VIBRATORY HAMMER COMPACTION OF BITUMIN STABILIZED MATERIALS

by

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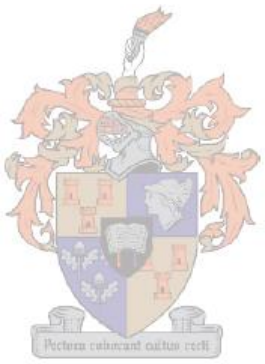
Thesis presented in partial fulfilment of the requirements for the degree of



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EXECUTIVE SUMMARY

There are currently well established compaction methods being used in laboratories globally to prepare specimens for material testing. None of these methods provides the repeatability and reproducibility, ease of execution or simulation and correlation to field compaction desired by engineers. The research presented in this report was aimed at the development of a new or adapted compaction method for bituminous stabilized materials (BSM) that would address the aforementioned factors, by making use of a vibratory hammer. Along with this, a new protocol was to be established.

The initial vibratory hammer that was tested was the Kango 637®. This specific vibratory hammer suffered irreparable damage to the gearbox during the research. A replacement Kango hammer could not be purchased, therefore a substitute hammer was purchased i.e. a Bosch GSH 11E®, for which back-up service and replacement parts are readily available throughout South Africa.

Significant progress had been made with the development of a laboratory compaction protocol for BSM using the Kango Hammer. The specifications of the Bosch® hammer showed it was superior in terms of power, weight and other technical features. Comparative testing was therefore carried out. This allowed for the adaptation of the results achieved to that point.

Extensive experimentation was then carried out using two types of BSM i.e. foamed bitumen (80/100 bitumen) and bitumen emulsion (60/40 Anionic Stable Grade) stabilized material. The initial material used for the experimentation was a G2 quality graded crushed stone. Additional material was also obtained from a recycling project taking place along the N7 near Cape Town. The N7 material was used to perform correlation experiments so as to determine how representative the laboratory compacted specimens were to field compacted material.

Results showed that the vibratory hammer is capable of producing specimens for testing in the laboratory as well as providing a possible benchmark method for accurately controlling the quality of work on site i.e. field density control. This was done by identifying the time to and level of refusal density compaction. The level of refusal density compaction was expressed as a percentage of Mod AASHTO compaction and using current specifications, a potentially new site compaction level specification was determined.

In order to asses the material applicability of the vibratory hammer compaction method, tests regarding moisture sensitivity analysis were carried out on a G5 material. The vibratory compaction protocol includes a specification for the type of hammer, guide-frame, surcharge weight, compaction moisture and number of layers. Vibratory compaction can be used to prepare two types of specimens:

- Specimens for triaxial testing with a diameter of 150mm and a height of 300mm
- Specimens for laboratory testing with a diameter of 150mm and a height of 125mm.

Tests showed that the material properties prove to have an influence on the compactability of the material. Material from the N7 recycling project had been milled out thus altering the grading and including some RAP. This in turn influenced compaction. The vibratory hammer moisture curve was found to shift slightly to the left when compared to the Mod AASHTO moisture curve. The variability of the vibratory hammer was found to be well below the specified variability of 15%. Repeatability experiments on G5 material indicate that vibratory hammer compaction may be used on lesser quality granular materials.

A recommended procedure for the compaction of BSM was developed following the experimentation results.

OPSOMMING

Daar is reeds gevestigde kompaksiemetodes wat wêreld wyd in laboratoriums gebruik word. Dié kompaksie-metodes word gebruik om monsters voor te berei vir die toets van materiale. Nie een van dié metodes voorsien die herhaaldelikheid, reprodisering, uitvoerbaarheid of simulasie en korrelasie van terrein-kompaksie wat ingenieurs benodig nie. Die ondersoek fokus op die doel om met behulp van 'n vibrasie-hamer 'n nuwe kompaksiemetode vir Bitumineus-Gestabiliseerde Materiale (BSM) te ontwerp met die doel om bogenoemde faktore aan te spreek. Tans word gepoog om 'n protokol vir die nuwe kompaksiemetode te ontwikkel en te vestig.

Vir die bogenoemde kompaksie is die Kango 637® vibrasiehamer oorspronklik gebruik. Dié hamer se ratkas het permanente skade opgedoen gedurende die navorsing. Weens die feit dat Kango® nie meer op die Suid-Afrikaanse mark beskikbaar is nie, is die hamer vervang met 'n Bosch GSH 11E®.

Voortreflike progressie met die gebruik van 'n Kango® hamer is gemaak in die ontwikkeling van die kompaksiemetode protokol vir die BSM. Die spesifikasie van die Bosch GSH 11E® hamer bewys dat dit superieur in terme van krag, gewig en ander tegniese kenmerke is. Vergelykingstoetse tussen die Bosch® en die Kango® was ook uitgevoer. Die toetse laat toe dat die resultate van die Kango-eksperimente aangepas kan word, om die Bosch® te akkommodeer.

