A STUDY INTO THE MECHANICAL PROPERTIES OF FOAMED BITUMINOUS STABILISED MATERIALS

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DECLARATION

I, the undersigned, hereby declare that the work contained in this thesis is primarily my own original work and has not previously in its entirety or in part been submitted at any tertiary institution for any degree.

The opinions contained in this thesis are my own and not necessarily those of Peninsula Technikon.

Signed:_____

Carl T. Weston

Date:_____

Dedicated to Denise

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SYNOPSIS

Of the most essential objectives of a good mix design procedure is to be able to assess the compactibility of a mix in the laboratory, i.e. to relate laboratory compaction to compaction on site and to give insight into the prediction of the expected performance of the mix.

Foamed bitumen treated material has been used with success in many countries around the world. Regardless of the success story, it is also true that there is a dearth of knowledge concerning the understanding of the effect of the current used compaction methods on the mechanical and volumetric properties of foamed bitumen treated material.

The use of a variety of mix design and evaluation procedures around the world has led to difficulties in correlating and assessing results obtained in different environments. Experience and research have also revealed the tendency of current mix design methods to underrate the engineering properties of foamed bitumen treated material.

This project entails an investigation into the volumetric and mechanical properties of mixes with three types of granular materials. Test specimens were prepared using four of the most commonly used laboratory compaction methods and one field simulating compaction method.

The main objectives of the project were to:

- Determine and compare the influence of the different compaction methods on the volumetric and mechanical properties of foam bitumen mixes
- To make recommendations regarding the suitability of the different compaction methods for use in the mix design of foamed bitumen mixes.

Marshall, Hugo, Gyratory and Refusal Density with Kango Hammer compaction were employed as laboratory compaction methods. A Hydrostatic double-drum vibrating roller was used to simulate field compaction. Graded crushed stone and gravel material were used as the granular materials. Indirect tensile (strength and stiffness) and Semi-circular bending (strength) testing was used to assess the mechanical properties. Use was made of 80/100 and 150/200 penetration grade bitumen.

The study revealed that binder type has no influence on the mechanical properties of foamed mixes, whilst compaction method influences mechanical properties significantly. The SCB test was found to be inappropriate for foam mixes with low binder contents. All the laboratory compaction methods were found to be suitable for the design of foam mixes.

The results reported in this thesis needs to be validated by more extensive as testing was limited to only two types of granular materials.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

ANOVA	:	Analysis of Variance
CSRA	:	Committee for State Road Authorities
COV	:	Coefficient of Variation
CSIR	:	Council for Scientific and Industrial Research
Df	:	Degrees of freedom
F	:	F statistic
$F_{critical}$	:	Confidence coefficient
FI	:	Foam Index
ER_a	:	Actual Expansion Ratio
HMA	:	Hot Mix Asphalt
Hz	:	Hertz
ITS	:	Indirect Tensile Strength Test
ITT	:	Indirect Tensile Test
kPa	:	kilo Pascal
LVDT	:	Linear Voltage Displacement Transducer
MPa	:	Mega Pascal
Ms	:	Mean square
MTS	:	Materials Testing System

RAP	:	Reclaimed Asphalt Pavement
SABITA	:	South African Bitumen Association
SGC	:	Superpave Gyratory Compactor
SHRP	:	Strategic Highway Research Programme
TMH 1	:	Technical Method for Highways Volume 1
TRRL	:	Transportation and Road Research Laboratory
TRH 4	:	Technical Recommendations for Highways No. 4
TRH 14	:	Technical Recommendations for Highways No. 14
V	:	Total variation
V_B	:	Variation between treatments (also V_B)
V_C	:	Variation between blocks (also V_w)
V_E	:	Variation due to chance

CHAPTER 1 INTRODUCTION

1.1 Background

Foamed bitumen treated material has been used successfully in many countries around the world, since Dr Ladis Csanyi (1957) of Iowa State University used foamed bitumen to stabilize marginal material. Patent rights granted to Mobil Australia, which was extended to at least 14 countries worldwide, in 1971 resulted in limited application of the process on a global scale. South Africa, New Zealand, Japan, Germany are just some of the countries where foamed bitumen treated materials were used, but on a small scale in comparison to 2,9 million m^2 in Australia by 1982.

Patent rights lapsed in the early 1990's. The practical and economic advantages of foamed bitumen treatment have led to a number of projects, in which foamed bitumen stabilisation was used being completed in South Africa since 1994.

The use of a variety of mix design and evaluation procedures globally, has led to difficulties in correlating and assessing results obtained in different climatic and environmental (Bissada 1987). Experience and research have also revealed the tendency of current mix design methods to underrate the engineering properties of foamed bitumen treated material. Secretive approaches to the process by operators (due to patent rights) and a lack of fundamental guidelines had a negative effect upon the development of a formalized mix design procedure. A suitable mix design procedure has still to be developed for foamed bitumen treated material.

A proper mix design method will not only produce specimens that are representative of the field material in terms of preparation, but also in terms of volumetric and mechanical properties. This thesis focuses on the influence of some of the currently used laboratory compaction methods on the mechanical properties of foamed bitumen treated materials. The compaction methods used in the study include:

- Marshall
- Hugo
- Refusal density (Kango hammer)
- Superpave Gyratory compaction
- Roller (slab compaction)

The work presented in this thesis forms part of a project currently in progress at the University of Stellenbosch which is aimed at the development of a mix design procedure for cold mixes. Cold mixes consist of a granular material or reclaimed asphalt pavement material in which bitumen emulsion, foamed bitumen or cutback bitumen.

1.1 Scope & objectives

1.1.1 Scope

The selection of the granular materials, bitumen, compaction methods and mechanical tests was based on the objectives of this project. The selection of compaction methods was done as to cover the most commonly used in SA and also those used in other parts of the world. The scope is limited to the following:

- Two (2) types of granular materials
- Two(2) types of penetration grade bitumen
- Four laboratory compaction methods and one field compaction method.
- Three types of mechanical testing

1.1.2 Objectives

The main objective of the study is to investigate the suitability of the existing compaction method for the mix design of foamed bitumen treated materials.

The objectives are:

- To determine and compare the influence of the different compaction methods on the volumetric and mechanical properties of foamed bituminous materials.
- To determine whether bitumen penetration grade have an influence on the mechanical properties of foamed bitumen treated materials.
- To investigate the suitability of current laboratory compaction methods in the design of foamed bitumen treated materials.

1.2 Outline of study

The study has the following structure:

Chapter 1 includes the introduction consisting of a brief background to the study and statement of the scope and objectives of the study.

Chapter 2 focuses on the problem statement regarding the need for adequate compaction guidelines for foamed bitumen treated materials. This chapter also describes the research method and includes a layout of the overall test programme.

Chapter 3 presents a literature study on the history of foamed bitumen and material requirements for foamed bitumen treatment.

Chapter 4 deals with the engineering properties of foamed bitumen materials. A brief overview on the stress-strain behaviour of asphaltic materials and pavement design principles are also presented.

The laboratory work comprising mix designs, compaction and curing as well as the mechanical testing are discussed in Chapter 5.

The test results and a discussion thereof are presented in Chapter 6.

Chapter 7 comprise synthesis of the statistical analysis of the volumetric and mechanical properties as well as the compaction energy applied via the respective compaction methods.

The final conclusions and recommendations are made in Chapter 8, followed by the references.

CHAPTER 2 PROBLEM STATEMENT AND RESEARCH METHODOLOGY

2.1 Problem statement

In recent years, the focus of traditional mix design methods for HMA has shifted away from using a standardised compaction effort to evaluate volumetrics and simple mechanical properties. Terms like overall densification, refusal density, compactive effort, shear energy during compaction and compaction curves have become keywords in various mix design methods (Cooper, 1995). Furthermore, the effect of traffic compaction has been the focus of many a study over the past few years.

75 blows by means of Marshall compaction are currently used for laboratory compaction in the design of cold mixes (foam and emulsion stabilised mixes) (Jenkins, 2000). This compactive effort has been used for years for the design of HMA mixes and in is not necessarily applicable to cold mixes. The inadequacy of this compaction effort and the need for the establishment of sound guidelines for compaction of cold mixes necessitates the investigation of more appropriate compaction guidelines.

2.2 Research method

The research method entails a comparative analysis in which four laboratory compaction methods were compared in relation to their ability to produce specimens that are representative of field specimens in terms of mechanical properties. Compaction efforts for each of the laboratory compaction methods were appropriately selected in order to yield samples with volumetric properties imilar to the slabs.

2.3 Test program and layout

2.3.1 Overall test program

The details of the tests are as follows (refer to Table 2-1):

- Two types of granular materials
- Two bitumen types
- Five compaction methods
- Three types of mechanical tests

Table 2-1: Test layout

Compaction method	Bitumen types	Mechanical tests	Materials
Marshall	80/100 and 150/200	ITS, ITT and SCB	G2 and G7
Hugo	80/100 and 150/200	ITS, ITT and SCB	G2 and G7
Gyratory	80/100 and 150/200	ITS, ITT and SCB	G2 and G7
Kango	80/100 and 150/200	ITS, ITT and SCB	G2 and G7
Roller	80/100 and 150/200	ITS, ITT and SCB	G2 and G7

Figure 2-1 shows the basic flowchart of the program to be followed for each of the materials.

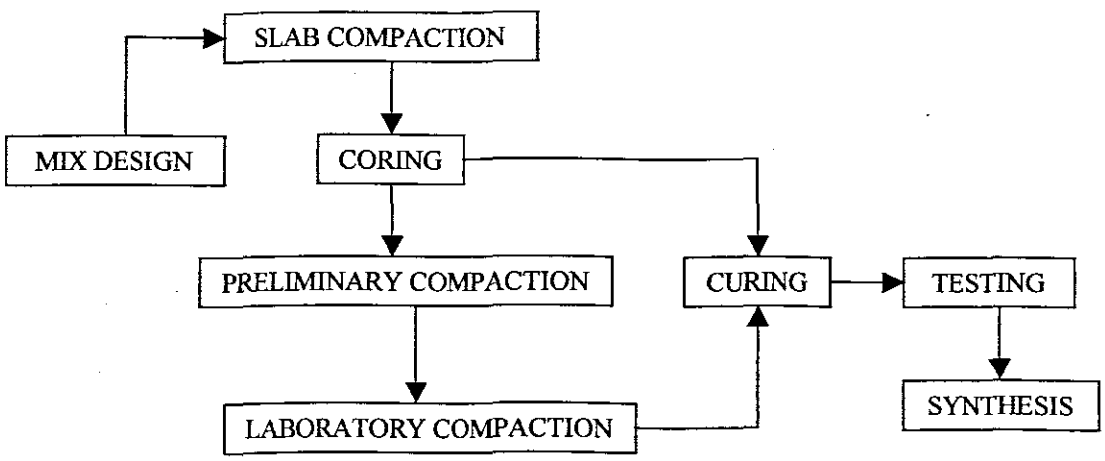


Figure 2-1: Schematic of test program

2.3.2 Mix design

The objective of the mix design was to determine the optimum binder content for compaction. The mix design started with the determination of the relevant aggregate and bitumen properties. A decision regarding the modification of aggregate properties to meet the requirements were made at this point.

2.3.3 Compaction, curing and testing

Roller compaction was used to simulated field compaction. Slabs with a thickness of approximately 110mm were compacted by means of a double drum hydrostatic roller.

The volumetric properties of the cores taken from the slabs were determined, followed by curing. Cores were then trimmed and mechanical tests performed on the cores.

Preliminary laboratory compaction was executed in order to determine to compactive effort required by each of the laboratory compaction methods to obtain briquettes with the same volumetric properties as the cores from the slabs.

Preliminary compaction was followed by compaction of specimens with the predetermined compactive efforts for each of the laboratory compaction methods.

Details regarding compaction, curing and testing are contained in Chapter 5.

CHAPTER 3 FOAMED BITUMINOUS MATERIALS - AN OVERVIEW

3.1 Foamed bitumen

The introduction of cold water into hot bitumen with a temperature of 170° C to 200° C results in the bitumen foaming, increasing the volume and surface energy of the bitumen (Lee, 1981). The foamed bitumen expands to volume ranging 10 to 15 times its original volume. While in this foam state, it has a low viscosity and when sprayed and mixed into cold moist aggregate a mixture is produced which will remain soft and brown until compaction and curing. Thereafter, it becomes harder and blacker and ultimately reaches strengths comparable with hot mix bituminous materials, depending upon the binder content used.

3.1.1 History of foamed bitumen

Foamed bitumen is currently being used in many countries across the world and a number of foaming systems are available.

Although the first foaming systems dates back as far as 1889, this product has only been used extensively over the past few years (Van der Walt, Botha, Semmelink, Engelbrecht and Salminen , 1999).

A brief overview of the history of foamed bitumen as stated by Van der Walt et al (1999) can be summarised as follows:

- 1889, Nebraska (USA) – the addition of bitumen to base coarse material in full depth pavement repairs.

- 1928, Darmastadt (Germany) – production of the first and patent of the hot bitumen foaming system.

- The first foamed bitumen processes were described when Professor Ladis Csanyi (1957) of Iowa demonstrated the addition of foamed bitumen to marginal quality aggregates (Maccorone, Hollerman, Leonard & Hey, 1994). His process consisted of steam injected, under pressure, into hot bitumen. Due to the complexity of equipment and difficulties with accurate water metering of the steam, the method was not found to be practical. Prof Csanyi also made attempts with water, air and gasses as foaming agents, but the availability of steam at asphalt plants, and because it was found to be the simplest and most efficient, made it to be the first choice as foaming agent. The

original spray nozzle used by Prof. Csanyi is depicted in Figure 3-1 below.

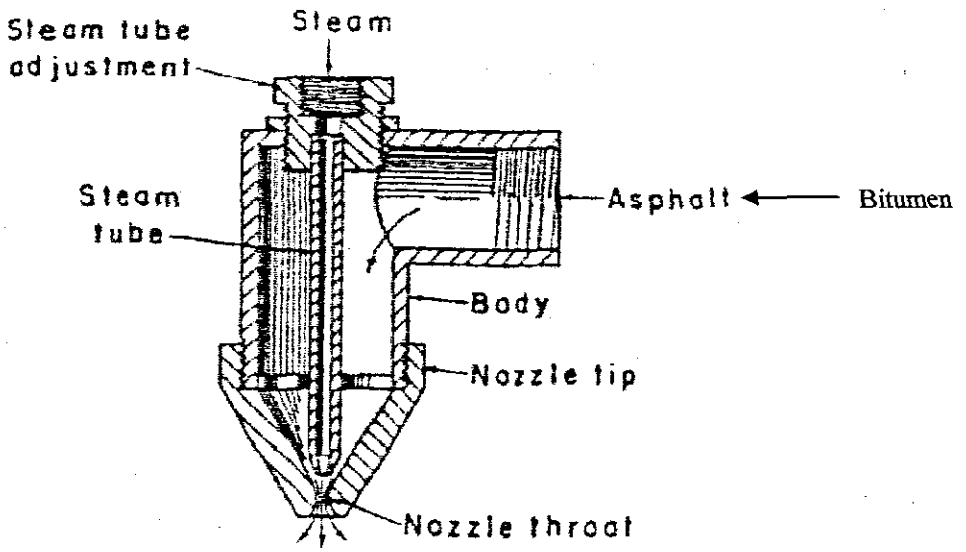


Figure 3-1: Original spray nozzle for foamed bitumen (Csanyi, 1957)

- Between 1968 and 1971, Mobil Oil Australia (M.O.A) modified the process (Roberts, Engelbrecht and Kennedy, 1984). Mobil patented foamed process involves the injection of cold water under controlled conditions and with certain additives into hot penetration grade bitumen before application through specially designed nozzles and spray bar and suitably designed expansion chamber (Akeroyd, 1989). The new system incorporated the precise control of the flow of bitumen and quantities of water to be injected. Ultimately, the quality of foamed bitumen could be better controlled by minimisation of possible differences in quality, which can occur with individually adjustable nozzles.

- Countries that have used foamed bitumen before 1990 include the USA, UK, Canada and South Africa (Jenkins, 2000).

- Worldwide since 1991 – many new foaming systems were developed after the Mobil patent rights expired. Nestor Salmimen of Nesotec OY, Scandinavia, developed a new system in 1994 and this was followed by other "Home Made" systems such as Savalco in Sweden. In addition, many foaming systems were developed for use on in situ recycling machines, such as those of Wirtgen®.

3.1.2 Characterisation of foamed bitumen

A significant amount of variability is inherent in the foamed bitumen treatment process,

which in turn influences the mechanical properties of mixes. Ideally one would want to produce foamed bitumen with properties that will give the mix desirable mechanical properties and a low enough viscosity during the mixing and compaction process. The quality of foam produced is a major contributor to the variability. The following factors influence the quality of foam produced, amongst others:

- type of penetration grade,
- amount of water injected into the bitumen,
- type of foaming apparatus used,
- the addition of foamants

The influence of the bitumen composition in terms of SARA (Saturates Aromatics Resins and Asphaltenes) has not been documented.

Foamed bitumen is characterised according to two properties namely. Expansion Ratio and Half-life. The Expansion ratio is defined as the ratio of maximum foam volume to the volume of bitumen once the foam has subsided. Half-life is described as the time in seconds that the foam takes to settle to one half of the maximum volume, which it attained. The influence of water content on both Half-Life and Expansion Ratio are depicted in Figure 3-2 below.

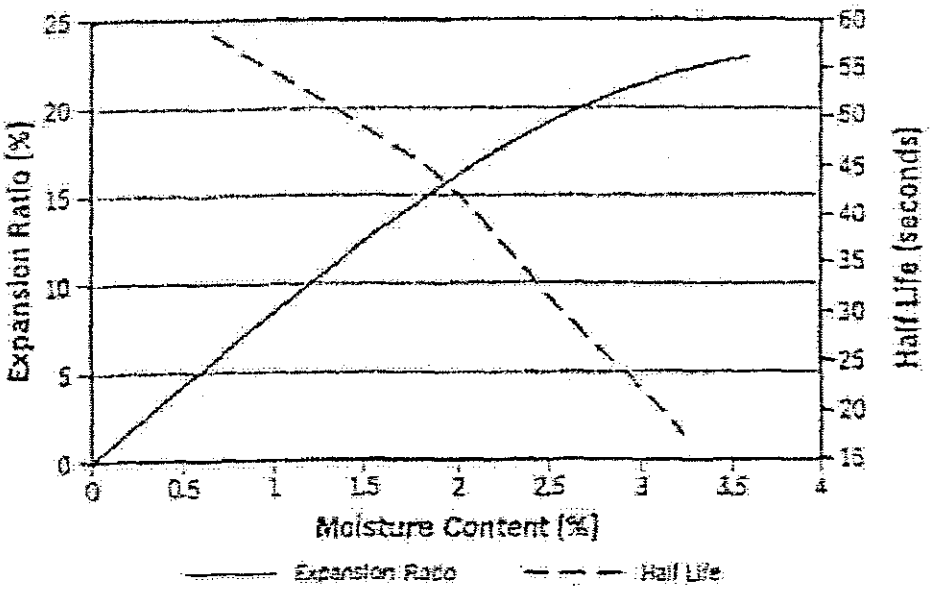


Figure 3-2: Effect of water on the Expansion Ratio and Half- life of foamed bitumen (Lewis, 1994)

Both Expansion Ratio and Half-life are influenced by the type of penetration grade bitumen used, as well as the quantity of water injected into hot bitumen during the foaming process. The expansion ratio increases with increasing addition of water.

However, increases in the addition of water cause a decrease in the foam's Half-life. Recommended minimum values by Ruckel et al (1983) and Acott and Myburgh (1983), for Half-Life tests in a 1 gallon container, are as follows:

- Expansion ratio (min) 8-15 times
- Half-Life (min) 20 seconds

More recent recommended values by CSIR (1998) include an Expansion Ratio of 10 timesoriginal bitumen volume and Half-Life of 12 seconds.

Recent research at the University of Stellenbosch, on bitumens from various origins, resulted in the introduction of a Foam Index (FI) and Actual Expansion Ratio (ER_a) as tools for characterising foamed bitumen (Jenkins, Van de Ven and de Groot, 1999). The Foam Index (FI) were proposed as a tool for optimising the application rate of foamant water and proposed additives, whilst the Actual Expansion Ratio represents an intrinsic measure of a bitumen's ability to expand during foaming at a fixed application of foamant water. More work is currently in progress to investigate the influence of FI on mix characteristics.

3.2 Characteristics of foamed bitumen treated materials

The distinct difference between mixtures produced using foamed bitumen and hot mixed asphalt, or mixes using emulsified bitumen, is the way in which the bitumen is dispersed through the aggregate.

Bitumen in HMA acts as glue and coats the small as well as large aggregates, as shown in Figure 3.3. Coating of the aggregates is dependent upon the free bitumen. More information about the interaction between filler and bitumen in HMA can be obtained elsewhere (Cooley, Stroup Gardiner, Hanson and Fletcher, 1998).

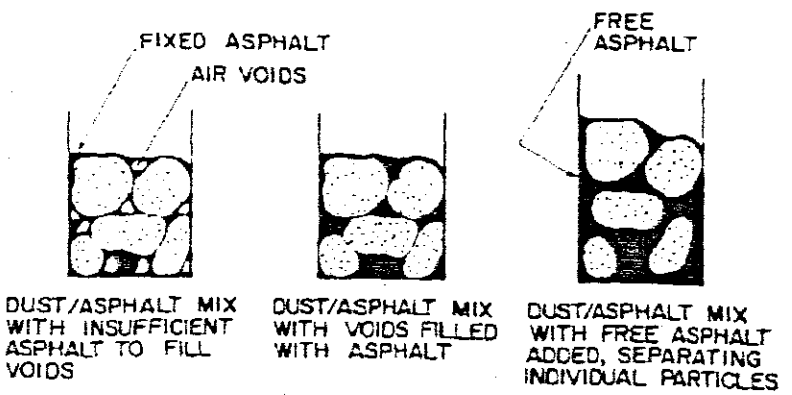


Figure 3-3: Bitumen interaction for HMA (Cooley et al, 1998)

Figure 3-4 below depicts the composition and phase diagrams of the mastic in foamed bituminous mixes.

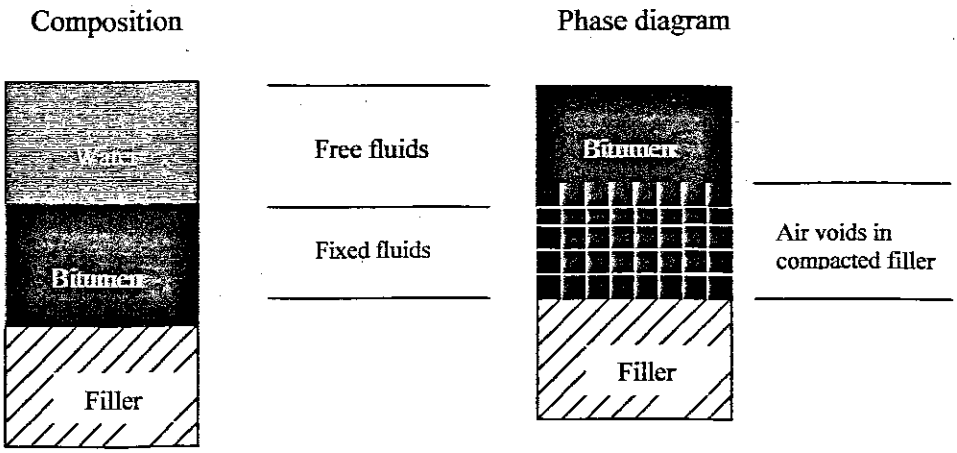


Figure 3-4: Foamed bitumen mastic

Foamed bitumen adheres to the fine particles and forms mortar globules that keep the granular matrix intact. The partial coating results in a small change in colour on the aggregates treated with foam compared to the same material when treated with bitumen emulsion, when they assume a much darker or even black colour.

More energy than evaporation at normal day temperature and low humidity is necessary to drive the water injected into the bitumen off at this stage, hence the shelf life characteristic of foamed bituminous materials.

The major advantages that foamed bitumen treated material has over hot mixed asphalt, cement stabilized or emulsion treated material are:

- It can be used with marginal and recycled materials at a lower cost. Transportation of large quantities of expensive aggregates to the job site and spoiling inadequate material is eliminated. Demand on quarry resources are also minimised by employing foamed (as well as other) recycling technology.

- Foamed bitumen treatment is usually less expensive than bitumen emulsion stabilisation or a combination of both.

- The partial coating in foamed mixtures makes the use of lower binder contents possible.

- No heating of aggregates is necessary. Energy is however required to heat the bitumen to 180 °C.

- Foamed bituminous mixtures have a shelf life, as it can be stockpiled and compacted after up to three months. No leaching or binder runoff takes place during the stockpile period.

- The strength gain is quick; resulting in earlier trafficking being possible than is normally the case for emulsion treated material.

- Construction time is shorter than for emulsion treatment. Suitable long "break time" is needed for emulsion to enable proper mixing and compaction and moisture control is imperative.

- Foam treated material has a balance of strength and flexibility versus cement or emulsion treated material and do not break down to the original strength properties of the parent material as quickly as cement treated material.

- Little or almost no environmental-side effects are inherent to foam treated material as no volatiles are discharged to the environment through evaporation.

3.3 Foamed bitumen stabilisation

Mobil Oil first carried out foamed bitumen stabilisation in Australia in the 1960's. Since then, foamed bitumen has been used successfully on a world-wide basis for the treatment of a wide variety of materials (Maccaronne, Holerman, Leonard and Hey, 1994). Materials used range from aggregates of sound and marginal quality to in-situ pavement material.

3.3.1 Suitability of aggregates

Suitable material as listed by Ruckel et al (1983) include crushed stone, rock, gravel sand, silty sand, sandy gravel, slag, reclaimed aggregate, ore tailings etc.

Mobil Oil Australia established guidelines for suitable gradations (Akeroyed & Hicks, 1988). As is the case with HMA, the grading of the aggregate is an important consideration. The grading envelope as shown in Figure 3.5 is used as a guide to the suitability of the aggregate grading for foam treatment (Maccarrone, Holleran, Leonard and Hey, 1994).

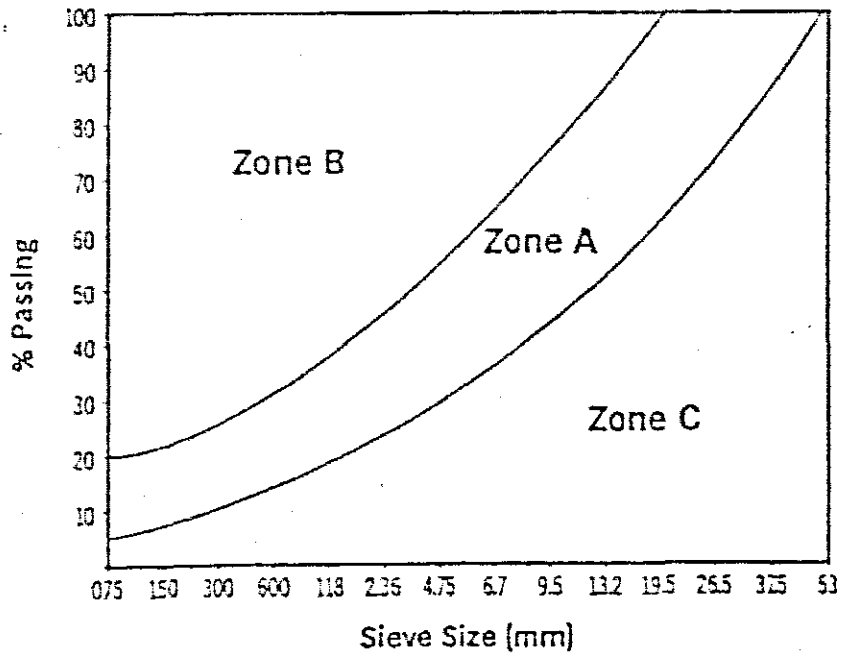


Figure 3-5: Guide for the selection of aggregate (Lewis, 1994)

Zone A represents good quality materials that are suitable for foamed bitumen treatment. Materials falling in **Zone B** and **Zone C** are too fine and too coarse respectively and need treatment. The addition of aggregate fractions to shift the gradation to **Zone A** is required for this two type of materials.

As mentioned before, foamed bitumen attaches to the fine material and partially coat the large aggregate particles. The amount of fines (i.e. <0.075mm) is thus another critical parameter to be considered. Ruckel et al (1982) indicated that a minimum of 3% is adequate, but the general rule is to maintain the fines content higher than 5%.

Bowering and Martin (1976) experienced that high plasticity gravels needed modification before foamed bitumen treatment. Lee (1981) on the other hand stated that a limited percentage of plastic fines are acceptable. Lime pre-treatment may be advisable and economic if the PI >8%. Lancaster et al (1994) suggested a maximum Plasticity Index of 12% before lime modification is required. Further work by Bowering and Martin (1976) and later Ruckel et al (1982) led to the establishment of guidelines by means of a Table which ranks the various materials and also provides and indication of the optimum binder content as shown in Table 3-1 below. The Unified Soil Classification system is applicable to the material types.

Table 3-1: Ranking suitability for foamed bitumen treated material (Ruckel et al, 1982)

Soil type	Suitability for foamed mix	Optimum binder content (% m/m)	Comments
Well graded gravel, little or no fines	Good	2.0 – 2.5	Permeable (improve with crushed fraction)
Well graded gravel + some clayey silt	Good	2.0 – 4.0	Permeable (improve with crushed fraction)
Well graded gravel + sandy clay	Good	2.0 – 4.0	Permeable (improve with crushed fraction)
Poorly graded gravel + sandy clay	Good	2.5 – 3.0	Low permeability (improve with crushed fraction)
Clayey gravel	Poor	4.0 – 6.0	Improve with lime
Well graded sand	Fair	4.0 – 5.0	Needs filler
Well graded silty sand	Good	2.5 – 4.0	
Poorly graded silty sand	Poor	3.0 – 4.5	Use low pen bitumen
Silty sand	Fair	2.5 – 5.0	Needs a filler
Silty sand	Good	2.5 – 4.5	
Slightly clayey, silty sand	Good	4.0	
Clayey sand	Poor	4.0 – 6.0	Needs small % Lime
	Good	3.0 – 4.0	After lime modification

Further guidelines by Ruckel et al (1982) for the selection of a design binder content are depicted in Table 3-2 below. Filler contents for different material can vary significantly and may range from non-plastic to fines with high plasticity. The guidelines provided are very broad and do not address all these possibilities.

Table 3-2: Foamed bitumen content (Ruckel et al, 1982)

% Passing 4.75 mm sieve	%Passing 0.075 mm sieve	(%) Foamed bitumen content
< 50 (gravels)	3 – 5	3
	5 – 7	3.5
	7.5 – 10	4
	> 10	4.5
> 50 (sands)	3 – 5	3.5
	5 – 7.5	4
	7.5 – 10	4.5
	> 10	5

The guidelines currently used in South Africa are shown in Table 3-3 below (Jenkins, 1999).

Table 3-3: Recommended Aggregate Characteristics (after Jenkins)

Parameter	Limits
Particle size	53 mm (max)
Grading modulus	1.8 (min)
Plasticity Index	10* (max)
Fine fraction (<0.075 mm)	5% (min) 15% (max)
Natural soaked CBR at 93% Mod AASHTO	20 (min)

*PI's of up to 15% can be tolerated if road lime is used as a modifier.

3.3.2 Mixing methods

"The foamed bitumen process is analogous to a baker beating an egg, which is viscous, into a foam of low viscosity before mixing it with flour. This step is required in order to produce a mix of acceptable quality and consistency" (Jenkins et al, 1999).

The importance of utilising a laboratory mixing procedure that simulates the mixing that takes place on site is an important factor to be considered. According to the literature search, mixes prepared were primarily in scaled foam plants and Hobart ® type mixers. Application of foamed bitumen is directly from the foam plant to the agitated aggregate in the mixer. Laboratory blenders have a rotary mixing motion, which do not simulate site manufacturing.

Site manufacturing mixers include twin-shaft pugmills, drum mixers, free fall mixers and milling drum mixers. Sufficient volume in the mixing chamber and energy of agitation is necessary to ensure that the airborne aggregate and the foam make contact.

Ruckel et al (1982) and Maccorone (1994) basically applied an approach developed by the Swede, K. G. Ohlson. Ruckel et al suggested the division of the material into two fraction groups according to which the <0.475mm fraction is first mixed with foamed bitumen; whereafter the blending (by hand) of the coarse fraction takes place for 30 seconds. The mix darkened appreciably in comparison with the colour of moistened natural aggregate. Reliance upon the particle coating of large aggregates for its efficacy is the key to this procedure. An added advantage of this procedure was that no deleterious effects have been noted and shortening of mixing time achieved. The separation of aggregate fractions is however not possible on site.

