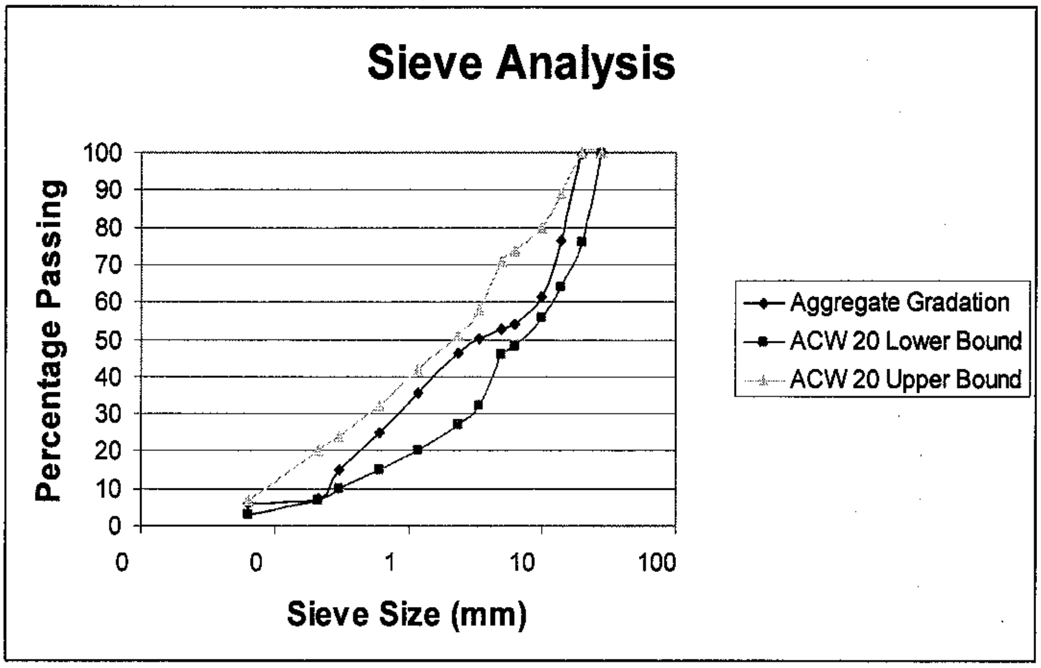

Figure 4.1: Aggregate Gradation Curve

4.1.2 Marshall Mix Design Results and Discussion

There are 4 graphs that have to be plotted for the analysis of the Marshall Mix Design in order to determine the optimum binder content, which are:

(i) Bulk Density vs. Bitumen Content (Figure 4.2)

(ii) Stability vs. Bitumen Content (Figure 4.3)

(iii)Porosity vs. Bitumen Content (Figure 4.4)

(iv)Flow vs. Bitumen Content (Figure 4.5)

Based on the plots, an optimum binder content (OBC) of 5.7% is obtained.

There were no major problems encountered in the values obtained from the Marshall Mix Design. However, it must be said here that there were some rounding up of values in order to get a smoother curve on the graphs.

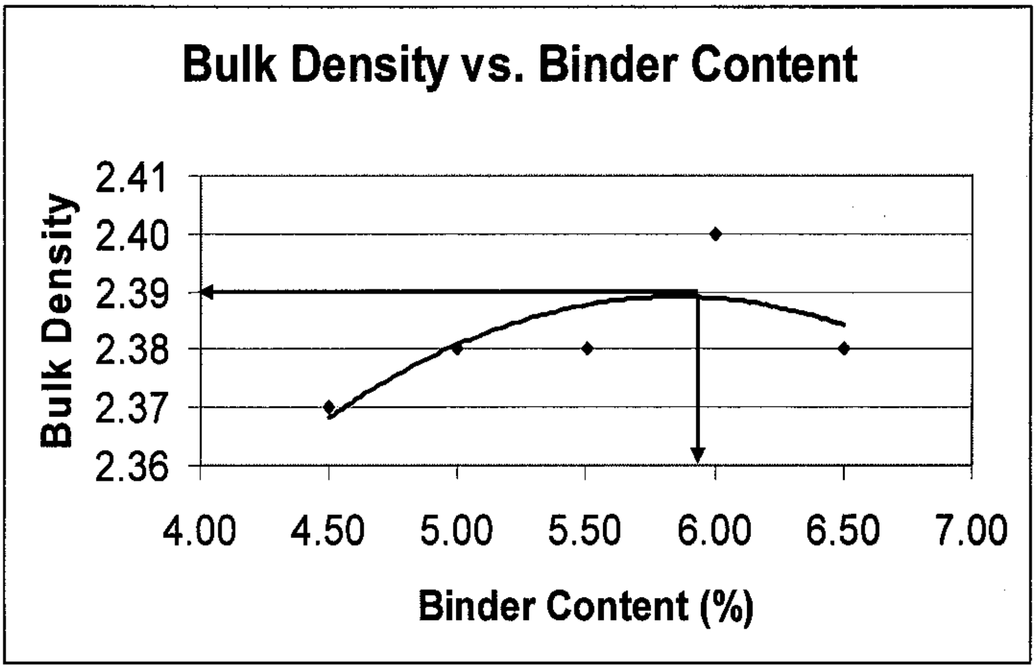

Figure 4.2: Bulk Density vs. Binder Content Graph

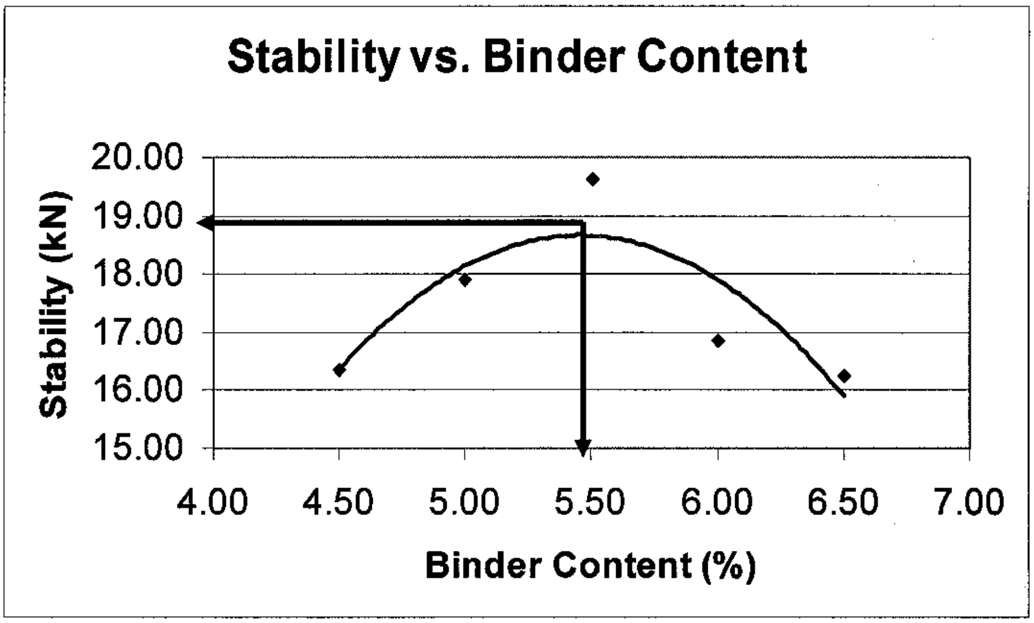

Figure 4.3: Stability vs. Binder Content Graph

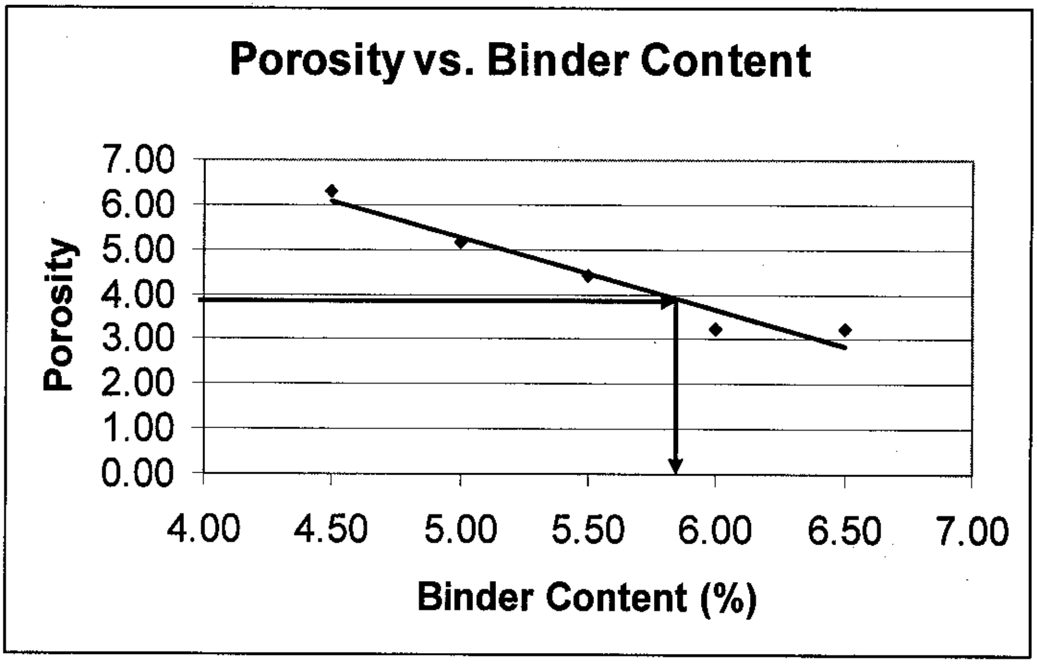

Figure 4.4: Porosity vs. Binder Content Graph

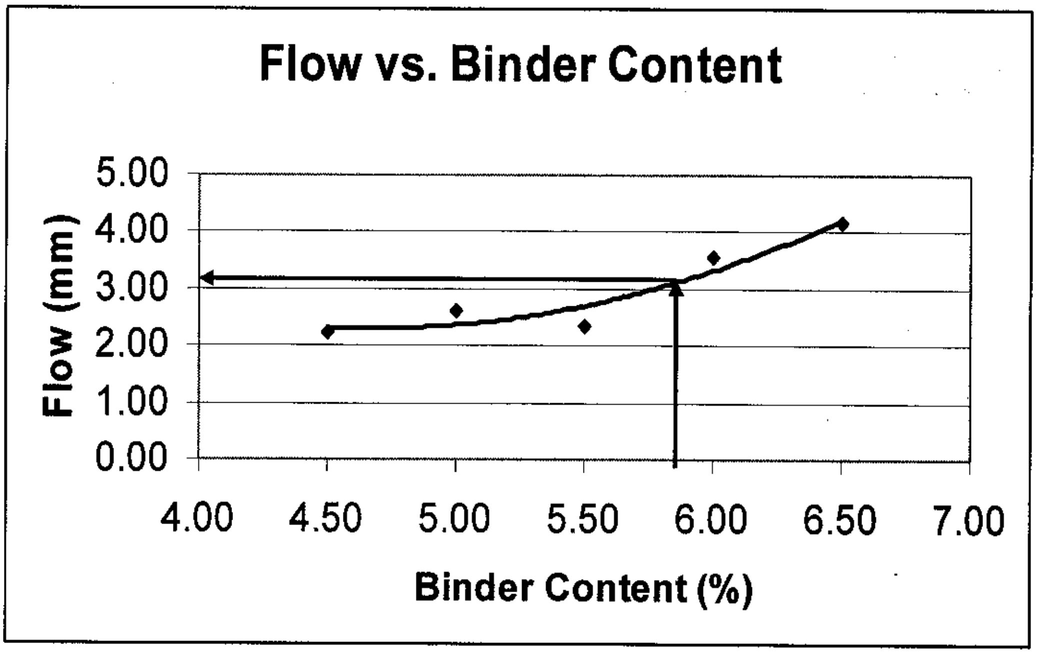

Figure 4.5: Flow vs. Binder Content Graph

4.1.3 Particle Density and Water Absorption Test Results and Discussion

Tables 4.1 and 4.2 show results of particle density for fine aggregate and coarse aggregate respectively. A particle density of **2.62** for coarse aggregate and **2.47** for fine aggregate can be assumed.

Table 4.1: Particle Density (Fine Aggregate)

	Test No. 1 (g)	Test No. 2 (g)	Average (g)
Mass of saturated surface-dried sample in air (A)	0.477	0.482	
Mass of vessel containing sample and filled with water (B)	1.809	1.811	
Mass of vessel filled with water only (C)	1.533	1.533	
Mass of oven dried sample in air (D)	0.46	0.47	
Particle density on an oven-dried basis	2.289	2.293	2.29
Particle density on a saturated and surface-dried basis	2.373	2.284	2.33
Apparent particle density	2.500	2.435	2.47
Water absorption (% of dry mass)	3.7%	2.6%	3.2%

Table 4.2: Particle Density (Coarse Aggregate)

	Test No. 1 (g)	Test No. 2 (g)	Average (g)
Mass of saturated surface-dried sample in air (A)	1.000	1.000	-
Mass of vessel containing sample and filled with water (B)	2.045	2.048	-
Mass of vessel filled with water only (C)	1.433	1.433	-
Mass of oven dried sample in air (D)	0.91	0.992	-
Particle density on an oven-dried basis	2.554	2.645	2.60
Particle density on a saturated and surface-dried basis	2.577	2.667	2.62
Apparent particle density	2.615	2.631	2.62
Water absorption (% of dry mass)	0.9%	0.8%	0.9%

4.2 Static Creep Test

4.2.1 Static Creep Test Results and Calculation

For this test, 7 samples were tested, to be grouped under 4 ranges of sample specific gravity, which are 2.16-2.17, 2.18-2.19, 2.20-2.21 and 2.22-2.23. The results that were obtained from the laboratory tests are in appendix table 4 & 5 of this report. From the permanent deformation curve, values of mix stiffness would be calculated, based on the slope of the graph at the instantaneous time that the slope is measured (eg. 1 second, 10 seconds, 100 seconds). The bitumen stiffness was derived from a nomograph which is also available in the figure 5 in the appendix of this report.