Verder is eksperimente uitgevoer op twee tipes BSM, naamik skuimbitumen (80/100 penetrasie) en bitumen-emulsie (60/40 Anioniese Stabiele Graad) gestabiliseerde materiaal. Die oorspronklike materiaal wat gebruik was vir die eksperimente was 'n G2 kwaliteit gegradeerde vergruisde klip. Om terrein-kompaksie te simuleer in die laboratorium is korrelasie-eksperimente uitgevoer op addisionele materiaal. Dié addisionele materiaal was bekom deur middel van 'n herwinningsprojek wat op die N7 naby Kaapstad plaasgevind het.

Die resultate van die eksperimente toon dat die vibrasiehamer suksesvol was in die produsering van monsters in die laboratorium. Die resultate toon ook dat die vibrasiehamer gebruik kan word as 'n maatstaf vir die vlak van terrein kompaksie en die spesifikasie daarvan.

Om te bevestig dat die vibrasiehamer ook op laer kwalitiet materiale gebruik kan word, was daar vogsensitiwiteits-analise-eksperimente op 'n G5 materiaal gedoen. Die kompaksieprotokol wat vir die vibrasie hamer ontwerp is, sluit die volgende in:

- Tipe vibrasiehamer,
- Gidsraam (guide-frame),
- gewig van die dooielas,
- Kompaksie-vog
- en die aantal lae vir kompaksie.

Twee tipe monsters kan geproduseer word met hierdie kompaksieprotokol, naamlik:

- Monsters vir die drie-assige toets met 'n deusnee van 150mm en 'n hoogte van 300mm
- Monsters vir laboratorium toetse met 'n deursnee van 150mm en hoogte van 120mm

Verder toon eksperimente ook dat die eienskappe van die materiaal wel 'n invloed op die kompaksie van die materiaal het. As gevolg van die maalproses is die gradering van die N7 materiaal verander en herwinde asfalt plaveisel (RAP) is bygevoeg. Dit alles beinvloed die eienskappe van die materiaal. In vergelyking met die Mod AASHTO vogkurwe het die vibrasiehamer se vogkurwe meer na die linkerkant geneig. Daar is ook gevind dat die veranderlikheid van die vibrasie hamer ver onder die gespesifiseerde persentasie van 15% is. Die herhaling van die eksperimente op die laer kwaliteit G5 materiaal dui aan dat die vibrasiehamer-kompaksie gebruik kan word vir laer kwaliteit granulêre materiale.

Die eindresultaat van die eksperimente is 'n moontlike kompaksie prosedure vir BSM.

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TABLE OF CONTENTS

Page

LIST OF TABLES AND FIGURES

LIST OF SYMBOLS AND ABBREVIATIONS

Symbol Description

Φ Diameter

Φ Statistical number of defective samples expressed as a percentage

Δ Delta

Σ Sigma

$\overline{X}$ The average level of compaction of the vibratory hammer as a % of Mod AASHTO

z Dimensionless factor

S Standard deviation

ABBREVIATIONS

AASHTO	American Association of State and Highway Transportation Officials
ASTM	American Society for Testing and Materials
BSM	Bitumen Stabilized Material
CE	Compaction Energy
COV	Coefficient of Variation
DD	Dry Density
Gs	Specific Gravity
HVS	Heavy Vehicle Simulator
ITS	Indirect Tensile Strength
J	Joules
kg/m^3	kilogram per cubic metre
KJ	Kilo Joules
MC	Moisture Content
MDD	Maximum Dry Density
MMLS	model mobile load simulator
Mod-U	Mod AASHTO of Untreated Material
OMC	Optimum Moisture Content
OWC	Optimum Water Content
RAP	Recycled Asphalt Pavement
RD	Relative Gravity
St Dev	Standard Deviation
TU Delft	Technical University at Delft
UCS	Unconfined Compressive Stress
US	University of Stellenbosch
W	Watt
HMA	Hot Mix Asphalt

1 Introduction

1.1 Background of Research

In the civil engineering practice, properties of granular materials (treated and untreated) are tested in various ways, including tri-axial testing, California Bearing Ratio (CBR) etc. However, before tests can take place, specimens of material first have to be prepared. Specimen preparation includes (among others) some or other form of compaction, including into a cylindrical form (for triaxial tests) and into block form for model mobile load simulator (MMLS) type tests. However, laboratory results and experience have shown that tests used to determine material properties in the laboratory are not as fair and consistent a representation of the field results as the industry would like. This is believed to be as a result of laboratory compaction methodologies currently being used for specimen preparation.