Maccorone took the above-mentioned step further by first treating the >0.475mm fraction with bitumen emulsion and treating the <0.475mm with foamed bitumen. This method is however costly.

HMA differs from foam treated material in that the bitumen permeates the entire mass forming a semi-solid-plastic cement which holds the aggregates in place. The low viscosity of the binder in hot mix asphalt at high mixing temperature facilitates the mixing process. Engineering properties like durability, resistance to moisture and mix consistency is influenced by the binder content and more importantly the coating of the mineral aggregate particles. Experience with HMA have proven that durability is improved by using the penetration type bitumen in relatively thick, dense aggregate packing and sound durable aggregate which resist the stripping of the binder films. Thus proper mixing facilitates the distribution of binder in the mix.

3.3.3 Influence of aggregate temperature

Aggregate temperature during stabilisation with foamed bitumen has been for decades considered as a critical parameter, which influences the quality of the mix (Jenkins, 2000). Temperature influence the behaviour of the mix at the following stages:

- mixing
- compaction, and
- in service

It was found that foamed treated materials are not necessarily more susceptible to temperature than HMA.

Bowering and Martin (1976) identified a window of 13-23°C for minimum mixing aggregate temperatures below which poor quality mixes would result. However, this observation was based on experiences during research. Humberto Castedo Franco and Wood (1982) reported improvement in Hveem Stability when investigating the influence of aggregate temperature with a range of ambient temperatures (10°C, 20°C and 38°C). Figure 3-6 below depicts the influence of aggregate mixing temperature on Hveem Stability.

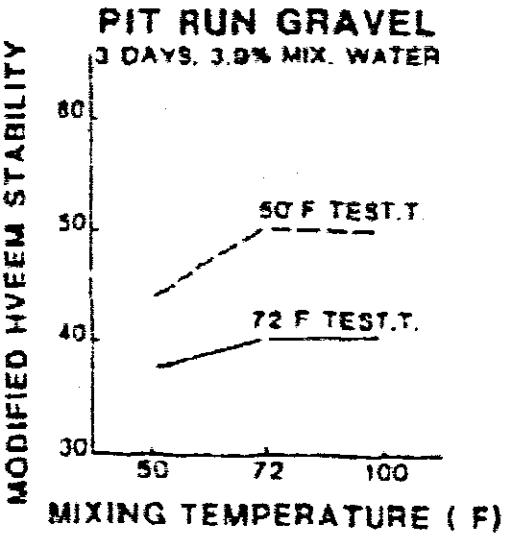


Figure 3-6: The influence of mixing temperature on Hveem S value (Humberto Castedo Franco and Wood, 1982)

Bowering and Martin compared properties of surfacing mixes heated to 110°C for curing and compaction purpose to the same mix at 23°C. Improved densities and significantly increased cohesion, but variable Marshall Stability were achieved. Roberts et al (1984) recorded substantially higher densities and engineering properties (tensile strengths and stability) when they used recycled materials.

During the study of stabilisation of incinerator slag using foamed bitumen, increases of 25 – 158% in stability values were recorded by Bushkühl et al (1990). Marginal stabilities for the mix caused them to increase the mix temperature to 60°C before compaction. Further work by Eggers et al (1990) with the same slag included the addition of additives called tensides prior to mixing. The optimum tenside content was determined before preparation of test mixes. By using a post mixing temperature of 115°C, the stability values increased by a further 100%. Engelbrecht et al (1985) also achieved improvement in strengths and improved densities when they heated RAP mixtures to a temperature of 160°C before mixing.

The behaviour of different types of HMA at different test temperatures is well researched. Limited work has also been done regarding the dependence of the engineering properties of foamed mixes on test temperature. The typical visco-elastic behaviour of foamed bitumen bound material was shown in the decreasing of Resilient Modulus (M_r) with an increase in testing temperature has however been mentioned in numerous studies.

Little et al (1983) recommended the use of a sensitivity analysis entailing repeated load (cyclic) Indirect Tensile Testing at a frequency of 10Hz and temperatures of 0°C, 23°C

and 50°C, as a tool to assess the temperature susceptibility of candidate mixes.

3.3.4 *Curing methods*

Similar to cutback and emulsion treated material, foamed treated material need to cure in order to gain strength. The gain in strength is a result of the drop in moisture content. Curing takes place via the evaporation, particle repulsion and pore pressure repulsion.

Factors that influence field curing include:

- air temperature and relative humidity on site,
- rainfall for the area,
- the depth of the layer and temperature of the layer,
- moisture content of the mix after compaction,
- air permeability of the compacted layer on site,
- drainage conditions at the boundary of the layer, including the depth of the water table

Air temperature, relative humidity and rainfall are directly influenced by climatic conditions. The gradation and binder content of the mix influence air permeability. Drainage and depth of water table is dependent upon the topography, subsoil conditions etc. Laboratory curing will not be able to simulate all the above-mentioned factors. Table 3-4 below (Jenkins 2000) summarises the curing methods, adopted by various researchers and the targeted field curing periods.

Table 3-4: Different curing methods utilised for foam mixes (Jenkins, 2000)

Curing method	Equivalent field cure	Reference
3 days @ 60°C + 3 days in mould	Not specified	Bowering, 1970
3 days @ 60°C	Construction period + early field life	Bowering and Martin, 1979
3 days @ 60°C	Between 23 and 200 days from vane shear tests	Acott, 1980
1 day in mould	Short term	Ruckel et al, 1982
1 day in mould 3 days @ 40°C	Between 7 days and 14 days (intermediate)	Ruckel et al, 1982
1 day in mould 3 days @ 40°C	30 days (long term)	Ruckel et al, 1982
1 day @ 38°C	7 days	Asphalt Institute
10 days in air + 50 hours @ 60°C	Unspecified	Van Wijk Leonard and Wood 1983
3 days at ambient temperature + 4 days vacuum dessication	Unspecified	Little et al, 1983
3 days @ 60°C	Unspecified	Roberts et al, 1984
3 days @ 60°C	Unspecified	Lancaster et al, 1994
3 days @ 60°C	1 year	Maccarone

An important aspect of curing is that field curing may take place over weeks, months or even years (Acott, 1980). Lee (1981) found that the strength of foamed bitumen stabilised sand was still increasing after a period of 3 years in the field.

3.3.5 Compaction

The quality and performance of a pavement is largely influenced by the degree of the compaction achieved during construction. The degree of compaction, together with mix design and good construction practice is an important parameter in the construction of layer works. One important objective of laboratory compaction is to produce specimens with mechanical and volumetric properties that can relate closely to those of comparable compacted field mixtures.

The main characteristics of laboratory compaction methods can be summarised as follows:

- Direct compression which require high force intensity. Particle orientation is minimum, excessive degradation of aggregates may take place with sidewall effects being disproportionately large.

- Vibratory compaction produces excellent particle orientation, but correlation with field in terms of strength characteristics has yet to be found.

- Impact compaction uses a flat hammer and little particle orientation takes place. The stress intensities, inertia and flow resistance is high with some degradation taking place.

- Gyratory compaction has the characteristic of using low intensity forces with horizontal components causing particle adjustments and orientation similar to field compaction. Differences in strength characteristics compared with field mixes are still evident.

The application of forces in the majority of the laboratory compaction methods is predominantly in a vertical direction with a solid foundation, whilst field compaction involves the application of shear forces to the mix. Foundation conditions in the field vary and are dependent upon the type of material underlying the material being compacted. Sidewall effects due confinement in moulds are not applicable in field compaction.

Mix properties and type of compaction method does not only influence the final compaction density, but also the engineering properties of the compacted mix. Specimens compacted by means of different compaction methods may have the same void contents, but the mechanical properties may differ due to the different orientation of the particles obtained by the different methods (Grobler, 1990).

Compaction of asphalt must also not be seen as mere densification, since a number of factors influence the degree of compaction obtained. Finn & Epps (1980) identified four factors namely:

- aggregate properties (particle shape and texture, grading, amount of filler and stone size);
- binder properties (bitumen type and type of modifier, if included);
- mix properties (binder content, moisture content and temperature);
- conditions during compaction (environmental, type of equipment and manpower);

The influence of the above-mentioned factors has been well researched for HMA. Table 3-5 below summarises the various techniques that have been used for foamed bituminous mixes over several decades.

Table 3-5: Summary of laboratory compaction techniques used for foamed mix design (Jenkins, 2000)

Compaction method	Settings/ temperature	Remarks	Reference
Kneading compactor	Ambient temperature	-	Shackel (1974)
Kneading compactor	Ambient temperature	-	Bowering & Martin (1976)
Gyratory compactor	Angle =1°, Ram pressure = 1.38 Mpa	Optimum Bitumen content = f (degree of compaction)	Tia and Wood (1982)
Texas Gyratory compactor	25° C	-	Little et al. (1983)
Gyratory	20 revs with Ram pressure = 1.38 Mpa	12% higher density than 75 blows Marshall	Brennen et al. (1983)
Gyratory Compactor	150 cycles, angle = 2° Ram pressure = 0.24 Mpa for 100mm Ø 150 cycles, angle =3° Ram pressure = 0.54 MPa for 150mm Ø		Maccarrone et al. (1994)
PCG (French Gyratory Compactor)	200 cycles at French standard settings	LCPC carousel: PCG 200 gyrations. ≡ 85% solid density	Brosseaud et al. (1997)

From the information listed in the table it is evident that the work done on the establishment of appropriate compaction guidelines for foamed treated materials is limited.

3.4 Conclusions

Based on the findings of the study of literature on foamed bitumen treated materials, the following conclusions are drawn:

- Foamed bitumen treatment has been carried out for over four(4) decades in a variety of climates and environments and on a variety of materials.

- A distinct difference between foam treated material and HMA is the distribution of binder within the mix as well as the binder/filler interaction. Shelf life characteristics of foamed bitumen treated materials are attributed to trapped water in the foamed bitumen.

- The quality of foamed bitumen produced is one of the major contributors to variability in foamed bitumen stabilization. The effect of foam bitumen properties on the engineering properties has not been quantified as yet. Bitumen type and composition, amount of water injected into bitumen, type of foaming apparatus and the addition of foamants influence the quality of foamed bitumen

produced.

- Foamed bitumen is characterised according to Expansion Ratio and Half-life. Recommended minimum values of 8-10 times and 12-20 seconds for Expansion Ratio and Half-life are recommended respectively.

- Suitable aggregates for foam bitumen treated include crushed stone, rock, gravel sand, silty sand, sandy gravel, slag, reclaimed aggregate, ore tailings etc. Guidelines for material suitability have been developed by Mobil Oil Australia. Most suitable material have a continuous gradation with the fraction smaller than 0.075 mm having a lower and upper limit of 5% and 15% respectively, and a minmum CBR of 20%. Altering the gradations can modify unsuitable materials.

- Mixing has been identified as an important factor influencing the properties of foam mixes. Laboratory mixing was primarily carried out with Hobart® mixers according to the literature studied. The rotary motions of laboratory blenders do not closely simulate site mixing. Temperature during mixing also has been proven to influence the engineering properties of foamed bitumen treated materials.

- Aggregate temperature during mixing, compaction and in service has a significant influence on mix behaviour.

- Curing of foamed mixes is an important factor influencing performance. Field curing takes place over weeks, months or even years. Air temperature and relative humidity on site, moisture content etc, influence the behaviour and performance of foam mixes. Various curing methods have been used over the years. Suitable laboratory curing techniques need to be developed for foam mixes.

- Pavement performance is largely influenced by the quality and degree of compaction. The main objective of laboratory compaction is to simulate field compaction. Research into compaction methods is necessary in order to develop guidelines for the compaction of foamed bitumen treated materials.

CHAPTER 4 ENGINEERING PROPERTIES OF FOAMED TREATED MATERIALS

4.1 Background

4.1.1 The stress-strain behaviour of asphaltic material

Asphaltic materials, consisting of bitumen and aggregates (granular material), are some of the most extensively used materials in road pavements (Molenaar, 1993). Aggregates comprise of stone (material with a diameter larger than 2 mm), sand (material with a diameter between 63μm and 2mm) and filler (material smaller than 63 μm). The combination of bitumen and filler builds up a mix, which is called the mortar. The volumetric composition, together with the properties of the bitumen are the main characteristics that influence the mix performance, as will be seen hereafter.

Application of a stress to elastic materials will yield proportionality between applied stress (σ) and strain (ε). The deformation induced may be completely recovered upon removal of the applied stress – Hooke's Law governs i.e. the linear elastic behaviour:

$$\sigma = E.\varepsilon$$

where E = modulus of elasticity (Youngs Modulus)

Other materials will flow and continue to do so with stress at a constant level. Apart from deformation being irrecoverable, the material may also develop different levels of stress – i.e. viscous behaviour.

$$\gamma = \eta.\frac{dy}{dt}$$

where: η = coefficient of viscosity (Ns/m^2),

γ = shear stress, and

$\frac{dy}{dt}$ = rate of shear strain (s^{-1})

Some materials are neither purely elastic nor purely viscous. They exhibit elastic response when loaded extremely rapidly and viscous when loaded very slowly. Intermediate rates of loading results in a response that is a combination of both viscous and elastic response.

The visco-elastic properties of asphalt are governed by the presence of bitumen, whereas the mineral skeleton influences the elastic properties. The consistency of bitumen varies

with temperature (i.e. the viscosity of bitumen change by a factor of 10 for a 5°C change in temperature). Thus, both time and temperature must be considered when evaluating the mechanical properties of asphalt.

Simple models consisting of springs and dashpots can be used to schematically represent the behaviour of asphalt. A typical model used is Burger's Model as depicted in Figure 4-1. The model consists of a spring element E_1 connected in series with a dashpot η_1 and a parallel arrangement of spring E_2 and dashpot η_2.

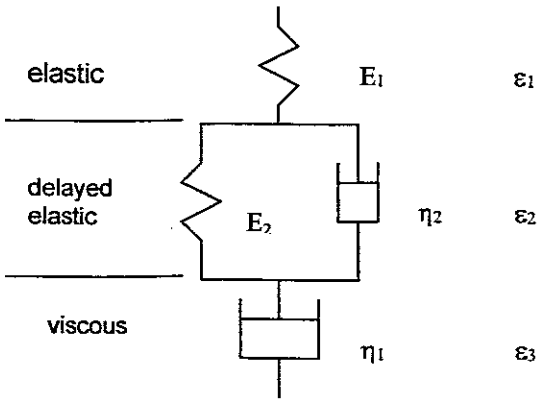


Figure 4-1: Burger's Model (Molenaar, 1993)

Upon application of a stop load, the total strain at any time can be divided into the following elements:

- an instantaneously recoverable component represented by spring E_1,
- a retarded recoverable (which is time- dependent) component represented by elements E_2, η_2, and
- irrecoverable element (permanent deformation) mainly due to viscous flow represented by dashpot η_1.

The response ε due to the stress σ can be described according to :

Elastic part $\varepsilon_1 = \sigma_1/E_1$

Viscous part $\varepsilon_2 = \sigma_2/\eta_1$

Delayed elastic part $\eta_2 . \varepsilon_3 . + E_2 . \varepsilon_3 = \sigma_3$

For the overall model holds: $\sigma_1 = \sigma_2 = \sigma_3 = \sigma$ and $\varepsilon_1 = \varepsilon_2 = \varepsilon_3 = \varepsilon$

4.1.2 Structural analysis of pavement response to loading

The wheel load of a vehicle causes a pavement to deflect and various stresses, strains and deflections are induced (Paterson, 1977). Pavement response to traffic loading is mechanistically modelled by computing stresses and strains within the layers. The stresses and strains are dependent upon the layer properties, material properties and the interaction of the layers within the pavement under the given load.

The stress condition within a pavement structure can be reproduced with great difficulty as it varies on a single element with time, as shown in Figure 4-2. The associated patterns of principal stresses illustrating the rotation of principal planes, which takes place, are shown in Figure 4-3.

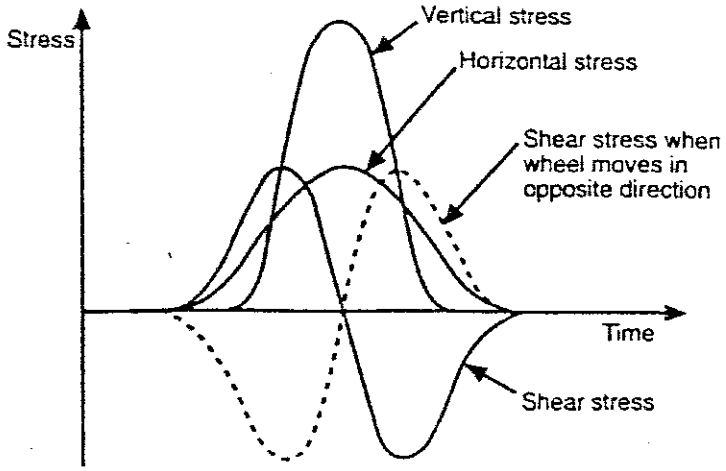
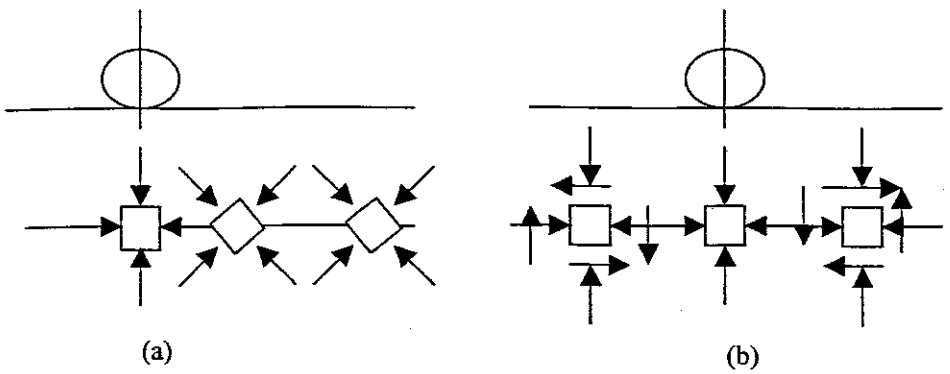


Figure 4-2: Variation of stress with time (Shell, 1990)



(a) principal stresses – element rotates **(b) no rotation – shear stress reversal**

Figure 4-3: Stresses on an element (after Shell, 1990)

An element of material directly underneath the wheel load will experience a compressive stress, whilst lower in the structure the stresses will be shear stresses. As the wheel load moves forward, the compressive stress changes to shear stress.

The pavement structure is schematized as a set of horizontal layers, with each layer having it's own elastic modulus and Poisson's Ratio (Molenaar, 1994). Although not completely true, a full friction condition is usually assumed between the various layers. Wheel loads are represented as uniformly distributed vertical contact pressures acting on circular contact areas. Figure 4.4 below depicts a typical schematic representation of a multi-layer system showing the required input needed in the structural analysis as part of determining the stresses and strains.

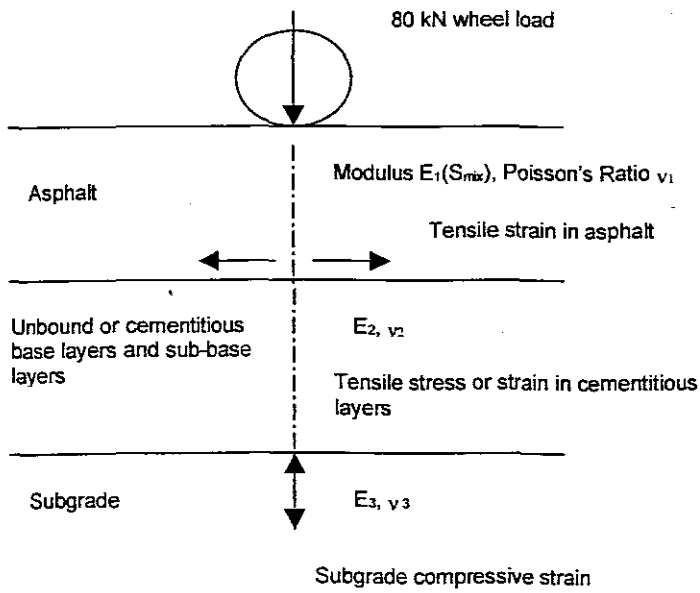


Figure 4-4: Schematic representation of multi-layer pavement structure (after Molenaaar, 1994)

Two important material properties relevant to mechanistic pavement design are:

- load deformation or stress strain characteristics required for structural analysis, and
- performance characteristics which determine the mode of failure

The two principal performance criteria of asphaltic material are:

- fatigue cracking, and
- excessive permanent deformation

The failure mode of each material used in the pavement structure determines the position of critical stresses and strains calculated at specific positions in the structure under the design loading. The relationship between the value of the critical parameters and the number of load repetitions that a material can withstand until some terminal condition is reached, is represented by a transfer function for the specific material Theyse et al. (1996).

The mode of failure for foamed bitumen treated materials are not clearly defined in literature. Crushing was adjudged to be a representative failure mechanism for foamed treated material by the CSIR (1998) due to the brittle nature of the material. Transfer functions for foamed stabilised materials still have to be developed and the mode of failure needs more clear definition.

4.2 Engineering properties of foamed bituminous material

Foamed bituminous materials have been subjected to a variety of tests over several decades. Selection of tests was based on the preference of the researcher and the availability of test equipment. An overview of the tests performed on foamed bitumen treated mixes is given in Table 4-1 below.

Table 4-1: Historical test methods for foamed mixes and their function (Jenkins, 2000)

Performance property	Mix (engineering) property	Test
Workability	Cohesion	Vane Shear
Fracture resistance Fatigue Resistance	Tensile strength & fracture energy Tensile strain & stiffness	Indirect Tensile strength (ITS) Hveem Cohesiometer Long term pavement performance (LTPP)
Permanent deformation resistance	Plastic deformation Shear strength	Static Creep, Dynamic Creep Triaxial Hveen Cohesiometer Vane Shear Marshall Stability Hveem Resistance
Load spreading and stress distribution	Resilient Modulus M_r or stiffness	Indirect tensile Test (ITT) Dynamic or Static Triaxial
Moisture susceptibility	Retained strength or stiffness after moisture exposure	Marshall Stability Indirect Tensile Strength (ITS) Indirect Tensile Strength, (ITT) Triaxial
Crushing Resistance	Compressive strength	Unconfined Compressive strength (UCS)

Limit values for test properties are not well defined for foamed bitumen treated materials. Limitations of semi-empirical test method such as Hveem and Marshall test methods have caused a move to more fundamental test methods for HMA. More emphasis is now placed on the engineering properties that relate to performance. Properties such as elastic stiffness, fatigue and resistance to permanent deformation, which are important from a mechanistic pavement design perspective forms the backbone of the SHRP activities on asphalt mixtures. The aforementioned developments have a direct influence on the procedures used for foamed bitumen treated material.

4.2.1 Stiffness

The stiffness (M_r) of asphalt is the relationship between stress and strain as a function of volumetric composition, bitumen characteristics, loading time and temperature. The stiffness characteristics serve as a basis to assess behaviour of a mix.

Increased asphalt stiffness at high temperatures is desirable in order to counter rutting, whereas decreased stiffness at low temperature is desirable for resistance to low temperature shrinkage cracking. Proper selection of aggregate and good mix design procedure is essential to increase resistance to rutting at high temperatures. Table 4-5 illustrates the relationship between mix stiffness, temperature and loading time.

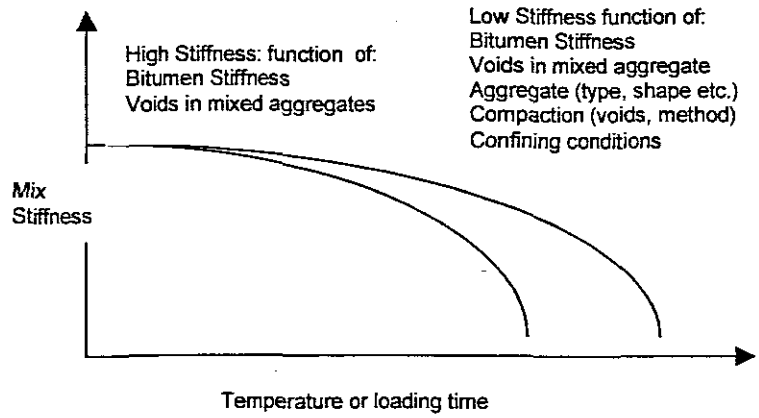


Figure 4-5: Mix stiffness as a function temperature or loading time (Shell, 1990)

Stiffness can basically be categorised into two categories; i.e. elastic stiffness under conditions of low temperatures or short loading times, and viscous stiffness at high temperatures or low loading times. Elastic stiffness is used in the calculation of critical strains in the pavement structure in analytical design. Viscous stiffness is used to assess the resistance to permanent deformation.

A variety of test methods can be used in order to determine the stiffness of asphalt; e.g. bending or vibration tests on a beam or direct uniaxial or triaxial tests on cylindrical

specimens. The loading type can also be varied, depending upon whether elastic or viscous stiffness need to be determined. Apart from testing, there are also a number of tools available of which the Shell nomograph is a typical example. The stiffness at any temperature and loading time can be estimated to accuracy acceptable for most design purposes.

In their study of numerous foam treated sands, Acott and Myburgh (1982) did deflection measurements. They proposed the determination of M_r of a mix over short, medium and long term cure conditions as a means to relate the minimum desirable curing period to minimum stiffness required to limit the tensile strength in the surfacing to an acceptable level.

The visco elastic behaviour of foamed mixes was confirmed by a number of researchers. Triaxial tests done by Shackel indicated a maximization of Resilient Modulus (M_r) for a breccia with 4% binder at approximately 60% saturation. Increase in M_r was also reported for mixes with both 85/100 and 150/210 penetration foamed bitumen at binder contents of 5% and 6% respectively. A certain envelope was identified in which both softer (high penetration grade) and harder (low penetration bitumens) provided higher mix stiffness.

Humberto and Wood (1982) who found that the binder content at the peak M_r value was independent of the curing time reported similar findings as Shackel (1974).

The selection of the optimum binder content in terms of peak M_r was also used by Lancaster et al (1994) who proposed the used of this approach for both dry cure and soaked (24 hours at 60°C) repeated load ITT test. Relationships between filler contents and mix stiffness were developed by Maccarone et al (1994).

4.2.2 Resistance to permanent deformation

Permanent deformation can be simply defined as the accumulation of plastic strain caused by the combined effect of consolidation and shear movement as a result of traffic loading. The permanent deformation characteristics of asphalt are dependant upon the mix characteristics, temperature and loading time.

An analysis of the low stiffness response (high temperatures and long loading times) needs to be carried out to determine the permanent deformation properties of asphalt (Shell, 1990). Mix behaviour is much more complex than it is in the elastic zone at a stiffness < $5x10^6$Pa. Apart from bitumen and aggregate volume, factors like aggregate shape, gradation, texture and interlock, and method and degree of compaction also influence the stiffness.

Resistance to permanent deformation of foamed mixes was found by Shackel et al (1974) to be dependent upon the following properties:

- binder content, and
- degree of saturation (% voids filled with water by volume)

4.2.2.1 Stability

Various tests have been used over the years to determine the stability characteristics of foamed treated materials. Acott and Myburgh (1982) used Rt value tests for a variety foam treated sands, whilst Modified Relative Stability at 60°C to analyse resistance to shear failure was utilized by Bowering and Martin (1976) and Little et al (1983).

Extremely high Marshall Stability was recorded for RAP materials stabilized with 0.5% to 1% by Brennen et al (1983). Lee (1981) found Marshall Stability values that were in general higher than the equivalent HMA.

4.2.2.2 Dynamic testing

Shackel et al (1974) identified the triaxial test as the most preferred method to assess the rutting potential of foam mixes. Numerous triaxial tests on foamed treated Sydney breccia in Australia, combined with full scale accelerated pavement testing and wheel tracking tests were undertaken in this research effort. Good correlations were found between static and dynamic modes in terms of permanent deformation. Resistance to permanent deformation were found to be a function of binder content and the degree of saturation (% voids filled with water by volume).

4.2.2.3 Compressive strength

The CSIR (1998) considers the Unconfined Compressive Strength (UCS) to be more appropriate and advocates more robust tests methods for foamed bitumen treated material. The CSIR reported UCS values for foam treated materials that were in the lower half of the range of UCS values for cement treated materials. The study included preliminary assessment of the structural properties of pavements with foamed bituminous layers.

Guidelines for foamed bitumen bound layers underneath thin asphalt layers established by Bowering and Martin (1970), included a compressive strength of 700kPa for a 3 day cured specimen and 500k Pa for as 4 day soaked specimen. An extension of the work by Bowering and Martin (1976) stated that UCS for foam mixes at ambient temperature is commonly found in the range of 1.8Mpa to 5.4MPa.

UCS of a sand and calcrete dust mixture treated with 5% foamed bitumen was found to be dependant upon the percentage of filler in the mix when tested at 25C in accordance with (NITRR, 1986) by Semmelink (1991).

4.2.2.4 Moisture susceptibility

Foam mixes differs form HMA due with respect to the following aspects:

- partial coating of larger aggregate in the mix,
- lower binder contents used in foam mixes, resulting in higher void contents and voids in the mineral aggregate,
- reduced binder adhesion due to aggregate being moist in the mixing process

Lee (1981) suggested that Immersion Marshall Stability values after 24 hours may be unrealistically severe evaluate foamed bitumen stabilised mixes and noted the need to evaluate water susceptibility of foam mixes.

Vacuum saturation testing to determine moisture susceptibility in terms of the Resilient Modulus of a mix was a method used by Lee et al. (1983). As stipulated in the Asphalt Institute Manual, specimens are vacuum saturated at 100mm of Mercury for 1 hour followed by release of vacuum and further saturation for 1 hour (measuring the mass of absorbed water). Foamed bitumen treated siliceous gravels and sands were found to be very moisture susceptible when applying this method. Ruckel et al (1983), when using the same technique, at 23°C in water, stated that it simulated the effects of prolonged exposure the sub-surface moisture.

Van Wyk and Wood (1983) studied the moisture-exposure effects of foamed mixes in terms f Marshall Stability tests, using vacuum saturation. The moisture susceptibility of both RAP and virgin mixes were found to be highlighted by the procedure Hotte(1995) found that the Retained Marshall Stability for 1 hour of vacuum soaking compared to 4 days of soaking at atmospheric conditions to be 6.4% higher on average for six materials.

Roberts et al (1994) introduced a wet curing cycle of 3 days at 24°C and found a 50% decrease inst rength compared to dry cured specimens.

4.2.3 Fatigue

Fatigue can be simply defined as the phenomenon of cracking of asphalt layers under repeated loading and occurs as a result of a progressive reduction in mix stiffness due to repeated tensile stress applications. The magnitude of the repeated stress applied is generally less than the tensile strength of the asphalt. Flexible pavement structures are subject to continuous flexing under traffic loading.

Fatigue characteristics is significantly affected by mix composition especially binder content. Higher binder contents yield longer fatigue life. Input parameters for the prediction of the fatigue of HMA mixes are:

- volume of bitumen (%),
- penetration index of the bitumen,
- stiffness modulus of the mix,
- the initial strain

The fatigue characteristics of foamed treated materials with a relative high binder content (>3.5%) are expected to be similar than that of HMA (Theyse, 1999). A number of researchers have investigated the fatigue behaviour of foamed treated material. Little et al (1983) performed controlled stress beam tests on HMA, foamed bitumen treated material and high quality emulsion mixes. Lower fatigue lifes were recorded for the foam treated materials in this study. No comparison of binder contents was made in the study.

Repeated Indirect Tensile Testing is employed as a test to assess the fatigue behaviour of asphaltic materials. Minimum ITS (applicable to bases) values at 25°C (0.87mm/second) of 200kPa (dry) and 100kPa (soaked) after curing was recommended for foamed bitumen treated material by Macarrone (1994). Curing condition has a significant influence on the tensile strength of foam mixes, as noted by Engelbrecht et al (1985). Higher curing temperature cause low moisture contents and higher tensile strengths of test specimens.

Upon the study of the tensile strength of RAP materials with various binder for cold mixes, Roberts, Engelbrecht and Kennedy concluded that the tensile strength of foam mixes is superior to cut-back and emulsion mixes. Acott and Myburgh (1982) recorded lower fatigue lifes than for HMA for a range of hot mixes.

4.3 Conclusions

Conclusions can be summarised as follows:

- Asphaltic materials are one of the most extensively used pavement materials.