From the calculations done, the average values of each range were plotted in the following figure.

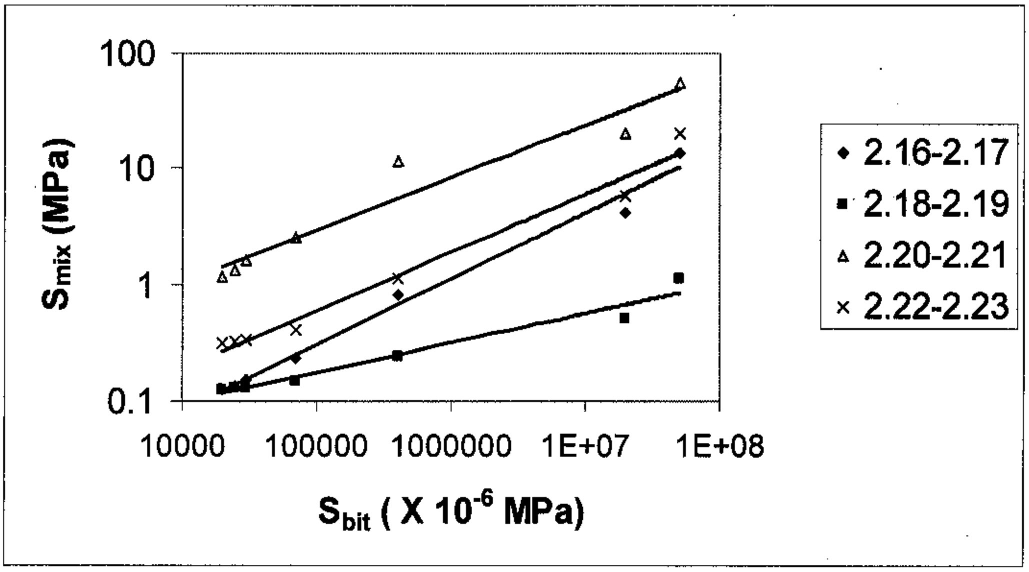

Figure 4.6: Relationships between mix stiffness and bitumen stiffness for various compaction levels

From this figure, the equations of each linear line was derived and used in the calculation of the appropriate mix stiffness based on the pre-calculated bitumen stiffness using the following equation [Hills, 1974]:

$$(S_{bit})v = \frac{3\eta}{NT_W}$$

Where :

$(S_{bit})v$ = the viscous component of the stiffness modulus of the bitumen

η = the viscosity of the bitumen as a function of PI and ring and ball temperature

N = the number of wheel passes in standard axles

T_w = the time of loading for one wheel pass

The rut depth is then calculated based on the stiffness linear relationship obtained previously. The formula [Van der Loo, 1974] used is as below:

$$R_d = C_m \times H \times \left(\frac{\sigma_{av}}{S_{mix}} \right)$$

Where:

R_d	= calculated rut depth of the pavement
C_m	= correlation factor for dynamic effect, varying from 1.0 to 2.0
H	= pavement layer thickness
σ_{av}	= average stress in the pavement, related to wheel loading and stress
S_{mix}	= stiffness of the design mixture derived from creep test at a certain value of stiffness which is related to the viscous part of the bitumen

From the equations above, a graph shown in Figure 4.7 was derived, detailing the various rut depth with respect to cycles of standard axial loading.

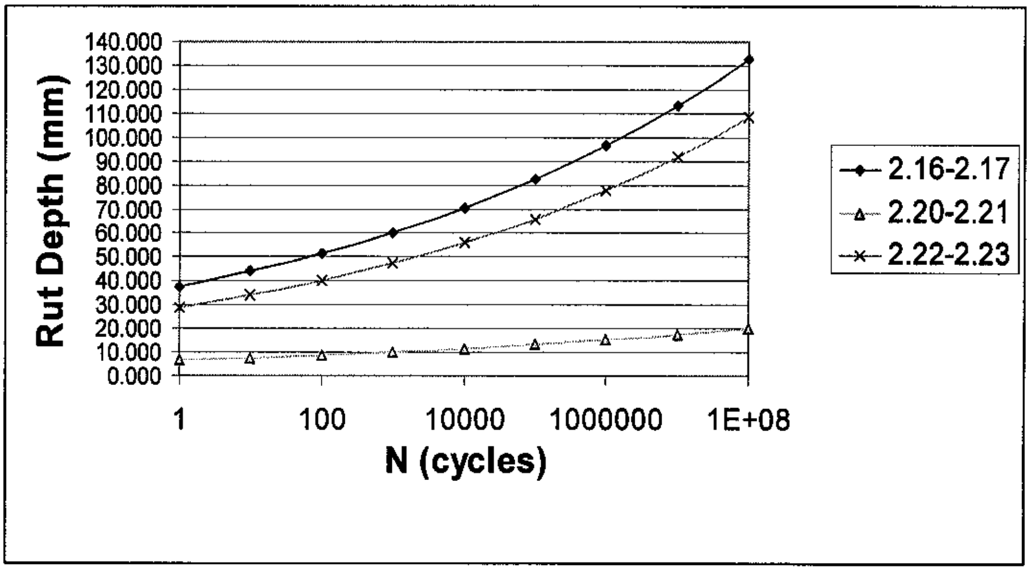

Figure 4.7: Estimated rut depth of road pavement for various compaction ranges

The graph above was derived from the following table, which detail the exact rut depth at the corresponding standard axial load cycles. There was no foreseeable need to include table blab la in the plotting of the graph above, as the values were too far off the charts to be taken into consideration for further cost analysis.

Table 4.3: Sample with density range 2.16 – 2.17

N	S_{bit} (MPa)	S_{mix} (MPa)	R_d (mm)
1	7.5	1.505	37.381
10	0.75	1.284	43.797
100	0.075	1.096	51.315
1000	0.0075	0.936	60.124
10000	0.00075	0.799	70.444
100000	0.000075	0.682	82.537
1000000	0.0000075	0.582	96.705
10000000	0.00000075	0.496	113.304
100000000	0.000000075	0.424	132.754

Table 4.4: Sample with density range 2.18 – 2.19

N	S_{bit} (MPa)	S_{mix} (MPa)	R_d (mm)
1	7.5	0.260	216.550
10	0.75	0.234	240.469
100	0.075	0.211	267.029
1000	0.0075	0.190	296.523
10000	0.00075	0.171	329.275
100000	0.000075	0.154	365.644
1000000	0.0000075	0.139	406.031
10000000	0.00000075	0.125	450.878
100000000	0.000000075	0.112	500.678

Table 4.5: Sample with density range 2.20 – 2.21

N	S_{bit} (MPa)	S_{mix} (MPa)	R_d (mm)
1	7.5	8.416	6.683
10	0.75	7.344	7.659
100	0.075	6.408	8.778
1000	0.0075	5.591	10.060
10000	0.00075	4.879	11.529
100000	0.000075	4.257	13.213
1000000	0.0000075	3.715	15.143
10000000	0.00000075	3.241	17.354
100000000	0.000000075	2.828	19.888

Table 4.6: Sample with density range 2.22 – 2.23

N	S_{bit} (MPa)	S_{mix} (MPa)	R_d (mm)
1	7.5	1.967	28.597
10	0.75	1.665	33.785
100	0.075	1.409	39.913
1000	0.0075	1.193	47.154
10000	0.00075	1.010	55.708
100000	0.000075	0.855	65.814
1000000	0.0000075	0.723	77.753
10000000	0.00000075	0.612	91.858
100000000	0.000000075	0.518	108.522

4.2.2 Static Creep Test Discussion

From the rut depth graph obtained from figure 4.7 above, there is a stark contrast between the rut depths of samples in the 2.16-2.19 range and that of the 2.20-2.21 range. Taking a maximum rut depth of 15mm before maintenance works has to be carried out, only the specimens within the 2.20-2.21 range qualify for any form of consideration. The other ranges that were plotted, which were the 2.16-2.17 range and even the higher density range of 2.22-2.23 do not come close to the specified rut depth, with the predicted rut depths at 37mm and 28mm respectively after just 1 cycle.

Logically, this does not seem possible, as one standard axial load cycle is generally not enough to cause a rut as deep as 30mm on its first cycle. Hence the feeling that the static creep tests conducted were not accurate. It is a well known fact that laboratory tests are never accurate and furthermore, to duplicate similar results would be nearing impossible.

There was clear difficulty, as mentioned earlier, in obtaining the theoretical maximum specific gravity of 2.274, as mentioned in the earlier sections of this report. Moreover, there was also difficulty in obtaining consistent permanent deformation values from similar samples that were tested with the static creep test.

This could be due to several factors. Chiefly, the quality of the samples that were fabricated were difficult to achieve and maintain. While there was control on the amount of material that was used, the mixing bowl, and the gyratory compactor used showed signs of wear and tear. There were also problems with obtaining the exact density to be achieved by every specimen, even though theoretically, this can be computer controlled, through the usage of appropriate software.

Secondly, there is suspicion that inferior materials were ordered by the laboratory for experiment usage. While there were ready assumptions detailing that materials and temperature shall not be taken into account when reasoning experiment results, the materials that were used were clearly not of the highest quality. The coarse aggregate that was used looked to c onsisted mainly o f limestone which chipped e asily d uring mixing, while the fine aggregate were clearly filled with impurities that were very difficult to sieve out and extract.

Thirdly, during the process of mixing and fabricating each sample, segregation between coarse aggregate and fine aggregate, which is very difficult to avoid, had taken place.

Segregation basically means that loading within the sample is not distributed equally, causing certain samples of the same density to react differently to loading (from the static creep test for instance) and fail earlier.

There are also discrepancies with regard to inverse trends within the projected rut depth graph. For instance, samples with a higher density (2.22-2.23 range) should have a higher resistance to rutting. However, this does not seem to be the case with regard to the results of the static creep test obtained and displayed above. As the author has mentioned in previous paragraphs, this could be due to segregation, which causes certain samples to fail earlier. This could also be due to the fact that a difference of 0.01 Specific Gravity is not much to be used to differentiate between both ranges. Hence there could be not much difference between the performance of a sample with a density of 2.21 and a sample with a density of 2.22.

Taking all these considerations into account, the rut depth values that were obtained for samples within the 2.20-2.21 range were considered rather acceptable, with a 15mm rut depth projected at 1,000,000 cycles. However, it must be mentioned here that a 2.20-2.21 density range only amounts to about 58% compaction. So, with 100% compaction, what would be expected would be 15mm rut depth to be achieved at a much higher total load cycle value, of which the exact value cannot be determined here, due to the failure to obtain a sample with the maximum theoretical density needed for such a conclusion.

4.3 Wheel-Tracking Test

The test results are relatively straight-forward, with each sample being subjected to a constant wheel-loading for a duration of 45 minutes. From this, the rut depth measurements were taken via the computer software available and the subsequent rut depth versus time graph was plotted. Figure 4.8 shows the results of the wheel tracking test:

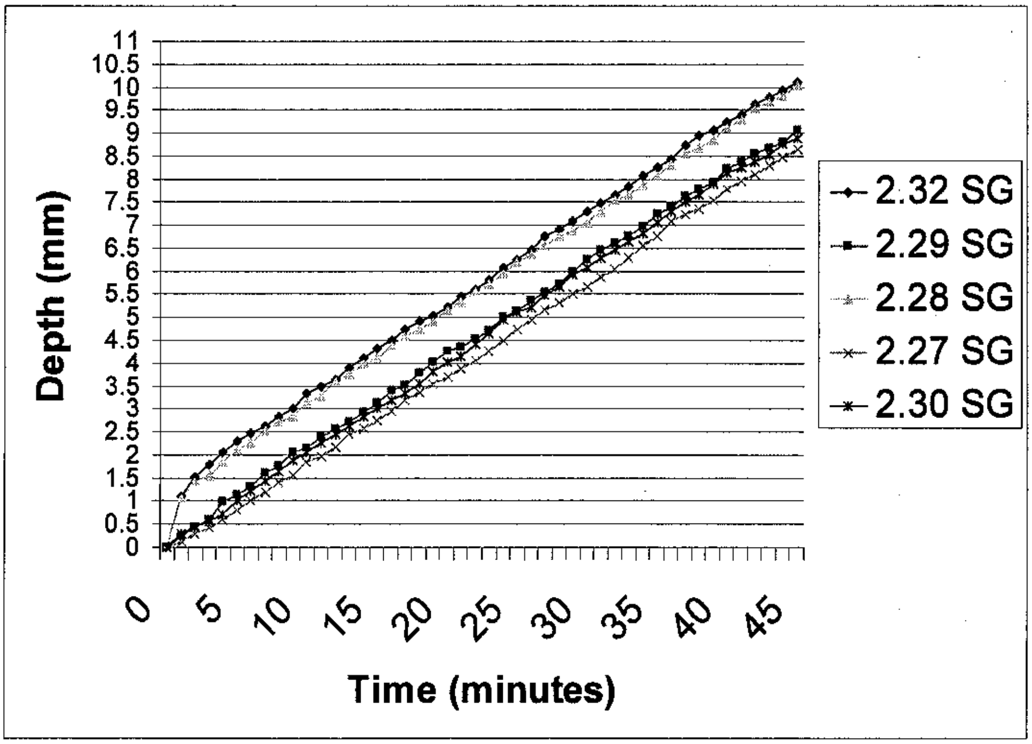

Figure 4.8: Relationship of Rut depth with respect to time for the various compaction levels.