In the laboratory, compaction procedures include methods such as Modified American Association of State Highway and Transportation Officials (Mod AASHTO) compaction, Marshall Hammer, gyratory compaction and Vibratory Table compaction, etc. These methods all have their advantages and disadvantages. The main factor affecting the final outcome of the material properties is believed to be the type of compaction method used.

Mod AASHTO and Marshall Hammer compaction are both impact laboratory compaction methods. Field compaction on the other hand is done by means of high amplitude and high frequency vibratory compaction. This poses a problem when trying to compare the properties of the site compacted material to the properties of the laboratory compacted material. This is because factors such as particle orientation, packing as so forth are influenced by the compaction method and this in turn influences the material properties of the specimens (Theyse, 2004). Other differences in impact and vibratory compacted specimens include:

- the arrangement of the material particles (i.e. a different skeleton structure);
- void contents;
- Final densities typically achieved on site may be much higher than that achieved in the laboratory (e.g. site compaction may be as high as 104% of Mod AASHTO compaction density).

Gyratory compaction, on the other hand allows for the particles to be "worked" against each other, thus giving a different skeletal structure and particle orientation to that of Mod AASHTO and Marshall Hammer compaction. This also results in different voids content. Although the specimens produced by gyratory compaction are different from the Mod AASHTO, they are still not as representative of site compaction as engineers would like. According to results from research done by the Council for Scientific and Industrial Research (CSIR) (HL Theyse, 2004), vibratory table laboratory compaction gives the best results in terms of producing the same material properties in the laboratory as those which are obtained on site. The skeleton structure and voids content are more similar than the other compaction methodologies when compared to site compacted material.

As a result of the inconsistencies occurring between the field and laboratory properties of the compacted material, it was proposed that an alternative laboratory compaction method be identified and researched. One that would allow field compaction results to be simulated as closely as possible in the laboratory. Feedback received during the launch of the Technical Guidelines 2 (TG2) in 2002 indicates that vibratory compaction could be a possible alternative. The research of this alternative compaction method was funded by the South African Bitumen Association (SABITA) and was to be assigned to a student at master's level.

A study was performed by SABITA and Gauteng Department of Transport and Public Works (Gautrans) together with Professor KJ Jenkins to identify gaps in the industry with respect to laboratory compaction methods. From their work they identified that laboratory compaction methods use in South Africa, does not produce specimens representative of site compaction. As a consequence test results from such specimens are inaccurate in terms of predicting the in-field or site engineering characteristics. Accordingly, as a series of objectives to bridge the gaps between site and laboratory compaction, were proposed in their work.

It was these objectives that formed the basis for this research project, for which the particular study objectives are detailed in Section 1.2 below.

1.2 Objectives

The objectives of the research project are as follows:

- Identify appropriate international laboratory refusal density compaction methods, that can possibly be adapted to produce laboratory compaction of specimens of foamed bitumen stabilised materials (BSM-foam) and bitumen emulsion stabilised materials (BSM-emulsion) in South Africa;
- Using the preferred method (Above), develop an experimental procedure and perform refusal density compaction tests on BSM-foam and BSM-emulsion, expressing the achieved Dry Densities as a percentage of a reference density to indicate the level of compaction achieved;
- Develop a compaction procedure from the above results, to simulate realistic field compaction levels in order to perform material test (triaxial test) on bitumen stabilised material (BSM), and hence classify it;
- From the overall results, establish a laboratory refusal density compaction method.

1.3 Layout of the report

The layout of the report is as follows:

- Section 1 - Introduction - background to the research is given as well as the objectives and a layout of the structure of this report;
- Section 2 - Literature study - a summary of various literature that were studied for background on materials and compaction methods is made;
- Section 3 - Experimental work - an explanation and description of the experiment design is given;
- Section 4 - Results and Interpretations– shows experiment results and interpretations;
- Section 5 - Conclusions;
- Section 6 Recommendations – Presents recommendations made with regard to vibratory hammer compaction and describes the proposed vibratory hammer laboratory compaction method.

2 Literature study

2.1 Introduction

The first objective of the literature study was to provide background information on:

- Compaction, including details on definition, types of compaction, material types, influence of moisture and energy requirements;
- Stabilising agents, specifically looking at bitumen emulsion and foamed bitumen. Details considered include, types of bitumen emulsions, definition of foamed bitumen, the range of materials bitumen emulsion and foamed bitumen can be used on for stabilisation, advantages and disadvantages of each, and how each stabilisation means respond to compaction. A comparison of the two stabilising agents is also done.