- Bitumen influences the visco-elastic properties of asphaltic materials, whilst mineral skeleton influences the elastic properties.

- Important material properties used in mechanistic pavement design are load deformation and performance characteristics, which determine the mode of failure. Fatigue cracking and excessive permanent deformation are used as principal distress modes of asphaltic materials.

- Transfer functions are used to describe the relationship between the value of critical parameters and the number of load repetitions that a material can take until some terminal condition is reached. Transfer functions for foam mixes need more clear establishment.

- Limitations of semi-empirical tests have caused a move to more fundamental tests for HMA and have also influenced the testing of foam mixes.

- Foamed bitumen stabilised materials have been subjected to various tests, but critical limit values for these tests are not well defined for foamed bitumen mixes. Higher Marshall Stability and resistance to permanent deformation than equivalent HMA mixes have been recorded for foam mixes. Recorded fatigue resistance, tensile strength and moisture susceptibility are in some cases poorer than for HMA.

CHAPTER 5 LABORATORY WORK

5.1 Mix design

The objective of the mix design was to determine the optimum foamed bitumen content binder content for the two materials. A Marshall mix design was carried out for the G2 and G7 material by compacting 150 mm ø briquettes at different binder contents (as outlined in Table 5-2) by means of the Marshall method. Suitable compaction binder contents were selected by considering the volumetric and ITS test results. A schematic representation of the mix design process is shown in Figure 5.1 below.

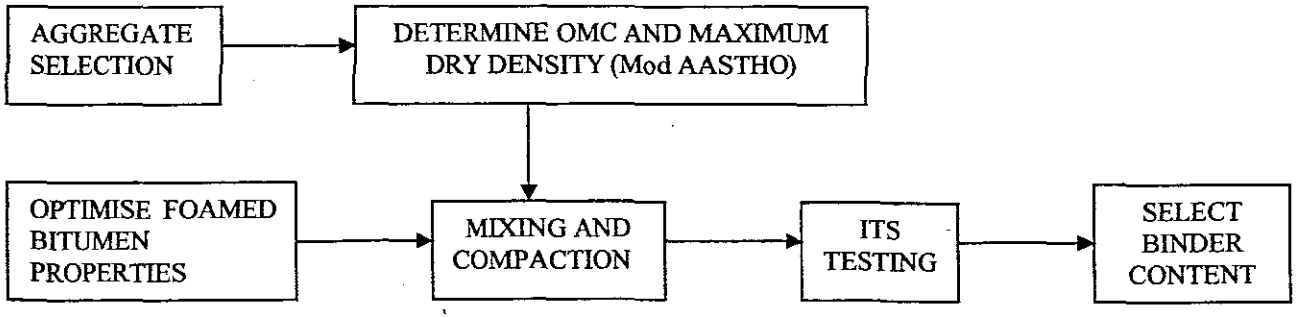


Figure 5-1: Schematic of mix design procedure

Section 5.1.1 to 5.1.6 comprises a description of the procedures followed in the mix design.

5.1.1 Material properties

5.1.1.1 Aggregate properties

The designations G2 and G7 are as used in the TRH 14 document (CSRA, 1987), which classify aggregates in terms of gradation, crushing strength, flakiness index, bearing capacity & swell, group index, field compaction and deleterious materials. Only the properties as shown in the Table 5.2 (based on Table 3-3) were determined using the applicable test methods as outlined in TMH1 (CSRA, 1987).

The G2 consisted of a blend of crushed Malmesbury Shale (Hornfels) and natural sand and was supplied by a local aggregate supplier. The G7 material consists of a blend of light grey brown, fine to coarse natural gravel, obtained from Sir Lowry's Pass Village, and 10% Phillipi sand. The G7 material had to be modified by adding 3% rock flour filler and 1% cement to satisfy the criteria of minimum filler content of 5%.

The gradations and aggregate properties are shown in Table 5-1 and 5-2 respectively.

Table 5-1: Aggregate gradations

Sieve Size (mm)	G2 % Passing	G7 % Passing
26.5	100	100
19	82	100
13.2	64	100
4.75	40	96.8
2.0	27	78
0.425	16	32
0.075	6	6

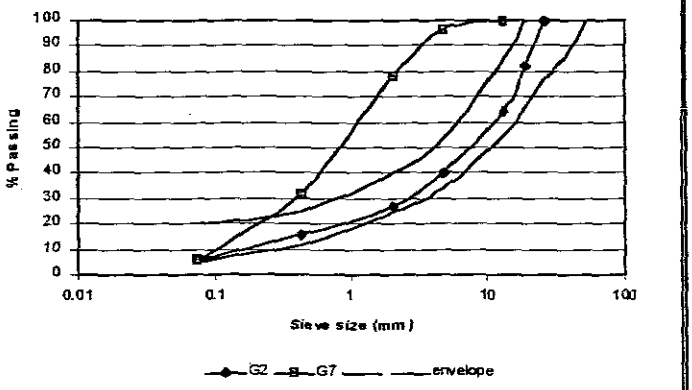


Table 5-2: Aggregate properties

Properties	G2	G7	Guidelines
Grading Modulus	2.5	2.2	1.8 (min)
Optimum Moisture Content (%)	6.1	7.0	N/A
Maximum Dry Density (kg/m^3)	2263	2118	N/A
Fine fraction (<0.075)	6	6	5% min
CBR @ 90% Mod	91	17	20 (min)
Plasticity index	SP	NP	10 max

5.1.1.2 Bitumen properties

150/200 bitumen was used in the mix design with determine a suitable compaction binder content for the candidate materials. A decision was made to use only the one penetration grade bitumen in the mix design using the assumption that the volumetric and ITS strength values would be the same for both bitumen types.

Foamed bitumen was produced in a Wirtgen® laboratory foamed bitumen dispenser as shown in Figure 5-2. Foaming of the bitumen took place at temperatures between 170 and 180 °C. Optimisation of foamed bitumen properties entails the injection of ranging quantities of water into hot bitumen and plotting Half-life and Expansion Ratios against water contents. Figure 5-3 and 5-4 depict the foam characteristics for both the 150/200 and 80/100 bitumen that were used in this study.

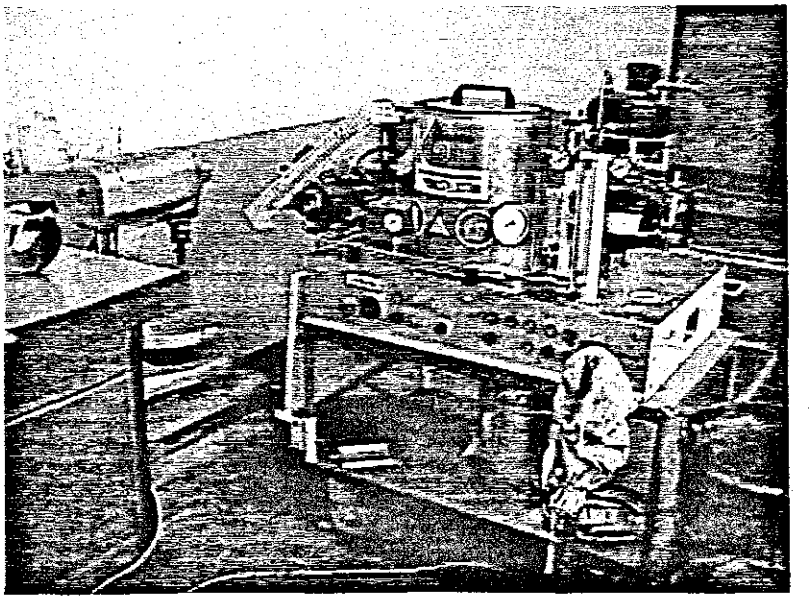


Figure 5-2: Foamed bitumen dispenser

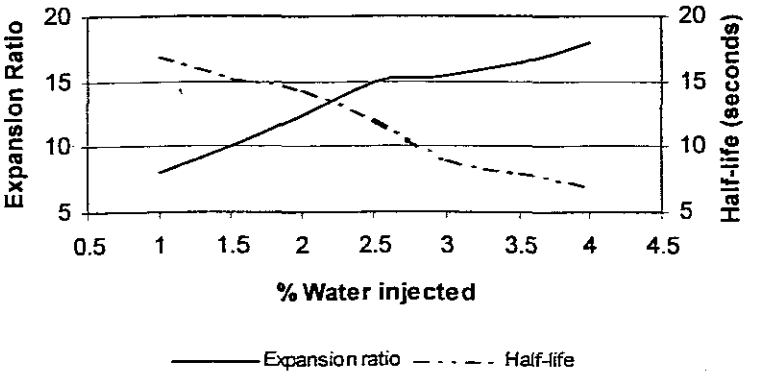


Figure 5-3: Foam characteristics for 150/200 bitumen

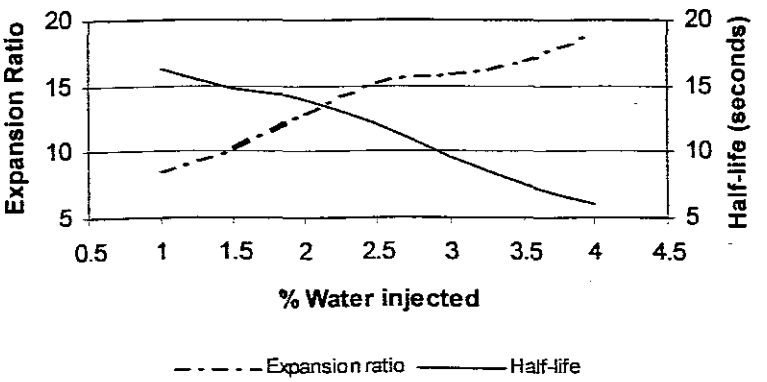


Figure 5-4: Foam characteristics for 80/100 bitumen

The characteristics selected for the two bitumens are shown Table 5-3 below.

Table 5-3: Foamed bitumen characteristics

Bitumen grade	Water content (%)	Expansion Ratio	Half-life (seconds)
150/200	2	13	15
80/100	2	12	14

5.1.2 Mixing and compaction

Mixing was carried out in a 20 litre Hobart ® mixer connected to the foamed bitumen dispenser. The first step in the mixing procedure was to determine the amount of hygroscopic moisture present in the aggregate. The required fluids content of the material before mixing was taken as 70% OMC of the material. Research has shown that this moisture content results in a maximum volume of aggregate and is known as the fluff point of the aggregate (Brennen et al, 1983). Moisture was added, in addition to the hygroscopic moisture, and mixed into the samples whereafter the injection of the foamed bitumen took place. The foamed bitumen (residual binder) was calculated as a percentage of the total mass of the sample (bitumen + dry aggregate) and the water content was calculated as a percentage of the dry aggregate. The relationship between total fluid content, residual binder content, added moisture and hygroscopic moisture are shown by the following formula:

$$TFC(\%) = H + A + R \text{ , or } TFC\ (\%) = 0.7 \times OMC$$

where,
- H = hygroscopic moisture
- A = added moisture
- R = residual binder, and
- TFC = hygroscopic moisture + added moisture + residual binder

Three (3) specimens per binder content were compacted with 75 blows per face in 150mm diameter moulds by means of an automated Marshall compaction apparatus. Table 5-4 shows the binder contents used in the mix design.

5.1.3 Volumetrics

Summaries of the calculated averages of the volumetric properties of the materials for the mix designs are shown in Table 5-4. Figures 5-5 to 5-7 show the volumetric relationships for these values and should be read in conjunction with Table 5-4.

Table 5-4: Marshall mix design volumetric properties

Binder content	Rice density		Bulk Relative density		Voids (%)	
	G2	G7	G2	G7	G2	G7
1.0	2.666		2.256		15.4	
1.5	2.652		2.273		14.3	
2.5	2.595	2.512	2.256	2.108	13.1	16.1
3.5	2.575	2.485	2.244	2.097	12.9	15.6
4.5	2.565	2.429	2.239	2.095	12.7	14.4
5.5		2.415		2.112		12.6

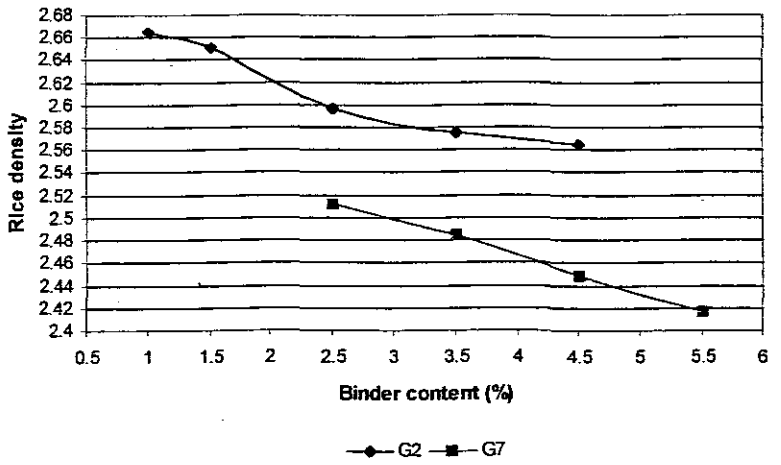


Figure 5-5: Maximum Theoretical Relative density versus binder content

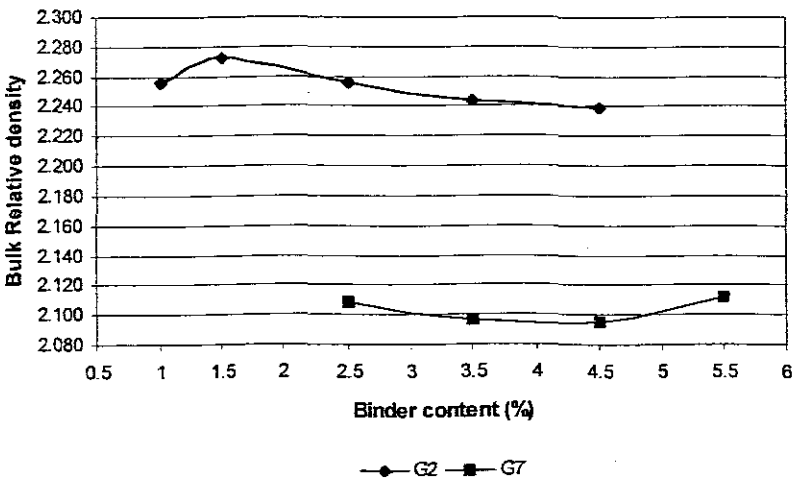


Figure 5-6: Bulk Relative Density versus binder content

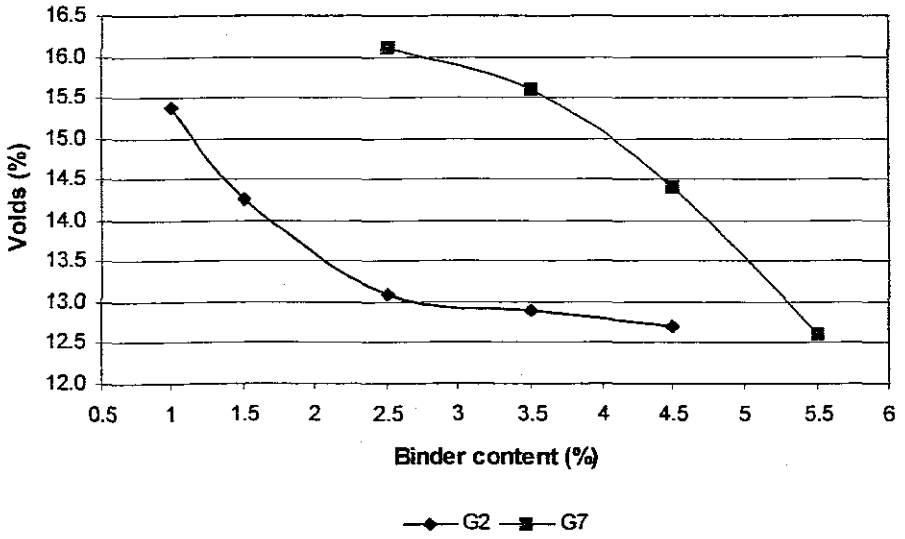


Figure 5-7: Binder content versus voids

5.1.4 Indirect Tensile Strength (ITS) Tests

Indirect Tensile strength tests were performed at a temperature of 25°C on six specimens per binder content of which three were dry and the other three soaked. A displacement rate of 50.8 mm/minute (Marshall speed) was used (refer to section 5.5.1 for ITS test description and details). The results of the ITS tests are shown in Tables 5-5 to Table 5-6. Figures 5-8 and 5-9 depict a graphical representation of the results.

Soaked ITS samples were treated according to the same procedure as used by Jenkins, Hugo and Van de Ven (Jenkins et al, 1997). This entails the immersion of briquettes in a Rices Apparatus for 1 hour at 25°C at a pressure of 30 mm of mercury. The pressure was then released and the specimens are left in the water for another hour, after which it was tested. G2 Specimens at low binder contents (1 and 1.5 %) collapsed after vacuum saturation. Therefore, the soaked ITS tests could not be determined for these binder contents.

Table 5-5: G2 Indirect Tensile Strength test results

Binder content (%)	Dry ITS	Standard Deviation (%)	Soaked ITS	Standard Deviation (%)	Retained ITS (%)
1	221	20			
1.5	243	15			
2.5	261	27	61	18	23
3.5	243	17	59	29	24
4.5	222	23	90	30	40

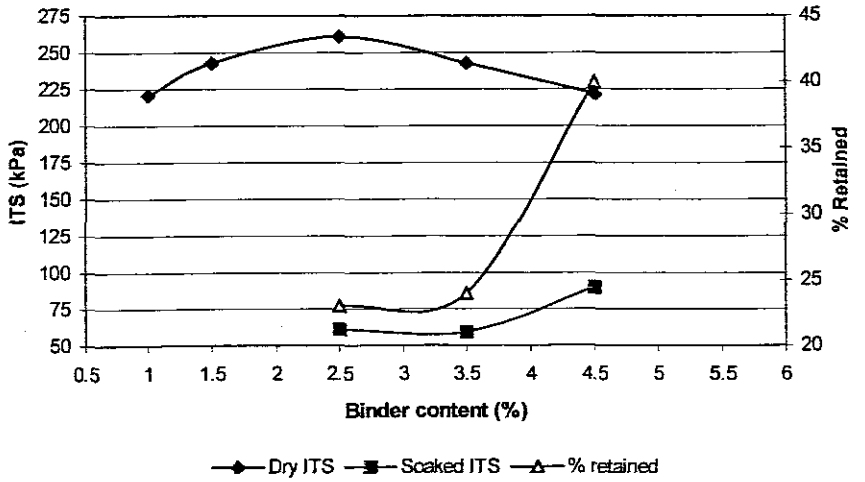


Figure 5-8: G2 Indirect Tensile Strength vs. binder content

Table 5-6: G7 Indirect Tensile Strength test results

Binder content (%)	Dry ITS(kPa)	Standard Deviation(%)	Soaked ITS	Standard Deviation	Retained ITS(kPa)
2.5	405	26	305	20	75
3.5	625	19	460	13	74
4.5	515	27	375	17	73
5.5	368	12	295	27	80

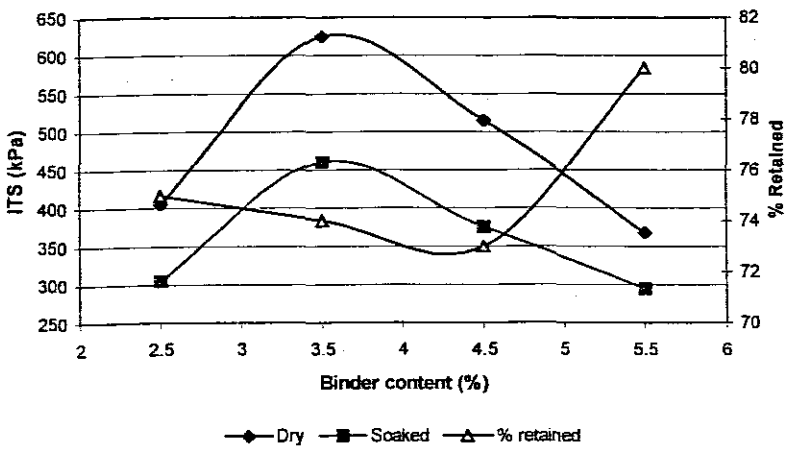


Figure 5-9: G7 Indirect Tensile Strength versus binder content

5.1.5 Discussion

5.1.5.1 Volumetrics

Computed densities for the G2 and materials are higher than the G7 material as one would expect well-graded crushed rock to be denser than gravel. Rice densities decrease with the increase of binder for both blends.

The Bulk Relative densities of the G2 material show a peak at 1.5 % and drops with an increase in binder content. However, the G7 densities do not show a difference of more than 20 kg/m^3 between the maximum and minimum densities and seems to be insensitive to binder variation.

Void contents for G2 peaks at 15.4 % at 1.0 % binder and decrease to 12.7% at 4.5 %. The maximum void content (16.1%) for G7 material occurs at a binder content of 2.5%. Thereafter a drop is evident with a minimum of 12.6 % at 5.5 %. Both curves for voids showed a decrease in voids with an increase of binder content. This is different to the normal trend for HMA mixes where voids decrease to a minimum value and increase with a further increase of binder content. Possible causes for the G2 mix can be that the 75 blows applied was too low a compactive effort. The insensitivity to the addition of binder of the bulk relative densities of the G2 material may also be a possible cause for the strange G2 curve.

5.1.5.2 ITS

The ITS results for the G2 material range from a minimum of 221kPa at 1% binder to a maximum of 261kPa at 2.5 % thereafter a drop in ITS values occur. The G7 material has much higher ITS values, which could be result of the presence of cement in the material. The range is from a minimum of 368 kPa at 5.5% to 625 kPa at 3.5% binder. G2 soaked ITS values range between 20% and 40%. The results show a steep increase from 3.5% to 4.5%. This is low in comparison to the emulsion mixes at the same binder contents. High void contents and partial coating of large aggregates within the mix may be the cause for the sensitivity to moisture of the G2 material.

Soaked ITS for the G7 material shows minimal effect of moisture exposure with the retained strength percentages being 75% as a minimum. This behaviour could be also being ascribed due to the presence of cement causing the high early strength of the material.

5.1.6 Conclusion

Mix design guidelines for foamed bitumen stabilised materials calls for the choice design binder content to be the one at which soaked ITS is maximised (CSIR, 1998). Based on

this rule, the design binder content for the G7 material would be 5.5% (too high). Optimum binder content, was chosen as 3.5 %, since the difference between the highest and lowest retained ITS strength varies by only 7% and all values retained ITS values were higher than 70%.

The G2 material retained ITS values were all below 50%. Use was made of Table 3-2 in to assist in the selection of the optimum binder content for the G2 material. The G2 material falls in the gravel category where the material with passing the 0.075 mm sieve falling between 5 and 7%. The suitable binder content for the G2 material is thus 3.5 %.

The optimum on binder content for both materials was used as 3.5% foamed bitumen.

5.2 Preliminary compaction

Preliminary compaction comprised an investigation into the compaction effort required for each of the candidate compaction methods to obtain the same volumetric properties at the mix design binder content (3.5% foamed bitumen). The following part of this chapter briefly describes each compaction method used in the study and the procedures followed.

5.2.1 Slab compaction

Slab compaction was used as a benchmarh for the volumetrics. Slabs were compacted in a parking embankment. Wooden frames being 850 x 700 mm and 110 mm deep were constructed and submerged into the ground with the top of the frames being level with the natural ground level. The mould was secured in the ground by using steel pegs as wedges. Material was excavated by means of a pick & shovel. Controlling the depth of excavation was done by dipping with a steel tape and a fish line. Thus, the material underlying the slabs can thus be considered as undisturbed.

G2 material was mixed at the design binder contents in batches of 10 kg and G7 material was mixed in 20 kg batches in the laboratory. Compaction was executed by placing the material in the mould and applying 15 to 20 roller passes. The required number of roller passes were determined by doing trial runs in which the number of passes was varied. The average slab thickness was 110 mm. Figures 5-11 to 5-13 depicts the coring and Figure 5-14 shows typical G2 cores after coring.

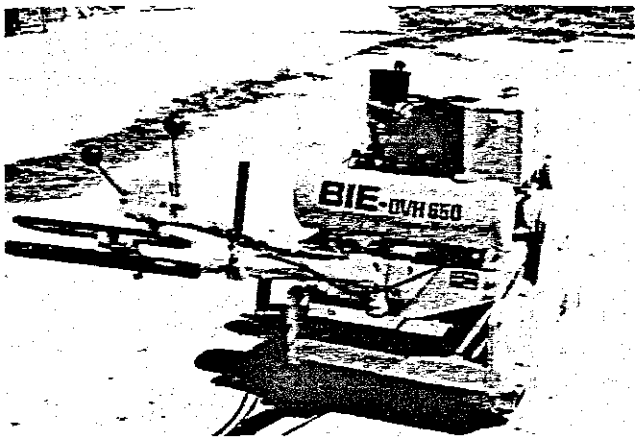


Figure 5-10: Pedestrian roller

The cores were trimmed to the required thickness by sawing with a diamond blade saw. It was found that some of the ends of the cores were frayed after sawing. Granular particles could also easily be removed from side of compacted G2 specimens. The cause for this particular problem is due to the foamed bitumen forming a mortar with the fines and this mortar only partially coating the large aggregate. Intact compacted foamed bitumen specimens may have the same appearance as conventional asphalt, but is very brittle in comparison.

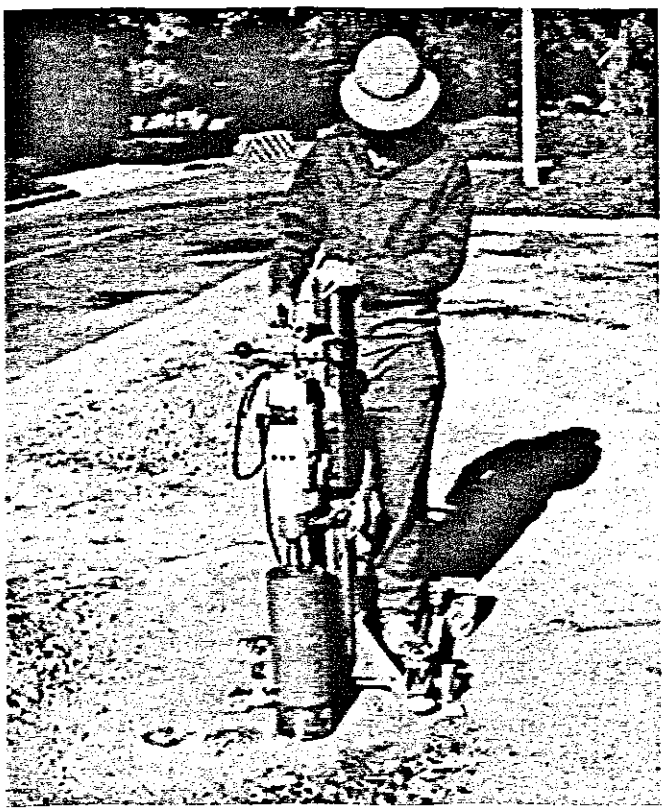


Figure 5-11: Coring in progress

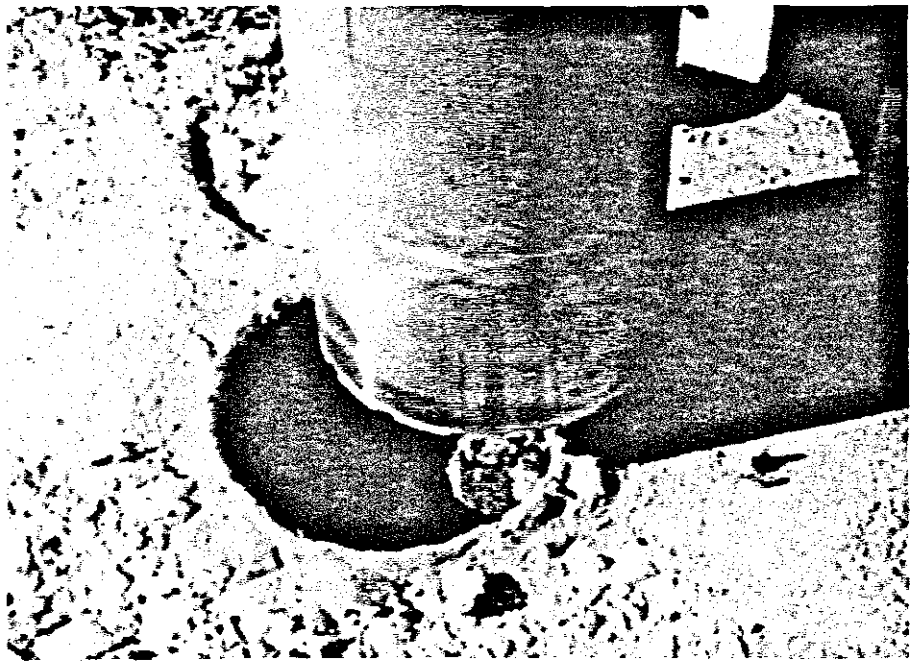


Figure 5-12: Close up view

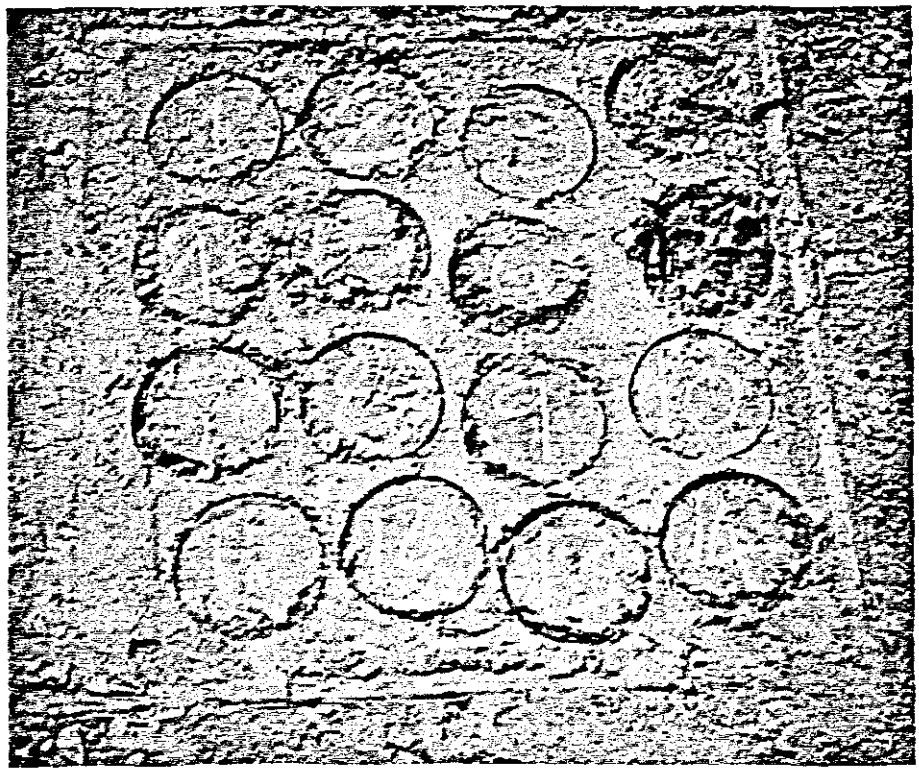


Figure 5-13: Typical G2 slab after cutting of cores

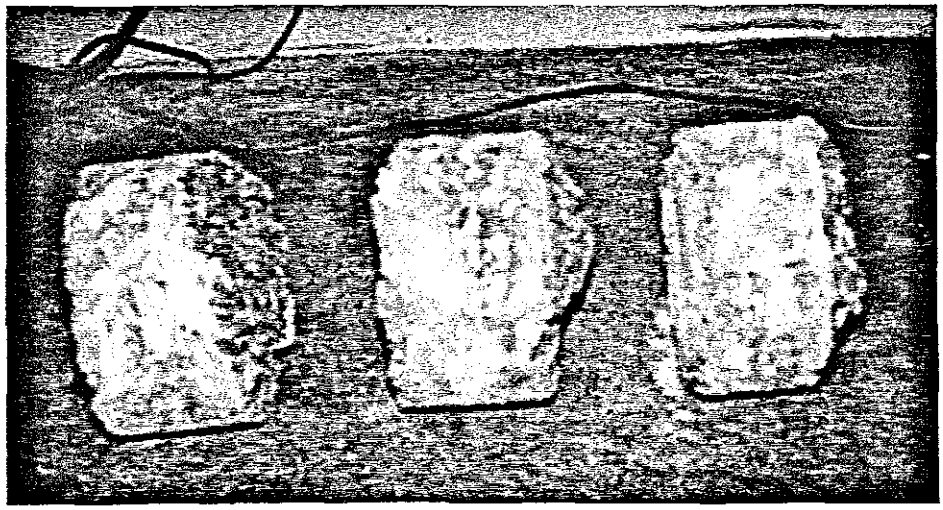


Figure 5-14: Typical G2 cores

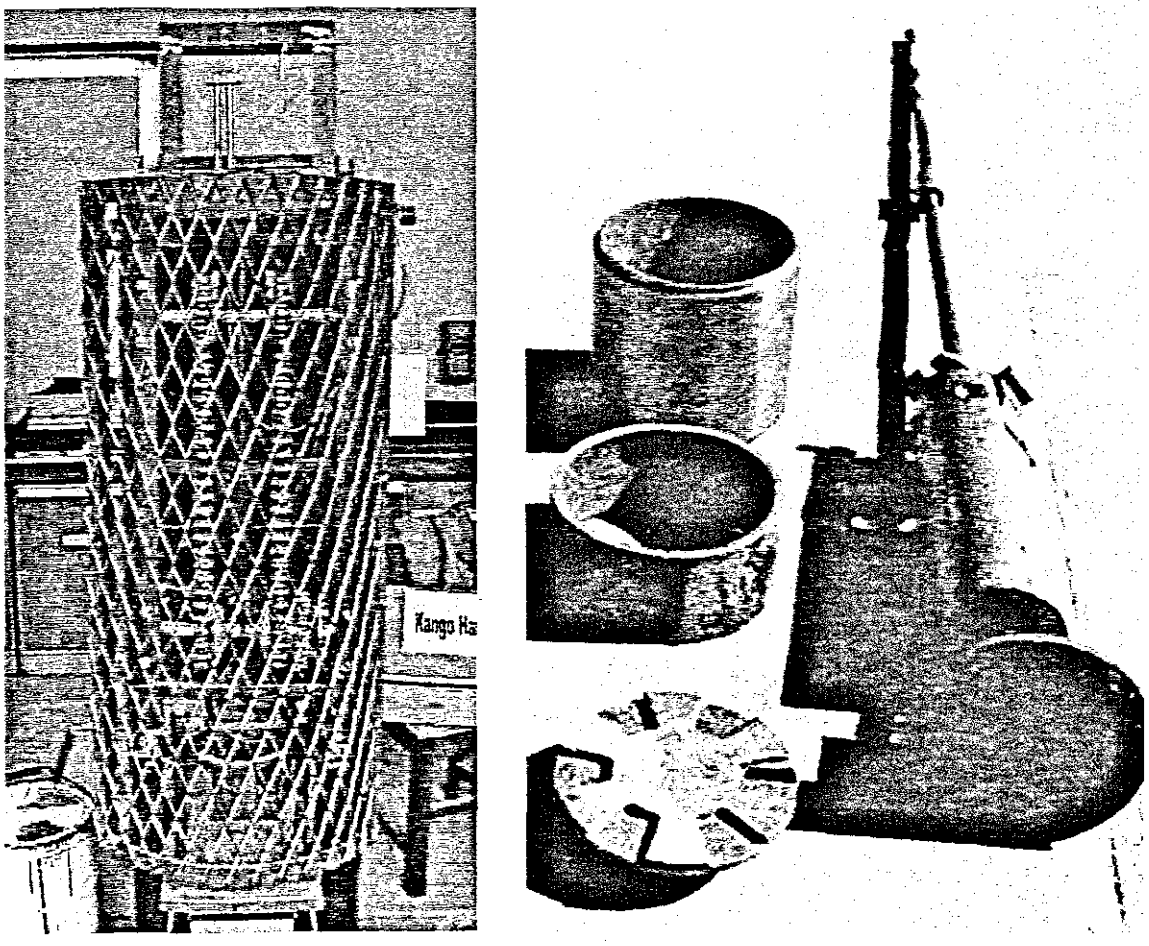
5.2.2 Marshall/Hugo compaction

The Marshall comaction method, the most commonly used world-wide, were developed by Bruce Marshall a former bituminous engineer with the Mississipi State Highway Department. (Asphalt Institute, 1969). A dropweight is used to apply impact compaction applied to a specimen in a mould with a collar in the Marshall compaction method . 75 blows per face for 100mm diameter and 110 blows for 150mm diameter specimens are normally used for HMA. The maximum stone size for which a 100mm diameter mould is used is 19mm. 150mm Diameter moulds are used for materials with maximum stone sizes larger than 19mm.