From figure 8, observations have yielded rather odd results. While the sample closest to 4% porosity (2.27 SG or 100 % compaction) has yielded the least rut depth, the same can not be mentioned regarding the other samples. For instance, sample 3 (2.28 SG) should exhibit comparable performance, followed by sample 2 (2.29 SG) and sample 5 (2.30 SG). This does not seem to be the case, as sample 5 (2.30 SG) displayed the second least rut depth, followed by sample 2 (2.29 SG) and then sample 3 (2.28 SG).

Sample 1 (2.32 SG) clearly displayed the deepest rut depth, due to the fact that it has been over-compacted, with a porosity of just 2.45%. This is clearly below the minimum JKR level of 3% porosity as ideal compaction. The mixed results, as mentioned earlier, could be due to the fact that the differences between samples 2, 3 and 5 are rather minute (less than 0.01 SG separating the 3 samples) and therefore may be interchangeable with regards to rut depth resistance.

The inexactness of the wheel tracking test itself, due to the cylindrical specimen being held in place by a solid mold, may entail the rut depth being measured by the computer to be an average value, based on the reading of the wheel on the specimen itself, and on the mould. There was no foreseeable way of controlling this phenomenon, or setting the software to specially cater for cylindrical samples instead of the usual bituminous slab.

4.4 Life-Cycle Cost Analysis

4.4.1 Life-Cycle Cost Calculation

Life cycle cost analysis can be done using a simple method of a cash flow diagram. For this, some assumptions have to be made, based on some figures obtained through a website [11] detailing the average construction costs for road works in New Zealand. The assumptions are as follows (per km of road):

- Initial cost, I = \$ 7.27 million (construction of road from scratch, including culvers, subgrade, subbase, base, drainage systems, railings, signage etc)
- Initial cost for increased compaction effort I1 = \$ 7.5 million (estimated figure based on increased personnel allocation, additional time spent on compaction, equipment operation, rental and maintenance etc)
- Resurfacing Costs, B = \$ 70,000
- Yearly Maintenance Costs, A = \$ 2,000
- Duration of road life = 20 years
- Interest Rates = 10%

- Resurfacing occurs at 15mm rut depth (yearly for 60% compacted roads, once in 3 years for fully compacted roads)

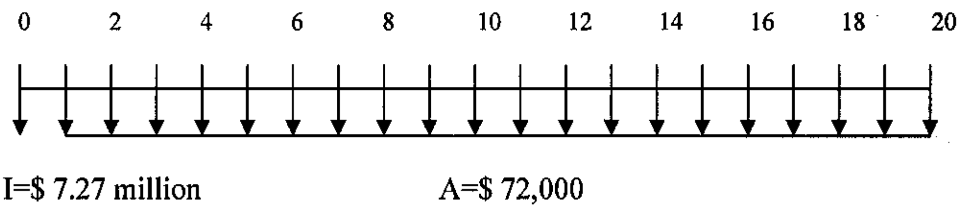

Figure 4.9: Cash flow diagram for pavement with 60% compaction

Present Worth of the project:[Sullivan, 2003]

PW = 7 270 000 + 72,000 (P/A, 10%, 20)

PW = 7 270 000 + 612 979

<u>**PW = $ 7 882 979**</u>

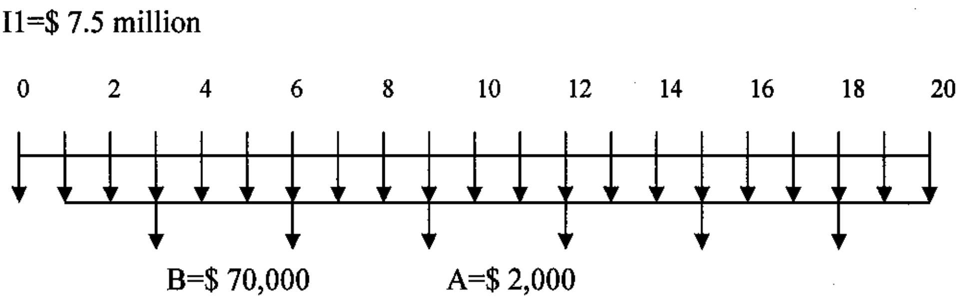

Figure 4.10: Cash flow diagram for pavement with 100% compaction

Present Worth of the project:[Sullivan, 2003]

PW = 7 500 000 + 2 000 (P/A, 10%, 20) + 70 000 [(P/F, 10%, 3) + (P/F, 10%, 6) + (P/F, 10%, 9) + (P/F, 10%, 12) + (P/F, 10%, 15) + (P/F, 10%, 18)]

PW = 7 500 000 + 17 027 + 173 446

<u>**PW = $ 7 690 473**</u>

4.4.2 Life-Cycle Cost Discussion

From the calculations above, potential savings from ensuring 100% compaction can be quantified to about \$ 200,000 in savings. While this seems to be a relatively small amount, \$ 200,000 is still a considerable amount of money, especially considering the very competitive road construction markets presently available.

It must be said though, that these assumed figures are somewhat exaggerated, due to the inability to obtain accurate accounting information regarding road building projects. Where possible, original figures have been used, except for the assumed figure for added initial investment, due to additional compaction effort. There is a very high possibility that additional savings could be achieved, possibly even doubling the original savings of \$ 200,000.

Costing is a very inexact science which really depends on the creativity of the person in charge of it. Certain values that would normally be under a category might and could be classified under a different category, in order to normalize the expenditure curves, as well as to make the project numbers look better. While this is indeed unethical, practices such as this are fairly common, with varying consequences.

CHAPTER 5

RECOMMENDATION

As part of future and on going research into the effects of additional compaction effort, there are some suitable recommendations to be made. Basically, the current research under the scope of this project has been centered on 2 very important and versatile tests, which are the static creep test, and wheel-tracking test. It would have been interesting to note of further findings if other tests were also done, for instance the indirect tensile test and the dynamic creep test. The presence of additional tests would further enforce the ongoing belief that compaction effort is indeed important in pavement construction and plays a pivotal role in ensuring overall increased lifespan of a particular bituminous pavement. Furthermore, if 100% compaction could be achieved for the samples, a definite compaction effort with respect to pavement lifespan relationship could be established.

With the additional tests too, further and more accurate relationships could be developed between pavement lifespan and life-cost cycle models for current and future road works. It would be very appropriate too, if proper project accounts figures could be obtained from the Public Works Department of Malaysia in order to further strengthen the current established belief of potential immense cost savings by an increased initial investment in increased compaction effort.

Additional steps could also feature case studies of failed roads, first by way of actual site inspection, followed by sample coring at the site itself. From this, specified tests could be done that would determine the compaction effort. These values could be cross-referenced to provide further depth to the current study and shed further light into actual costs incurred to rectify or maintain that particular case study road.

CHAPTER 6

CONCLUSION

This project started out with two main objectives, which were to establish the relationship between compaction effort and the lifespan of pavements, and the alterations in the life-cycle cost model of a bituminous pavement in the event of additional investment to ensure increased compaction.

With regards to the first objective, through the static creep test and the wheel-tracking test, a definite pattern was established between increased compaction effort and an increase rutting resistance, which is a function of pavement performance, and thus a function of the lifespan of pavements. However, due to some technical difficulties (due to the unexplainable failure to achieve maximum compaction for the 100mm samples), the exact compaction effort with respect to time relationship could not be established.

Furthermore, beyond the 60% compaction effort, pavement performance reduces to such an extent that further analysis on the samples would have been pointless. This was because of predicted rut depths that were much more than the control value of 15mm rut depth. So, if 100% compaction could have been achieved, it's corresponding number of cycles at 15mm rut depth could have been obtained and a subsequent compaction effort with respect to time relationship could have been derived. However, from the experiments conducted, a sample with about 55% compaction effort displayed an estimated rut depth of 15mm at 1,000,000 standard axial load cycles, while for the wheel-tracking test yielded best performance from the 100% compacted sample, with a final rut depth after 45 minutes of about 8.8mm.

The second objective stated a comparative analysis of the life-cycle cost analysis, to determine the potential savings from an increased investment in compaction effort. From the analysis that was carried out, the conclusion was that the potential savings amounted to roughly $200,000 over the entire project period. However, it was pointed out that most of the figures were rather generous and exaggerated. This basically meant that the potential savings would most likely have been more than the $200,000 value given as a rough estimate in this project.

Very regrettably, so much of this project relied on fabricating samples capable of achieving maximum compaction effort. Achieving maximum compaction is very different from extrapolation, as definite and exact values could have been obtained to prove concretely, beyond doubt that maximum compaction effort does lead to increased performance, increased lifespan, and significant cost savings.

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ENDNOTES

[1] Based on NF P 18-101 Standards

[2] Based on a paper published by Dorman R. for the First Irish Road Congress.

[3] Appendix Table 1 of the Appendix: Summary of Current Highway Agency Requirements for aggregates.

[4] Obtained from Asphalt Lakes in and around the Caribbean during the earlier days.

[5] Rock deposits that contain bituminous material.

[6] Obtained from distillation of coal.

[7] Obtained from distillation of crude oil. The most common of the bituminous binders for paving works.

[8] Appendix Table 2: Factors affecting compaction effort

[9] Appendix Figure 1: Effect of compaction to resistance to deformation

[10] Appendix Table 3: Differences between Field Conditions and Laboratory Conditions.

[11] Appendix Calculation 1: Maximum Bulk Density based on % air voids of 4.0%

[12] Appendix Figures 1 and 2: Models for life cycle costing.

[13] Taken from New Zealand Transportation Department Website.

[14] Appendix Table 4: List of Samples and its corresponding density, porosity and compaction effort

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CALCULATION 1: ACHIEVEMENT OF FINAL BULK DENSITY VALUE

CHARTS

CHART 1: GANTT CHART FOR FYP

Table 1: Highway Authority Requirements for Aggregates.

(Source: Hunter R.N. 2000)

Summary of main BS 812 test methods used to assess aggregates

Test method	Abbreviation	Property measured	BS 812 method	Typical limit
Sampling	—	Representative sample	Part 102	—
Sieve analysis	SA	Size distribution	Part 103 Section 103.1	Depends on use
Flakiness Index	FI	% flaky aggregate	Part 105 Section 105.1	<25%
Elongation Index	EI	% elongated aggregate	Part 105 Section 105.2	<25%
Aggregate Impact Value	AIV	Resistance to sudden impact	Part 112	<30%
Ten Per Cent Fines Value	TFV	Resistance to compressive loading	Part 111	>160 kN (dry)
Aggregate Abrasion Value	AAV	Resistance to dry abrasion	Part 113	<10, <12, <14, <16
Polished Stone Value	PSV	Skid resistance	Part 114	50, 55, 60, 65, 68+, 70+
Magnesium Sulphate Soundness Value	MSSV	Soundness	Part 121	>75%

Table 2: Factors Affecting Compaction Effort

(Source: George Washington University Website)

Environmental Factors	**Mix Property Factors**	**Construction Factors**
Temperature	Aggregate	Rollers
Ground temperature	Gradation	Type
Air temperature	Size	Number
Wind speed	Shape	Speed and timing
Solar flux	Fractured faces	Number of passes
	Volume	Lift thickness
	Asphalt Binder	Other
	Chemical properties	HMA production temperature
	Physical properties	Haul distance
	Amount	Haul time
		Foundation support

Table 3: Difference Between Field and Lab Conditions

(Source: George Washington University Website)

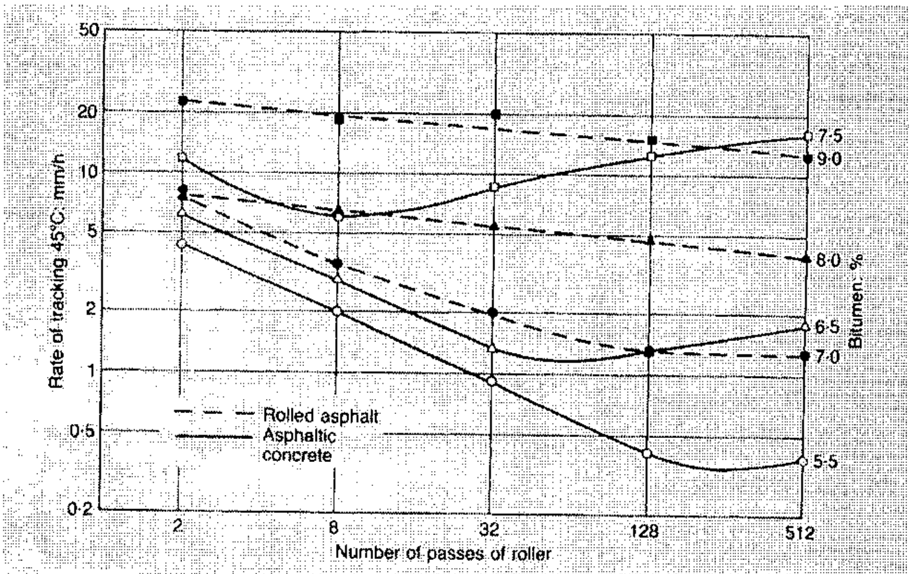
Laboratory Conditions	Field Conditions
Asphalt Binder	
Aging is simulated using the TFO, RTFO or PAV. All of these methods are only rough simulations of actual asphalt binder aging.	Aging is much more complex - especially after construction when it is highly dependent upon construction quality and the environment.
After mixing, the loose mix is generally aged to allow for asphalt binder absorption and an increase in viscosity.	After mixing the loose mix can be immediately transported to the construction site or can be placed in storage silos for up to a week.
Aggregate	
Gradation is carefully measured and controlled.	During the manufacturing process aggregate gradation will change slightly as it passes through the cold feed bins, aggregate dryer and drum mixer/pugmill.
Aggregate used is completely dry.	Even after drying, aggregates typically contains between 0.1 - 0.5 percent by weight moisture.
Oven heating of the aggregate usually results in uniform heating of the coarse and fine aggregate.	In a drum plant there is often a distinct temperature difference between the coarse and fine aggregate.
Fines are retained during the mixing process.	Some fines are collected in the mix plant baghouse. If all of these fines are not put back into the mix (practically, they cannot be because baghouse efficiencies are less than 100%) the aggregate gradation will change slightly.
If RAP is used, it is heated to the same uniform temperature as the virgin aggregate.	If RAP is used its degree of heating may be different than the virgin aggregate.
Mixing Process	
The mixing process occurs on essentially unaged asphalt binder for the Hveem and Marshall methods. The Superpave method roughly simulates short-term aging using the RTFO.	The mixing process can substantially age the asphalt binder. A mixing time of 45 seconds can increase asphalt binder viscosity by up to 4 times.
Compaction	
Compaction uses a laboratory device and a small cylindrical sample of HMA. This combination attempts to simulate the particle orientation achieved by field compaction with rollers.	Particle orientation and compactive effort can vary widely depending upon roller variables and the environment (e.g., temperature, wind speed).
Compaction is relatively quick (< 5 minutes) and thus occurs at an almost constant temperature.	Compaction can take a significant amount of time (30 minutes or more in some cases) and thus occurs over a wide range of mix temperatures.
Compaction occurs against a solid foundation.	Foundation rigidity will affect compaction. Compaction can occur against a range of foundations: some can be quite stiff (like old pavement) while some can be quite soft (like a clay subgrade).