The second objective of the literature study was to obtain information on existing laboratory compaction methods, specifically vibratory hammer compaction methods. The reason was to obtain relevant and background information from which to develop a new vibratory hammer compaction method to meet one objective of this research study (See Section 1.2 Objectives). Details considered include:

- Identifying vibratory hammer compaction methods that are currently used internationally, to produce laboratory specimens of granular materials;
- Identifying information from these methods that is relevant to the development of a vibratory hammer compaction method in South Africa (See Section 1.2 Objectives).

2.2 Compaction

As indicated in Section 2.1, this Section (2.2) considers compaction, specifically details on definition, types of compaction, material types, influence of moisture and energy requirements.

2.2.1 Definition of compaction

Material compaction is the method by which mechanical energy is used to increase the density of a given material. The density is increased by removing air and water from the pores of the material (Carson, 2004). The Soil Compaction Handbook (Carson, 2004) provides seven reasons why compaction is necessary. They are as follows:

- Compaction increases the load bearing capacity of a material;
- Material damage and frost damages are prevented;
- Compaction provides stability
- Compaction reduces water seepage;
- Reduces swelling;
- Reduces contraction;
- Compaction reduces consolidation of a material.

2.2.2 Types of compaction

The Soil Compaction Handbook identifies four types of material compaction methods, namely:

- Vibration;
- Impact;
- Kneading;
- Pressure.

These compaction methods can be divided in two principal compaction forces, namely static and vibratory forces (Carson, 2004). While Carson did not categorise impact, kneading and pressure compaction are examples of methods that use static compaction forces, while vibration uses vibratory forces.

In static force compaction the dead weight of a compaction machine applies a downward force on the material surface to compress the material particles. The effective compaction force is changed by adding or subtracting from the weight of the compaction machine. Static force compaction is confined to the upper layers of the material being compacted and is limited in depth.

Vibratory force compaction uses a mechanism, usually a rotating eccentric weight or piston/spring combination (in rammers), to induce a downward force in addition to the dead weight of the compaction machine. The purpose of this force is to overcome the cohesive nature of material particles and is based on the type of material being compacted. Vibratory compactors deliver a rapid sequence of blows to the surface of the material. This affects both the upper layers and the lower layers. Vibrations then move through the material. This sets the particles in motion and moves them closer together to achieve the target level of compaction.

2.2.3 Material types

According to the Soil Compaction Handbook there are three basic material groups. These are:

- Cohesive materials;
- Granular materials;
- Organic materials (These are not suitable for compaction and as such will not be discussed).

Cohesive materials include both clay and silt. Clay has a particle size which ranges from 0.0010 to 0.0508mm and is typically used in embankment fills and retaining pond beds. Silt has a particle size that ranges from 0.0051 to 0.0762mm and has a noticeably lower cohesion than clay. Cohesive materials are dense and are bound tightly together by molecular attraction. When wet, they are plastic and can be moulded but become very hard when dry. As a result, for proper compaction of these materials a sufficient water content and even distribution there of is critical. Even though the cohesion of silt is lower than that of clay, it is still heavily reliant on sufficient water content. To achieve compaction, a cohesive material requires an impact or pressure force to compact it.

Compared to cohesive materials, granular materials have particles sizes that are larger and they include sand and gravel. Sand particles range from 0.0762 to 2.032mm and gravel particles range from 2.03 to 25.40mm. These materials are well known for their free draining properties and also perform well under vibratory compaction but poorly under impact compaction.

The responses of a material to compaction are therefore influenced by its particle sizes and material properties. This is an important factor when selecting the appropriate compaction method for a specific material type.

2.2.4 Influence of moisture on compaction

One of the most important factors affecting the quality and level of compaction is moisture content of the material. Moisture acts as a lubricant during compaction allowing material particles to slide past each to achieve the desired density. Too little moisture impacts on this lubrication effect, with inadequate compaction as a result. Similarly, too much moisture, also affects compaction as water-filled voids are left in the material (after compaction) reducing the load bearing capacity of the material.

At certain moisture content a material will achieve a maximum density for a specific compaction type and effort. In 1933, Ralph R. Proctor developed a standardized compaction test by which the practically achievable Maximum Dry Density (MDD) and the Optimum Moisture Content (OMC) of a given material could be obtained. The method developed by Proctor was titled the Proctor Compaction Test, and is performed as follows:

- A specimen is prepared by compacting material in 3 layers in a mould with a volume of 2280cm^3. This is done by dropping a 2.5kg weight 55 times on each layer from a height of 300mm.

The Proctor Compaction Test was subsequently modified and was called the Modified Proctor Compaction Test. This test differs from the original Proctor Compaction Test and is performed as follows:

- A specimen is prepared by compaction material in 3 layers in a mould with a volume of 2280cm^3. This is done by dropping a 4.5kg weight 55 times on each layer from a height of 457mm.