The Hugo (modified Marshall) compaction method operates on the same principle as the Marshall with the difference in the footing configuration and the turning of the footing.

The mass of the drop weight used in the study was 10.438 kg and the height over which it was dropped is 456mm. The mechanised Marshall/Hugo compaction system and Marshall/Hugo compaction equipment are depicted in Figure 5-15 (a) and (b) respectively. The Marshall footing is fitted to the hammer.

200 Blows were applied to both sides of the specimens and the change in height and by using a Linear Variable Displacement Transducer (LVDT) deformation during compaction was captured. Figure 5-16 shows the fitted LVDT followed by Figure5-17 depicting typical output from LVDT readings.



(a) Mechanised pedestal (b) Hammer, mould and footings

Figure 5-15: Mechanised Marshall/Hugo compaction equipment

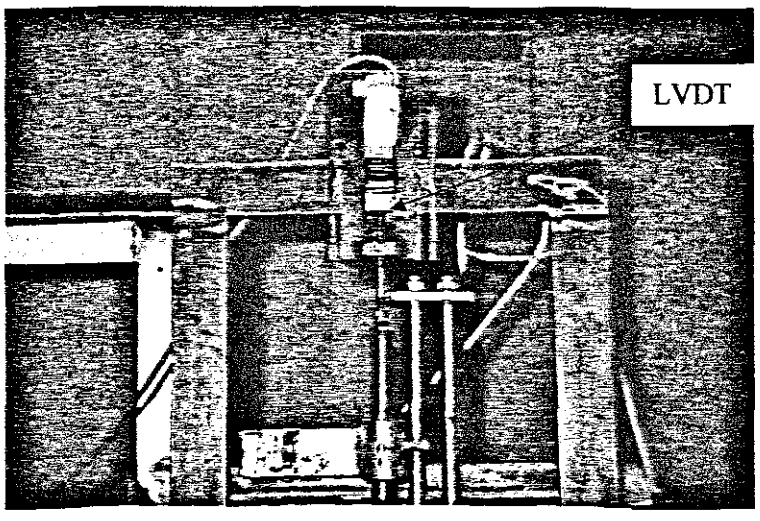


Figure 5-16: LVDT fitted to the mechanised hammer

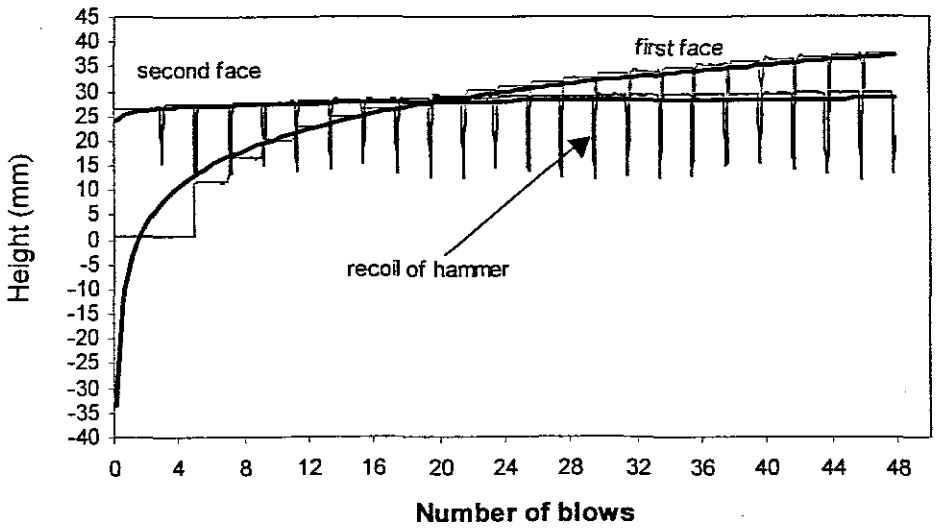


Figure 5-17: Typical Marshall/Hugo compaction curve before editing

Distortions in the graph represent the recoil of the compaction hammer due to the resilience of the specimen and the wooden block of the compaction equipment. Relative LVDT positions during compaction were captured by means of a program capable of capturing 16 readings per second. The hammer applied a blow to the specimens every two seconds. Peak deflections represented the actual deformation during compaction. A Turbo Pascal program was written and used to filter out all the peaks (the black curves) as shown in the Figure 5-17. Deformations during the first few blows after turning the specimens (see Figure 5-18) was high due and initial seating of the specimen.

Compaction curves for every specimen was constructed by means of the following steps:

1. measurement of the final height of every compacted specimen;
2. filtering all peaks of the compaction curve;
3. extraction of LVDT deflections after every 5^{th} blow of the hammer, as well the final blow;
4. construction of a displacement curve for compaction to both sides of the specimen;
5. calculation of the specimen height after every blow by incorporating the final specimen height; and
6. calculation of the density after every blow by using specimen height, diameter and mass.

The number of blows required to obtain the same density as the compacted cores could thus be read of the graphs as shown in Figures 5-18 to 5-21 below.

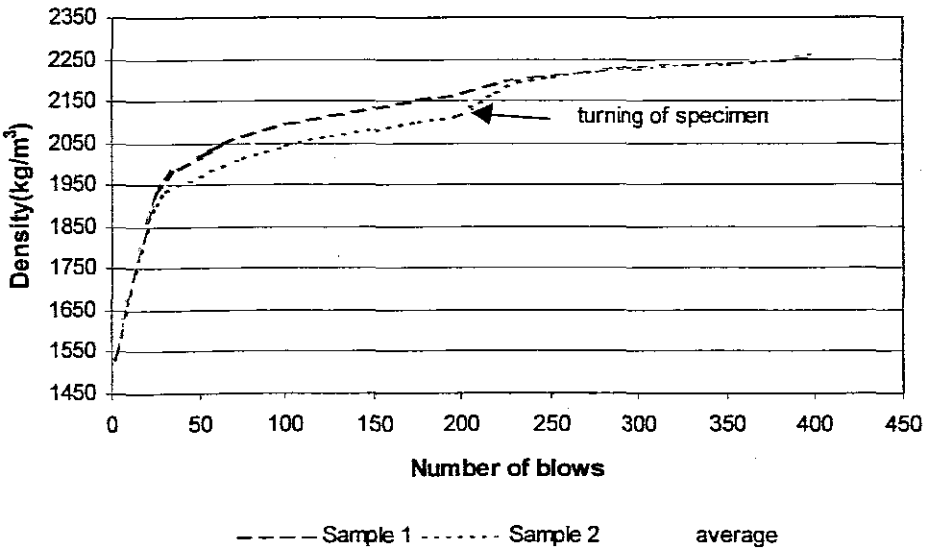


Figure 5-18: G2 Marshall preliminary compaction curve (3.5% foamed bitumen)

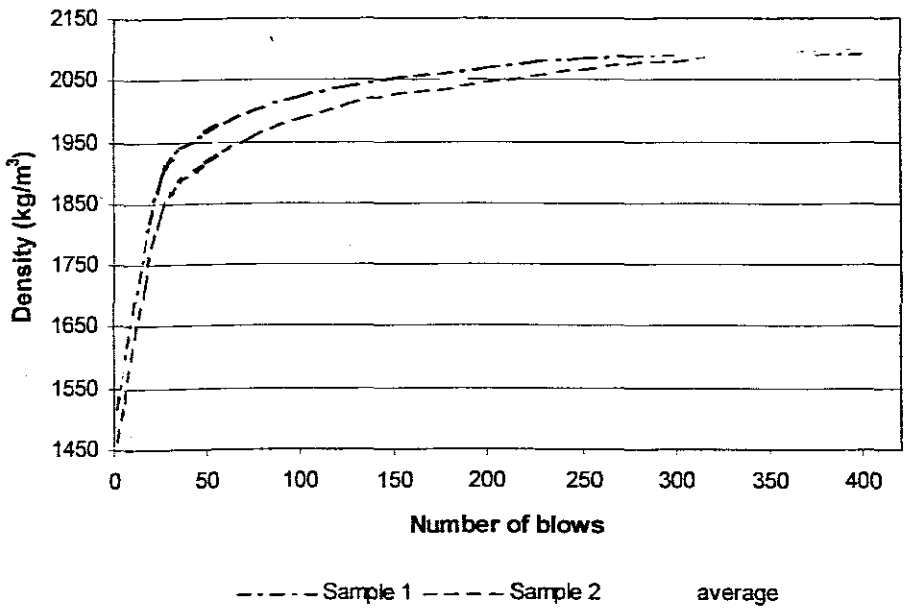


Figure 5-19: G7 Marshall preliminary compaction curve (3.5% foamed bitumen)

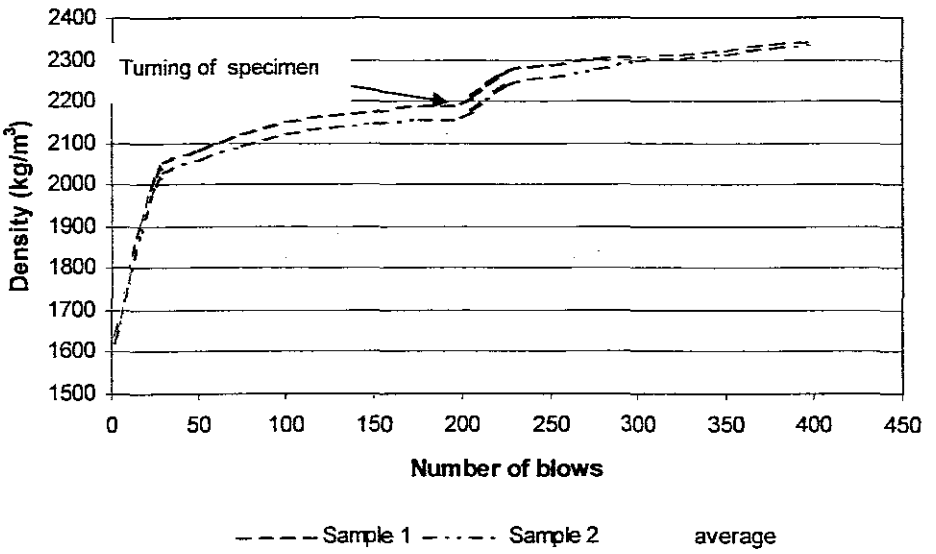


Figure 5-20: G2 Hugo compaction curves (3.5% foamed bitumen)

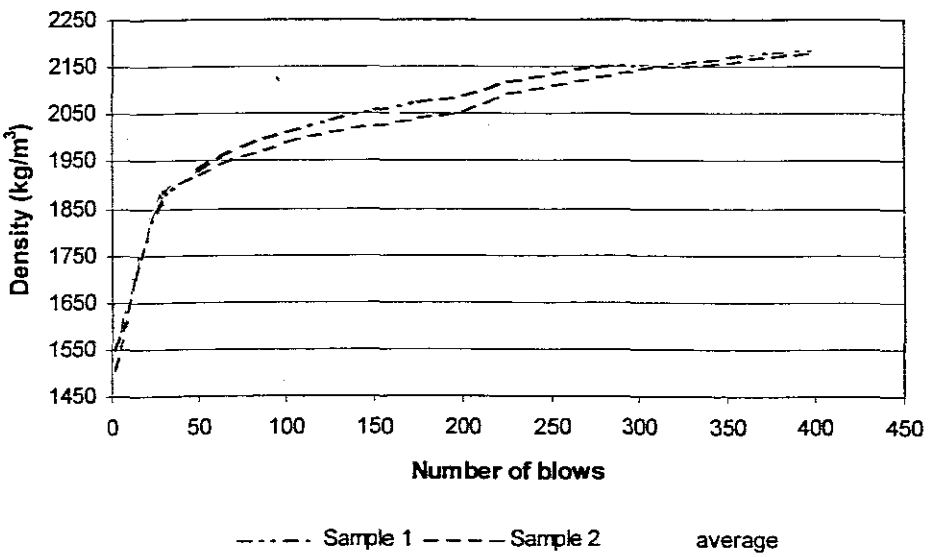


Figure 5-21: G7 Hugo compaction (3.5% foamed bitumen)

5.2.3 Gyratory compaction

The Superpave Gyratory Compactor (SGC), one of the developments of the Strategic Highway Research Programme (SHRP) was used in this study. The gyratory compactor is a mechanical device comprising of the following systems:

- reaction frame, rotating base, and motor

- loading system, loading ram, and pressure gauge
- height measuring and recording system, and
- cylindrical mould and baseplate

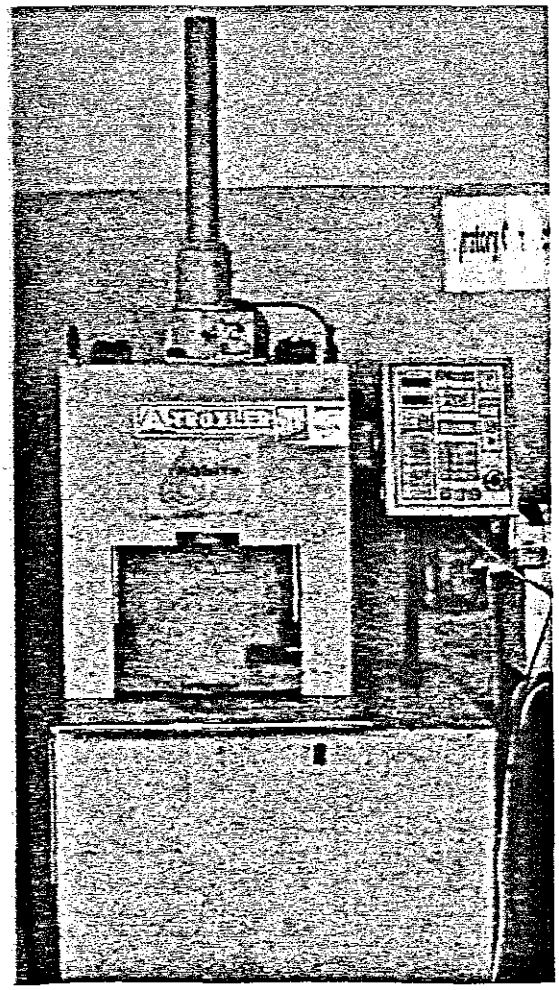


Figure 5-22: Superpave gyratory compactor

Gyratory compaction comprises the application of a constant pressure of 600 kPa to the specimen in the mould whilst the mould is tilted at an angle of 1.25°. Reaction bearings are used to tilt the mould during compaction resulting in a kneading action taking place. Compaction takes place at a rate of 30 revolutions per minute. The mix variables for gyratory compaction are level of compaction and compactive effort (number of gyrations). Figure 5-23 below shows a diagrammatic representation of gyratory kinematics. More detailed information about the gyratory compactor can be obtained elsewhere (McGennis et al, 1995).

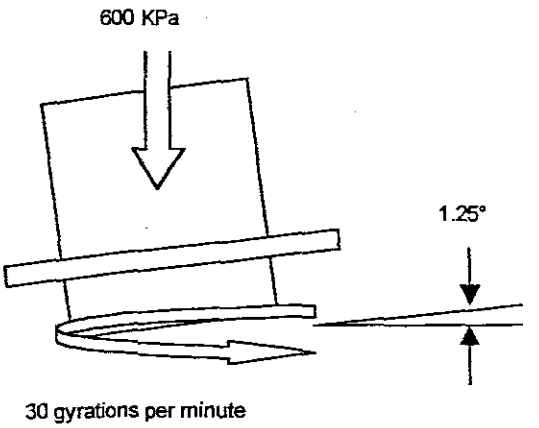


Figure 5-23: Gyratory kinematics (Brown & Mallick, 1998)

200 Gyrations were applied to two specimens in order to plot compaction curves. G2 and G7 gyratory compaction output is displayed in Figures 5-24 and 5-25 below.

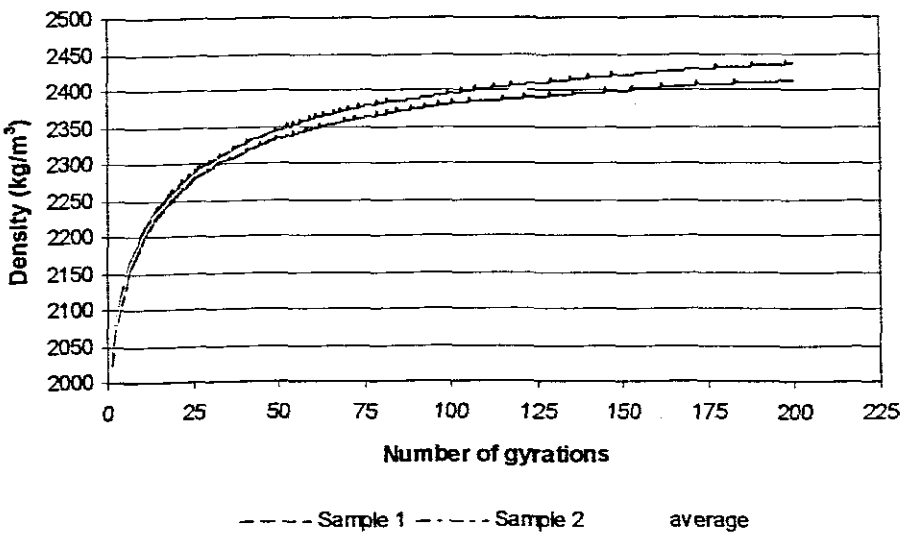


Figure 5-24: G2 Gyratory compaction curves (3.5% foamed bitumen)

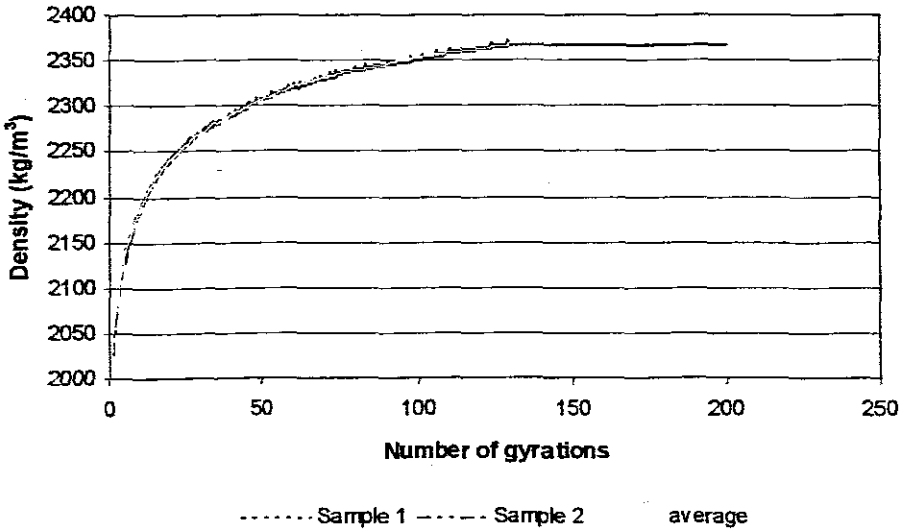


Figure 5-25: G7 Gyratory compaction curves (3.5% foamed bitumen)

5.2.4 Kango Hammer compaction

The Kango hammer (Refusal Density) compaction method, involving the use of the Refusal Density equipment, was developed at the University of Nottingham (Brown et al, 1991).

The Refusal Density equipment comprise a 152 (±2) mm diameter split mould and two baseplates, an electrically powered vibrating hammer and two compaction feet of 100 and 150 mm Ø respectively, that can be fitted to the hammer. The power consumption of the vibrating hammer is 750 Watt and the operating frequency is 20 – 50 Hz.

The material is initially compacted with the 100mm diameter compaction foot fitted to the hammer. Care should be taken as to hold the hammer firmly in a vertical position as the compaction is carried out in a prescribed order. To identify the position of compaction, one can use the points of a compass, with the sequence North, South, West, East, North West, South East, South West, North East. The duration of the compaction at each point is between 2 and 10 seconds. Compaction duration is 2 minutes ± 5 seconds after which the 150mm diameter compaction foot is used to smooth the surface of the specimen.

The mould with the specimen is turned over onto the spare base plate and the top baseplate removed. The compaction procedure is repeated after the specimen is driven onto the baseplate with the hammer. Two important considerations regarding the procedure are:

- the mass of the material compacted in the mould should give the same height as the layer to be compacted in the field,
- the number of compaction cycles used should result in absolute refusal density

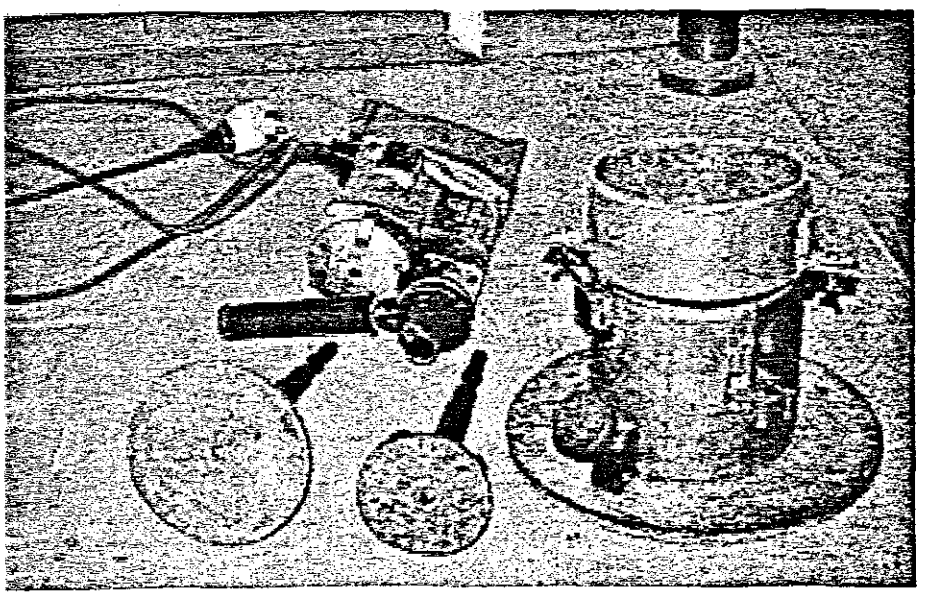


Figure 5-26: Kango hammer, split mould and compaction footings

Preliminary compaction curves for the G2 and G7 specimens are depicted in Figures 5-27 and 5-28.

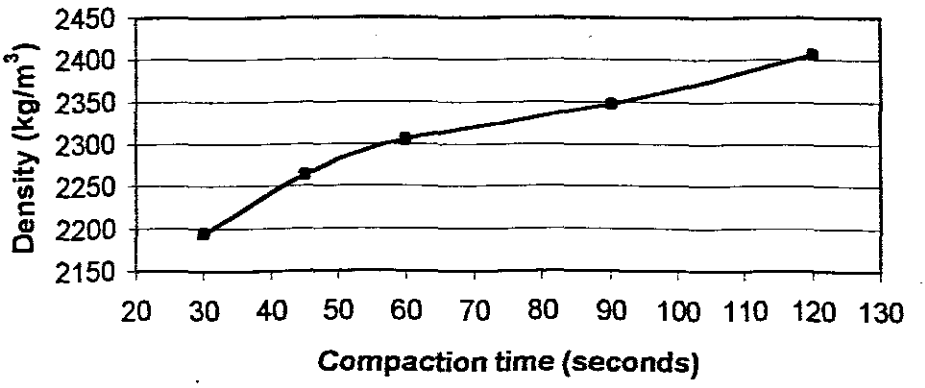


Figure 5-27: G2 Kango preliminary compaction curve (3.5% foamed bitumen)

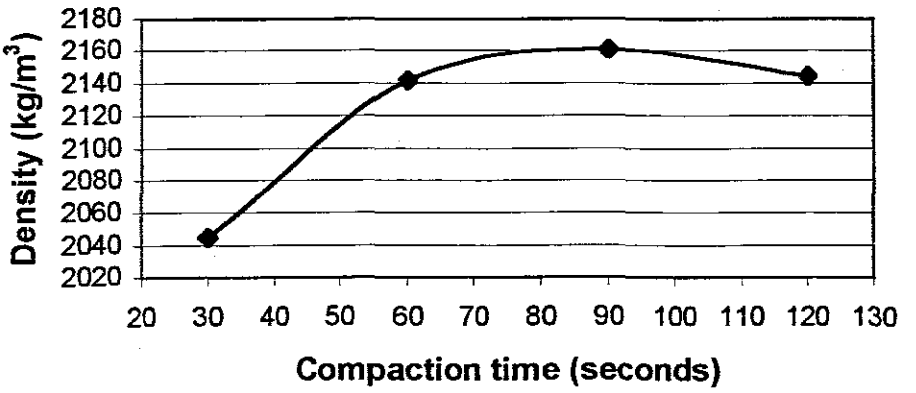


Figure 5-28: G7 Kango preliminary compaction curve (3.5% foamed bitumen)

5.3 Compaction and curing

5.3.1 Compaction

The compaction efforts for each compaction method to achieve target densities for the G2 and G7 materials were obtained by reading it form the preliminary compaction curves. No correction factors were applied to values that were read from the graphs. Table 5-7 below summarises the compaction effort employed in each of the compaction methods.

Table 5-7: Compaction effort

Compaction method	G2	G7
Marshall	175	60 blows
Hugo	150	50 blows
Kango	45 seconds	30 seconds
Gyratory	30 gyrations	5 gyrations
Slab	20 roller passes	16 roller passes

5.3.2 Curing

The approach followed in the curing process was not to obtain strengths representing specific curing periods in the field, but rather to be consistent in the treatment of all the specimens compacted by means of the different methods.

Slabs were cored after an average period of about four weeks. The average moisture content of the slabs was determined by taking moisture samples. These samples were oven dried at a temperature of 100° C overnight. Cores were cured directly after they were taken from the slab.

The effect of the different air temperatures and relative humidities to which the slabs were exposed outside the building could not be simulated in the laboratory.

Laboratory compacted specimens were extracted after 24 hours in the moulds. The bulk density of every specimen was calculated by measuring their heights with a caliper. The next critical step was to allow the specimens to lose moisture, as the target moisture content was the moisture content of the cored slab specimens. The mass and height, subsequently the bulk density, of the specimens were determined by measuring their heights.

Laboratory compacted specimens were allowed to dry at ambient temperature for about two(2) days before curing was done as the average time to obtain the target moisture was approximately 48 hours after extraction. Summaries of the compaction results are included in Appendix A.

Curing of the specimens entailed the placement of the specimens in sealed containers in a draft oven for 3 days at a temperature of 40°C. Typical G7 specimens before placement in the draft oven are shown in Figure 5-29 below. The curing procedure followed is based on work done by Jenkins et al (1999).

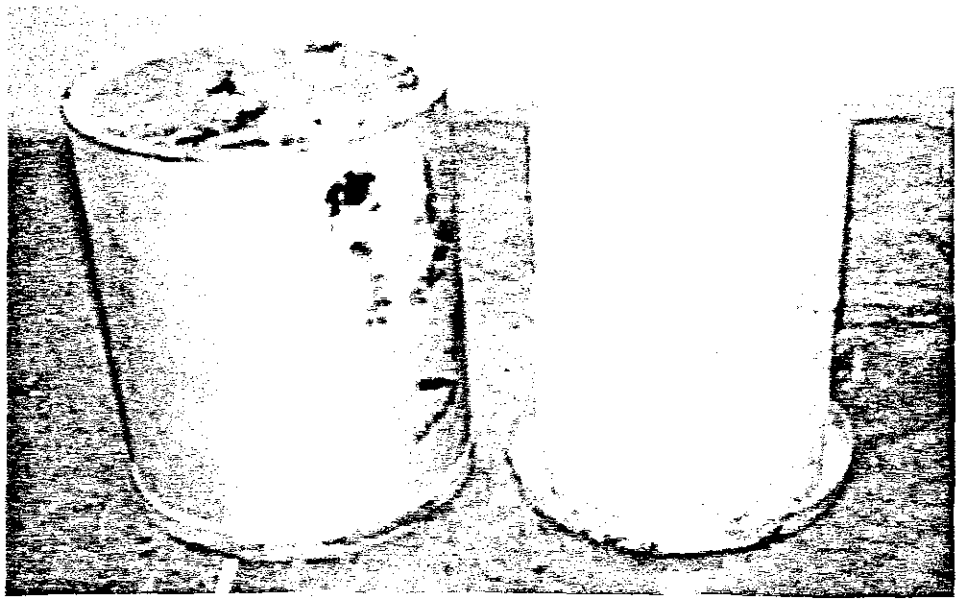


Figure 5-29: G7 specimens before curing

5.4 Mechanical testing

The mechanical testing was undertaken in the servo-hydraulic Materials Testing System (MTS) at the University of Stellenbosch. The MTS consist of a hydraulic system, being able to provide a maximum compressive load of 10 ton. Figure 5-31 below shows the MTS machine with temperature chamber and computers. Mechanical test results are included in Appendix B. Copies the data capturing software, developed at the University of Stellenbosch are included in Appendix D.