Table 4: List of Samples Prepared for Laboratory Work (100 mm)

Sample	Height	Weight (air)	Weight (water)	Volume	Density	Porosity	Range
1.00	68.80	1264.00	692.40	571.60	2.21	6.85	58.38
2.00	39.20	1243.50	677.40	566.10	2.20	7.47	53.53
3.00	69.70	1252.80	684.00	568.80	2.20	7.22	55.38
4.00	70.00	1241.20	676.80	564.40	2.20	7.37	54.31
5.00	71.00	1321.40	726.30	595.10	2.22	6.47	61.85
6.00	70.30	1249.60	682.60	567.00	2.20	7.17	55.82
7.00	70.80	1263.60	691.20	572.40	2.21	7.01	57.05
8.00	70.70	1221.60	660.10	561.50	2.18	8.36	47.86
9.00	71.50	1243.30	671.40	571.90	2.17	8.43	47.48
10.00	72.60	1290.20	706.30	583.90	2.21	6.92	57.77
11.00	72.50	1238.90	669.00	569.90	2.17	8.43	47.45
12.00	72.70	1198.40	647.00	551.40	2.17	8.45	47.33
13.00	69.20	1269.10	700.20	568.90	2.23	6.03	66.31
14.00	69.00	1245.10	686.00	559.10	2.23	6.19	64.59
15.00	69.40	1259.40	692.50	566.90	2.22	6.42	62.29
16.00	69.20	1235.00	678.10	556.90	2.22	6.59	60.73
17.00	70.70	1293.10	711.60	581.50	2.22	6.33	63.19
18.00	70.00	1272.60	702.20	570.40	2.23	6.02	66.44
19.00	70.80	1246.90	679.50	567.40	2.20	7.43	53.82
20.00	71.30	1260.50	691.40	569.10	2.21	6.70	59.69
21.00	72.00	1276.50	688.70	587.80	2.17	8.52	46.93
22.00	72.80	1248.80	673.30	575.50	2.17	8.60	46.54
23.00	73.00	1242.10	666.20	575.90	2.16	9.15	43.72
24.00	73.30	1262.10	684.30	577.80	2.18	7.99	50.06
25.00	69.00	1240.00	683.00	557.00	2.23	6.23	64.25
26.00	70.50	1303.10	718.60	584.50	2.23	6.09	65.68
27.00	64.80	1276.10	697.00	579.10	2.20	7.18	55.73
28.00	63.70	1247.70	673.80	573.90	2.17	8.42	47.50

Table 5: List of Samples Prepared for Laboratory Work (150 mm)

150mm samples							
Sample	Height	Weight (air)	Weight (water)	Volume	Density	Porosity	Range
s1		2523.00	1433.60	1089.40	2.32	2.45	163.59
s2		2450.00	1379.50	1070.50	2.29	3.60	111.26
s3		2511.70	1411.80	1099.90	2.28	3.81	105.01
s4		2517.30	1410.70	1106.60	2.27	4.18	95.73
s5		2542.80	1436.30	1106.50	2.30	3.20	125.04



Effect of compaction on the resistance to deformation of asphaltic concretes and rolled asphalts[8]

Figure 1: Effect of compaction on the resistance to deformation

(Source: Hunter R.N. 2000)

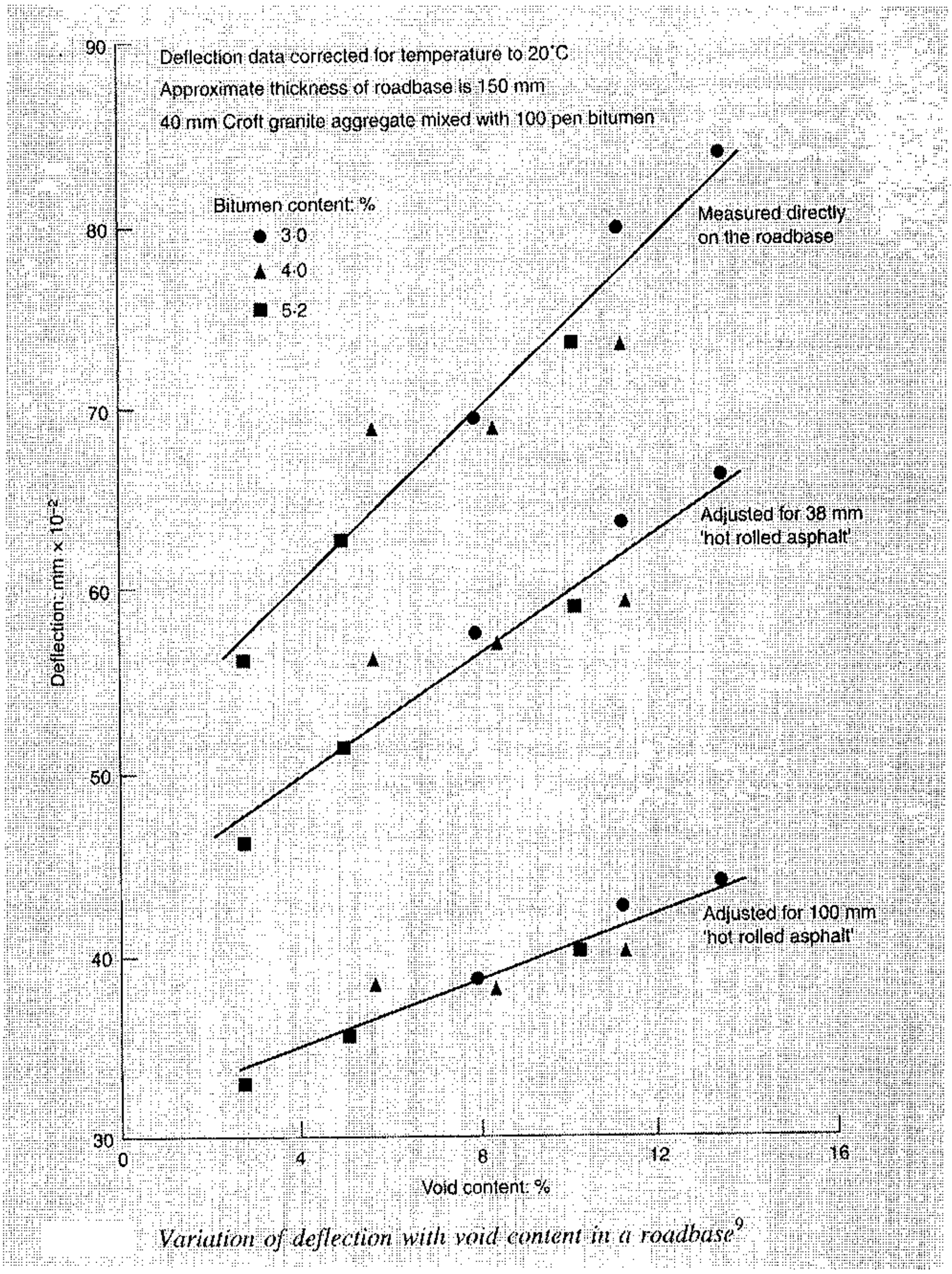


Figure 2: Deflection with respect to void content

(Source: Hunter R.N. 2000)

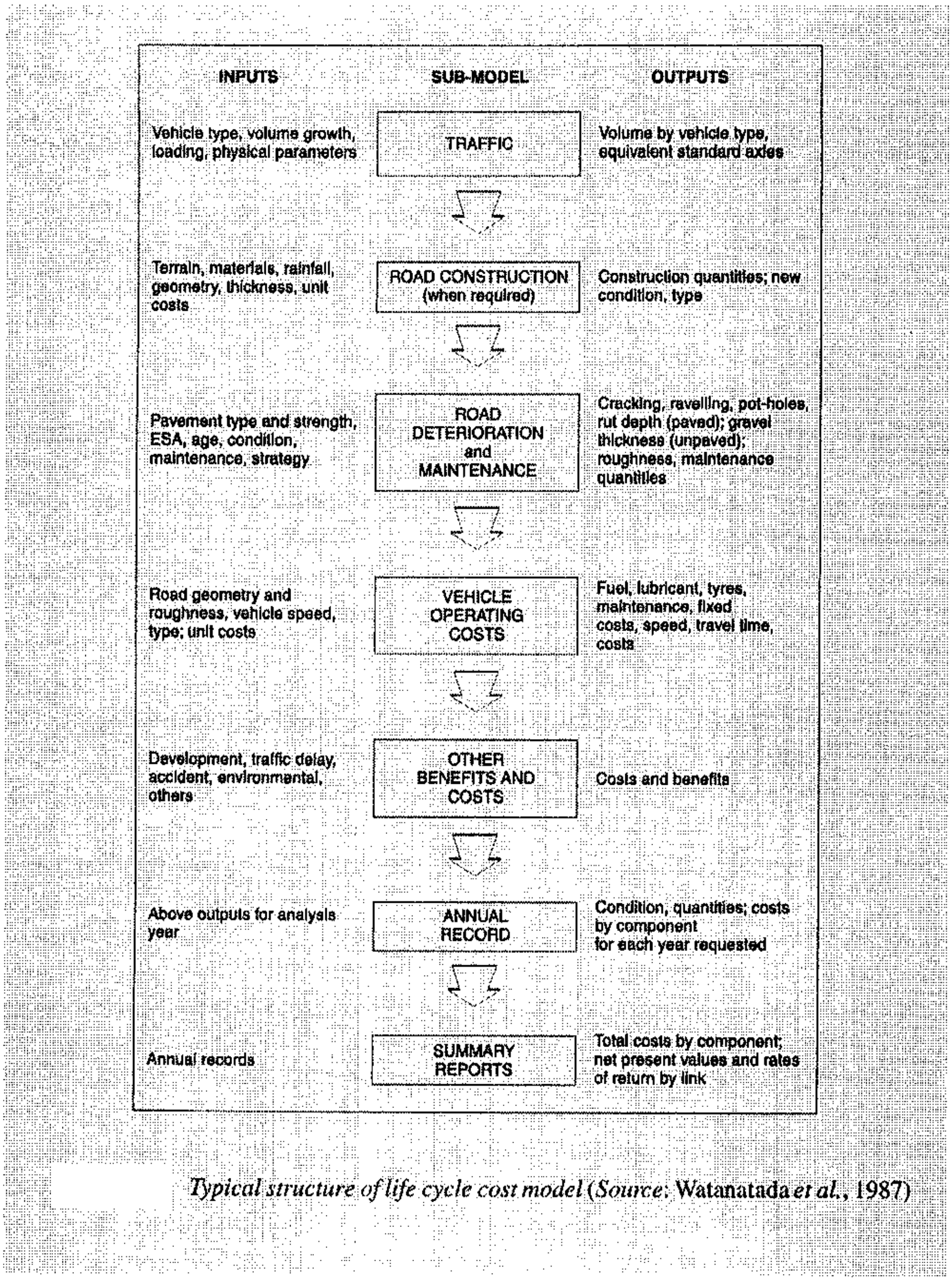


Figure 3: Typical Life Cycle Cost Model

(Source: Robinson et al, 1998)