Either one of these methods may be used to prepare what is called a moisture-density relationship. Here the material is compacted at different moisture contents and the achieved dry density is plotted against the moisture content. Figure 2-2 below shows a typical moisture curve:

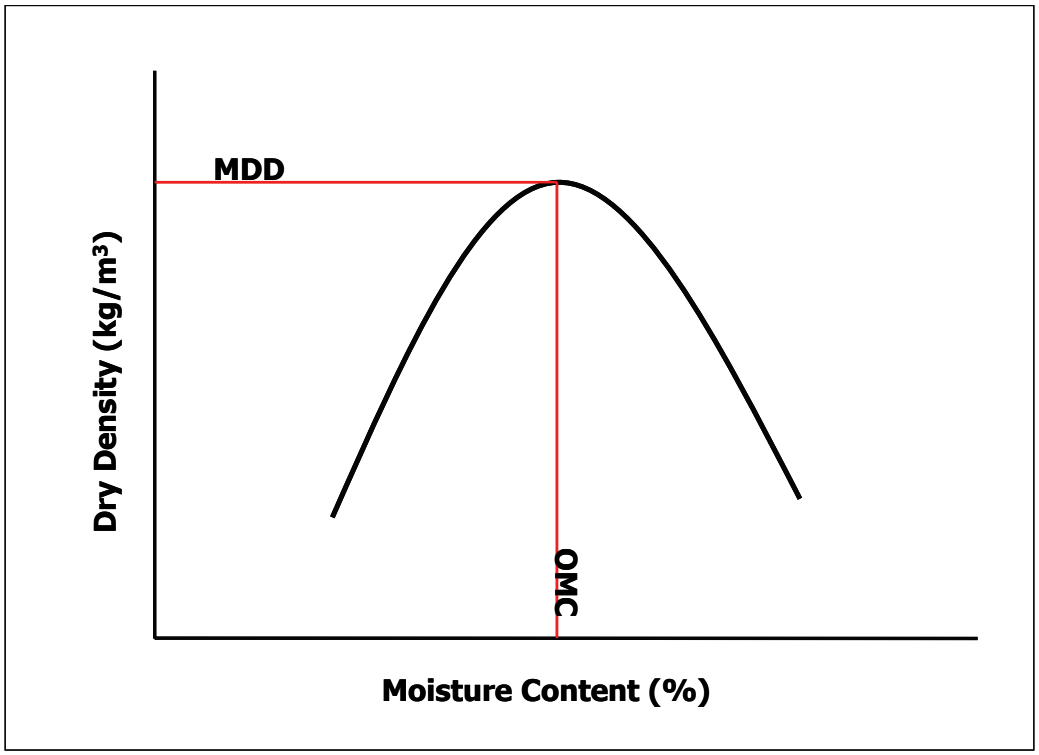


FIGURE 2-1 FIGURE 2-2: SCHEMATIC OF A TYPICAL MOISTURE-DENSITY RELATIONSHIP

This section (2.2.4) therefore shows that moisture content of a material is an important factor when compacting material. This influences the level of compaction achieved on a specific type of material.

2.2.5 Compaction energy

The compaction energy is a measure of the compaction effort applied during the compaction of a material. If the compactive effort per unit volume of a specimen is altered the moisture-density relationship will also be altered. This alteration may be observed by the position of the moisture-density relationship relative to the zero Air Voids line, (i.e. the line denoting the density at which a specimen would be compacted to have an air voids content of 0% at specific moisture content). The typical trend indicated in Figure 2-3 shows that as the compaction effort increases, the Dry Density will also increase but the OMC of the material will decrease.