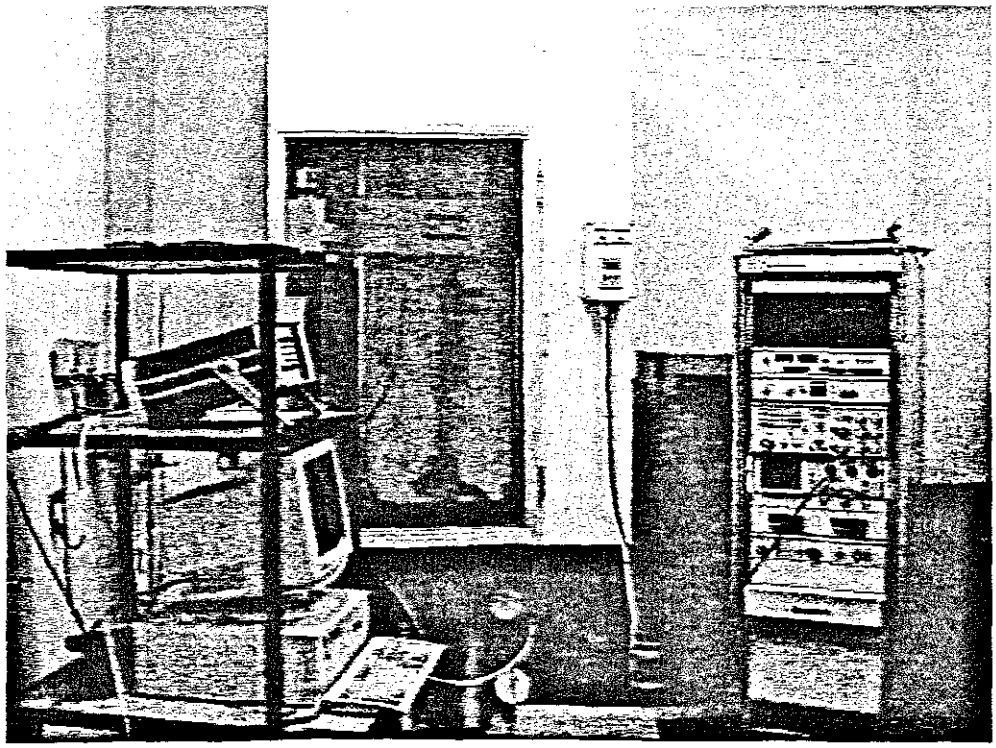


Figure 5-30: MTS system

5.4.1 Indirect Tensile Strength testing

The Indirect Tensile Strength (ITS) splitting and Indirect Tensile Test (ITT) are used to determine the tensile strength and stiffness (resilient modulus) of asphaltic materials respectively. Cylindrical specimens are loaded in the diametral plane as shown in Figure 5-31.

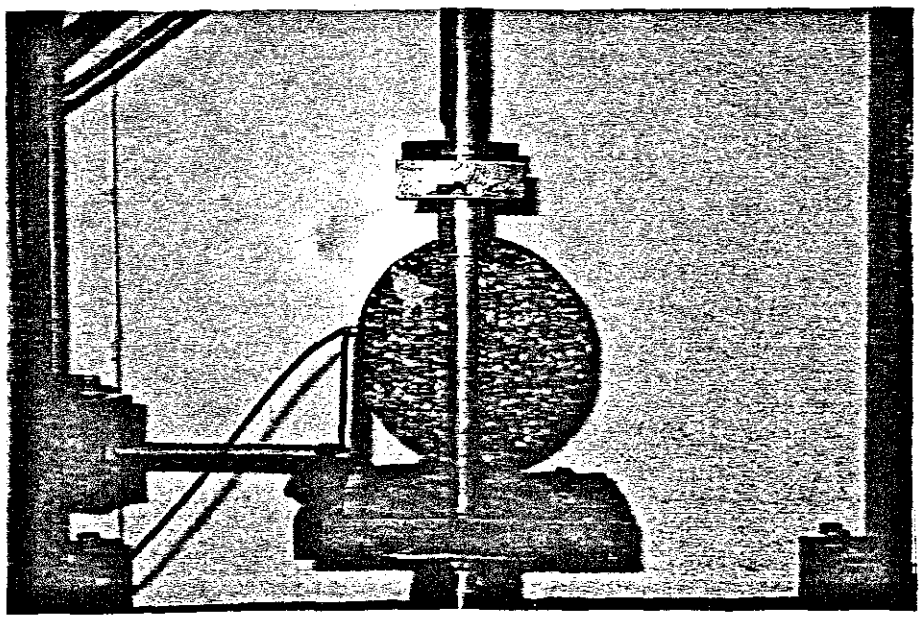


Figure 5-31: ITS test setup

The ITS test is a displacement-controlled test in which a monotonic load is applied to specimens. Figure 5-32 below shows a typical ITS curve.

Test conditions are as follows:

- Loading rate – 50 mm/minute (Marshall speed)
- Temperature – 25 °C

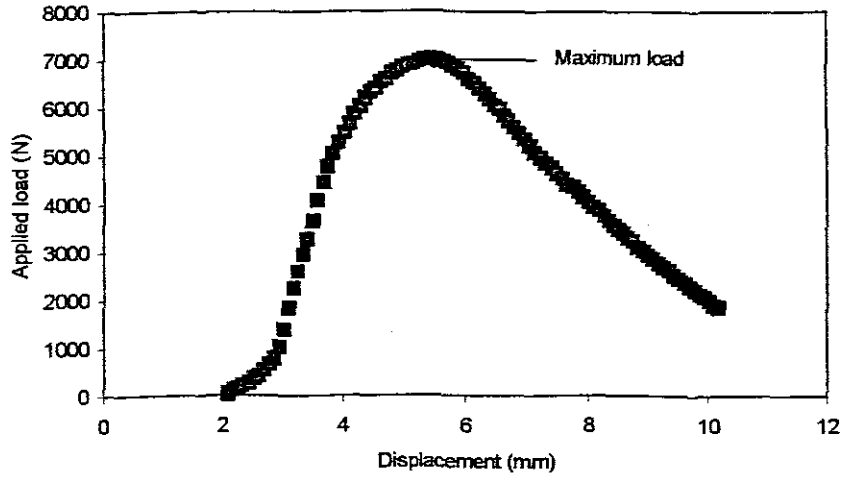


Figure 5-32: Typical ITS curve showing load and displacement

The area under the load displacement curve represents the energy consumed during the test. The following formula was used to calculate the ITS strength:

$$\sigma_t = \frac{2 \cdot P}{\pi \cdot t \cdot D}$$

where :

P = maximum load at failure (N)
σ_t = maximum tensile stress (kPa)
t = thickness of specimen (m)
D = diameter of specimen (m)

5.4.2 Indirect Tensile Strength testing

A repeated load in the order of 10% to 40% of the ITS maximum load with a haversine signal is usually applied in the ITT test. Test conditions for this project were:

- Load function – 10 Hz haversine wave
- Load magnitude – 30 % ITS strength (to get better seating at loading points)
- Temperature – 25 °C
- 80 condition cycles prior to testing

The following equation, derived by elimination of the horizontal deformation, was used for the calculation of the ITT resilient modulus (Smit et al, 1997):

$$M_r = \frac{.359 \cdot P}{\Delta V}$$

where:

M_r = resilient modulus (MPa)
P = applied load (N)
ΔV = elastic deformation (mm)

Typical ITT load and displacement curves are shown in the Figures below.

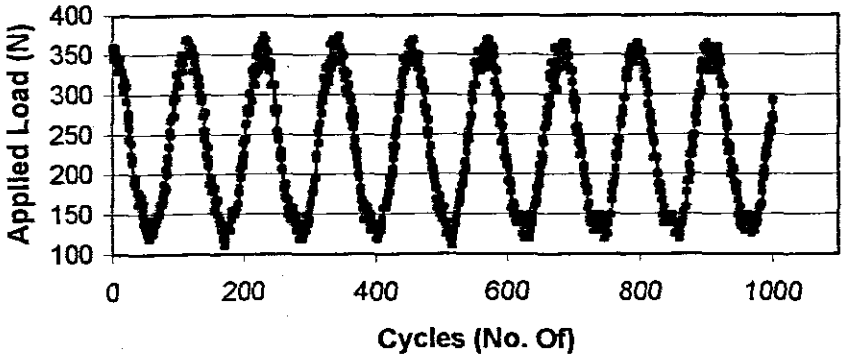


Figure 5-33: Typical ITT load curve

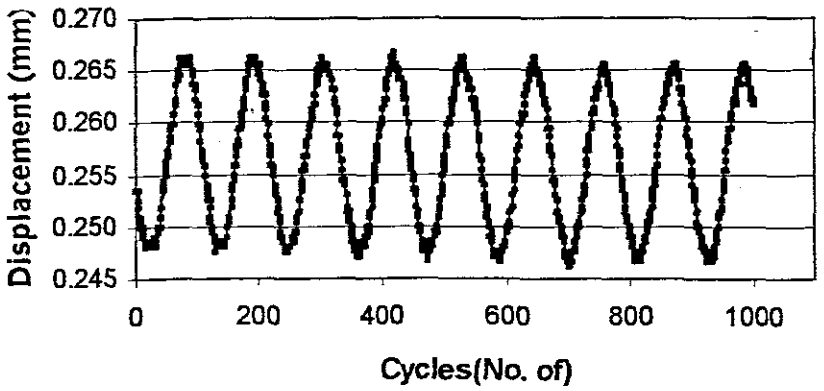


Figure 5-34: Typical ITT displacement curve

5.4.3 Semi-Circular Bending testing

The semi-circular bending (SCB) test is done on semi-cicular asphalt specimens and used to measure the indirect tensile strength and strain at break. Krans et al (1996) reported on the background of the SCB test and this information can be obtained in this reference. The SCB load displacement curve has the same shape as the one for the ITS. Figure 5-35 below displays the SCB test setup.

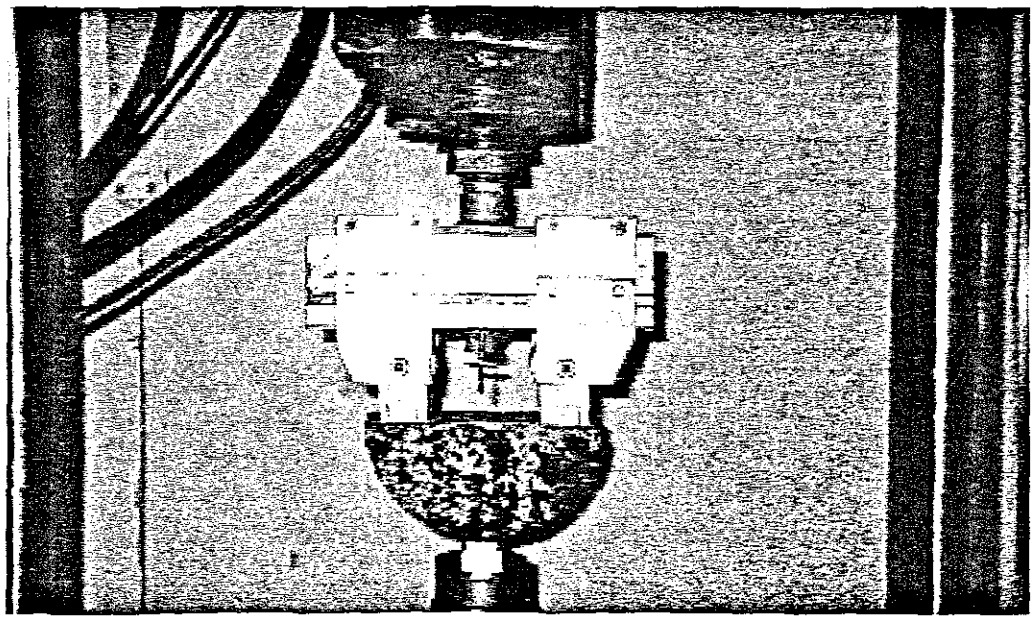


Figure 5-35: SCB test setup

The following equation was used in the calculation of the SCB strength (Smit et al, 1997):

$$\sigma_x = \frac{4.263 \cdot P}{D}$$

where:

σ_x = maximum tensile stress (kPa)
P = maximum failure load per unit of specimen thickness (N/m)
D = diameter of specimen (m)

Test conditions for this project were:

- Loading rate – 20 mm/minute
- Temperature – 25 °C

5.5 Comments

Samples for the determination of actual binder contents were sent to a commercial laboratory. Actual foamed bitumen contents varied between 3.0% and 3.8%.

A particular problem encountered was that the G2 SCB specimens collapsed during trimming with the diamond blade saw. Partial coating of large aggregates and low binder contents may be the main causes for this phenomenon.

Marshall, Hugo and Slab G2 with 80/100 grade binder were rejected after it became known that the binder supplied did not conform to the SABS specifications applicable to 80/100 bitumen. Due to time constraints, it was decided not to include the 80/100 test results in the report. Therefore, the variance due to binder type was only considered for the G7 results.

Moisture content during compaction, curing, and testing is an important consideration for cold mixes. It was decided that the determination of the Bulk Relative densities of the through submersion in a waterbath was not an option for this project. Extra specimens were used to determine Bulk Relative densities at the mix design stage by means of submersion. Densities for all the specimens at the preliminary compaction and final compaction stages were calculated by physical measurement of specimen heights with a caliper. Therefore no direct comparison between densities and voids calculated during the mix design stage and final; compaction stage can be made.

Aggregate temperatures before mixing and compaction varied between 18°C and 27°C. After the addition of foamed bitumen mix temperatures during mixing and compaction ranged between 25°C and 30°C.

CHAPTER 6 TEST RESULTS

6.1 Compaction

Table 6-1 shows a layout of the number of specimens compacted and Tables 6-2 and 6-3 summarise the volumetric properties. Compaction test results are included in Appendix A.

Table 6-1: Compaction matrix showing the number of specimens compacted

Compaction method	G2	G7	
	150/200	80/100	150/200
Marshall (M)	14	15	15
Hugo (H)	14	14	15
Kango (K)	13	15	14
Gyratory (G)	15	15	15
Slab (cores) (S)	9	13	13

Table 6-2: G2 Volumetric properties

Compaction method	150/200	
	Bulk Relative density	Voids (%)
Marshall	2.248	12.7
Hugo	2.263	12.1
Kango	2.249	12.7
Gyratory	2.219	13.8
Slab	2.284	11.3

Table 6-3: G7 Volumetric properties

Compaction method	80/100		150/200	
	Bulk Relative density	Voids (%)	Bulk Relative density	Voids (%)
Marshall	2.042	17.8	2.080	16.3
Hugo	2.017	18.8	2.065	16.9
Kango	2.036	18.1	2.051	17.5
Gyratory	2.073	16.6	2.037	18.0
Slab	2.010	19.1	1.995	19.7

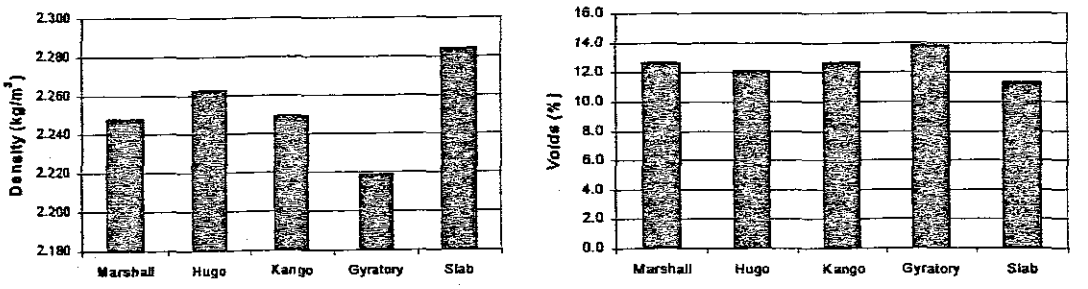


Figure 6-1: G2 150/200 density and voids (averages)

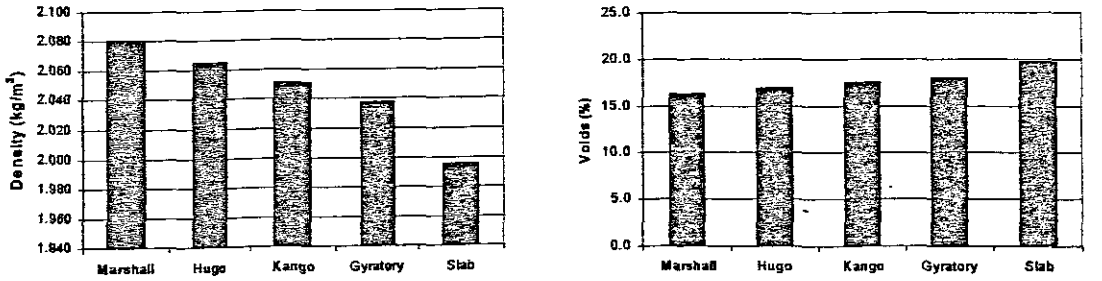


Figure 6-2: G7 150/200 Densities and voids (averages)

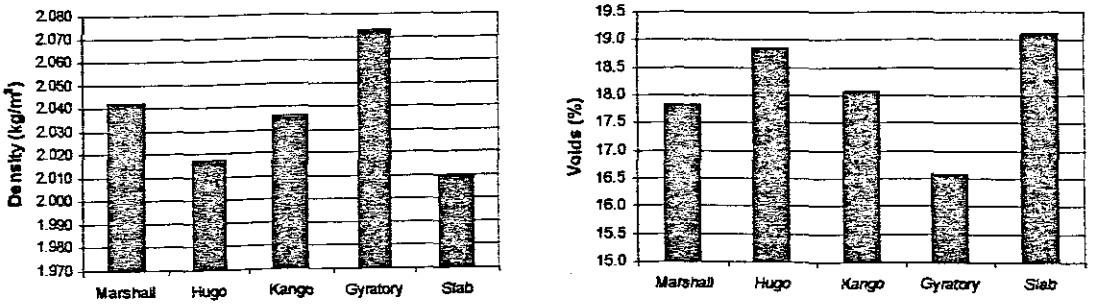


Figure 6-3: G7 80/100 Densities and voids (averages)

Overall G2 Bulk Relative densities ranged between 2.220 kg/m^3 and 2.250 kg/m^3. Maximum and minimum voids contents recorded were 11.3% and 12.75 respectively. Overall G7 densities had a maximum and minimum values of 1.950 kg/m^3 and 2.080 kg/m^3 respectively. Voids ranged between 16.3% and 19.7%.

6.2 Mechanical properties

Tables 6.2 and 6.3 show the matrix of the mechanical tests performed for the G2 and G7 material respectively. The mechanical test results are included in Appendix B.

Table 6-4: G2 Mechanical test matrix

	150/200				
	M	H	K	G	S
ITS	3	3	2	3	3
ITT	3	4	4	4	2
SCB	3	3	4	4	3

Table 6-5: G7 Mechanical test matrix

	80/100					150/200				
	M	H	K	G	S	M	H	K	G	S
ITS	3	3	4	3	3	3	4	3	3	3
ITT	3	3	3	3	3	3	4	4	3	2
SCB	3	4	4	3	3	2	3	4	4	3

6.2.1 ITS

The ITS and COV test results are summarised in Table 6-6 below and depicted in Figures 6-4 to 6-7 below.

Table 6-6: ITS test results

Compaction methods	G2		G7			
	150/200		80/100		150/200	
	ITS (kPa)	COV	ITS (kPa)	COV	ITS (kPa)	COV
Marshall	216	24	359	21	353	18
Hugo	307	4	313	8	322	7
Kango	452	14	357	30	418	21
Gyratory	249	26	401	6	385	17
Slab	301	5	625	31	645	44

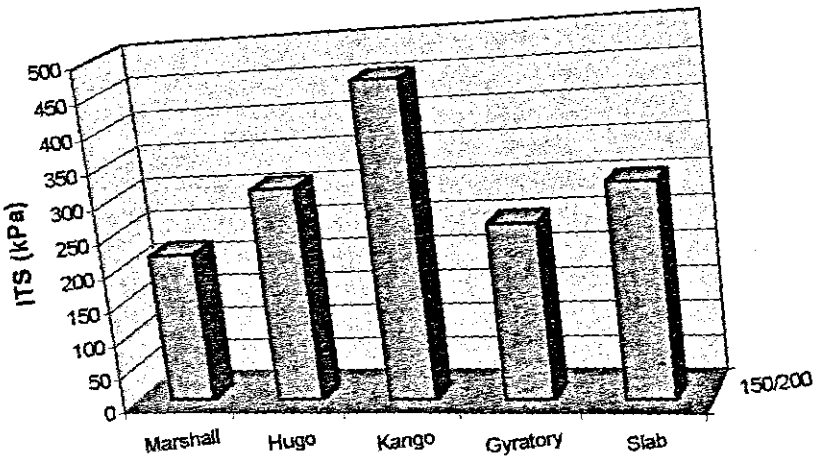


Figure 6-4: G2 ITS values

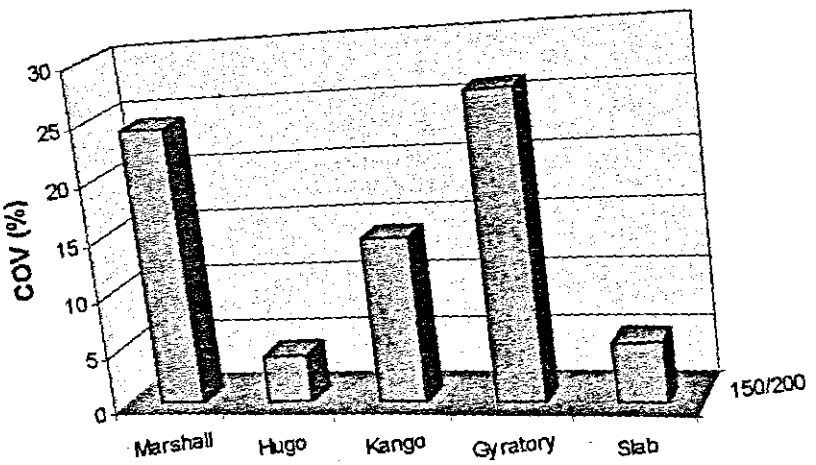


Figure 6-5: G2 ITS COV values

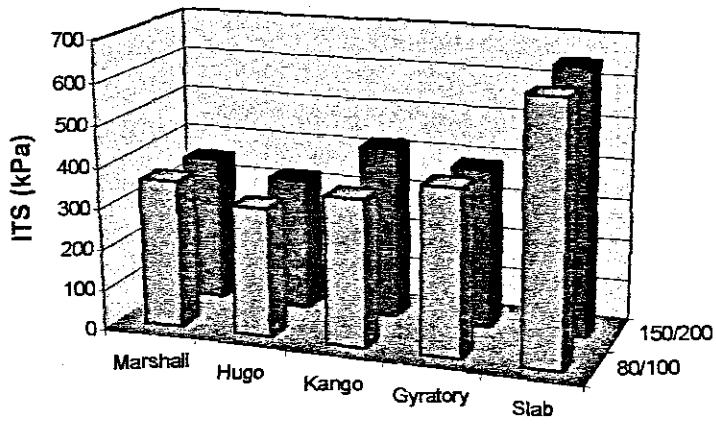


Figure 6-6: G7 ITS values

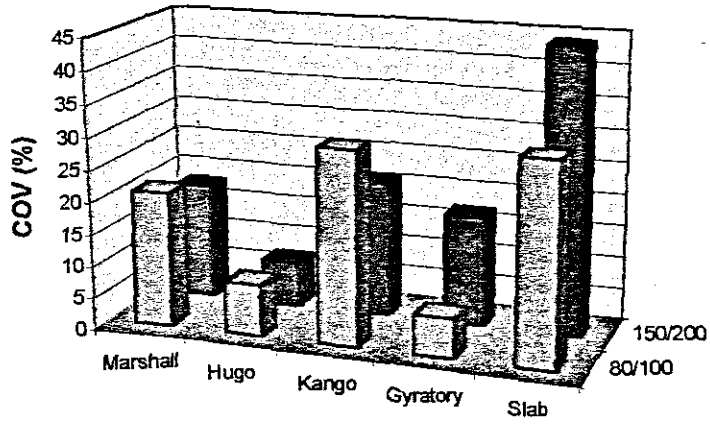


Figure 6-7: COV values for G7 ITS results

6.2.2 ITT

Recorded ITT test results and COV values for the G2 and G7 material are summarised and depicted in Table 6-7 and Figures 6-8 to 6-11 respectively.

Table 6-7: ITT test results

Compaction method	G2		G7			
	150/200		80/100		150/200	
	ITT(MPa)	COV	ITT(MPa)	COV	ITT(MPa)	COV
Marshall	1333	14	1107	10	1607	15
Hugo	2266	18	2018	6	1991	10
Kango	1534	14	1894	5	1537	6
Gyratory	1428	15	2018	6	1830	25
Slab	1057	4	1474	7	1783	17

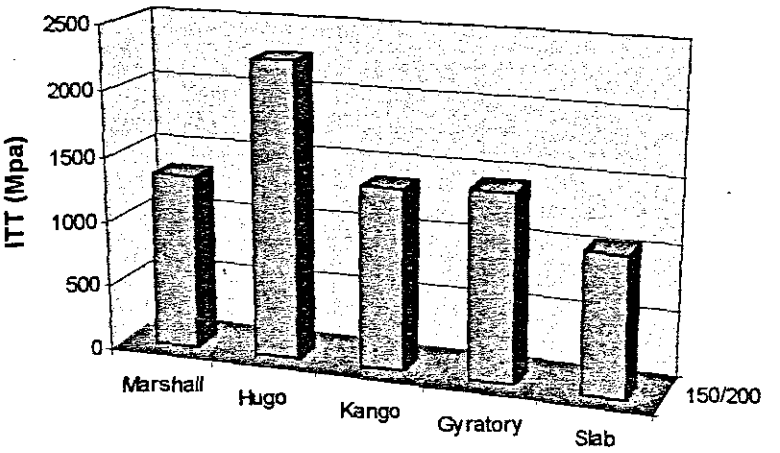


Figure 6-8: G2 ITT values

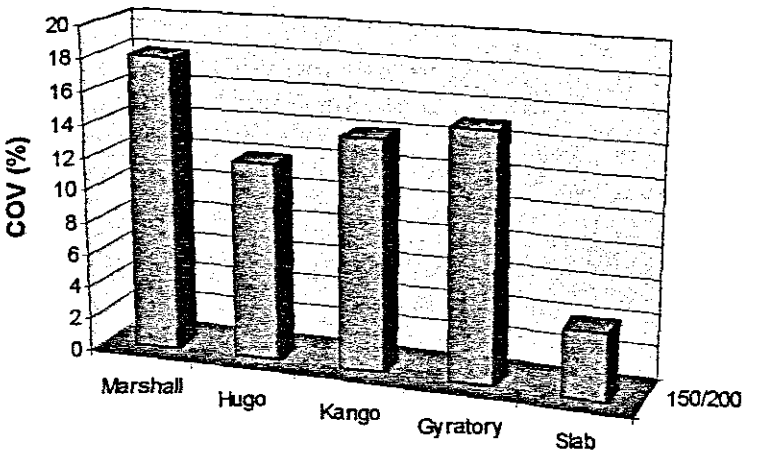


Figure 6-9: COV values for G2 ITT results

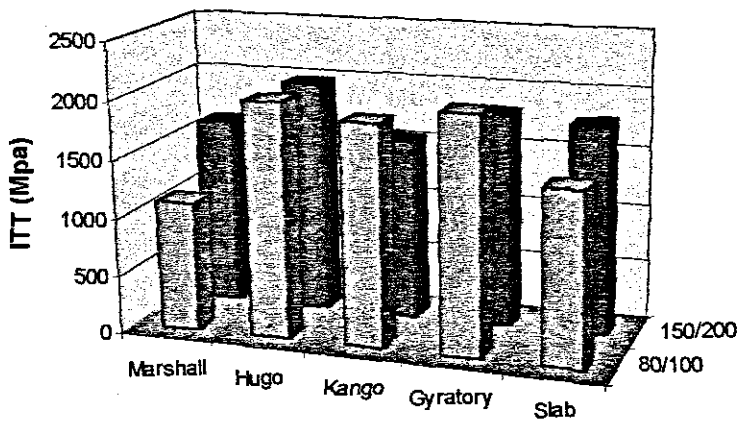


Figure 6-10: G7 ITT values

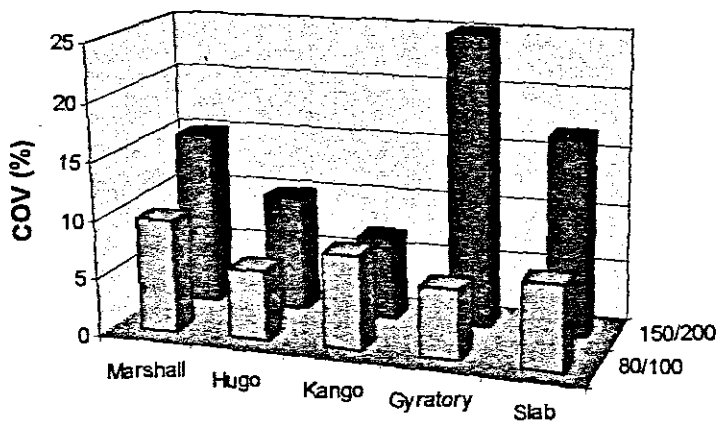


Figure 6-11: COV values for G7 ITT values

6.2.3 SCB

SCB test and COV values are summarised and displayed in Table 6-8 and Figures 6-12 to 6-15 below.