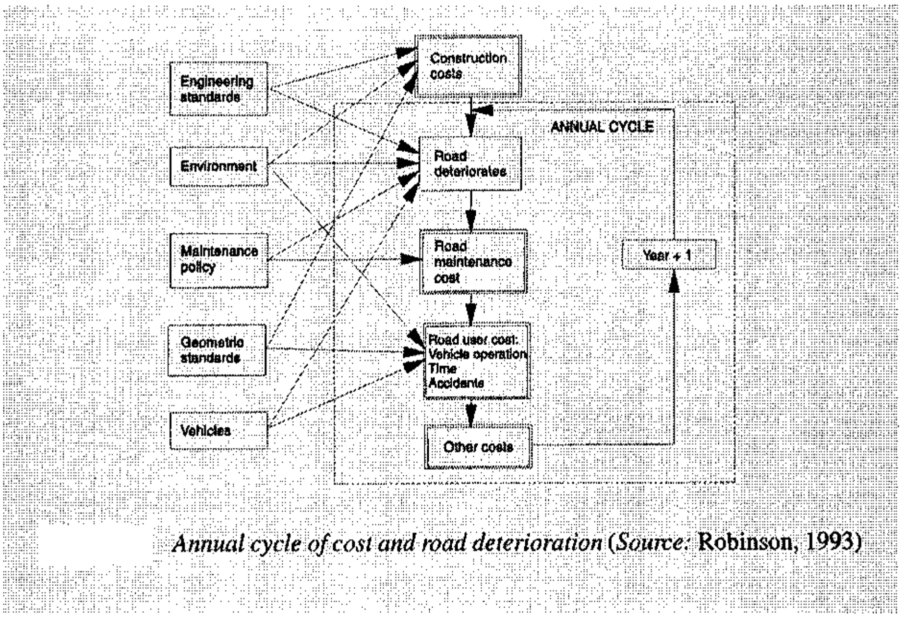
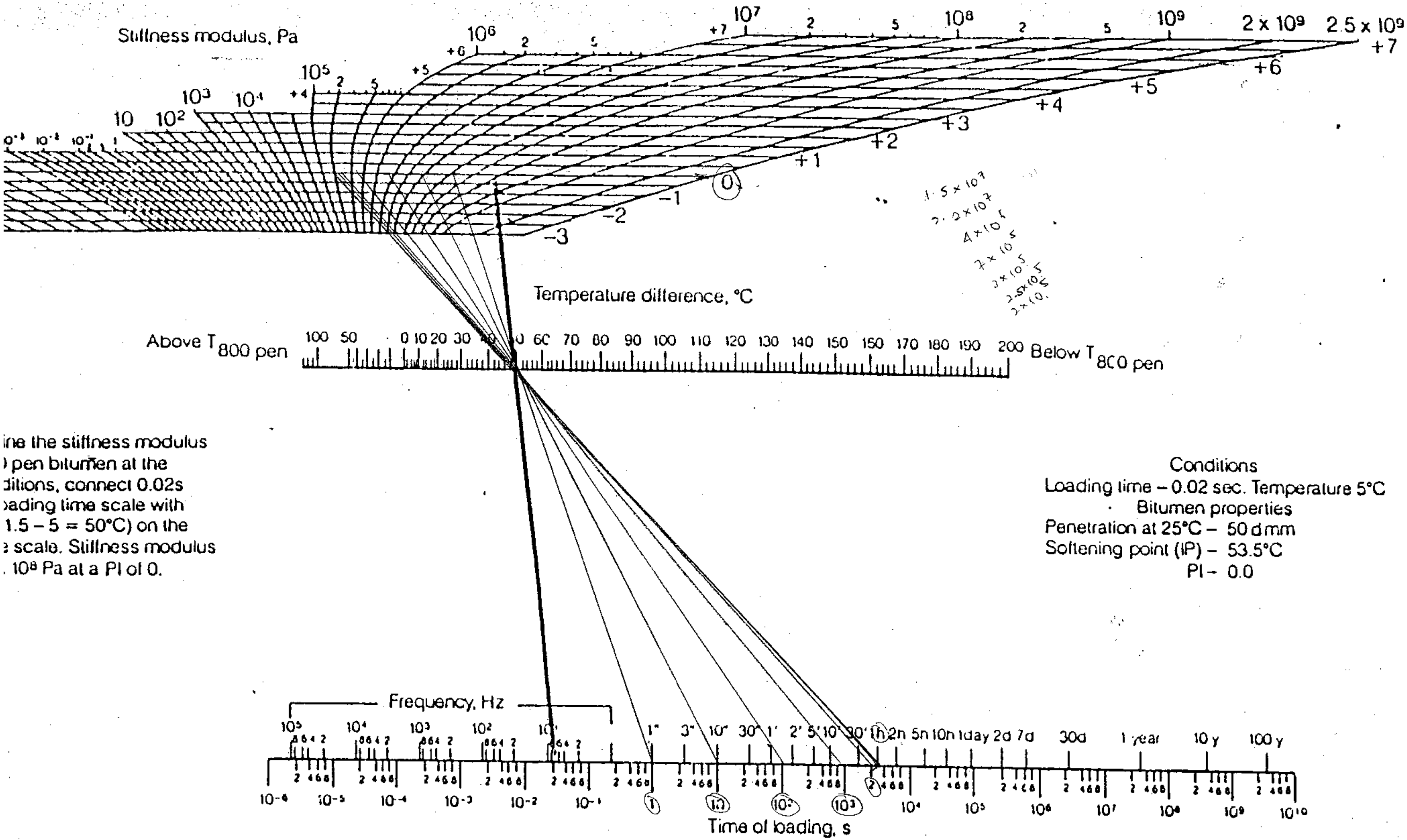


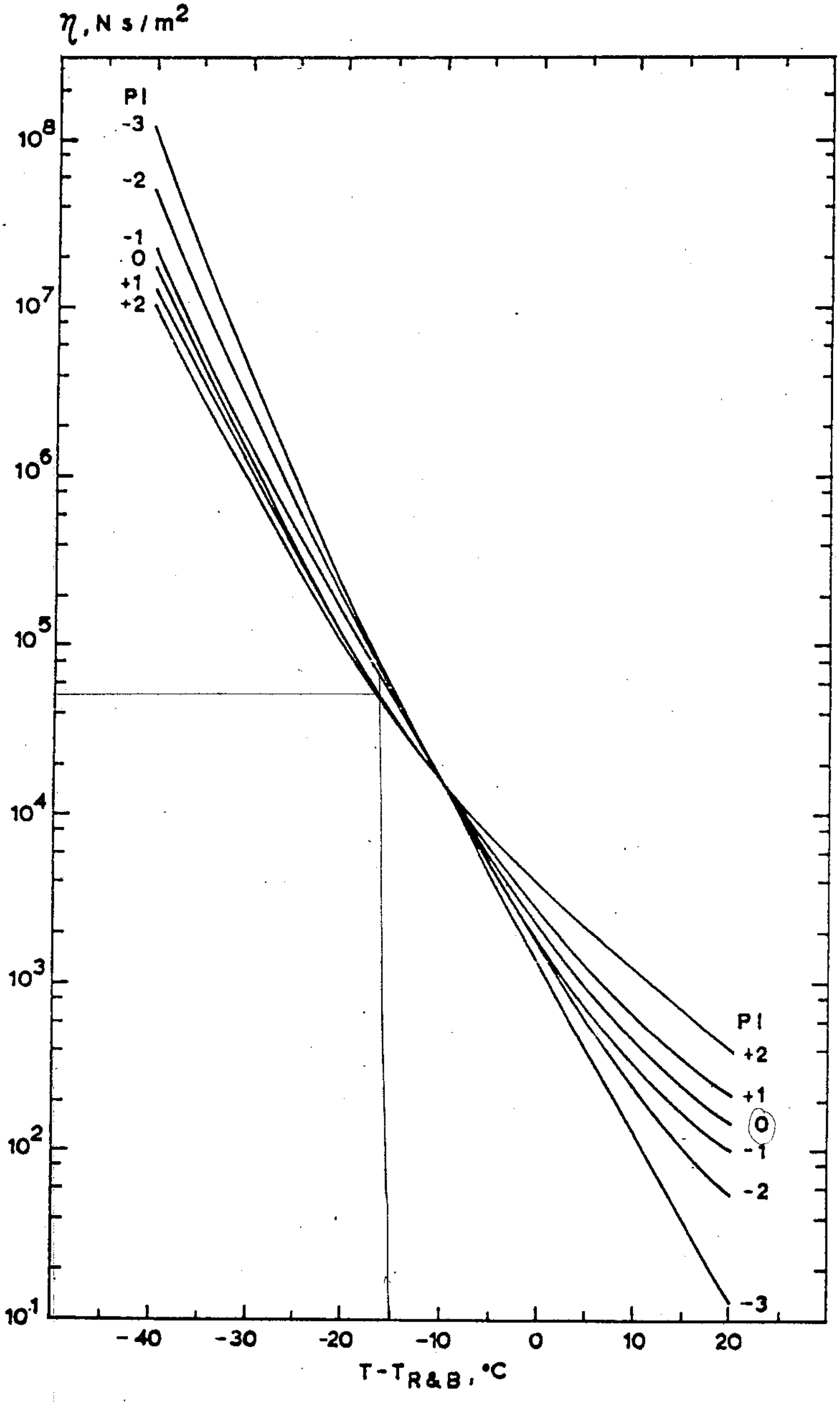
Figure 4: Annual Cycle of costs

(Source: Robinson et al, 1998)



ine the stiffness modulus
) pen bitumen at the
ditions, connect 0.02s
oading time scale with
1.5 – 5 = 50°C) on the
e scale. Stiffness modulus
. 10^8 Pa at a PI of 0.

Figure 5.9 Nomograph for Determining the Stiffness Modulus of Bitumens [114]



Viscosity of bitumen as a function of $(T - T_{R\&B})$ and PI

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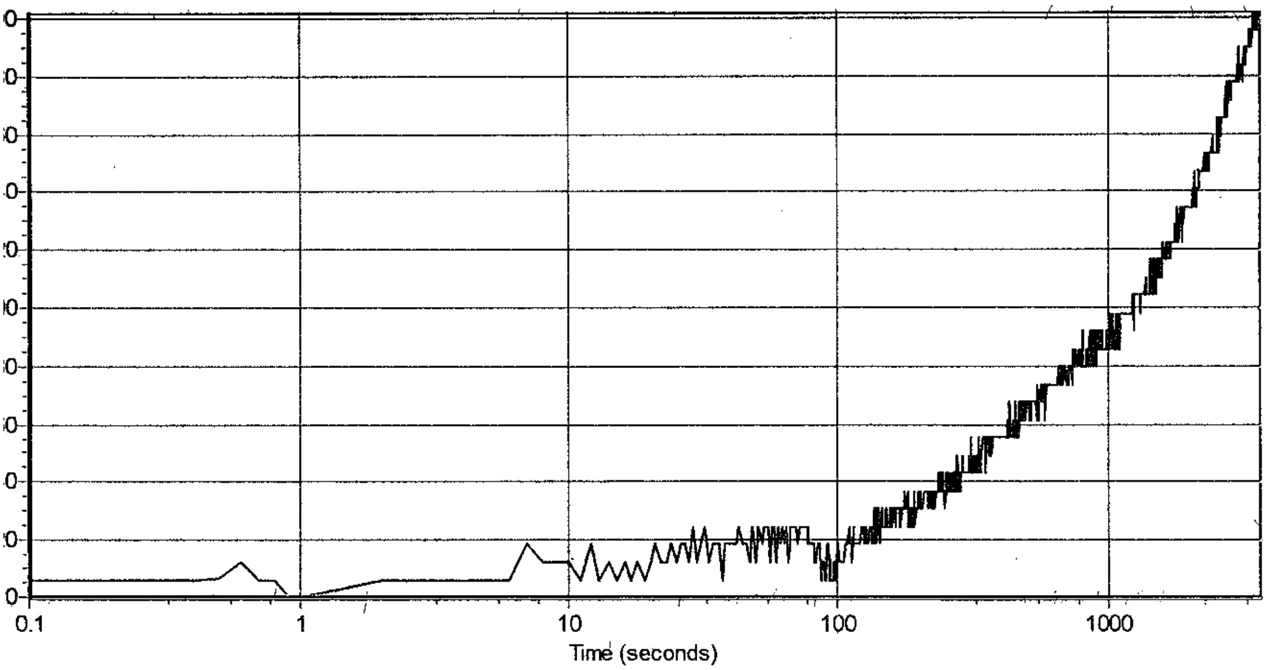

e and time: Tuesday, November 30, 2004, at 10:51 AM		Timer (hh:mm:ss) 1:00:00		Timer (seconds) 3600	

iperature (deg.C):	39.9	**Axial**			
iperature (deg.C):	39.8	Permanent deformation (mm)	0.0202	Compliance Parameters	
g pressure (kPa):	0.0	Permanent micro-strain:	202	Instantaneous Compliance (D0):	0.01636
Vertical load (kN):	-0.006	Creep Modulus (MPa):	-1.8	Regression start time (sec):	10.0
itact stress (kPa):	-0.4	Compliance (1/MPa):	0.00000	Regression end time (sec):	1000.0
ator stress (kPa):	-0.4			Intercept (D1):	1.00000
ator stress (kPa):	0.0	Flow time (sec):		Slope (M1):	0.0000
		Actuator			
		Permanent deformation (mm)	0.0000	Compliance Parameters	
		Permanent micro-strain:	0	Instantaneous Compliance (D0):	0.28374
		Creep Modulus (MPa):	0.0	Regression start time (sec):	10.0
		Compliance (1/MPa):	0.00000	Regression end time (sec):	1000.0
				Intercept (D1):	1.0000
		Flow time (sec):		Slope (M1):	0.0000

Operator: amir
Test method: US: NCHRP 9-19 Superpave Models Draft Test Method W1
es/comments:

i Information
ion: specimen 2

Core/Sample Number:

ns	Point 1	Point 2	Point 3	Point 4	Point 5	Point 6	Average	Std Dev.
(mm)	100						100	
im)	69.2						69.2	

Cross-Sectional Area: 7853.982
Volume: 543495.5

s/Properties:

ameters

	Confining	Loading	Termination	
stress (kPa): 71	Pressure (kPa):	Contact stress (kPa): 71	Axial strain (%):	0
e (seconds): 60	Hold time (seconds):	Deviator stress (kPa): 0	Radial strain (%):	
			Actuator strain (%):	0
			Time (second):	3600