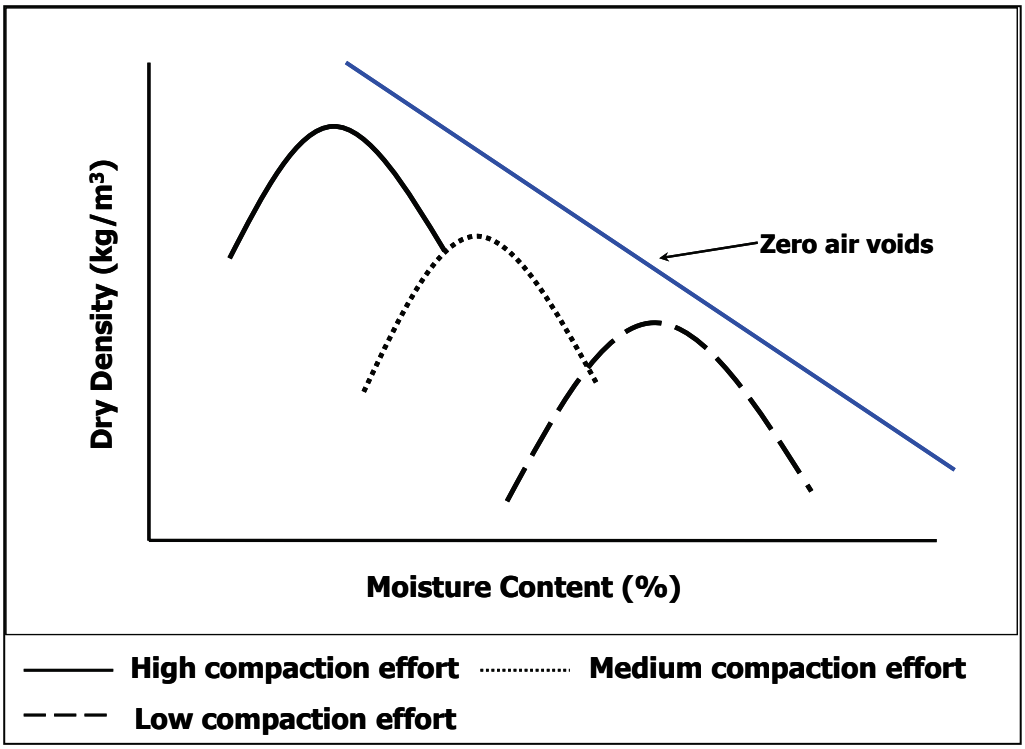


FIGURE 2-3: SCHEMATIC MOISTURE DENSITY RELATIONSHIP VS. ZERO AIR VOIDS LINE

The energy used by a compaction method therefore has an influence on the moisture content (which is already an important factor) and on the achieved level of compaction (Dry Density). This makes compaction energy an important parameter as compaction methods using higher energy will produce specimens with higher Dry Densities but with lower OMCs. Stabilising agents as indicated in Section 2.1, this Section 0 considers stabilising agents, specifically looking at bitumen emulsion and foamed bitumen.

Details considered for bitumen emulsions include:

- Types of emulsions;
- Range of material bitumen emulsion can be used on for stabilization;
- Advantages and disadvantages of bitumen emulsion;
- Compaction of bitumen emulsion stabilised material.

The above details are discussed in Sections 2.2.6 to 2.2.9 bellow.

Details considered for foamed bitumen include:

- Definition of foamed bitumen;
- What influences the foaming of bitumen?
- Range of materials foamed bitumen can be used on for stabilisation;
- Advantages and disadvantages of using foamed bitumen;
- Compaction of foamed bitumen stabilised material.

The above details are discussed in Sections 2.2.10 to 2.2.14 below.

2.2.6 Types of bitumen-emulsions

Bitumen emulsion is a solution of bitumen and water, which are mixed together in specific proportions. According to a US Patent (US Patent, 2002) there are three main types of bitumen emulsion, namely:

- Cationic emulsions;
- Anionic emulsions;
- Non-ionic emulsions,

Typically anionic or cationic bitumen emulsions are the most frequently encountered types of bitumen emulsions. This helps identify the appropriate type of bitumen emulsion to be used for laboratory stabilisation and compaction of materials so as to produce site representative specimens.

2.2.7 Range of material bitumen emulsion can be used on for stabilisation

Bitumen emulsion may be used across a variety of material types. These types as listed by Professor Kim Jenkins in his PhD dissertation (Jenkins, 2000) are:

- Crushed rock;
- Gravel;
- Recycled Asphalt Pavement (RAP).

The importance of this is to help determine whether or not the material type being used can undergo stabilisation by means of bitumen emulsion treatment. Sands and silts for example will not be stabilised with bitumen emulsion, but course aggregates will as these are either crushed rock or gravel.

2.2.8 Advantages and disadvantages of bitumen emulsion

The use of bitumen emulsion is advantages in certain respects. These are:

- Well executed applications result in good performance levels under high traffic stresses (The Shell Bitumen Handbook);
- Materials can be treated at ambient temperatures (Jenkins, 2000).

There are also various disadvantages to the use of bitumen emulsion. According to construction company Miller Group as well as the CSIR (Theyse, 2004), disadvantages include:

- Bitumen in the emulsion coats smaller particles selectively;
- Specimens of bitumen emulsion stabilised materials have shown lower stiffness than that from hot mix asphalt (HMA);
- The surface of a bitumen emulsion stabilised material (BSM-emulsion) is relatively fragile when compared to the surface of HMA;
- Increasing the bitumen content of a bitumen emulsion has a negative effect on the unconfined compressive strength (UCS) and indirect tensile strength (ITS) of a material stabilised with it (Theyse, 2004).