Table 6-8: SCB test results

Compaction methods	G2		G7			
	150/200		80/100		150/200	
	ITS (kPa)	COV	ITS (kPa)	COV	ITS (kPa)	COV
Marshall	289	32	525	10	732	10
Hugo	311	29	504	15	539	17
Kango	309	27	839	27	727	9
Gyratory	202	26	649	7	782	9
Slab	662	19	864	27	743	8

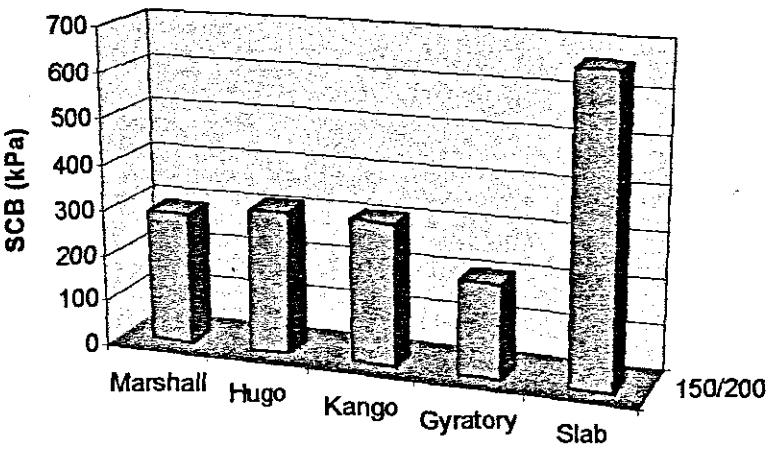


Figure 6-12: G2 SCB tensile strength values

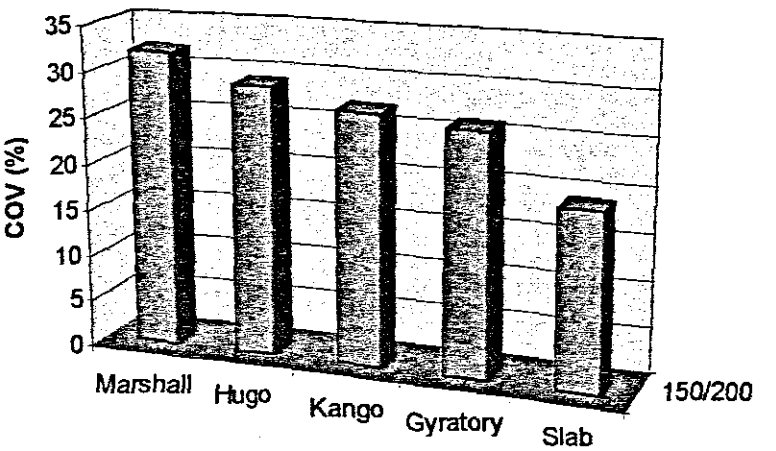


Figure 6-13: COV values for G2 SCB tensile strength test results

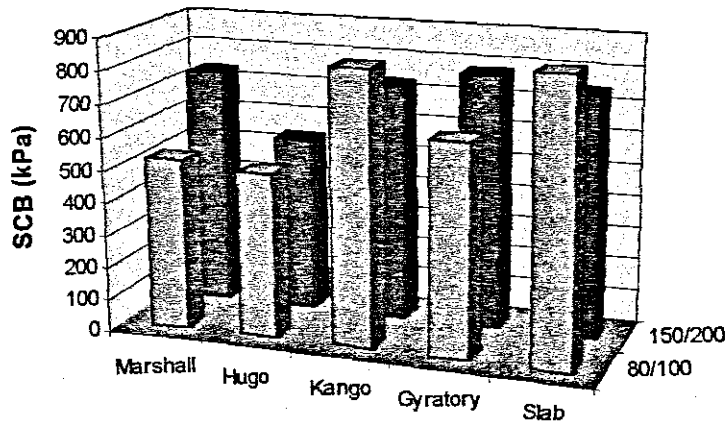


Figure 6-14: G7 SCB tensile strength values

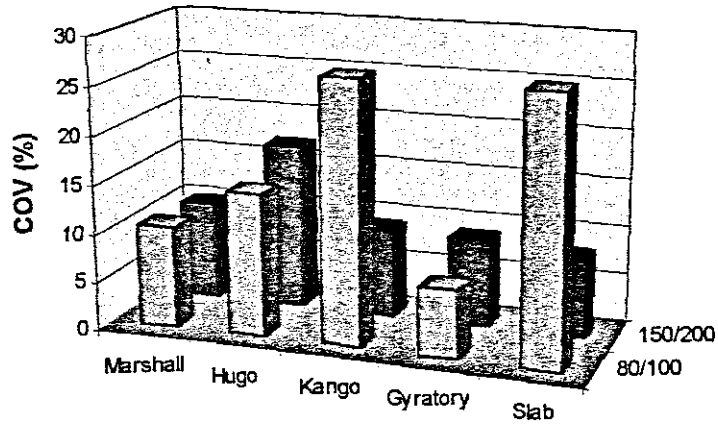


Figure 6-15: COV values for G7 SCB tensile strength test results

6.2.4 Discussion

6.2.1.1 ITS

ITS values for both materials and types of bitumen showed no specific trends. No marked difference was visible between results from different compaction methods for both material the G2 and G7 ITS strength values. The effect of compaction method is not clearly visible from the results. The ITS values recorded do not consistently reflect the influence of any type of the two grades of bitumen giving higher or lower values than the other.

G2 ITS values ranged between 200 and 450 kPa, except for Kango values being much higher than the rest (Figure 6-4). Overall variations recorded had a minimum and maximum value of 4% and 26% respectively. Variations for Marshall and Gyratory compaction results were the highest overall.

Slab ITS values was the highest for the G7 material. The rest of the values ranged between 200 and 300 kPa. Also, the highest (44%) and lowest (4%) variations were recorded for slab ITS strengths. These high variations ascribed due to an outlier being recorded with the 150/200 results and the limited amount of tests done.

Figure 6-8 indicates that Hugo G2 compaction had the highest ITT stiffness values. Interestingly, the ITS values for Hugo G2 was in the same order as the rest of the values. COV values ranged between 3%(min) and 17%(max).

Apart from the Marshall G7 (80/100 bitumen), the rest of the G7 stiffness values ranged between 1400 and 2100 MPa.

6.2.1.2 ITT

As with ITS and ITT results, no visible trends were visible from the graphs produced. G2 SCB results were in the same region as the ITS values. The ratio between SCB and ITS strength values for HMA is generally 2.5:1. Lower G2 values can be ascribed due to the brittleness of the material (3.5%) of the specimens was lower than the normal >4% used in HMA mixes. High variability in G2 results is an indication of the unsuited semi-circular specimens. Partial coating if the large aggregates may also be a factor.

6.2.1.3 SCB

In contrast to G2 specimens, the G7 briquettes stayed composed during halving. G7 SCB results recorded were much higher than the ITS values (approximately 2×ITS). SCB values ranged between 500 and 800kPa. Variations for Slab and Kango results were the highest with both being 27%. The rest of the variations had a maximum and minimum value of 17% and 7% respectively.

CHAPTER 7 SYNTHESIS

7.1 Statistical analysis of mechanical test results

An Analysis of Variance (ANOVA) was performed to determine the statistical significance of each compaction method on the mechanical properties (ITS, ITT and SCB values). The ANOVA is included in Appendix C.

7.1.1 Methodology

The following factors formed part of the analysis:

- 2 material types
- 2 binder types
- 5 compaction methods

The purpose of the ANOVA was to assess the effect of compaction method and binder type on the mechanical and volumetric properties. Thus, sources of variation were either binder type or compaction method. Assessments for the materials was done as follows:

- ANOVA on density and voids to determine whether the densities and voids achieved by the compaction methods differed significantly
- The influence of compaction method on G2 mechanical test properties
- The influence of binder type and compaction method on G7 mechanical properties

A null hypothesis that a mix variable did not have a significant influence on the mechanical properties was formulated. A statistic, indicating the significance of mix variables at the 95% confidence level (0.05) was calculated. If the probability of this null was very small, the conclusion was that the mix variable has a significant effect.

Individual test results was considered for the G2 material, whilst the mean values of results were considered in the ANOVA for G7 material in the calculation of

Tables 7-1 to 7-5 outlines the summaries of the results of the ANOVA and should be read in conjunction with Appendix C. Table 7.1 and 7.2 depicts the ANOVA for density information as calculated.

Table 7-1: Variation between densities

Material	Source of variation	F	$F_{critical}$	Conclusion
G2	compaction method	0.02	<1	no significant difference
G7	compaction method	1.67	6.39	no significant difference
G7	binder type	0.4	<1	no significant difference

Table 7-2: Effect of compaction method and binder type on voids

Material	Source of variation	F	$F_{critical}$	Conclusion
G2	compaction method	0.02	<1	no significant difference
G7	compaction method	1.67	6.39	no significant difference
G7	binder type	0.4	<1	no significant difference

Table 7-3: Effect of compaction method and binder type on ITS values

Material	Source of variation	F	$F_{critical}$	Conclusion
G2	compaction method	8.83	3.18	significant difference
G7	compaction method	70.22	6.39	significant difference
G7	binder type	1.04	7.71	no significant difference

Table 7-4: Effect of compaction method and binder type on ITT values

Material	Source of variation	F	$F_{critical}$	Conclusion
G2	compaction method	5.28	3.06	significant difference
G7	compaction method	2.58	6.39	no significant difference
G7	binder type	0.05	<1	no significant difference

Table 7-5: Effect of compaction method and binder type on SCB values

Material	Source of variation	F	$F_{critical}$	Conclusion
G2	compaction method	3.63	3.18	significant difference
G7	compaction method	2.58	6.39	no significant difference
G7	binder type	0.18	<1	no significant difference

7.2 Compaction energy input analysis

An investigation into the compaction energy required for each of the compaction methods to achieve the same volumetric properties (at the same compaction moisture and foamed bitumen content) was carried out. Certain laboratory compaction methods may be able to produce specimens with fatigue or stiffness properties identical to field values, but fails to produce comparable ITS strengths. On the other hand another method may produce ITS values comparable to field values, but fatigue values may not be equivalent. The focus of the analysis was limited to the calculation of the energy applied.

7.2.1 Marshall/Hugo compaction

Marshall and Hugo compaction comprise impact compaction. Since the height of drop is fixed and mass of the hammer if fixed, the energy input during compaction is determined by the number of blows applied and is calculated by means of the following formula:

Energy = weight x drop height x number of blows
= 9.81m/s^2 x 10kg x 0.456m x number of blows
= 0.0447 x number of blows (J)

7.2.2 Kango Hammer compaction

The Kango hammer is basically a vibrating hammer. Energy input is dependant upon the following factors:

- frequency of the vibration
- amplitude
- mass of the hammer
- degree of confinement (the hammer is manually operated)
- time duration of compaction

The specifications of the hammer utilized in the utilized in the project were:

- Rated watts input = 750 Watt
- Blows per minute = 2750
- Mass = 7.5 kg

The energy applied during compaction can be calculated by means of the following formula:

Energy = weight of hammer x number of blows x drop height

where:

number of blows = compaction time in second/60 x 2750
weight of hammer = 73.6N
drop height = function of the amplitude of hammer vibration

Since the Kango hammer is manually operated, the drop height during compaction is also a function of the degree to which the operator is able to confine the movement of the hammer during compaction. To simplify calculations, it was assumed that the drop height was 7mm. Energy applied was calculated via the following formula:

Energy = 73.6N x 0.007m x 2750(time in seconds/60)
= 23.605 x compaction time in seconds (J)

7.2.3 Gyratory compaction

Burger and Dempers (1997) developed a method to determine the energy input during Superpave Gyratory compaction. As it was not possible to simply measure the energy

input directly due to the uniqueness of the motor of the compactor, the method as described below was followed.

The torque during compaction was measured by attaching a specially designed brake consisting of a steel plate, steel rod and brake belt to the gyratory compactor. It was found that a linear relationship existed between applied torque and electrical current. Calculation of the power can be done using the following formula:

$$P = T \times \omega$$

Where

P = power (Watt), and
ω = angular velocity (radians/second)

The conversion from power to energy is as follows:

Energy (J) = Power x Time (seconds)

During their study (Burger & Dempers, 1997), it was also established that the initial power required for compaction was high, whereafter it drop and stayed constant. This initial process was then considered to be the warming up of the compactor. Warming up for this study was done by compacting two(2) dummy specimens for 200 gyrations each before the actual specimens was compacted, thereafter the average power for gyratory compaction remained constant at 40W. Therefore, the energy during gyratory compaction was calculated as follows:

Energy (J) = 40 x Time (seconds)

The Superpave gyratory compactor applies 30 gyrations per minute (see Figure 5-22).

7.2.4 Roller compaction

Vibratory rollers basically consist of a frame and drum. These parts are separated by means of rubber elements. Two eccentric weights are placed either side of the center of gravity of the plate and rotated out of phase in opposite direction. The resulting combination of forces acts upon the soil surface to cause compaction. The frequency is a function of the speed of vibration.

The compactive effort of vibratory rollers is influenced by the following parameters:

- Static weight
- Number of vibrating drums
- Roller speed
- Ratio between frame and drum weight

- Drum diameter

Simplified, the compaction energy during roller compaction can be calculated as follows:

Energy = weight x number of blows x drop height

The weight of the roller can easily be calculated, whilst determining the number of blows during compaction is a function of the vibration frequency and the speed of rolling. Drop height is dependant upon the weight of the roller, amplitude, and calibration of eccentric and the stiffness of the layer being compacted. On a stiff concrete surface the height to which a roller can lift may be as high as 2 mm, whilst the lift in loose uncompacted soil can be as low as 0mm since all the energy is absorbed by the soil.

The number of blows is dependant upon the roller speed, length of one pass across slab and the vibrations per minute. The mass of the roller used was 650kg. The following assumptions was made to simplify the calculations:

- 0.5mm and was used as the average drop height,
- equal distribution of the mass between the two wheels exists,
- the roller covered the whole area of the slab with every pass,
- average roller speed is 2.70 km/h (0.75m/s)and frequency 30 Hz (CSIR, 2000),
- average number of passes during compaction was 16 and 20 for G7 and G2 slabs respectively, and
- length of the slab was 850mm, therefore the time for one roller pass was calculated as 1.133 seconds (based on assumptions)

The following formula was derived for calculation of the energy considering the above-mentioned assumptions:

$$\text{Energy} = 650\text{kg} \times 9.81\text{m/s}^2 \times 30\text{ Hz} \times 1.133\text{ secs} \times 0.005\text{m} \times \text{no. of passes}$$
$$= 108.369 \times \text{number of passes (J)}$$

7.2.5 Compaction energy

The compaction energy for each of the compaction methods are summarised in Table 7-6 and depicted in Figure 7-1 below.

Table 7-6: Compactive efforts and energy

Compaction method	G2		G7	
	Compactive effort	Energy (kJ)	Compactive effort	Energy (kJ)
Marshall	175 blows	7.8	60 blows	2.7
Hugo	150 blows	6.7	50 blows	2.2
Kango	45 seconds	1.1	30 seconds	0.7
Gyratory	30 gyrations	2.4	5 gyrations	0.4
Roller	20 passes	2.2	16 passes	31.7

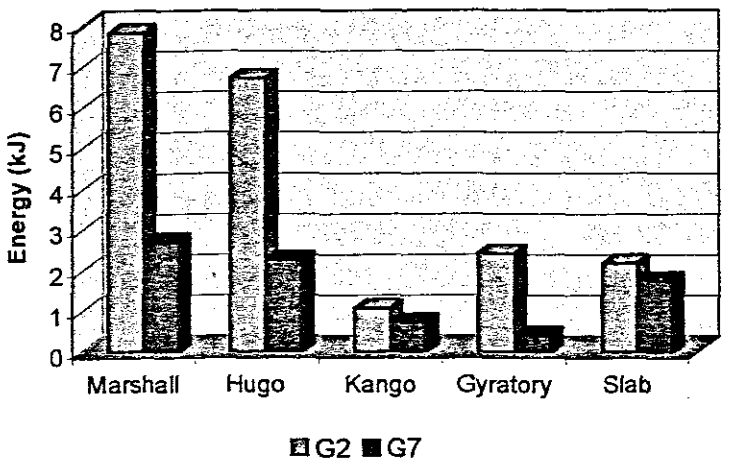


Figure 7-1: Compaction energy applied

7.3 Conclusions

The following conclusions can be drawn, based upon the ANOVA and analysis of compaction energy:

- All laboratory compaction methods were able to produce densities and voids comparable to field compaction.

- SCB test results are not sensitive to compaction method whilst ITS and ITT results are sensitive to compaction method making it a possible test to use in mix designs.

- The type of penetration grade bitumen has no significant effect on the mechanical properties of foamed mixes.

- The type of penetration grade bitumen has no significant effect on the mechanical properties of foamed mixes.

- Marshall and Hugo compaction required more energy than the other methods, especially for the crushed stone mix (G2).

- The Kango Hammer and Superpave Gyratory compactor seemed to be the most effective compaction methods based on compaction energy, based on the lowest energy requirement for these methods

CHAPTER 8 CONCLUSIONS AND RECOMMENDATIONS

8.1 Conclusions

Based on the findings, the following conclusions can be drawn:

- The type of binder used has no significant effect on the mechanical properties of foamed bituminous material.
- Compaction method has a significant influence on ITS and ITS test results.
- SCB test results are not sensitive to compaction method.
- The SCB test should not be considered for mixes with low binder contents as sawing of the specimens result in spalling.

8.2 Recommendations

Based on the findings, the recommendations are as follows:

- Marshall, Hugo, Kango and Superpave Gyratory compaction may be employed in the design of foamed bituminous mixes.
- ITS and ITT testing can be used for mix design of foam mixes.

Recommendations for further work include:

- The possibility of incorporating more robust test methods in the design of foamed bituminous mixes. The brittle nature of foamed stabilized materials calls for test methods, which does not necessitate trimming and sawing of test specimens.
- Factors like aggregate temperature and curing did not receive adequate attention. The degree to which the foamed bitumen in the slabs cured before testing could not be quantified. More work is needed in these areas.
- Foamed stabilization has been proven to be suitable for various types of granular material. This study was focused on two types of materials; more research is necessary on the other types of material before an appropriate mix design procedure can be formalized.

- An analysis of the energy requirements for the different compaction methods to achieve the same density and voids was done in this study. A more detailed investigation into the compaction kinematics is needed. Energy applied during Kango compaction needs to be assessed in more detail.

- The Kango hammer could be a useful tool in the compaction of foamed bituminous material and shows potential to be used on site. However, manual operation of the hammer induces the factor of human error. Standardisation by means of automating the compaction method would reduce the human factor.

- Air void structure and particle orientation was not covered in this study. More work should be done in this area especially permeability of foam mixes.

- The influence of binder type on the mechanical properties of foamed bituminous materials needs more attention. A study into the rheology of foamed bitumen is necessary in order to explore the influence of binder type on mix properties.

- The establishment of different compaction levels for different road categories in the mix designs also needs attention.

REFERENCES

1. Accot S. M., 1980: The Stabilisaion of a Sand by Foamed Bitumen – a Laboratory and Field Performance Study. Dissertation for Master of Science in Engineering, University of Natal.

2. Accot, S. M. and P.A. Myburgh 1983: Design and Performance Study of Sand Bases Treated with Foamed Asphalt. Transportation Research Record 898, pp 290-296. Transportation Research Board, Washington DC.

3. Akeroyd, F.M.L and Hicks B. J. 1988: Foamed Bitumen in Road Recycling. Highways, January, London. Pp 42-45.

4. Asphalt Institute 1992: A Basic Asphalt Emulsion Manual. Manual Series No. 19, Second Edition. Maryland.

5. Bissada, A.F. 1987: Structural Response of Foamed-Asphalt-Sand Mixtures in Hot Environments. Transportation Research Record 1115, pp 134 – 149. Transportation Research Board, Washington DC.

6. Bowering R. H., 1970: Upgrading Marginal Road Building Materials with Foamed Bitumen Asphalt. Highway Engineering in Australia. Mobil Oil Australia, Melbourne South.

7. Bowering R. H. and C. L Martin, 1976: Foamed Bitumen Production and Application of Mixtures Evaluation and Performance of Pavements. Proceedings of the annual meeting of the Association of Asphalt Paving Technologists Volume 45, pp 453-477. New Orleans, Louisiana.

8. Brennen, M., M. Tia, A. Altschaeffl and L.E. Wood 1983: Laboratory Investigation on the Use of Foamed Asphalt for Recycled Bituminous Pavements. Transportation Research Record 911, pp. 80 – 87. Transportation Research Board, Washington DC.

9. Brown E. R. and R. B. Mallick 1998: An Initial Evaluation of N_{design} Superpave Gyratory Compactor. Proceedings of the annual meeting of the Association of Asphalt Paving Technologists, Boston.

10. Brown S.F., J. N. Preston and K.E. Cooper 1991: Application of New Concepts in Asphalt Mix Design. Proceedings of the annual meeting of the Association of Asphalt Paving Technologists, Seattle, Washington D.C.

11. Burger, A. F. and K. Dempers 1997: Comparison Between Field and Laboratory Compaction. Undergraduate Thesis, University of Stellenbosch.

12. Bushkühl G., J. Gapsi and R. Gründel 1990: Bituminose Tragschchten aus Müllverbrennungssasche und Schaumbitumen. Diploarbeit, Fachbeeich Bauingenieurwesen, Fachhochschule Hamburg. Germany.

13. Cooley L.A., M. Tsroup-Gardiner, E.R. Brown, D.I Hanson and M.O.Fletcher, 1998: Characterisation of Asphalt-filler Mortars with Superpave Binder Tests. Annual Meeting of the Association of Asphalt Paving Technologists, Boston.

14. Cooper K. E. 1995: Developments in Mix Design. Bituminous Pavements Course Notes, University of Nottingham.

15. Committee for State Road Authorities 1987: Guidelines for Roadbuilding Materials. Manual 14. Pretoria.

16. Committee for State Road Authorities 1987: Test Methods for Roadbuilding Materials. TMH1. Pretoria.

17. Csanyi L.H., 1956: Mortar Theory for Use of Ungraded Aggregates in Bituminous mixes. Highway Research Board Bulletin No. 109, pp 1-49.

18. Csanyi L.H., 1957: Foamed Asphalt in Bituminous Paving Mixes. American Road Builders Association (ARBA) Technical Bulletin, Volume 240, pp 3-14.

19. CSIR Transportek, 1998: Preliminary Assessment of the Structural Properties of Pavements with Foamed Bitumen Base Layers. Websitehttp:// jh3.csir.co.za/foamasph/trb68.htm.

20. CSIR Tranportek, 1998: Foamed Asphalt, Mix Design. Website http://foasph.csir.co.za:81/appa.htm.

21. CSIR, Transportek 2000: Course Notes: Practical Compaction Guidelines. Divisional Publication DP 200/1.

22. Ebels, L. J. 1998: Bitumen Stabilised Paving Blocks – Development of Labour Intensive Block Manufacture and Road Structures using Bitumen Stabilised Paving Blocks in South Africa. M. Eng. Thesis, Delft University of Technology, Delft, Netherlands.

23. Eggers C., M. Holshausen and J. Bartels 1990: Bituminose Tragschichten aus Mullverbrennenungsssasche und Schaumbitumen under Besonderer Berucksichtgung von Unterschiedlichen Tensiden. Diplomarbeit, Fachhbereich Bauingenieurswesen, Fachhochschulle Hamburg. Germany.

24. Engelbrecht J.C., F.L. Roberts and T.W. Kennedy 1985: Cold Recycled Mixtures, with mphasis on the Curing of Foamed Specimens – A Laboratory Study. Annual Transportation Convention, S350 Volume T1. Pretoria, South Africa.

25. Finn, F. N. and J. A. Epps 1983: Compaction of Hot Mix Asphalt Concrete. Engineering, Economy and Energy Considerations in Design, Construction and Materials. Research Report 214-21, August 1980.

26. Grobler, J. E. 1990: Development of Procedures For Large Stone Asphalt Mix Design. Dissertation for Master of Science in Engineering, University of Stellenbosch.

27. Hotte P. 1995: Six Years of Recycling with Foam Bitumen. Proceedings ARRA. San Diego, USA.

28. Humberto Castedo Franco L. and L.E. Wood, 1982: Stabilisation with Foamed Asphalt of Aggregates Commonly used in Low Volume Roads. Transportation Research Record 898, pp 297-302.

29. Jenkins, K. J. 1999: Personal communication.

30. Jenkins, K. F Hugo and M. Van de Ven 1997: Development of Labour Intensive Block Manufacture and Road Construction Techniques using Bitumen Emulsion and Foamed Bitumen Stabilised Paving Blocks. South African Transportation Convention, Johannesburg, South Africa.

31. Jenkins K.J., M.F.C. Van de Ven, and J.L.A. De Groot, 1999: Characterisation of Foamed Bitumen. Proceedings of the 7th Conference on Asphalt Pavements for Southern Africa Conference. Victoria Falls, Zimbabwe.

32. Jenkins, K 2000: Mix Design Considerations for Cold and Half-Warm Bituminous mixes with the emphasis on foamed bitumen. PhD Dissertation. University of Stellenbosch.

33. Krans, R. L., F. Tolman and M.F.C Van de Ven, 1996: Semi-circular Bending Test: A Practical Growth Test using Aphalt Cores. Third International RIILEM Conference on Reflective Cracking in Pavements, Maastricht.

34. Lancaster, J., L. Mcarthur and R. Warwick 1994: Vicroads Experience with Foamed Bitumen Stabilisation (1994), Proceedings of 17th ARRB Conference Part 3, pp 193-211.

35. Lee, D.Y. 1981: Treating marginal aggregates and soils with Foamed Asphalt. Proceedings of the Association of Asphalt Paving Technologists Technical Sessions Volume 50, pp211 – 150. Association of Asphalt Paving Technologists, New Orleans, Louisana.

36. Lewis, A.J.N., M.G. Barron and G.P. Rutland 1994: Foamed bitumen – Recent experience in South Africa. Proceedings of the 17th ARRB Conference, Part 3, Gold Coast.

37. Little D. N. J.W. Button and J.A. Epps, 1983: Structural Properties of Laboatory Mixtures Containing Foamed Asphalt and Marginal Aggregates. Transportation Research Record 911. Pp 104-113.

38. Maccarone, S., G. Holleran, D.J. Leonard and S. Hey 1994: Pavement Recycling using Foamed Bitumen. Proceedings of the 17th ARRB Conference, Part 3, Gold Coast.

39. Maccarone S 1994: Cold Asphalt Systems as an Alternative to Hotmix, Proceedings of the 9th AAPA international Asphalt Conference.

40. McGennis, R., R.M. Anderson, T.W. Kennedy and Solaimanian1995: Background of Superpave Asphalt Mixture Design and Analysis. Publication No. FHWA-SA-95-003, US Department of Transportation.

41. Molenaar, A. A. A. 1993: Asphaltic Materials. Lecture Notes e52, Road Materials. Delft University of Technology.

42. Molenaar, A. A. A. 1994: Design of Flexible Pavements. Lecture notes e54, Structural Pavement Design. Delft University of Technology, Delft

43. Paterson, W.D O 1977: Considering the pavement as a mechanism. National Institute for Transport and Road Research, Technical Report RP/3/77.

44. Roberts, F.L., J.C. Engelbrecht and T.W. Kennedy 1984: Evaluation of Recycled Mixes using Foamed Asphalt. Transportation Research Record 968, pp 78-85. Transportation Research Board, Washington DC.

45. Roberts, F. L., P.S. Khandhal, E.R. Brown, D. Lee and T. W. Kennedy 1991: Hot Mix Asphalt Materials, Mixture Design and Construction. National Centre for Asphalt Technology. NAPA Research and Education Foundation, Lanham, Maryland.

46. Ruckel, P.J., S.M. Accot and R.H. Bowering 1982: Foamed asphalt mixtures: Preparation of Design Mixes and Treatment of Test Specimens. Transportation Research Record 911, pp 88- 95.

47. Shell 1990: Shell bitumen handbook. Shell bitumen, UK.

48. Shackel, B. K Makuichi and J. R. Derbyshire 1974: The Response of a Foamed Bitumen Stabilised Soil to Repeated Triaxial Loading. Proceedings of the Australian Research Board Conference, Adelaide. Australia.

49. Smit, A. D. F., M. Van de Ven and E. Fletcher 1997: Towards the use of the Semi-Circular Bending Test as a Performance Related Specification Test. South African Transportation Convention, Johannesburg, South Africa.

50. Theyse, H.L., M. De Beer and F.C. Rust, 1996: Overview of the South African Mechanistic Pavement Design and Analysis Method. Transportek CSIR. Divisional Pubication DP –96/005. Pretoria, South Africa.

51. Van der Walt, N., P. Botha, C Semmelink, F. Englebrecht and N. Salminen 1999: The use of Foamed Bitumen in Full-depth In-place Recycling of Pavement Layers Illustrating the Basic Concept of Water Saturation in the Foaming Process. Proceedings of the 7th Conference on Asphalt Pavements for Southern Africa. Victoria Falls, Zimbabwe.

APPENDIX B: MECHANICAL TEST RESULTS

ITS TEST RESULTS

MARSHALL G2

150/200			
Sample ID	Thickness (mm)	Load (N)	ITS (kPa)
5	57.9	2184	160
1	55.9	3439	261
14	42.4	2267	227
		Average	**216**
		COV	**24**

MARSHALL G7

80/100				150/200			
Sample ID	Thickness (mm)	Load (N)	ITS (kPa)	Sample ID	Thickness (mm)	Load (N)	ITS (kPa)
7	59.9	3899	276	13	58.0	4378	320
3	56.0	5613	425	7	55.9	5604	425
10	59.0	5240	377	11	56.0	4148	314
		Average	**359**			**Average**	**353**
		COV	**21**			**COV**	**18**

HUGO G2

150/200			
Sample ID	Thickness (mm)	Load (N)	ITS (kPa)
1	55.0	4033	311
14	64.0	4799	318
4	59.3	4093	293
		Average	**307**
		COV	**4**

HUGO G7

80/100				150/200			
Sample ID	Thickness (mm)	Load (N)	ITS (kPa)	Sample ID	Thickness (mm)	Load (N)	ITS (kPa)
3	52.0	3771	308	10	64.3	4448	295
12	55.5	4451	340	13	61.0	4456	310
14	62.3	4208	290	1	55.3	4465	343
				4	56.0	4467	339
		Average	**313**			**Average**	**322**
		COV	**8**			**COV**	**7**

KANGO G2

150/200			
Sample ID	Thickness (mm)	Load (N)	ITS (kPa)
5	59.0	5660	407
2	55.0	6443	497
		Average	**452**
		COV	**14**

KANGO G7

80/100				150/200			
Sample ID	Thickness (mm)	Load (N)	ITS (kPa)	Sample ID	Thickness (mm)	Load (N)	ITS (kPa)
8	61.0	5915	412	15	56.6	3999	300
2	57.3	6370	472	9	52.6	5053	400
12	56.0	4095	310	4	53.6	6179	472
	61.6	3377	235	1	50.6	5964	500
		Average	**357**			**Average**	**418**
		COV	**30**			**COV**	**21**

GYRATORY G2

150/200			
Sample ID	Thickness (mm)	Load (N)	ITS (kPa)
2	57.0	3238	241
4	54.1	4052	318
14	51.9	2289	187
		Average	**249**
		COV	**26**

GYRATORY G7

80/100				150/200			
Sample ID	Thickness (mm)	Load (N)	ITS (kPa)	Sample ID	Thickness (mm)	Load (N)	ITS (kPa)
2	57	5,656	421	2	59	6,397	460
9	50	4,797	407	12	58	4,771	349
11	52.5	4,628	374	5	56	4,580	347
		Average	**401**			**Average**	**385**
		COV	**6**			**COV**	**17**

SLAB G2

150/200			
Sample ID	Thickness (mm)	Load (N)	ITS (kPa)
1	50.1	3,496	296
4	53.0	3,623	290
6	49.0	3,673	318
		Average	**301**
		COV	**5**

SLAB G7

80/100				150/200			
Sample ID	Thickness (mm)	Load (N)	ITS (kPa)	Sample ID	Height (mm)	Load (N)	ITS (kPa)
5	54	10,590	832	6	47.0	3,545	320
1	53	5,609	449	3	42.0	7,534	761
9	74	10,344	593	2	54.0	10,883	855
		Average	**625**			**Average**	**645**
		COV	**31**			**COV**	**44**

ITT RESULTS

MARSHALL G2

150/200			
Sample ID	Thickness (mm)	Displ. (mm)	ITT (Mpa)
10	61.1	0.0490	1535
14	61.1	0.0640	1166
13	49.2	0.0360	1297
		Average	**1333**
		COV	**14**

MARSHALL G7

80/100				150/200			
Sample ID	Thickness (mm)	Displ. (mm)	ITT (Mpa)	Sample ID	Thickness (mm)	Displ. (mm)	ITT (Mpa)
4	60.0	0.078	1083	13	58.7	0.0282	1532
8	59.3	0.068	1250	7	61.3	0.0293	1412
15	58.3	0.088	991	11	58.5	0.0231	1877
2	58.7	0.078	1104				
		Average	**1107**			**Average**	**1607**
		COV	**10**			**COV**	**15**

HUGO G2

150/200			
Sample ID	Thickness (mm)	Displ. (mm)	ITT (Mpa)
3	51.0	0.0195	2022
5	54.0	0.0147	2533
6	59.0	0.0185	1842
1	55.0	0.0137	2668
		Average	**2266**
		COV	**18**

HUGO G7

80/100				150/200			
Sample ID	Thickness (mm)	Displ. (mm)	ITT (Mpa)	Sample ID	Thickness (mm)	Displ. (mm)	ITT (Mpa)
4	53.5	0.0439	1916	14	0.0391	62.5	1877
13	58.0	0.039	1990	3	0.0342	57.8	2277
10	61.5	0.0341	2147	6	0.039	63.5	1818
				8	0.039	58.0	1990
		Average	**2018**			**Average**	**1991**
		COV	**6**			**COV**	**12**

KANGO G2

150/200			
Sample ID	Thickness (mm)	Displ. (mm)	ITT (Mpa)
6	55	0.0116	1576
3	51	0.0156	1263
5	57	0.0136	1297
		Average	**1379**
		COV	**12**

KANGO G7

80/100				150/200			
Sample ID	Thickness (mm)	Displ. (mm)	ITT (Mpa)	Sample ID	Thickness (mm)	Displ. (mm)	ITT (Mpa)
8	57.5	0.0537	1903	12	74.3	0.0286	1450
2	59	0.0488	2041	3	55.7	0.0336	1647
12	12	0.0537	1737	14	53.8	0.0391	1465
				6	53	0.0367	1585
		Average	**1894**			**Average**	**1537**
		COV	**8**			**COV**	**6**