ı Information

escription	Filename	Transducer description	Span	Units	Date	Linearised
rce	H30634.CAR	FBC Load-cell STC-2000 S/N.H30634	12	kN	23/01/03	No
· LVDT	A211-14.CAR	FBC Displacement AC-15 S/N.A211-14	30	mm	04/12/02	No
'DT #1	53268.CAR	Creep LVDT1 D5-200ag S/N.53268	5	mm	04/12/02	Yes
'DT #2	53269.CAR	Creep LVDT2 D5-200ag S/N.53269	5	mm	04/12/02	Yes
'DT #3	J500330.CAR	Int.axial(upper)LVDT S/N.J500330	6	mm	09/01/03	Yes
mperature	403.CAR	Core Temp. PT100 S/N.403	100	Deg.C	11/01/03	Yes
mperature	404.CAR	Skin Temp. PT100 S/N.404	100	Deg.C	11/01/03	Yes
ıg Pressure	R074222.CAR	Conf.pressure IT2000 S/N.R074222	1200	kPa	11/01/03	No
.VDT #1	J0105.CAR	Int.radial(lower)LVDT S/N.J0105	5	mm	09/01/03	Yes
VDT #2	J0111.CAR	Int.radial(upper)LVDT S/N.J0111	5	mm	09/01/03	Yes
.VDT #3		Undefined/Not Used	1	?		No
.VDT #4		Undefined/Not Used	1	?		No

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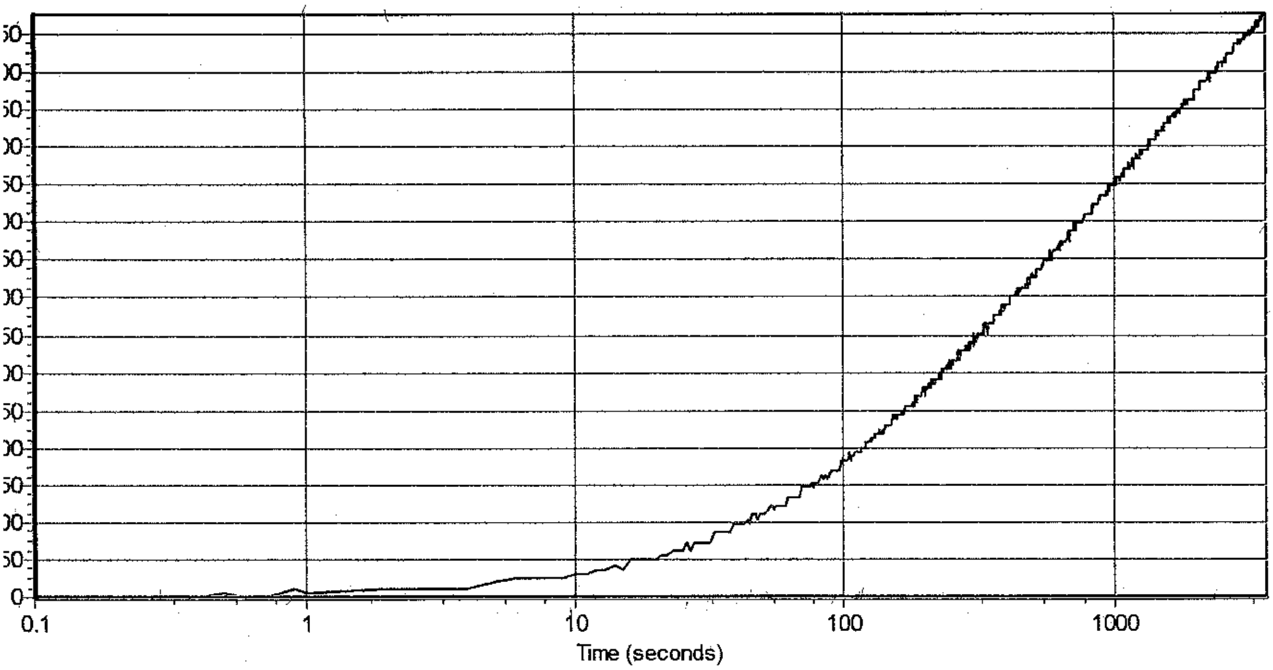

e and time: Tuesday, November 30, 2004, at 4:49 PM   Timer (hh:mm:ss) 1:00:00   Timer (seconds) 3600

nperature (deg.C):	40.4	**Axial**			
nperature (deg.C):	40.5	Permanent deformation (mm)	0.0777	Compliance Parameters	
ng pressure (kPa):	0.0	Permanent micro-strain:	777	Instantaneous Compliance (D0):	0.00000
Vertical load (kN):	-0.003	Creep Modulus (MPa):	0.0	Regression start time (sec):	10.0
ntact stress (kPa):	-0.4	Compliance (1/MPa):	0.00000	Regression end time (sec):	1000.0
iator stress (kPa):	0.0			Intercept (D1):	1.00000
iator stress (kPa):	0.0	Flow time (sec):		Slope (M1):	0.0000
		Actuator			
		Permanent deformation (mm)	0.0073	Compliance Parameters	
		Permanent micro-strain:	105	Instantaneous Compliance (D0):	0.00000
		Creep Modulus (MPa):	0.0	Regression start time (sec):	10.0
		Compliance (1/MPa):	0.00000	Regression end time (sec):	1000.0
				Intercept (D1):	1.0000
		Flow time (sec):		Slope (M1):	0.0000

Operator: amir
Test method: US: NCHRP 9-19 Superpave Models Draft Test Method W1
tes/comments:

n Information

tion: specimen 4   Core/Sample Number:

ns	Point 1	Point 2	Point 3	Point 4	Point 5	Point 6	Average	Std Dev.
r (mm)	100						100	
nm)	70						70	

Cross-Sectional Area: 7853.982
Volume: 549778.7

ts/Properties:

rameters

d	Confining	Loading	Termination
Stress (kPa): 71	Pressure (kPa):	Contact stress (kPa): 71	Axial strain (%): 0
ne (seconds): 60	Hold time (seconds):	Deviator stress (kPa): 0	Radial strain (%):
			Actuator strain (%): 0
			Time (second): 3600

Information

scription	Filename	Transducer description	Span	Units	Date	Linearised
ce	H30634.CAR	FBC Load-cell STC-2000 S/N.H30634	12	kN	23/01/03	No
LVDT	A211-14.CAR	FBC Displacement AO-15 S/N.A211-14	30	mm	04/12/02	No
DT #1	53268.CAR	Creep LVDT1 D5-200ag S/N.53268	5	mm	04/12/02	Yes
DT #2	53269.CAR	Creep LVDT2 D5-200ag S/N.53269	5	mm	04/12/02	Yes
DT #3	J500330.CAR	Int.axial(upper)LVDT S/N.J500330	6	mm	09/01/03	Yes
mperature	403.CAR	Core Temp. PT100 S/N.403	100	Deg.C	11/01/03	Yes
mperature	404.CAR	Skin Temp. PT100 S/N.404	100	Deg.C	11/01/03	Yes
g Pressure	R074222.CAR	Conf.pressure IT2000 S/N.R074222	1200	kPa	11/01/03	No
VDT #1	J0105.CAR	Int.radial(lower)LVDT S/N.J0105	5	mm	09/01/03	Yes
VDT #2	J0111.CAR	Int.radial(upper)LVDT S/N.J0111	5	mm	09/01/03	Yes
.VDT #3		Undefined/Not Used	1	?		No
.VDT #4		Undefined/Not Used	1	?		No

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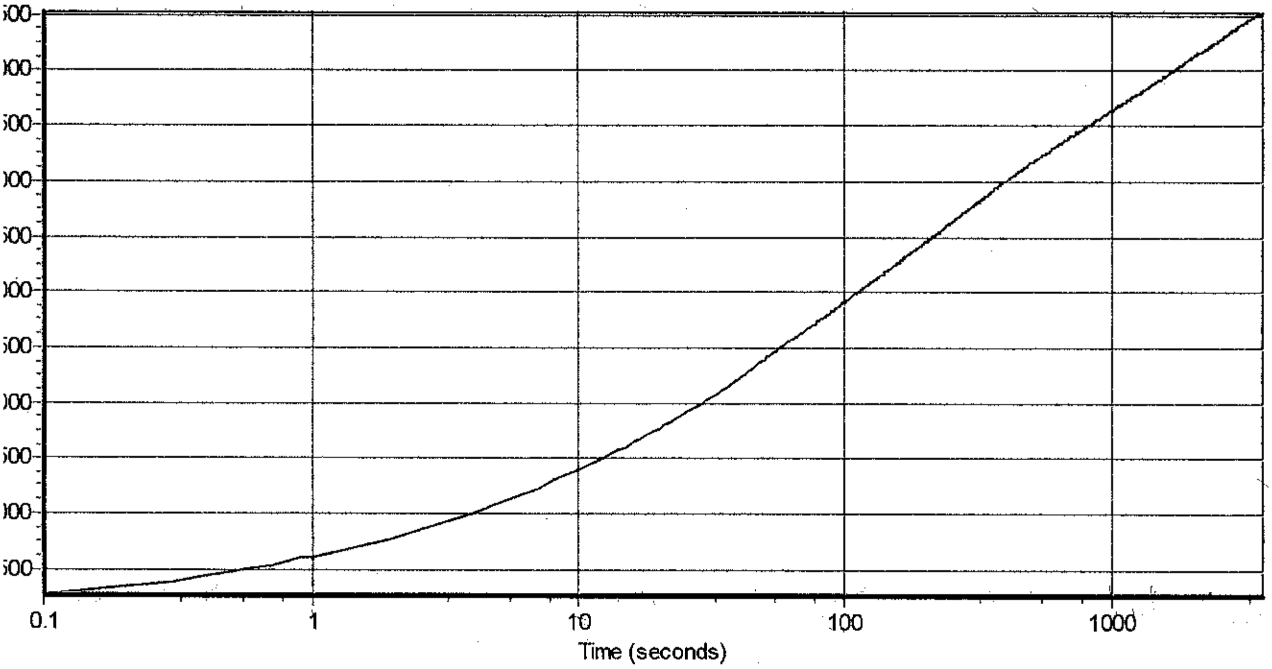

e and time: Tuesday, November 30, 2004, at 2:27 PM   Timer (hh:mm:ss) 1:00:00   Timer (seconds) 3600

perature (deg.C): 40.5
perature (deg.C): 40.7
g pressure (kPa): 0.0
Vertical load (kN): -0.003
tact stress (kPa): -0.7
iator stress (kPa): 0.4
iator stress (kPa): 0.4

Axial

Permanent deformation (mm) 0.5531
Permanent micro-strain: 5531
Creep Modulus (MPa): 0.1
Compliance (1/MPa): 14.09168
Flow time (sec): 1996

Compliance Parameters
Instantaneous Compliance (D0): 0.73206
Regression start time (sec): 13.0
Regression end time (sec): 990.0
Intercept (D1): 2.17287
Slope (M1): 0.2528

Actuator

Permanent deformation (mm) 0.0073
Permanent micro-strain: 104
Creep Modulus (MPa): 3.6
Compliance (1/MPa): 0.27772
Flow time (sec): 1

Compliance Parameters
Instantaneous Compliance (D0): 0.00000
Regression start time (sec): 21.0
Regression end time (sec): 965.0
Intercept (D1): 0.2777
Slope (M1): 0.0000

Operator: amir
Test method: US: NCHRP 9-19 Superpave Models Draft Test Method W1
es/comments:

n Information
ion: specimen 8

ns	Point 1	Point 2	Point 3	Point 4	Point 5	Point 6	Average	Std Dev.
(mm)	100						100	
m)	70.7						70.7	

Core/Sample Number:
Cross-Sectional Area: 7853.982
Volume: 555276.5

s/Properties:

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ameters

	Confining	Loading	Termination
:tress (kPa): 71	Pressure (kPa):	Contact stress (kPa): 71	Axial strain (%): 0
; (seconds): 60	Hold time (seconds):	Deviator stress (kPa): 71	Radial strain (%):
			Actuator strain (%): 0
			Time (second): 3600

ı Information

escription	Filename	Transducer description	Span	Units	Date	Linearised
rce	H30634.CAR	FBC Load-cell STC-2000 S/N.H30634	12	kN	23/01/03	No
r LVDT	A211-14.CAR	FBC Displacement AC-15 S/N.A211-14	30	mm	04/12/02	No
'DT #1	53268.CAR	Creep LVDT1 D5-200ag S/N.53268	5	mm	04/12/02	Yes
'DT #2	53269.CAR	Creep LVDT2 D5-200ag S/N.53269	5	mm	04/12/02	Yes
'DT #3	J500330.CAR	Int.axial(upper)LVDT S/N.J500330	6	mm	09/01/03	Yes
mperature	403.CAR	Core Temp. PT100 S/N.403	100	Deg.C	11/01/03	Yes
mperature	404.CAR	Skin Temp. PT100 S/N.404	100	Deg.C	11/01/03	Yes
ıg Pressure	R074222.CAR	Conf.pressure IT2000 S/N.R074222	1200	kPa	11/01/03	No
.VDT #1	J0105.CAR	Int.radial(lower)LVDT S/N.J0105	5	mm	09/01/03	Yes
VDT #2	J0111.CAR	Int.radial(upper)LVDT S/N.J0111	5	mm	09/01/03	Yes
.VDT #3		Undefined/Not Used	1	?		No
.VDT #4		Undefined/Not Used	1	?		No