2.2.9 Compaction of bitumen emulsion stabilised material (BSM-emulsion)

The CSIR conducted experiments on material to determine compactability of bitumen emulsion stabilised materials using (Theyse, 2004). Three compaction methods were used for this experimentation, namely:

- Mod AASHTO;
- Gyratory;
- Vibratory table.

In order to perform these experiments two granular material types were used, namely:

- Crushed Hornfels (G1 quality);
- Decomposed granite (Gauteng granite).

These two materials both had the same maximum particle size but differed in their respective grading's and plasticity indexes (PIs). The crushed Hornfels had a continuous grading and a low PI. The decomposed granite however, had a surplus of fines and a high PI.

The experimentation entailed treating the material with bitumen emulsion as well as with either active filler (Cement) or inert filler (Fly-ash). The main aim of the study performed by the CSIR was to draw comparisons between the ease of compaction of:

- Untreated aggregates;
- Aggregates treated with only cement or fly-ash;
- Bitumen stabilised material prepared using only bitumen emulsion;
- Bitumen stabilised material prepared using a combination of bitumen emulsion and one of the fillers.

Compaction experiments were performed by compacting BSM at different bitumen content using the different compaction methods. The produced specimens were then cured in a controlled environment for 28 days. UCS and ITS testing were then performed on the cured specimens.

The CSIR assessed their experimental results in terms of volumetric composition, and not in terms of gravimetric density analysis, nor by expressing density as a percentage of a reference density. Volumetric analysis resulted in distinguishing between two volume types, namely:

- Volume filled (Vf): Total volume filled with aggregate, filler and bitumen during compaction. A positive effect on this would be that more of the constituents would fill the volume of the specimen produced. A negative effect would be the direct opposite of the positive.
- Volume of Solids (Vs): Volume filled with aggregate and filler during compaction. A positive effect on this would be that more of the aggregate and filler would fill the volume of the specimen produced. A negative effect would be the direct opposite.

The findings for the two materials used, are set out in Table 2-1.

Table 2-1 CSIR bitumen-emulsion compaction experiment results (Theyse, 2004)

Compaction method	Results
Crushed Hornfels	
Vibratory Table compaction	• At low to intermediate emulsion contents (below 1.5 %) with no filler, there was a strong positive effect on the compaction of the crushed Hornfels. I.e. a positive effect on both the Vf and Vs.
	• Where cement was used in combination with emulsion, there was a negative effect on the compaction of the crushed Hornfels. I.e. a negative effect on both the Vf and Vs.
Modified AASHTO compaction	• Where the bitumen content was increased there was a negative effect on the Vs. Here significant reductions took place at the highest bitumen contents.
	• No significant interaction took place between the filler and emulsion after the filler was added. Only the individual effects of the bitumen and filler were reflected.
gyratory compaction	• Increasing the bitumen content resulted in an improvement of the Vf but a reduction in the Vs. This means that more of the aggregate,
	• No significant interaction took place between the filler and emulsion when cement and fly-ash were used in combination with the emulsion.
Decomposed Granite	
Vibratory Table compaction	• Increasing the bitumen content had a slight negative effect on the compaction in terms of the Vs. I.e. a reduction in the Vs took place.
Modified AASHTO compaction	• Increasing the bitumen content had a negative impact in terms of a decrease in the Vs.
gyratory compaction	• Increasing the bitumen content improved the Vf but resulted in a slight reduction in the Vs for the BSM with no filler.
	• No significant interaction took place between the filler and emulsion when cement and fly-ash were used in combination with the emulsion.

Following their compaction results of Table 2-1 the CSIR made the following conclusions:

- Grading and Atterberg Limits influence the optimal compaction methods for different materials;
- The crushed Hornfels was found to be more conducive to vibratory compaction, where the decomposed granite was more conducive to gyratory compaction. For materials such as crushed Hornfels vibratory compaction in both the field and laboratory is the preferred method of compaction;
- Bitumen emulsion with an intermediate bitumen contents acted as a compaction lubricant during vibratory compaction of the crushed Hornfels. This was in terms of both Vf and Vs results. As a result bitumen emulsion at low to intermediate bitumen (bitumen) content levels (<1.5 %) may therefore assist as a compaction aid for crushed stone. It may also assist to improve the workability of recycled old crushed stone bases;
- The benefit of the lubricant was not found when using Mod AASHTO or gyratory compaction;
- There was a negative effect on the UCS of the crushed Hornfels due to increased bitumen content;
- UCS and ITS requirements of the TG2 document could be achieved using bitumen such as bitumen emulsion in combination with cement.