GYRATORY G2

150/200			
Sample ID	Thickness (mm)	Displ. (mm)	ITT (Mpa)
6	59	0.0127	1298
2	52	0.0127	1473
9	58	0.0137	1224
11	55	0.0103	1717
		Average	**1428**
		COV	**15**

GYRATORY G7

80/100				150/200			
Sample ID	Thickness (mm)	Displ. (mm)	ITT (Mpa)	Sample ID	Thickness (mm)	Displ. (mm)	ITT (Mpa)
3	51	0.0195	1916	13	66	0.0089	1681
5	54	0.0147	1990	14	54	0.0078	2344
6	59	0.0185	2147	7	53	0.0127	1467
		Average	**2018**			**Average**	**1830**
		COV	**6**			**COV**	**25**

SLAB G2

150/200			
Sample ID	Thickness (mm)	Displ. (mm)	ITT (Mpa)
4	61.5	0.069	1083.0
7	46	0.097	1020.0
		Average	**1052**
		COV	**4**

SLAB G7

80/100				150/200			
Sample ID	Height (mm)	Displ. (mm)	ITT (Mpa)	Sample ID	Height (mm)	Displ. (mm)	ITT (Mpa)
5	54	0.0537	1570	6	47.0	0.0137	1996
1	53	0.0488	1493	3	42.0	0.0127	1570
9	74	0.0537	1359				
		Average	**1474**			**Average**	**1783**
		COV	**7**			**COV**	**17**

SCB RESULTS

MARSHALLG2

150/200			
Sample ID	Thickness (mm)	Load (N)	SCB (kPa)
1(a)	57.5	469	232
12(b)	59.0	494	238
8(a)	61.0	850	396
		Average	**289**
		COV	**32**

MARSHALL G7

80/100				150/200			
Sample ID	Thickness (mm)	Load (N)	SCB (kPa)	Sample ID	Thickness (mm)	Load (N)	SCB (kPa)
9(a)	60.0	1010	478	6(b)	58.0	1384	678
13(b)	61.0	1255	585	1(b)	53.0	1466	786
5(b)	61.0	1097	511	10(b)	59.0	flop	
		Average	**525**			**Average**	**732**
		COV	**10**			**COV**	**10**

HUGO G2

150/200			
Sample ID	Thickness (mm)	Load (N)	SCB (kPa)
11(a)	57.0	450	224
8(a)	53.0	723	403
12(a)	55.0	593	306
		Average	**311**
		COV	**29**

HUGO G7

80/100				150/200			
Sample ID	Thickness (mm)	Load (N)	SCB (kPa)	Sample ID	Thickness (mm)	Load (N)	SCB (kPa)
	51.0	915	510		50	771	438
	55.0	1001	517		54	1062	559
	57.0	1011	504		56	1208	613
	56	952	483				
		Average	**504**			**Average**	**537**
		COV	**3**			**COV**	**17**

KANGO G2

150/200			
Sample ID	Thickness (mm)	Load (N)	SCB (kPa)
4(a)	55	1198	364
4(b0	55	604	183
7(a)	59	1159	344
7(b)	59	145	345
		Average	**309**
		COV	**27**

KANGO G7

80/100				150/200			
Sample ID	Thickness (mm)	Load (N)	SCB (kPa)	Sample ID	Thickness (mm)	Load (N)	SCB (kPa)
11(a)	58.0	1447	682	4(b)	55	1657	746
7(a)	56.0	1312	640	10(b)	58	1590	749
7(b0	58.0	2395	1128	10(a)	58	1657	781
2(b)	58.0	1926	907	14(a)	53	1226	632
		Average	**839**			**Average**	**727**
		COV	**27**			**COV**	**9**

GYRATORY G2

150/200			
Sample ID	Thickness (mm)	Load (N)	SCB (kPa)
8(b)	51.0	391	218
13(a)	54.0	464	244
3(b)	57.0	249	124
5(b)	55.0	426	220
		Average	**202**
		COV	**26**

GYRATORY G7

80/100				150/200			
Sample ID	Thickness (mm)	Load (N)	SCB (kPa)	Sample ID	Thickness (mm)	Load (N)	SCB (kPa)
2(a)	54.0	1155	608	1(a)	52.5	1589	860
8(b)	57.0	1276	636	10(b)	56.0	1561	792
14(a)	51.0	1260	702	6(a)	58.5	1630	792
				8(a)	53.0	1276	684
		Average	**649**			**Average**	**782**
		COV	**7**			**COV**	**9**

SLAB G2

150/200			
Sample ID	Thickness (mm)	Load (N)	SCB (kPa)
11(a)	63	1778	802
8(a)	49.6	1112	637
8(b)	49.6	956	548
		Average	**662**
		COV	**19**

SLAB G7

80/100				150/200			
Sample ID	Thickness (mm)	Load (N)	SCB (kPa)	Sample ID	Height (mm)	Load (N)	SCB (kPa)
3(a)	53.6	1311	695	1(a)	52.9	1364	733
3(b)	53.6	1454	771	1(b)	52.9	1508	810
10(a)	58.1	2302	1126	4(b)	45.4	1094	685
		Average	**864**			**Average**	**743**
		COV	**27**			**COV**	**8**

APPENDIX A: COMPACTION RESULTS

G2 MARSHALL - 150/200 SPECIMENS

Sample number	Mass of mould (g)	Mould + material (g)	Sample mass (g)	Height (mm)	Bulk density (kg/m^3)	Dry density (kg/m^3)	Target mass (g)	Final density (kg/m^3)
1	4,370	8,219	3,849	98.3	2,215	2,215	3,849	2,215
2	4,421	8,266	3,845	95.4	2,280	2,280	3,845	2,280
3	4,369	8,215	3,846	95.4	2,280	2,280	3,846	2,280
4	4,358	8,206	3,848	94.9	2,294	2,294	3,848	2,294
5	4,369	8,227	3,858	97.5	2,238	2,238	3,858	2,238
6	4,358	8,200	3,842	96.5	2,252	2,252	3,842	2,252
7	4,358	8,228	3,870	98.1	2,231	2,231	3,870	2,231
8	4,369	8,214	3,845	96.1	2,263	2,263	3,845	2,263
9	4,385	8,244	3,859	97.8	2,232	2,232	3,859	2,232
10	4,369	8,199	3,830	97.5	2,222	2,222	3,830	2,222
11	4,421	8,247	3,826	96.8	2,236	2,236	3,826	2,236
12	4,369	8,219	3,850	96.8	2,250	2,250	3,850	2,250
13	4,421	8,268	3,847	97.5	2,232	2,232	3,847	2,232
14	4,357	8,211	3,854	97.1	2,245	2,245	3,854	2,245
							Average final density	**2,248**
							COV	**1**

Container ID	Empty mass (g)	Bowl + wet sample (g)	Bowl+ dry sample (g)	Moisture content
56	237.6	756.8	736.0	4.2
25	248.6	865.6	841.5	4.1
			Average compaction moisture content	**4.1**
			Moisture before curing (%)	**2.4**

G7 MARSHALL - 150/200 SPECIMENS

Sample number	Mass of mould (g)	Mould + material (g)	Sample mass (g)	Height (mm)	Bulk density (kg/m^3)	Dry density (kg/m^3)	Target mass (g)	Final density (kg/m^3)
1	4,359	8,138	3,779	105.8	2,020	2,020	3,839	2,053
2	4,346	8,195	3,849	107.2	2,031	2,031	3,911	2,063
3	4,385	8,232	3,847	106.3	2,047	2,047	3,909	2,080
4	4,421	8,272	3,851	107.0	2,036	2,036	3,913	2,068
5	4,370	8,222	3,852	106.8	2,040	2,040	3,914	2,073
6	3,922	8,210	4,288	107.6	2,254	2,254	4,357	2,290
7	4,345	8,198	3,853	107.3	2,031	2,031	3,915	2,064
8	4,386	8,234	3,848	106.2	2,050	2,050	3,910	2,082
9	4,421	8,266	3,845	106.9	2,035	2,035	3,907	2,067
10	4,370	8,226	3,856	107.3	2,033	2,033	3,918	2,065
11	4,358	8,207	3,849	108.0	2,016	2,016	3,911	2,048
12	4,346	8,191	3,845	107.1	2,031	2,031	3,907	2,063
13	4,385	8,239	3,854	106.6	2,045	2,045	3,916	2,078
14	4,421	8,278	3,857	107.3	2,033	2,033	3,919	2,066
15	4,358	8,206	3,848	108.7	2,002	2,002	3,910	2,034
							Average final density	**2,080**
							COV (%)	**3**

Container ID	Empty mass (g)	Bowl + wet sample (g)	Bowl+ dry sample (g)	Moisture content
14	224.5	809.3	782.6	4.8
29	235.5	799.9	776.1	4.4
23	230.4	786.0	761.4	4.6
			Average compaction moisture content	**4.6**
			Moisture before curing (%)	**1.6**

G7 MARSHALL - 80/100 SPECIMENS

Sample number	Mass of mould (g)	Mould + material (g)	Sample mass (g)	Height (mm)	Bulk density (kg/m^3)	Dry density (kg/m^3)	Target mass (g)	Final density (kg/m^3)
1	4,646	8,203	3,557	108.2	1,860	1,860	3,614	1,889
2	4,346	8,203	3,857	108.0	2,020	2,020	3,919	2,052
3	4,346	8,197	3,851	108.1	2,015	2,015	3,913	2,047
4	4,370	8,220	3,850	107.8	2,020	2,020	3,912	2,053
5	4,370	8,220	3,850	108.4	2,009	2,009	3,912	2,041
6	4,345	8,197	3,852	107.5	2,027	2,027	3,914	2,059
7	4,421	8,272	3,851	109.1	1,997	1,997	3,913	2,029
8	4,358	8,211	3,853	107.9	2,020	2,020	3,915	2,052
9	4,421	8,257	3,836	106.9	2,030	2,030	3,897	2,062
10	4,358	8,215	3,857	107.3	2,033	2,033	3,919	2,066
11	4,358	8,214	3,856	108.0	2,020	2,020	3,918	2,052
12	4,385	8,239	3,854	107.1	2,036	2,036	3,916	2,068
13	4,385	8,208	3,823	106.6	2,029	2,029	3,884	2,061
14	4,385	8,239	3,854	107.3	2,032	2,032	3,916	2,064
15	4,370	8,220	3,850	108.7	2,003	2,003	3,912	2,036
							Average final density	**2,042**
							COV (%)	**2**

Container ID	Empty mass (g)	Bowl + wet sample (g)	Bowl+ dry sample (g)	Moisture content
99	231.3	687.6	666.5	4.848
33	240.5	684.9	664.9	4.713
80	173.5	640.6	619.2	4.801
			Average compaction moisture content	**4.8**
			Moisture before curing (%)	**1.6**

G2 HUGO - 150/200 SPECIMENS

Sample number	Mass of mould (g)	Mould + material (g)	Sample mass (g)	Height (mm)	Bulk density (kg/m^3)	Dry density (kg/m^3)	Target mass (g)	Final density (kg/m^3)
1	4,337	8,144	3,807	100.7	2,138	2,138	3,807	2,138
2	3,990	7,847	3,857	97.8	2,231	2,231	3,857	2,231
3	4,380	8,324	3,944	96.9	2,302	2,302	3,944	2,302
4	4,382	8,222	3,840	96.6	2,249	2,249	3,840	2,249
5	4,378	8,235	3,857	96.8	2,254	2,254	3,857	2,254
6	4,416	8,270	3,854	97.2	2,243	2,243	3,854	2,243
7	4,355	8,223	3,868	95.1	2,301	2,301	3,868	2,301
8	4,367	8,221	3,854	97.0	2,247	2,247	3,854	2,247
9	4,385	8,268	3,883	95.1	2,310	2,310	3,883	2,310
10	3,859	7,723	3,864	95.4	2,291	2,291	3,864	2,291
11	4,386	8,252	3,866	96.8	2,259	2,259	3,866	2,259
12	4,387	8,242	3,855	96.0	2,271	2,271	3,855	2,271
13	4,344	8,197	3,853	94.5	2,306	2,306	3,853	2,306
14	4,367	8,192	3,825	94.8	2,282	2,282	3,825	2,282
							Average final density	**2,263**
							COV (%)	**2**

Container ID	Empty mass (g)	Bowl + wet sample (g)	Bowl+ dry sample (g)	Moisture content
67	235.1	755.1	737.0	3.6
23	248.6	863.2	840.5	3.8
			Average compaction moisture content	**3.7**
			Moisture before curing (%)	**1.0**

G7 HUGO - 150/200 SPECIMENS

Sample number	Mass of mould (g)	Mould + material (g)	Sample mass (g)	Height (mm)	Bulk density (kg/m^3)	Dry density (kg/m^3)	Target mass (g)	Final density (kg/m^3)
1	4,419	8,279	3,860	106.0	2,060	2,060	3,860	2,060
2	3,991	7,855	3,864	107.0	2,043	2,043	3,864	2,043
3	4,338	8,204	3,866	105.5	2,073	2,073	3,866	2,073
4	4,388	8,257	3,869	106.5	2,055	2,055	3,869	2,055
5	4,390	8,262	3,872	107.0	2,047	2,047	3,872	2,047
6	4,346	8,213	3,867	106.5	2,054	2,054	3,867	2,054
7	4,382	8,255	3,873	106.0	2,067	2,067	3,873	2,067
8	4,369	8,228	3,859	106.5	2,050	2,050	3,859	2,050
9	4,385	8,236	3,851	107.0	2,036	2,036	3,851	2,036
10	4,369	8,280	3,911	108.5	2,039	2,039	3,911	2,039
11	4,358	8,243	3,885	108.0	2,035	2,035	3,885	2,035
12	3,861	7,727	3,866	106.5	2,053	2,053	3,866	2,053
13	4,379	8,246	3,867	97.5	2,243	2,243	3,867	2,243
14	4,296	8,170	3,874	106.5	2,058	2,058	3,874	2,058
							Average final density	**2,065**
							COV (%)	**3**

Container ID	Empty mass (g)	Bowl + wet sample (g)	Bowl+ dry sample (g)	Moisture content
2	233.5	815.3	791.6	4.2
29	239.5	803.9	780.1	4.4
			Average compaction moisture content	**4.4**
			Moisture before curing (%)	**1.0**

G7 HUGO - 80/100 SPECIMENS

Sample number	Mass of mould (g)	Mould + material (g)	Sample mass (g)	Height (mm)	Bulk density (kg/m^3)	Dry density (kg/m^3)	Target mass (g)	Final density (kg/m^3)
1	11,834	15,656	3,822	103.2	2,095	1,999	3,706	2,031
2	12,134	15,959	3,825	103.9	2,082	1,987	3,709	2,019
3	12,285	16,125	3,840	104.4	2,081	1,986	3,723	2,017
4	11,470	15,311	3,841	103.4	2,101	2,005	3,724	2,037
5	13,144	16,971	3,827	103.9	2,084	1,988	3,711	2,020
6	13,161	16,990	3,829	104.1	2,081	1,986	3,713	2,017
7	11,470	15,296	3,826	103.5	2,091	1,995	3,710	2,027
8	11,833	15,652	3,819	104.3	2,071	1,977	3,703	2,008
9	12,134	15,968	3,834	104.6	2,073	1,979	3,717	2,010
10	11,469	15,310	3,841	103.8	2,093	1,998	3,724	2,029
11	11,831	15,676	3,845	105.1	2,069	1,975	3,728	2,006
12	12,282	16,132	3,850	105.0	2,074	1,979	3,733	2,011
13	13,143	16,963	3,820	104.0	2,078	1,983	3,704	2,015
14	13,158	16,998	3,840	104.8	2,073	1,978	3,723	2,010
15	13,142	16,989	3,847	105.4	2,065	1,970	3,730	2,002
							Average final density	**2,017**
							COV (%)	**1**

Container ID	Empty mass (g)	Bowl + wet sample (g)	Bowl+ dry sample (g)	Moisture content
45	231.3	687.6	666.5	4.8
43	240.5	684.9	664.9	4.7
B	173.5	640.6	619.2	4.8
			Average compaction moisture content	**4.8**
			Moisture before curing (%)	**1.6**

G2 KANGO - 150/200 SPECIMENS

Sample number	Mass of mould (g)	Mould + material (g)	Sample mass (g)	Height (mm)	Bulk density (kg/m^3)	Dry density (kg/m^3)	Target mass (g)	Final density (kg/m^3)
1	2,972	6,831	3,859	95.5	2,286	2,183	3,774	2,235
2	3,231	7,095	3,864	95.0	2,301	2,210	3,800	2,263
3	2,976	6,850	3,874	94.7	2,314	2,222	3,810	2,276
4	3,032	6,899	3,867	94.5	2,315	2,223	3,803	2,276
5	2,739	6,602	3,863	96.0	2,276	2,186	3,799	2,239
6	3,000	6,874	3,874	95.5	2,295	2,204	3,810	2,257
7	4,358	8,228	3,870	96.5	2,268	2,179	3,806	2,231
8	4,369	8,214	3,845	94.5	2,302	2,210	3,782	2,264
9	4,385	8,244	3,859	95.5	2,286	2,195	3,795	2,248
10	3,032	6,903	3,871	94.6	2,315	2,223	3,807	2,276
11	2,739	6,614	3,875	97.6	2,246	2,157	3,811	2,209
12	2,993	6,854	3,861	96.5	2,263	2,174	3,797	2,226
13	2,977	6,839	3,862	96.0	2,276	2,186	3,798	2,238
							Average final density	2,249
							COV (%)	1

Container ID	Empty mass (g)	Bowl + wet sample (g)	Bowl+ dry sample (g)	Moisture content
14	224.5	806.3	782.6	4.2
29	235.5	799.9	776.1	4.4
23	230.4	784.3	761.4	4.3
			Average compaction moisture content	4.3
			Moiture before curing (%)	2.4

G7 KANGO - 150/200 SPECIMENS

Sample number	Mass of mould (g)	Mould + material (g)	Sample mass (g)	Height (mm)	Bulk density (kg/m^3)	Dry density (kg/m^3)	Target mass (g)	Final density (kg/m^3)
1	2,739	6,574	3,835	94.0	2,134	2,050	3,461	2,083
2	3,001	6,846	3,845	94.6	2,126	2,042	3,470	2,075
3	3,231	7,058	3,827	96.4	2,076	1,995	3,453	2,026
4	2,846	6,690	3,844	97.2	2,068	1,987	3,469	2,019
5	2,972	6,840	3,868	95.0	2,129	2,046	3,490	2,078
6	2,993	6,832	3,839	95.1	2,111	2,028	3,464	2,061
7	2,972	6,823	3,851	95.8	2,102	2,020	3,475	2,052
8	2,739	6,583	3,844	95.7	2,101	2,018	3,469	2,050
9	3,032	6,868	3,836	96.1	2,088	2,005	3,462	2,038
10	2,977	6,811	3,834	95.7	2,095	2,013	3,460	2,045
11	2,739	6,564	3,825	93.3	2,144	2,060	3,452	2,093
12	2,847	6,693	3,846	95.8	2,100	2,017	3,471	2,049
13	3,033	6,860	3,827	94.6	2,116	2,032	3,453	2,065
14	2,976	6,782	3,806	96.5	2,063	1,982	3,435	2,013
15	2,976	6,812	3,836	97.3	2,062	1,981	3,462	2,012
							Average final density	2,051
							COV (%)	1

Container ID	Empty mass (g)	Bowl + wet sample (g)	Bowl+ dry sample (g)	Moisture content
14	221.3	827.2	802.2	4.3
29	240.4	799.9	779.2	3.8
23	276	799.1	778.3	4.1
			Average compaction moisture content	4.1
			Moisture before curing (%)	1.6

G7 KANGO - 80/100 SPECIMENS

Sample number	Mass of mould (g)	Mould + material (g)	Sample mass (g)	Height (mm)	Bulk density (kg/m^3)	Dry density (kg/m^3)	Target mass (g)	Final density (kg/m^3)
1	2,977	6,831	3,854	96.9	2,080	1,995	3,418	2,027
2	3,001	6,842	3,841	95.7	2,099	2,013	3,406	2,045
3	3,033	6,858	3,825	95.3	2,099	2,013	3,392	2,045
4	2,740	6,539	3,799	93.5	2,125	2,038	3,369	2,071
5	2,972	6,777	3,805	94.6	2,104	2,018	3,374	2,050
6	2,993	6,674	3,681	97.4	1,976	1,896	3,264	1,926
7	3,232	7,073	3,841	95.1	2,112	2,026	3,406	2,058
8	2,994	6,826	3,832	98.5	2,035	1,951	3,398	1,983
9	3,231	7,067	3,836	95.0	2,112	2,025	3,402	2,058
10	3,032	6,856	3,824	96.0	2,083	1,998	3,391	2,030
11	3,231	7,052	3,821	94.0	2,126	2,039	3,388	2,072
12	2,994	6,806	3,812	95.8	2,081	1,996	3,380	2,028
13	2,977	6,839	3,862	94.6	2,135	2,048	3,425	2,081
14	2972	6816	3844	96.5	2,083	1,998	3,409	2,030
							Average final density	**2,036**
							COV (%)	**2.0**

Container ID	Empty mass (g)	Bowl + wet sample (g)	Bowl+ dry sample (g)	Moisture content
60	250	630.1	615.2	4.1
20	197.3	710	687.5	4.6
P	280.9	660.2	645.2	4.1
			Average compaction moisture content	**4.3**
			Moisture *before curing* (%)	**1.6**

G2 GYRATORY - 150/200 SPECIMENS

Sample number	Mass of mould (g)	Mould + material (g)	Sample mass (g)	Height (mm)	Bulk density (kg/m^3)	Dry density (kg/m^3)	Target mass (g)	Final density (kg/m^3)
1	12,080	15,909	3,829	100.7	2,151	2,064	3,762	2,113
2	12,286	16,155	3,869	97.8	2,238	2,147	3,801	2,199
3	11,510	15,350	3,840	96.9	2,242	2,151	3,773	2,202
4	13,106	16,965	3,859	96.6	2,260	2,168	3,792	2,220
5	13,086	16,940	3,854	96.8	2,252	2,161	3,787	2,213
6	12,285	16,163	3,878	97.2	2,257	2,165	3,810	2,217
7	11,508	15,368	3,860	95.1	2,296	2,203	3,793	2,256
8	12,078	15,955	3,877	97.0	2,261	2,169	3,809	2,221
9	12,297	16,153	3,856	95.1	2,294	2,201	3,789	2,254
10	13,095	16,933	3,838	95.4	2,276	2,184	3,771	2,236
11	11,510	15,382	3,872	96.8	2,263	2,171	3,804	2,223
12	12,709	16,429	3,720	96.0	2,192	2,103	3,655	2,154
13	12,286	16,127	3,841	94.5	2,299	2,206	3,774	2,259
14	13,080	16,942	3,862	94.8	2,304	2,211	3,795	2,264
15	13,106	16,974	3,868	95.7	2,286	2,194	3,800	2,246
							Average final density	**2,219**
							COV (%)	**1.8**

Container ID	Empty mass (g)	Bowl + wet sample (g)	Bowl+ dry sample (g)	Moisture content
29	209.9	680.1	660	4.5
77	234.1	720.9	702.3	4.0
			Average compaction moisture content	**4.2**
			Moisture *before curing* (%)	**2.4**

G7 GYRATORY - 150/200 SPECIMENS

Sample number	Mass of mould (g)	Mould + material (g)	Sample mass (g)	Height (mm)	Bulk density (kg/m^3)	Dry density (kg/m^3)	Target mass (g)	Final density (kg/m^3)
1	11,831	15,648	3,817	102.2	2,113	2,016	3,701	2,048
2	12,286	16,111	3,825	102.9	2,103	2,007	3,709	2,039
3	12,136	15,966	3,830	102.9	2,105	2,009	3,713	2,041
4	11,471	15,328	3,857	102.9	2,120	2,023	3,740	2,056
5	13,159	16,986	3,827	102.3	2,116	2,019	3,711	2,052
6	13,143	16,993	3,850	103.9	2,096	2,000	3,733	2,032
7	11,512	15,354	3,842	103.3	2,104	2,008	3,725	2,040
8	12,139	15,996	3,857	104.7	2,084	1,989	3,740	2,020
9	12,246	16,090	3,844	104.7	2,077	1,982	3,727	2,014
10	12,834	16,697	3,863	104.6	2,089	1,994	3,745	2,025
11	13,156	16,997	3,841	103.4	2,101	2,005	3,724	2,037
12	13,143	16,977	3,834	102.7	2,112	2,015	3,717	2,047
13	13,158	16,987	3,829	103.1	2,101	2,005	3,713	2,037
14	13,142	16,976	3,834	103.6	2,093	1,998	3,717	2,030
15	15,159	19,014	3,855	104.2	2,093	1,997	3,738	2,029
							Average final density	2,037
							COV	1

Container ID	Empty mass (g)	Bowl + wet sample (g)	Bowl+ dry sample (g)	Moisture content
16	224.5	806.3	777.6	5.2
22	235.5	799.9	776.1	4.4
39	230.4	784.3	761.4	4.3
		Average compaction moisture content		4.6
		Moisture before curing (%)		1.6

G7 GYRATORY - 80/100 SPECIMENS

Sample number	Mass of mould (g)	Mould + material (g)	Sample mass (g)	Height (mm)	Bulk density (kg/m^3)	Dry density (kg/m^3)	Target mass (g)	Final density (kg/m^3)
1	11,834	15,656	3,822	103.2	2,095	1,999	3,706	2,031
2	12,134	15,959	3,825	103.9	2,082	1,987	3,818	2,079
3	12,285	16,125	3,840	104.4	2,081	1,986	3,833	2,077
4	11,470	15,311	3,841	103.4	2,101	2,005	3,834	2,098
5	13,144	16,971	3,827	103.9	2,084	1,988	3,820	2,080
6	13,161	16,990	3,829	104.1	2,081	1,986	3,822	2,077
7	11,470	15,296	3,826	103.5	2,091	1,995	3,819	2,087
8	11,833	15,652	3,819	104.3	2,071	1,977	3,812	2,068
9	12,134	15,968	3,834	104.6	2,073	1,979	3,827	2,070
10	11,469	15,310	3,841	103.8	2,093	1,998	3,834	2,090
11	11,831	15,676	3,845	105.1	2,069	1,975	3,838	2,066
12	12,282	16,132	3,850	105.0	2,074	1,979	3,843	2,070
13	13,143	16,963	3,820	104.0	2,078	1,983	3,813	2,074
14	13,158	16,998	3,840	104.8	2,073	1,978	3,833	2,069
15	13,142	16,989	3,847	105.4	2,065	1,970	3,840	2,061
							Average final density	2,073
							COV (%)	1

Container ID	Empty mass (g)	Bowl + wet sample (g)	Bowl+ dry sample (g)	Moisture content
45	231.3	687.6	666.5	4.848
43	240.5	684.9	664.9	4.713
B	173.5	640.6	619.2	4.801
		Average compaction moisture content		4.8
		Moisture before curing (%)		1.6

G2 SLAB 150/200 CORES

Sample number	Sample mass (g)	Height (mm)	Bulk density (kg/m^3)
1	1,318	37.8	2,266
2	1,505	43.4	2,251
3	1,490	42.1	2,296
4	2,087	61.5	2,203
5	1,906	54.5	2,271
6	2,240	63.8	2,278
7	1,579	45.9	2,233
8	1,798	49.6	2,355
9	1,895	54.8	2,246
11	2,277	63.7	2,323
12	2,109	59.3	2,308
13	1,931	56.7	2,212
14	1,771	47.0	2,446
		Average density	**2,284**
		COV (%)	**3**

Moisture content at compaction

Container ID	Empty mass (g)	Bowl + wet sample (g)	Bowl+ dry sample (g)	Moisture content
13	306.5	1845.9	1785.2	4.1
21	336	1464	1417.7	4.3
		Average moisture content before curing		**4.2**

Moisture content after coring and before curing

Container ID	Empty mass (g)	Bowl + wet sample (g)	Bowl+ dry sample (g)	Moisture content
25	201	627.2	617.8	2.3
17	317.2	525.3	520.1	2.6
		Average moisture content before curing		**2.4**

G7 SLAB 150/200 CORES

Sample number	Sample mass (g)	Height (mm)	Bulk density (kg/m^3)
1	1,670	52.9	2,049
2	1,667	54.1	2,003
3	1,308	42.1	2,015
4	1,356	45.5	1,937
5	1,323	43.8	1,964
6	1,473	47.1	2,029
7	1,353	44.6	1,968
8	1,040	32.4	2,088
9	1,540	48.3	2,070
		Average density	**1,995**
		COV (%)	**3**

Moisture content at compaction

Container ID	Empty mass (g)	Bowl + wet sample (g)	Bowl+ dry sample (g)	Moisture content
52	194.2	615	594.1	5.2
67	195.2	501	487.2	4.7
		Average moisture content before curing		**5.0**

Moisture content after coring and before curing

Container ID	Empty mass (g)	Bowl + wet sample (g)	Bowl+ dry sample (g)	Moisture content
66	237.5	596.6	591.4	1.5
72	233.3	573	568.5	1.3
		Average moisture content before curing		**1.4**

G7 SLAB 80/100 CORES

Sample number	Sample mass (g)	Height (mm)	Bulk density (kg/m^3)
1	1,674	51.8	2,097
2	2,101	66.1	2,064
3	1,573	53.6	1,905
4	1,578	52.1	1,965
5	1,898	59.8	2,060
6	1,952	65.7	1,928
7	1,622	52.2	2,016
8	1,814	57.1	2,064
9	2,295	75.5	1,974
10	1,830	58.1	2,045
11	1,593	50.9	2,033
12	1,588	50.7	2,033
13	1,662	55.4	1,947
		Average density	**2,010**
		COV (%)	**3**

Moisture at compaction

Container ID	Empty mass (g)	Bowl + wet sample (g)	Bowl+ dry sample (g)	Moisture content
66	356.2	1933.9	1860.1	4.9
72	401.8	1720.2	1663.8	4.5
		Average moisture content before curing		**4.7**

Moisture content after coring and before curing

Container ID	Empty mass (g)	Bowl + wet sample (g)	Bowl+ dry sample (g)	Moisture content
66	306.9	1933.9	1903.4	1.9
72	336.6	1711.9	1687.8	1.8
		Average moisture content before curing (%)		**1.8**

SUMMARY OF COMPACTION DATA

G2 150/200 SPECIMENS - AT COMPACTION

	Marshall	Hugo	Kango	Gyratory	Slab
Density	2.248	2.263	2.249	2.219	2.284
COV	1	2	1	2	3
MC(%)	4.1	3.7	4.3	4.2	4.2

G7 SPECIMENS - AT COMPACTION

	Marshall	Hugo	Kango	Gyratory	Slab	
Density	2.080	2.065	2.051	2.037	1.995	**150/200**
	2.042	2.017	2.036	2.073	2.01	**80/100**
COV	3	3	1	2	3	**150/200**
	2	1	2	1	3	**80/100**
MC(%)	4.6	4.4	4.1	4.6	5.0	**150/200**
	4.8	4.8	4.3	4.8	4.7	**80/100**

APPENDIX C: ANALYSIS OF VARIANCE

DENSITY ANOVA

G2 150/200

Marshall	Hugo	Kango	Gyratory	Slab	$V_{subtotals}$
2.215	2.138	2.235	2.113	2.266	0.034
2.280	2.231	2.263	2.199	2.251	0.004
2.280	2.302	2.276	2.202	2.296	0.008
2.294	2.249	2.276	2.220	2.203	0.006
2.238	2.254	2.239	2.213	2.271	0.002
2.252	2.243	2.257	2.217	2.278	0.002
2.231	2.301	2.231	2.256	2.233	0.004
2.263	2.247	2.264	2.221	2.355	0.012
2.232	2.310	2.248	2.254	2.246	0.004
2.222	2.291	2.276	2.236	2.323	0.008
2.236	2.259	2.209	2.223	2.308	0.006
2.250	2.271	2.226	2.154	2.212	0.012
2.232	2.306	2.238	2.259	2.446	0.041
2.245	2.282		2.264		10.140
			2.246		20.279
Total 31.470	31.685	29.237	33.278	29.689	
Mean 2.248	2.263	2.249	2.219	2.284	
Grand mean 2.252					

Variation		Df	MS	F	Fcritical
V_b	0.032	4	0.008	**0.02**	**<1**
V_w	30.531	68	0.449		
V	30.563				

G7 150/200

	80/100	150/200	Row total	Row mean
Marshall	2.042	2.080	4.122	2.061
Hugo	2.017	2.065	4.082	2.041
Kango	2.036	2.051	4.087	2.044
Gyratory	2.073	2.037	4.110	2.055
Slab	2.010	1.995	4.005	2.003
Column mean	2.036	2.046		
Grand total	20.406			
Grand mean	2.041			