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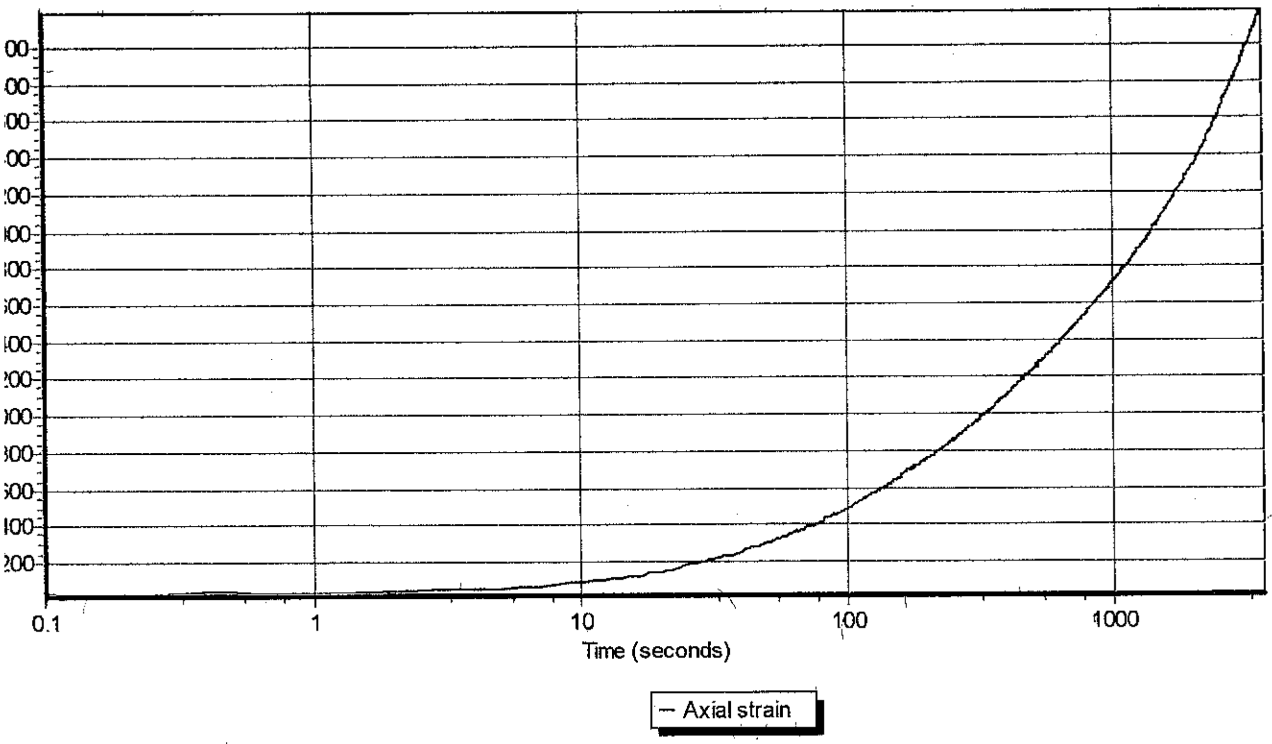

e and time: Tuesday, November 30, 2004, at 12:12 PM   Timer (hh:mm:ss) 1:00:00   Timer (seconds) 3600

nperature (deg.C):	40.7
nperature (deg.C):	40.7
ng pressure (kPa):	0.0
Vertical load (kN):	-0.003
ntact stress (kPa):	-0.7
iator stress (kPa):	0.4
iator stress (kPa):	0.4

Axial

Permanent deformation (mm)	0.3193	**Compliance Parameters**	
Permanent micro-strain:	3193	Instantaneous Compliance (D0):	0.00000
Creep Modulus (MPa):	0.1	Regression start time (sec):	11.0
Compliance (1/MPa):	8.55740	Regression end time (sec):	995.0
		Intercept (D1):	0.07584
Flow time (sec):	3163	Slope (M1):	0.6099

Actuator

Permanent deformation (mm)	0.0073	**Compliance Parameters**	
Permanent micro-strain:	101	Instantaneous Compliance (D0):	0.00000
Creep Modulus (MPa):	3.7	Regression start time (sec):	14.0
Compliance (1/MPa):	0.27083	Regression end time (sec):	955.0
		Intercept (D1):	0.2708
Flow time (sec):	0	Slope (M1):	0.0000

Operator: amir

Test method: US: NCHRP 9-19 Superpave Models Draft Test Method W1

tes/comments:

n Information

tion; specimen 11

ns	Point 1	Point 2	Point 3	Point 4	Point 5	Point 6	Average	Std Dev.
r (mm)	100						100	
mm)	72.5						72.5	

Core/Sample Number:

Cross-Sectional Area: 7853.982

Volume: 569413.7

its/Properties:

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meters

	Confining	Loading	Termination
ress (kPa): 71	Pressure (kPa):	Contact stress (kPa): 71	Axial strain (%): 0
(seconds): 60	Hold time (seconds):	Deviator stress (kPa): 0	Radial strain (%):
			Actuator strain (%): 0
			Time (second): 3600

Information

scription	Filename	Transducer description	Span	Units	Date	Linearised
ce	H30634.CAR	FBC Load-cell STC-2000 S/N.H30634	12	kN	23/01/03	No
LVDT	A211-14.CAR	FBC Displacement AC-15 S/N.A211-14	30	mm	04/12/02	No
DT #1	53268.CAR	Creep LVDT1 D5-200ag S/N.53268	5	mm	04/12/02	Yes
DT #2	53269.CAR	Creep LVDT2 D5-200ag S/N.53269	5	mm	04/12/02	Yes
DT #3	J500330.CAR	Int.axial(upper)LVDT S/N.J500330	6	mm	09/01/03	Yes
nperature	403.CAR	Core Temp. PT100 S/N.403	100	Deg.C	11/01/03	Yes
nperature	404.CAR	Skin Temp. PT100 S/N.404	100	Deg.C	11/01/03	Yes
g Pressure	R074222.CAR	Conf.pressure IT2000 S/N.R074222	1200	kPa	11/01/03	No
VDT #1	J0105.CAR	Int.radial(lower)LVDT S/N.J0105	5	mm	09/01/03	Yes
VDT #2	J0111.CAR	Int.radial(upper)LVDT S/N.J0111	5	mm	09/01/03	Yes
.VDT #3		Undefined/Not Used	1	?		No
VDT #4		Undefined/Not Used	1	?		No

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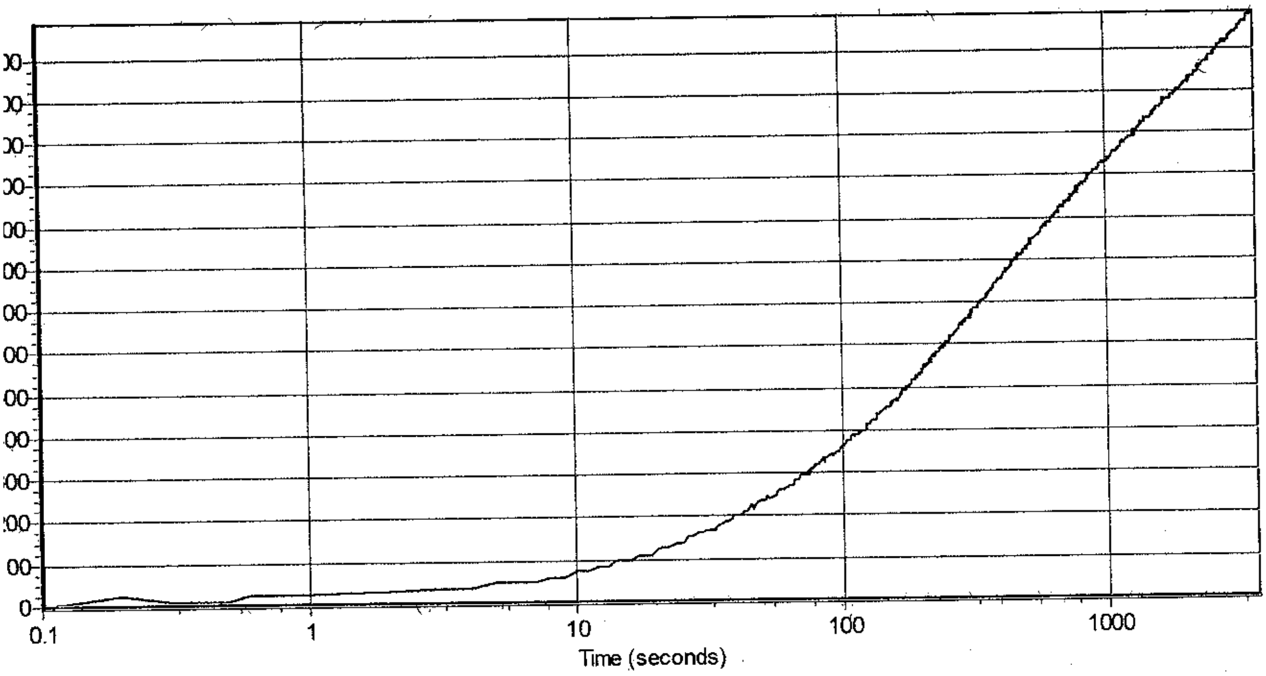

e and time: Tuesday, November 30, 2004, at 1:22 PM | Timer (hh:mm:ss) 1:00:00 | Timer (seconds) 3600

ıperature (deg.C): 40.8
ıperature (deg.C): 40.9
ıg pressure (kPa): 0.0
Vertical load (kN): -0.003
ıtact stress (kPa): -0.4
iator stress (kPa): 0.0
iator stress (kPa): -0.4

Axial

Permanent deformation (mm) 0.1381
Permanent micro-strain: 1381
Creep Modulus (MPa): 0.0
Compliance (1/MPa): 0.00000
Flow time (sec):

Compliance Parameters
Instantaneous Compliance (D0): 0.00000
Regression start time (sec): 10.0
Regression end time (sec): 1000.0
Intercept (D1): 1.00000
Slope (M1): 0.0000

Actuator

Permanent deformation (mm) 0.0000
Permanent micro-strain: 0
Creep Modulus (MPa): 0.0
Compliance (1/MPa): 0.00000
Flow time (sec):

Compliance Parameters
Instantaneous Compliance (D0): 0.00000
Regression start time (sec): 10.0
Regression end time (sec): 1000.0
Intercept (D1): 1.0000
Slope (M1): 0.0000

Operator: amir
Test method: US; NCHRP 9-19 Superpave Models Draft Test Method W1
otes/comments:

n Information
ation: specimen 15

ons	Point 1	Point 2	Point 3	Point 4	Point 5	Point 6	Average	Std Dev.
r (mm)	100						100	
mm)	69.4						69.4	

Core/Sample Number:
Cross-Sectional Area: 7853.982
Volume: 545066.3

ts/Properties:

:\UTM4\UTM_52\amir\specimen 15.B52

meters

	Confining	Loading	Termination
tress (kPa): 71	Pressure (kPa):	Contact stress (kPa): 71	Axial strain (%): 0
(seconds): 60	Hold time (seconds):	Deviator stress (kPa): 0	Radial strain (%):
			Actuator strain (%): 0
			Time (second): 3600

Information

scription	Filename	Transducer description	Span	Units	Date	Linearised
rce	H30634.CAR	FBC Load-cell STC-2000 S/N.H30634	12	kN	23/01/03	No
LVDT	A211-14.CAR	FBC Displacement AC-15 S/N.A211-14	30	mm	04/12/02	No
DT #1	53268.CAR	Creep LVDT1 D5-200ag S/N.53268	5	mm	04/12/02	Yes
DT #2	53269.CAR	Creep LVDT2 D5-200ag S/N.53269	5	mm	04/12/02	Yes
DT #3	J500330.CAR	Int.axial(upper)LVDT S/N.J500330	6	mm	09/01/03	Yes
mperature	403.CAR	Core Temp. PT100 S/N.403	100	Deg.C	11/01/03	Yes
mperature	404.CAR	Skin Temp. PT100 S/N.404	100	Deg.C	11/01/03	Yes
g Pressure	R074222.CAR	Conf.pressure IT2000 S/N.R074222	1200	kPa	11/01/03	No
VDT #1	J0105.CAR	Int.radial(lower)LVDT S/N.J0105	5	mm	09/01/03	Yes
VDT #2	J0111.CAR	Int.radial(upper)LVDT S/N.J0111	5	mm	09/01/03	Yes
VDT #3		Undefined/Not Used	1	?		No
VDT #4		Undefined/Not Used	1	?		No

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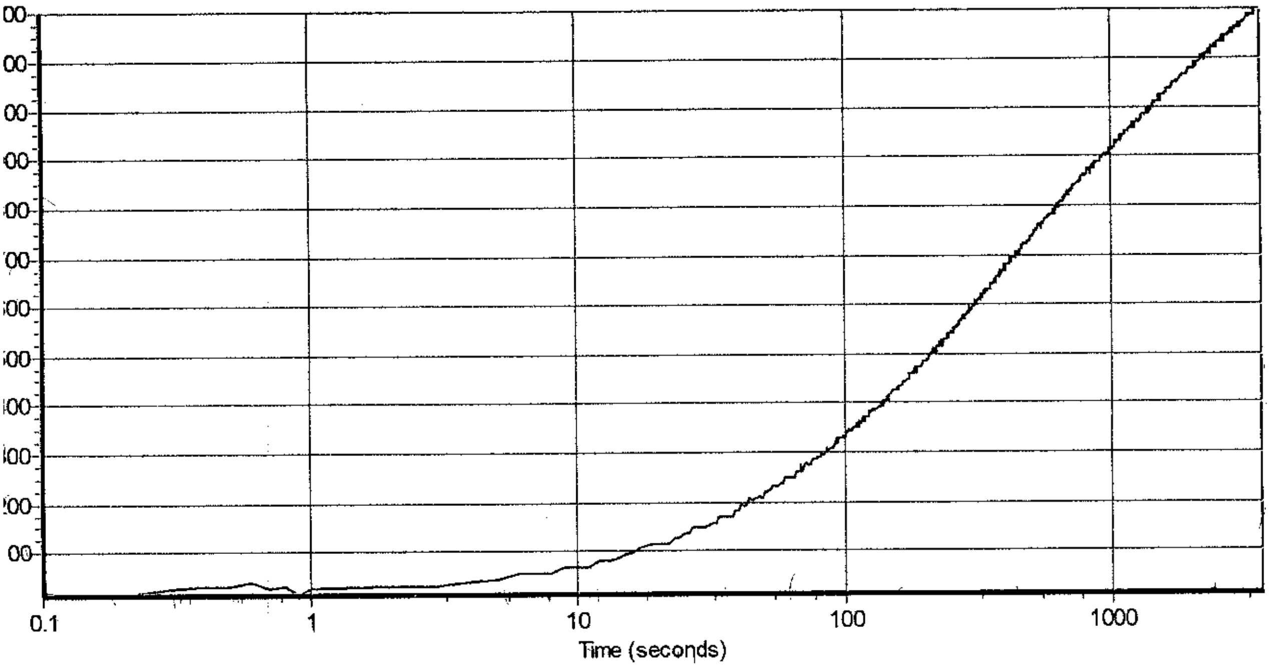


e and time: Tuesday, November 30, 2004, at 3:39 PM   Timer (hh:mm:ss) 1:00:00   Timer (seconds) 3600

iperature (deg.C):	40.5	**Axial**			
iperature (deg.C):	40.6	Permanent deformation (mm)	0.1202	Compliance Parameters	
ig pressure (kPa):	0.0	Permanent micro-strain:	1202	Instantaneous Compliance (D0):	0.00000
Vertical load (kN):	-0.003	Creep Modulus (MPa):	0.0	Regression start time (sec):	0.8
itact stress (kPa):	-0.4	Compliance (1/MPa):	0.00000	Regression end time (sec):	0.8
iator stress (kPa):	0.0			Intercept (D1):	1.00000
iator stress (kPa):	0.0	Flow time (sec):	1	Slope (M1):	0.0000