Variation		Df	Mean square	F	$F_{critical}$
V_r	0.0042	4	0.0010	**1.67**	**6.39**
V_c	0.0003	1	0.0003	**0.40**	**<1**
V_e	0.0025	4	0.0006		
V	0.0069				

VOIDS ANOVA

G2 150/200

Marshall	Hugo	Kango	Gyratory	Slab	$V_{subtotals}$
19.7	22.4	18.9	23.3	17.8	1,675.658
17.3	19.1	17.9	20.3	18.4	1,339.426
17.3	16.5	17.5	20.1	16.7	1,188.290
16.8	18.4	17.4	19.5	20.1	1,318.648
18.8	18.2	18.8	19.7	17.6	1,346.552
18.3	18.6	18.1	19.6	17.4	1,307.788
19.1	16.6	19.1	18.2	19.0	1,304.157
17.9	18.5	17.9	19.4	14.6	1,199.998
19.0	16.2	18.5	18.3	18.5	1,261.253
19.4	16.9	17.4	18.9	15.8	1,198.642
18.9	18.1	19.9	19.4	16.3	1,328.137
18.4	17.6	19.3	21.9	19.8	1,478.109
19.0	16.3	18.8	18.1	11.3	1,086.840
18.6	17.2		17.9		744.366
			18.5		284.989
Total	258.5	250.7	239.5	293.0	223.1
Mean	18.5	17.9	18.4	19.5	17.2
Grand mean	18.3				

Variation		Df	MS	F	Fcritical
V_b	42.1	4	10.536	**0.02**	**<1**
V_w	18,020.7	68	265.010		
V	18,062.9				

G7 150/200

	80/100	**150/200**	**Row total**	**Row mean**
Marshall	17.8	16.3	34.1	17.1
Hugo	18.8	16.9	35.7	17.9
Kango	18.1	17.5	35.5	17.8
Gyratory	16.6	18.0	34.6	17.3
Slab	19.1	19.7	38.8	19.4
Column mean	18.1	17.7		
Grand total	178.8			
Grand mean	17.9			

Variation		Df	MS	F	$F_{critical}$
V_r	6.749	4	1.687	**1.67**	**6.39**
V_c	0.405	1	0.405	**0.40**	**<1**
V_e	4.044	4	1.011		
V	11.197				

ITS ANOVA

G2 150/200

				Total	Mean
Marshall	160	261	227	**648**	**216**
Hugo	311	318	293	**922**	**307**
Kango	407	497		**904**	**452**
Gyratory	241	318	187	**746**	**249**
Slab	296	290	318	**904**	**301**
				Grand mean	**295**

Variation		**Df**	**MS**	**F**	**Fcritical**
V_b	68,576	4	17,144	**8.83**	**3.18**
V_w	25,227	13	1,941		
V	93,803				

G7 150/200

		80/100	**150/200**	**Row total**	**Row mean**
Marshall		359	353	**712**	**356**
Hugo		313	322	**634**	**317**
Kango		357	418	**775**	**388**
Gyratory		401	385	**786**	**393**
Slab		625	645	**1,270**	**635**
Column mean		411	425		
Grand total		4,177			
Grand mean		418			

Variation		**Df**	**MS**	**F**	**$F_{critical}$**
V_r	125,294	4	31323	**70.22**	**6.39**
V_c	464	1	464	**1.04**	**7.71**
V_e	1,784	4	446		
V	127,542				

ITT ANOVA

G2 150/200

					Total	Mean
Marshall	1535	1166	1297		**3998**	**1333**
Hugo	2022	2533	1842	2668	**9065**	**2266**
Kango	1576	1263	1297		**4136**	**1379**
Gyratory	1298	1473	1224	1717	**5712**	**1428**
Slab	1083	1030			**2113**	**1057**
					Grand mean	**1472**

Variation		Df	MS	F	Fcritical
V_b	2,952,811	4	738,203	**5.28**	**3.06**
V_w	2,096,207	15	139,747		
V	5,049,018				

G7 150/200

	80/100	150/200	Row total	Row mean
Marshall	1,107	1,607	2,714	1,357
Hugo	2,018	1,991	4,009	2,005
Kango	1,894	1,537	3,431	1,716
Gyratory	2,018	1,830	3,848	1,924
Slab	1,474	1,783	3,257	1,629
Column mean	1,702	1,750		
Grand total	17,259			
Grand mean	1,726			

Variation		Df	MS	F	$F_{critical}$
V_r	525,087	4	131,272	**2.09**	**6.39**
V_c	3,370	1	3,370	**0.05**	**<1**
V_e	251,131	4	62,783		
V	779,589				

SCB ANOVA

G2 80/200

					Total	Mean
Marshall	232	238	396		**866**	**289**
Hugo	224	403	306		**933**	**311**
Kango	364	183	344	345	**1236**	**309**
Gyratory	218	244	124	220	**806**	**202**
Slab	802	637	548		**1987**	**662**
					Grand mean	**416**

Variation		Df	MS	F	Fcritical
V_b	308,915	4	77,229	**3.63**	**3.18**
V_w	276,735	13	21,287		
V	585,651				

G7 150/200

	80/100	150/200	Row total	Row mean
Marshall	525	732	1,257	629
Hugo	504	537	1,041	521
Kango	839	727	1,566	783
Gyratory	649	782	1,431	716
Slab	864	743	1,607	804
Column mean	676	704		
Grand total	6,902			
Grand mean	690			

Variation		Df	MS	F	$F_{critical}$
V_r	109,388	4	27347	**2.58**	**6.39**
V_c	1,960	1	1960	**0.18**	**<1**
V_e	42,446	4	10612		
V	153,794				

APPENDIX D: COMPUTER SOFTWARE

ITS data capturing computer program

```
Program ADDemo;

USES
   Dos, Crt, Graph;

type
 ADdata = ARRAY[0..3] of integer;  {4 channel type to place your data in}

CONST
 MaxSampleArray   = 2000;
 {InitialSampleRate = MTempo;} {Hz}
 BaseAdress       = $360;
 PCclock          : byte = 0;
 SampleRateCounter   : word = 0;
 CheckForSampleRate  : word = 0;
 vp1 : ViewPortType = (x1: 10; y1: 80; x2: 100; y2: 150;
 Clip : ClipOn);
 vp2 : ViewPortType = (x1: 110; y1: 0; x2: 200; y2:  70;
 Clip : ClipOn);



VAR
 PCclock55ms   : Procedure;
 SampledArray  : array[1..4,0..MaxSampleArray] of integer;
 Dat           : ADData;
 Head,Tail,i,teller   : integer;
 Vector1       : pointer;
 f : text;
 Leernaam : String;
 MaksMonsters,InitialSampleRate,AantalKanale  : integer;
 tyd,tydini : word;
 GraphDriver, GraphMode : Integer;


{-------------------------------------------------------}

Procedure GetSampleInterrupt;  {This is the ISR for each sample at samplerate}
interrupt;

begin
 inline ($FA);        { Stop Intrr. }
 inc(PCclock);        { Increment the time }
 inc(SampleRateCounter);
 if (PCclock >= 64) then { If this is the 64th call, then call PC clock handler }
 begin
  inline ($9C);
  PCclock55ms;        {Call 55ms PC Timer handler}
  PCclock := 0;       {reset check counter}
 end                  { Otherwise, Check and clear the interrupt controller }
 else
 begin
  IF SampleRateCounter >= CheckForSampleRate then {Do We Sample?}
   begin
    SampleRateCounter := 0;                       {Reset check counter}
    {********** INSERT YOUR A/D CODE HERE **********}
    asm
     mov dx,BaseAdress
```

```
      out dx,al            {Start conversion}
      mov cx,100H
      mov dx,BaseAdress+2
    @1:
      out dx,al            {Clock interrupt line in latch}
      in al,dx             {Poll BaseAdress interrupt}
      and al,80H
      loopnz @1
      mov di,offset DAT
      mov cx,4
    @2:
      mov dx,BaseAdress
      in al,dx             {Read low byte}
      mov bl,al
      mov dx,BaseAdress+2
      in al,dx             {Read high byte}
      and al,0FH
      mov bh,al
      and al,08H
      jz @3
      sub bx,1000H
    @3:
      mov [di],bx          {Store channel A/D data}
      inc di
      inc di
      loop @2
    end;
    SampledArray[1,Head] := Dat[0];   {Place in data cyclic buffer}
    SampledArray[2,Head] := Dat[1];
    SampledArray[3,Head] := Dat[2];
    SampledArray[4,Head] := Dat[3];

    {********** END OF YOUR A/D CODE ************}
    inc(Head,1);
    IF (Head>MaxSampleArray) then Head := 0;
   end;
  port[$20] := $20;          {End of interrupt}
 end;
 inline ($FB);
end;

{-------------------------------------------------------}
{ This routine will start the fast clock rate by installing the
  GetSampleInterrupt routine as the interrupt service routine for the clock
  interrupt and then setting the interrupt rate up to its higher speed
  by programming the 8253 timer chip.}
Procedure Start_PCfastclock;

begin
    CheckForSampleRate := trunc(1165/InitialSampleRate);
       asm cli end;                  { Disable interrupts }
       getIntvec($08,@PCclock55ms);      { Store the old interrupt handler }
       setIntvec($08,addr(GetSampleInterrupt)); { Install the new interrupt handler }
                                     { Increase the clock rate }
       port[$43]:=$36;  { Set up for count to be sent}
       port[$40]:=$00;  { LSB = 00 \_together make 2^10 = 1024}
       port[$40]:=$04;  { MSB = 04 /       }
       asm sti end;                  { Enable interrupts }
end;
```

```
{-------------------------------------------------}

Procedure Stop_PCfastclock;

begin
        asm cli; end;                { Disable interrupts }
     SetIntVec($08,Addr(PCclock55ms)); { Reinstate the old interrupt handler *}
                        { Reinstate the clock rate to 18.2 Hz *}
        port[$43] := $36;          {/ Set up for count to be sent}
        port[$40] := $00;          {/ LSB = 00  \_together make 65536 (0)}
        port[$40] := $00;          {/ MSB = 00  /                    }
        asm sti end;                 { Enable interrupts }
end;


{-------------------------------------------------}

Procedure Time;

var
 h, m, s, hund : Word;
begin
 GetTime(h,m,s,hund);
  {Writeln('Time is now ',3600*h+60*m+s,'secs');}
 tyd:=3600*h+60*m+s
end;

{-------------------------------------------------}



{-------------------------------------------------}

Procedure ServiceTheSample;
VAR a : integer;
begin
IF Head<>Tail then   {Check cyclic buffer counters}
begin
  {gotoXY(1,2);}
  {writeln(f,teller); }

  time;
  FOR a := 1 to AantalKanale do write(f,' ',SampledArray[a,Tail],' ');
  writeln(f);
  inc(Tail,1);
  inc(teller);
  IF (Tail>MaxSampleArray) then Tail :=0;
 end;
end;


Procedure Kry_Inligting;

begin;
 Write('Filename for data storage : ');
 Readln(Leernaam);
 assign(f,Leernaam);          {          }
 rewrite(f);                  {Maak leer oop}
 {writeln('Gee aantal kanale om te meet (1, 2, 3 of 4)');}
{ Read(AantalKanale);}
```

```
  AantalKanale:=4;
{ writeln('Gee aantal monsters per kanaal');}
{ Read(MaksMonsters);}
MaksMonsters:=400;
{ writeln('Gee monstertempo in Hertz');}
{ Read(InitialSampleRate);}
InitialSampleRate:=10
end;


{-------------------------------------------------}

begin

{ GraphDriver := Detect;
 InitGraph(GraphDriver,GraphMode,'');
 if GraphResult <> grOk then Halt(1);
 with vp1 do
 begin
   { Outline viewport 1 }
{   Rectangle(Succ(x1),Succ(y1),
          Pred(x2),Pred(y2));
   SetViewPort(x1, y1, x2, y2, ClipOn);
   OutText('ViewPort1');
 end;
 readln;
 { Full screen }
{ SetViewPort(0, 0, GetMaxX, GetMaxY,
          ClipOn);
 with vp2 do
 begin
   { Outline viewport 2 }
{   Rectangle(Succ(x1),Succ(y1),
          Pred(x2),Pred(y2));
   SetViewPort(x1, y1, x2, y2, ClipOn);
   OutText('ViewPort2');
end;
ReadLn;
CloseGraph;

}



clrscr;                 {Load all interrupts and timers}

writeln('ResAdF v1.00b ResMod (Horizontal)  Test - AdF Smit - Sept '96');
writeln;

Kry_Inligting;
Head:=0;
Tail:=0;
teller :=0;
writeln;
writeln('Press any key to start test...');
repeat until KeyPressed;
Time;
tydini:=tyd;
   Start_PCfastclock;
```

```
  clrscr;
  repeat
    time;
    gotoxy(1,1);
    writeln('Time : ',tyd-tydini);
    ServiceTheSample;
  until teller > MaksMonsters;

  Stop_PCFastClock;
  writeln;
  writeln('Head=',Head,'  Tail=',Tail);
  Time;
  close(f);
end.
```

ITT data capturing computer program

```
Program ADDemo;

USES
   Dos, Crt, Graph;

type
 ADdata = ARRAY[0..3] of integer;  {4 channel type to place your data in}

CONST
 MaxSampleArray   = 2000;
 {InitialSampleRate = MTempo;} {Hz}
 BaseAdress       = $360;
 PCclock          : byte = 0;
 SampleRateCounter   : word = 0;
 CheckForSampleRate  : word = 0;
 vp1 : ViewPortType = (x1: 10; y1: 80; x2: 100; y2: 150;
 Clip : ClipOn);
 vp2 : ViewPortType = (x1: 110; y1: 0; x2: 200; y2:  70;
 Clip : ClipOn);



VAR
 PCclock55ms   : Procedure;
 SampledArray  : array[1..4,0..MaxSampleArray] of integer;
 Dat           : ADData;
 Head,Tail,i,teller   : integer;
 Vector1       : pointer;
 f : text;
 Leernaam : String;
 MaksMonsters,InitialSampleRate,AantalKanale  : integer;
 tyd,tydini : word;
 GraphDriver, GraphMode : Integer;


{-------------------------------------------------------}

Procedure GetSampleInterrupt;  {This is the ISR for each sample at samplerate}
interrupt;

begin
 inline ($FA);         { Stop Intrr. }
 inc(PCclock);         { Increment the time }
 inc(SampleRateCounter);
 if (PCclock >= 64) then { If this is the 64th call, then call PC clock handler }
 begin
  inline ($9C);
  PCclock55ms;         {Call 55ms PC Timer handler}
  PCclock := 0;        {reset check counter}
 end                { Otherwise, Check and clear the interrupt controller }
 else
 begin
  IF SampleRateCounter >= CheckForSampleRate then {Do We Sample?}
    begin
     SampleRateCounter := 0;                    {Reset check counter}
     {********** INSERT YOUR A/D CODE HERE **********}
```

```
      asm
       mov dx,BaseAdress
       out dx,al          {Start conversion}
       mov cx,100H
       mov dx,BaseAdress+2
      @1:
       out dx,al          {Clock interrupt line in latch}
       in al,dx           {Poll BaseAdress interrupt}
       and al,80H
       loopnz @1
       mov di,offset DAT
       mov cx,4
      @2:
       mov dx,BaseAdress
       in al,dx           {Read low byte}
       mov bl,al
       mov dx,BaseAdress+2
       in al,dx           {Read high byte}
       and al,0FH
       mov bh,al
       and al,08H
       jz @3
       sub bx,1000H
      @3:
       mov [di],bx        {Store channel A/D data}
       inc di
       inc di
       loop @2
      end;
      SampledArray[1,Head] := Dat[0];   {Place in data cyclic buffer}
      SampledArray[2,Head] := Dat[1];
      SampledArray[3,Head] := Dat[2];
      SampledArray[4,Head] := Dat[3];

      {********** END OF YOUR A/D CODE ***********}
      inc(Head,1);
      IF (Head>MaxSampleArray) then Head := 0;
     end;
   port[$20] := $20;          {End of interrupt}
  end;
  inline ($FB);
end;

{-------------------------------------------------------}
{  This routine will start the fast clock rate by installing the
   GetSampleInterrupt routine as the interrupt service routine for the clock
   interrupt and then setting the interrupt rate up to its higher speed
   by programming the 8253 timer chip.}
Procedure Start_PCfastclock;

begin
      CheckForSampleRate := trunc(1165/InitialSampleRate);
         asm cli end;                  { Disable interrupts }
         getIntvec($08,@PCclock55ms);      { Store the old interrupt handler }
         setIntvec($08,addr(GetSampleInterrupt)); { Install the new interrupt handler }
                                       { Increase the clock rate }
         port[$43]:=$36;   { Set up for count to be sent}
         port[$40]:=$00;   { LSB = 00 \_together make 2^10 = 1024}
         port[$40]:=$04;   { MSB = 04 /       }
         asm sti end;                  { Enable interrupts }
```

```
end;

{-------------------------------------------------}

Procedure Stop_PCfastclock;

begin
        asm cli; end;                { Disable interrupts }
     SetIntVec($08,Addr(PCclock55ms)); { Reinstate the old interrupt handler *}
                          { Reinstate the clock rate to 18.2 Hz *}
        port[$43] := $36;        {/ Set up for count to be sent}
        port[$40] := $00;        {/ LSB = 00  \_together make 65536 (0)}
        port[$40] := $00;        {/ MSB = 00  /                    }
        asm sti end;               { Enable interrupts }
end;


{-------------------------------------------------}

Procedure Time;

var
 h, m, s, hund : Word;
begin
 GetTime(h,m,s,hund);
  {Writeln('Time is now ',3600*h+60*m+s,'secs');}
 tyd:=3600*h+60*m+s
end;

{-------------------------------------------------}



{-------------------------------------------------}

Procedure ServiceTheSample;
VAR a : integer;
begin
 IF Head<>Tail then   {Check cyclic buffer counters}
 begin
  {gotoXY(1,2);}
  {writeln(f,teller); }

  time;
  FOR a := 1 to AantalKanale do write(f,' ',SampledArray[a,Tail],' ');
  writeln(f);
  inc(Tail,1);
  inc(teller);
  IF (Tail>MaxSampleArray) then Tail :=0;
 end;
end;


Procedure Kry_Inligting;

begin;
 Write('Filename for data storage : ');
 Readln(Leernaam);
 assign(f,Leernaam);        {          }
 rewrite(f);              {Maak leer oop}
```

```
 {writeln('Gee aantal kanale om te meet (1, 2, 3 of 4)');}
{ Read(AantalKanale);}
  AantalKanale:=4;
{ writeln('Gee aantal monsters per kanaal');}
{ Read(MaksMonsters);}
MaksMonsters:=2000;
{ writeln('Gee monstertempo in Hertz');}
{ Read(InitialSampleRate);}
InitialSampleRate:=10000
end;


{-------------------------------------------------}

begin

{ GraphDriver := Detect;
 InitGraph(GraphDriver,GraphMode,'');
 if GraphResult <> grOk then Halt(1);
 with vp1 do
 begin
   { Outline viewport 1 }
{   Rectangle(Succ(x1),Succ(y1),
         Pred(x2),Pred(y2));
   SetViewPort(x1, y1, x2, y2, ClipOn);
   OutText('ViewPort1');
 end;
 readln;
 { Full screen }
{ SetViewPort(0, 0, GetMaxX, GetMaxY,
         ClipOn);
 with vp2 do
 begin
   { Outline viewport 2 }
{   Rectangle(Succ(x1),Succ(y1),
         Pred(x2),Pred(y2));
   SetViewPort(x1, y1, x2, y2, ClipOn);
   OutText('ViewPort2');
 end;
 ReadLn;
 CloseGraph;

 }


 clrscr;                {Load all interrupts and timers}

 writeln('ResAdF v1.00b ResMod (Horizontal)  Test - AdF Smit - Sept '96');
 writeln;

 Kry_Inligting;
 Head:=0;
 Tail:=0;
 teller :=0;
 writeln;
 writeln('Press any key to start test...');
 repeat until KeyPressed;
 Time;
 tydini:=tyd;
    Start_PCfastclock;
```

```
  clrscr;
  repeat
    time;
    gotoxy(1,1);
    writeln('Time : ',tyd-tydini);
    ServiceTheSample;
  until teller > MaksMonsters;

  Stop_PCFastClock;
  writeln;
  writeln('Head=',Head,'  Tail=',Tail);
  Time;
  close(f);
end.
```

SCB data capturing computer program

```
Program ADDemo;

USES
   Dos, Crt, Graph;

type
 ADdata = ARRAY[0..3] of integer;  {4 channel type to place your data in}

CONST
 MaxSampleArray   = 2000;
 {InitialSampleRate = MTempo;} {Hz}
 BaseAdress       = $360;
 PCclock          : byte = 0;
 SampleRateCounter   : word = 0;
 CheckForSampleRate  : word = 0;
 vp1 : ViewPortType = (x1: 10; y1: 80; x2: 100; y2: 150;
 Clip : ClipOn);
 vp2 : ViewPortType = (x1: 110; y1: 0; x2: 200; y2:  70;
 Clip : ClipOn);



VAR
 PCclock55ms   : Procedure;
 SampledArray  : array[1..4,0..MaxSampleArray] of integer;
 Dat           : ADData;
 Head,Tail,i,teller   : integer;
 Vector1       : pointer;
 f : text;
 Leernaam : String;
 MaksMonsters,InitialSampleRate,AantalKanale  : integer;
 tyd,tydini : word;
 GraphDriver, GraphMode : Integer;


{-------------------------------------------------------}

Procedure GetSampleInterrupt;  {This is the ISR for each sample at samplerate}
interrupt;

begin
 inline ($FA);         { Stop Intrr. }
 inc(PCclock);         { Increment the time }
 inc(SampleRateCounter);
 if (PCclock >= 64) then { If this is the 64th call, then call PC clock handler }
 begin
  inline ($9C);
  PCclock55ms;        {Call 55ms PC Timer handler}
  PCclock := 0;       {reset check counter}
 end                  { Otherwise, Check and clear the interrupt controller }
 else
 begin
  IF SampleRateCounter >= CheckForSampleRate then {Do We Sample?}
   begin
    SampleRateCounter := 0;                       {Reset check counter}
```

```
    {********** INSERT YOUR A/D CODE HERE **************}
    asm
     mov dx,BaseAdress
     out dx,al          {Start conversion}
     mov cx,100H
     mov dx,BaseAdress+2
    @1:
     out dx,al          {Clock interrupt line in latch}
     in al,dx           {Poll BaseAdress interrupt}
     and al,80H
     loopnz @1
     mov di,offset DAT
     mov cx,4
    @2:
     mov dx,BaseAdress
     in al,dx           {Read low byte}
     mov bl,al
     mov dx,BaseAdress+2
     in al,dx           {Read high byte}
     and al,0FH
     mov bh,al
     and al,08H
     jz @3
     sub bx,1000H
    @3:
     mov [di],bx        {Store channel A/D data}
     inc di
     inc di
     loop @2
    end;
    SampledArray[1,Head] := Dat[0];   {Place in data cyclic buffer}
    SampledArray[2,Head] := Dat[1];
    SampledArray[3,Head] := Dat[2];
    SampledArray[4,Head] := Dat[3];

    {********** END OF YOUR A/D CODE ************}
    inc(Head,1);
    IF (Head>MaxSampleArray) then Head := 0;
   end;
  port[$20] := $20;         {End of interrupt}
 end;
 inline ($FB);
end;

{-------------------------------------------------------}
{ This routine will start the fast clock rate by installing the
  GetSampleInterrupt routine as the interrupt service routine for the clock
  interrupt and then setting the interrupt rate up to its higher speed
  by programming the 8253 timer chip.}
Procedure Start_PCfastclock;

begin
    CheckForSampleRate := trunc(1165/InitialSampleRate);
       asm cli end;                  { Disable interrupts }
       getIntvec($08,@PCclock55ms);      { Store the old interrupt handler }
       setIntvec($08,addr(GetSampleInterrupt)); { Install the new interrupt handler }
                                     { Increase the clock rate }
       port[$43]:=$36;  { Set up for count to be sent}
       port[$40]:=$00;  { LSB = 00 \_together make 2^10 = 1024}
       port[$40]:=$04;  { MSB = 04 /       }
```

```
        asm sti end;                    { Enable interrupts }
end;

{-------------------------------------------------------}

Procedure Stop_PCfastclock;

begin
        asm cli; end;                   { Disable interrupts }
    SetIntVec($08,Addr(PCclock55ms)); { Reinstate the old interrupt handler *}
                                { Reinstate the clock rate to 18.2 Hz *}
        port[$43] := $36;       {/ Set up for count to be sent}
        port[$40] := $00;       {/ LSB = 00  \_together make 65536 (0)}
        port[$40] := $00;       {/ MSB = 00 /                   }
        asm sti end;                    { Enable interrupts }
end;


{-------------------------------------------------------}

Procedure Time;

var
 h, m, s, hund : Word;
begin
 GetTime(h,m,s,hund);
  {Writeln('Time is now ',3600*h+60*m+s,'secs');}
  tyd:=3600*h+60*m+s
end;

{-------------------------------------------------------}



{-------------------------------------------------------}

Procedure ServiceTheSample;
VAR a : integer;
begin
 IF Head<>Tail then   {Check cyclic buffer counters}
 begin
  {gotoXY(1,2);}
  {writeln(f,teller); }

  time;
  FOR a := 1 to AantalKanale do write(f,' ',SampledArray[a,Tail],' ');
  writeln(f);
  inc(Tail,1);
  inc(teller);
  IF (Tail>MaxSampleArray) then Tail :=0;
 end;
end;


Procedure Kry_Inligting;

begin;
 Write('Filename for data storage : ');
 Readln(Leernaam);
 assign(f,Leernaam);        {          }
```

```
 rewrite(f);                {Maak leer oop}
 {writeln('Gee aantal kanale om te meet (1, 2, 3 of 4)');}
{  Read(AantalKanale);}
  AantalKanale:=4;
{  writeln('Gee aantal monsters per kanaal');}
{  Read(MaksMonsters);}
MaksMonsters:=600;
{  writeln('Gee monstertempo in Hertz');}
{  Read(InitialSampleRate);}
InitialSampleRate:=10
end;


{-------------------------------------------------}

begin

{  GraphDriver := Detect;
 InitGraph(GraphDriver,GraphMode,'');
 if GraphResult <> grOk then Halt(1);
 with vp1 do
 begin
   { Outline viewport 1 }
{   Rectangle(Succ(x1),Succ(y1),
         Pred(x2),Pred(y2));
   SetViewPort(x1, y1, x2, y2, ClipOn);
   OutText('ViewPort1');
 end;
 readln;
 { Full screen }
{  SetViewPort(0, 0, GetMaxX, GetMaxY,
         ClipOn);
 with vp2 do
 begin
   { Outline viewport 2 }
{   Rectangle(Succ(x1),Succ(y1),
         Pred(x2),Pred(y2));
   SetViewPort(x1, y1, x2, y2, ClipOn);
   OutText('ViewPort2');
 end;
 ReadLn;
 CloseGraph;

 }


 clrscr;                {Load all interrupts and timers}

 writeln('ResAdF v1.00b ResMod (Horizontal)  Test - AdF Smit - Sept '96');
 writeln;

 Kry_Inligting;
 Head:=0;
 Tail:=0;
 teller :=0;
 writeln;
 writeln('Press any key to start test...');
 repeat until KeyPressed;
 Time;
 tydini:=tyd;
```

```
    Start_PCfastclock;
  clrscr;
  repeat
    time;
    gotoxy(1,1);
    writeln('Time : ',tyd-tydini);
    ServiceTheSample;
  until teller > MaksMonsters;

  Stop_PCFastClock;
  writeln;
  writeln('Head=',Head,'  Tail=',Tail);
  Time;
  close(f);
end.
```

Mechanised Hamer LVDT data capturing computer program

```
{-------------------------------------------------
MODULE ID  : ASA2 Demo program
FILENAME   : asademo2.pas
COMPILER   : TP7
FUNCTION   : Demo's hardware interrupt
LOCAL PROC : None
CHANGES    : Date       Version  Author
1          10/01/95   3.00     Paul Bailey}


Program ASA_Demo_Program;  {Leernaam: ASAHW.pas}

uses Crt, Dos,  ASA_Drv, SED_Intt;

CONST
 MaxSampleArray  = 20000;
 BaseAdress      = $360;

 Type
 SampleStructure = array[0..MaxSampleArray] of integer;

VAR
 SampledArray    : ARRAY[1..4] of ^SampleStructure;
 {MaxSampleArray  : Integer}
 Head,HeadPos,Tail : integer;
 InitialSamplerate : Integer;
 SampleRAte      : longint;
 Trigger         : byte;
 F               : Text;
 Start           : real;
 Skaal           : real;
 Stop            : boolean;
 Leernaam        : String;
 I               : integer;
 J,jjj           : integer;
 NoOfCh,monsters  : integer;
{-------------------------------------------------}

Procedure GetInterruptSample;  {ISR for each SampledArray at samplerate}
interrupt;

begin
 inline ($FA);                  { Stop Intrr. }

 ASA_AtoD(BaseAdress,Dat);          {Do A/D conversion}

 SampledArray[1]^[Head]  := Dat[0];  {1}
 SampledArray[2]^[Head]  := Dat[1];
 SampledArray[3]^[Head]  := Dat[2];
 SampledArray[4]^[Head]  := Dat[3];

 IF Head >= Monsters then Stop := True;

 inc(Head,1);
 IF (Head>MaxSampleArray) then Head := 0;

 port [$20] := $20;                 { Herstel 8259 }
```

```
 inline ($FB);
end;

{-------------------------------------------------------}

Procedure Kry_Inligting;

begin;
 {Writeln('Skaal: -2048=-10 Volt, 2048=+10 Volt');}
 writeln;
 repeat
  Writeln('Gee Leernaam om data te stoor (bv. T1.dat )');
  Writeln('Druk ENTER om te begin meet, CTRL BREAK om te stop');
  Readln(Leernaam);
 until Leernaam<>'';
 assign(f,Leernaam);          {          }
 rewrite(f);                  {Maak leer oop}
 {writeln('Gee aantal kanale om te meet (1, 2, 3 of 4)');
 Readln(NoOfCh);}
 NoOfCh:=1;
 {writeln('Gee aantal monsters per kanaal (20000 maks)');
 Readln(Monsters);}
 Monsters:=3840;
 {writeln('Gee monstertempo in Hertz (     16 Minimum)');
 Readln(InitialSampleRate);}
 InitialSampleRate:=16;
 {writeln('Gee skaalfaktor (bv. 0.036)');
 Readln(skaal);}
 skaal:=28.5;
end;

{-------------------------------------------------------}

begin
 jjj:=0;
repeat
 new(SampledArray[1]);
 new(SampledArray[2]);
 new(SampledArray[3]);
 new(SampledArray[4]);
 clrscr;
 writeln('--------- ASA Meetprogram ----------');
 writeln;

 Kry_Inligting;            {Maak leer oop}

 ASA_TimerControl(BaseAdress,$34);       {Setup timer for samplerate, Mode 2}
 SampleRAte := trunc(1000000/InitialSampleRate) and $FFFF;
 ASA_WriteTimerCounter(BaseAdress,0,SampleRAte); {Initial value @1MHz clock = 4Mhz/4}
 ASA_WriteDigitalCmndPort(BaseAdress,$90); {8255 PA in, PB,PC=Out}
 ASA_WriteDigitalPort(BaseAdress,2,$80);   {write to portC7, a value 1 to enable int1}
 SED_InitInterrupt_IRQ(5, @GetInterruptSample); {execute ISR}

 {This will be where you check for sampled data}
 Tail  := 0;
 Head  := 0;
 Stop  := False;

 repeat
   IF head<>Tail then
```

```
    begin
     gotoxy(60,10);
     IF Tail mod InitialSampleRAte = 0 then
     begin
      writeln(Tail,' ',SampledArray[1]^[Tail]/skaal:6:1);
     end;
     inc(Tail,1);
     IF (Tail>MaxSampleArray) then Tail := 0;
    end;
  until Stop;

  writeln;
  writeln;
  SED_StopInterrupt_IRQ; {Stop ISR}

  {Stoor data}
  FOR I := 1 to Monsters do
   begin
    For J:=1 to NoOfCh do
     begin
      write(f,SampledArray[J]^[I]/skaal:6:1);
     end;
     writeln(f,'');
   end;
  close(F);

  dispose(SampledArray[1]);
  dispose(SampledArray[2]);
  dispose(SampledArray[3]);
  dispose(SampledArray[4]);
until jjj=1
end.
```