Actuator

Permanent deformation (mm)	0.0000	Compliance Parameters	
Permanent micro-strain:	0	Instantaneous Compliance (D0):	0.00000
Creep Modulus (MPa):	0.0	Regression start time (sec):	10.0
Compliance (1/MPa):	0.00000	Regression end time (sec):	1000.0
		Intercept (D1):	1.0000
Flow time (sec):		Slope (M1):	0.0000

Operator: amir

Test method: US: NCHRP 9-19 Superpave Models Draft Test Method W1

tes/comments:

n Information

tion: specimen 16

Core/Sample Number:

ns	Point 1	Point 2	Point 3	Point 4	Point 5	Point 6	Average	Std Dev.
r (mm)	100						100	
nm)	200						200	

Cross-Sectional Area: 7853.982

Volume: 1570796

ts/Properties:

:\UTM4\UTM_52\amir\specimen 16.B52

meters

ress (kPa): 71
(seconds): 60

Confining
Pressure (kPa):
Hold time (seconds):

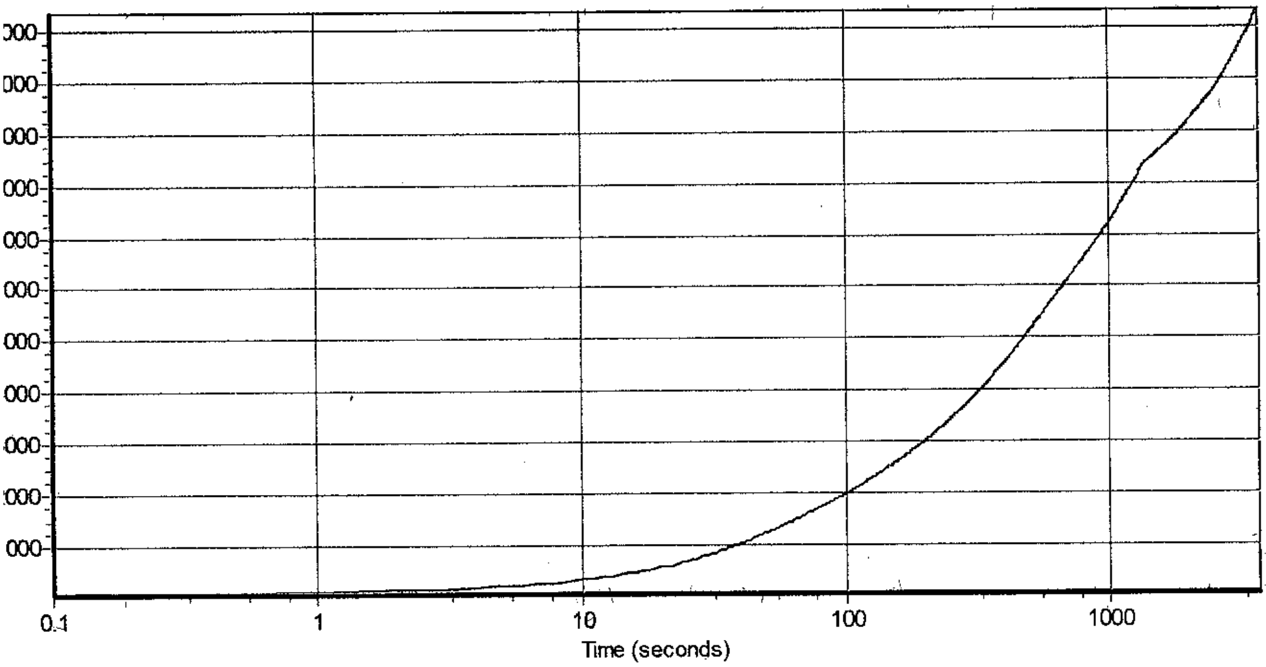
Loading
Contact stress (kPa): 71
Deviator stress (kPa): 0

Termination
Axial strain (%): 0
Radial strain (%):
Actuator strain (%): 0
Time (second): 3600

Information

scription	Filename	Transducer description	Span	Units	Date	Linearised
ce	H30634.CAR	FBC Load-cell STC-2000 S/N.H30634	12	kN	23/01/03	No
LVDT	A211-14.CAR	FBC Displacement AC-15 S/N.A211-14	30	mm	04/12/02	No
DT #1	53268.CAR	Creep LVDT1 D5-200ag S/N.53268	5	mm	04/12/02	Yes
DT #2	53269.CAR	Creep LVDT2 D5-200ag S/N.53269	5	mm	04/12/02	Yes
DT #3	J500330.CAR	Int.axial(upper)LVDT S/N.J500330	6	mm	09/01/03	Yes
mperature	403.CAR	Core Temp. PT100 S/N.403	100	Deg.C	11/01/03	Yes
mperature	404.CAR	Skin Temp. PT100 S/N.404	100	Deg.C	11/01/03	Yes
g Pressure	R074222.CAR	Conf.pressure IT2000 S/N.R074222	1200	kPa	11/01/03	No
VDT #1	J0105.CAR	Int.radial(lower)LVDT S/N.J0105	5	mm	09/01/03	Yes
VDT #2	J0111.CAR	Int.radial(upper)LVDT S/N.J0111	5	mm	09/01/03	Yes
.VDT #3		Undefined/Not Used	1	?		No
.VDT #4		Undefined/Not Used	1	?		No

:\UTM4\UTM_52\amir\specimen 23.B52



e and time: Tuesday, November 30, 2004, at 5:54 PM Timer (hh:mm:ss) 1:00:00 Timer (seconds) 3600

perature (deg.C):	40.4
perature (deg.C):	40.5
g pressure (kPa):	0.0
Vertical load (kN):	-0.003
tact stress (kPa):	-0.4
iator stress (kPa):	0.0
iator stress (kPa):	0.0

Axial

Permanent deformation (mm)	1.1375	**Compliance Parameters**	
Permanent micro-strain:	11375	Instantaneous Compliance (D0):	0.00000
Creep Modulus (MPa):	0.0	Regression start time (sec):	10.0
Compliance (1/MPa):	0.00000	Regression end time (sec):	1000.0
		Intercept (D1):	1.00000
Flow time (sec):		Slope (M1):	0.0000

Actuator

Permanent deformation (mm)	0.0000	**Compliance Parameters**	
Permanent micro-strain:	0	Instantaneous Compliance (D0):	0.00000
Creep Modulus (MPa):	0.0	Regression start time (sec):	10.0
Compliance (1/MPa):	0.00000	Regression end time (sec):	1000.0
		Intercept (D1):	1.0000
Flow time (sec):		Slope (M1):	0.0000

Operator: amir
Test method: US: NCHRP 9-19 Superpave Models Draft Test Method W1
tes/comments:

n Information
tion: specimen 23

Core/Sample Number:

ns	Point 1	Point 2	Point 3	Point 4	Point 5	Point 6	Average	Std Dev.
(mm)	100						100	
mm)	73						73	

Cross-Sectional Area: 7853.982
Volume: 573340.7

ts/Properties:

:\UTM4\UTM_52\amir\specimen 23.B52

meters

	Confining	Loading	Termination
tress (kPa): 71	Pressure (kPa):	Contact stress (kPa): 71	Axial strain (%): 0
(seconds): 60	Hold time (seconds):	Deviator stress (kPa): 0	Radial strain (%):
			Actuator strain (%): 0
			Time (second): 3600

Information

scription	Filename	Transducer description	Span	Units	Date	Linearised
rce	H30634.CAR	FBC Load-cell STC-2000 S/N.H30634	12	kN	23/01/03	No
LVDT	A211-14.CAR	FBC Displacement AC-15 S/N.A211-14	30	mm	04/12/02	No
DT #1	53268.CAR	Creep LVDT1 D5-200ag S/N.53268	5	mm	04/12/02	Yes
DT #2	53269.CAR	Creep LVDT2 D5-200ag S/N.53269	5	mm	04/12/02	Yes
DT #3	J500330.CAR	Int.axial(upper)LVDT S/N.J500330	6	mm	09/01/03	Yes
mperature	403.CAR	Core Temp. PT100 S/N.403	100	Deg.C	11/01/03	Yes
mperature	404.CAR	Skin Temp. PT100 S/N.404	100	Deg.C	11/01/03	Yes
g Pressure	R074222.CAR	Conf.pressure IT2000 S/N.R074222	1200	kPa	11/01/03	No
VDT #1	J0105.CAR	Int.radial(lower)LVDT S/N.J0105	5	mm	09/01/03	Yes
VDT #2	J0111.CAR	Int.radial(upper)LVDT S/N.J0111	5	mm	09/01/03	Yes
.VDT #3		Undefined/Not Used	1	?		No
.VDT #4		Undefined/Not Used	1	?		No

Calculation 1: Achievement of final Bulk Density Value

Range of air voids = 3% to 5% (JKR specification on porosity)

Middle value = (3+5)/2 = 4% air voids

SG Bitumen = 1.03

SG Mix Agg = 100/ [(48/2.62) + (45/2.47) + (7/3.1)]

= 2.71

SG theory = 100/ (5.7/1.03)+[(100-5.7)/2.71]

= 2.374

Based on the equation for air voids given,

$V_t = [(S_t-S_b)/S_t]\ 100$

$4.0 = [(2.374-S_b)/2.374)]\ 100$

$0.04 = (2.374-S_b)/2.374$

$0.0995 = 2.374-S_b$

$S_b = 2.2745$ (equivalent to 2274.5 kg/m^3)

FINAL YEAR PROJECT GANTT CHART

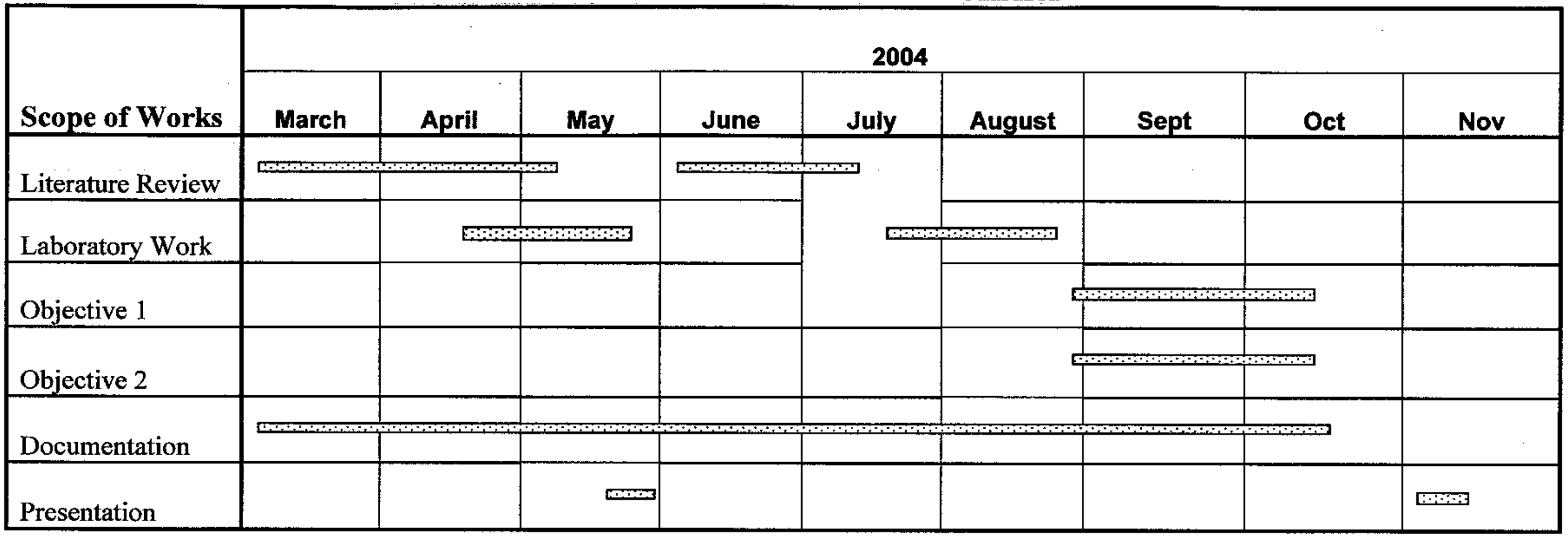


Chart 1: Gantt Chart of the FYP Project