2.2.10 Definition of foamed bitumen stabilisation

Foaming bitumen is produced by injecting a small quantity of cold water, e.g. 2% by mass, into hot bitumen. Generally, this is done by injecting a fine water mist into an expansion chamber. The following chain of events is believed to take place the moment a cold water droplet contacts with bitumen at 170 to 180^{0}C:

- The bitumen exchanges energy with the surface of the water droplet. The result is that heat exchange between the water droplet surrounding bitumen occurs, increasing the water surface temperature and decreasing the temperature of the bitumen around the droplet;
- As soon as the temperature of the water drop reaches 100^{0}C, the water starts to evaporate, forming steam. This process requires an energy transfer from the bitumen to the water droplet equivalent to the latent heat of steam, with an even further reduction in the temperature of bitumen surrounding the droplet;
- The generation of steam results in an explosive-type expansion. Steam bubbles, under pressure, are forced into the continuous phase of bitumen in the expansion chamber of the foaming system. In this way a bitumen bubble is formed which encapsulates the steam under pressure. The bubble formed is then held intact by the surface tension of the slightly cooler bitumen film around the bubble;
- During the explosive expansion, the surface tension of the bitumen film counteracts the pressure of the steam. As a result the bubble expands with ever-diminishing pressure until a state of equilibrium is reached;
- Bitumen and water both have low thermal conductivity properties. This bubble formed can therefore remain stable typically from 20 to 30 seconds.

This process occurs creates a multitude of bitumen bubbles to form a colloidal mass called foamed bitumen. As the foamed bitumen cools down, steam in the bubbles condenses and causes the bitumen bubbles to collapse and the foam to "decay" or "break".

In his PhD dissertation Professor Kim Jenkins (Jenkins, 2000) states that all types of foams in general can be classified into two distinct groups:

- Wet foam (also called gas emulsion) - well separated spherical bubbles in a liquid;
- Polyhedral foam - non spherical bubbles separated by surfactant-stabilised, thin liquid films called lamella.

Foamed bitumen is not definitively a member of either of these groups. Foamed bitumen could be classified as polyhedral, mainly in terms of its bubble form, and not its chemistry.

The foamed state is a temporary state of low viscosity. In this state bitumen may be added to and mixed with mineral aggregates which are at ambient temperatures and in situ moisture contents.

2.2.11 What influences the foaming of bitumen?

Various factors influence the quality and characteristics of foamed bitumen. Some of the factors that have a significant influence have been listed below (Jenkins, 2000):

- Bitumen type. Some bitumen has anti-foaming additives added during the refining process, which makes the foaming of the bitumen difficult and reduce the stability of the foamed bitumen;
- Viscosity. Lower viscosity bitumen foams more readily than higher viscosity bitumen. The lower viscosity bitumen' provide higher expansion ratios and half lives;
- Higher temperatures of the bitumen during foaming have a positive effect, allowing for better expansion of the bitumen during the foaming process, which aids in the coating of the aggregate being treated with foamed bitumen;
- Application rate of water during the foaming process. The water:bitumen ratio is critical – too little, and the achieved expansion ratio may be too low; too much – and the half-life will be too short.

The factors listed are therefore points that should be taken into account when preparing a BSM-foam.

2.2.12 Range of materials foamed bitumen can be used on

The rage of materials on which foamed bitumen can be used, are:

- Crushed rock;
- Gravel;
- Recycle asphalt pavement (RAP);
- Marginal (Sands);
- Contaminated materials.

As with the bitumen emulsion, the range of materials listed above help determine whether or not the material type being used is adequate for foamed bitumen stabilization.

2.2.13 Advantages and disadvantages of using foamed bitumen

The following advantages were outlined in the PhD dissertation of Professor Jenkins (Jenkins, 2000):

- Bitumen can be used on cold and damp aggregates, without preheating of the aggregate. The heating of aggregate consumes significantly higher energy than the heating of the bitumen. Therefore there is a conservation of heat energy that occurs when using foamed bitumen;
- The variety of aggregates that can be treated using foamed bitumen is larger than for bitumen emulsion;
- Less compaction-moisture problems occur with foamed bitumen. Where materials that require recycling, have high field moisture contents, foamed bitumen stabilisation results in less increase in the moisture content of the material being treated than using bitumen emulsion stabilisation;
- Early strength characteristics. After compaction, foamed bitumen stabilised materials (BSM-foam) has sufficient strength to take traffic immediately after compaction, without detrimental effects (Provided traffic volumes are not too high). Bitumen emulsion stabilised materials (BSM-emulsion) require a longer curing period, and thus longer before being able to take traffic;

- Stockpiling BSM-foam. BSM-foam can be stockpiled close to the point of application, placed and compacted at a later stage. This provides flexibility in the manufacturing techniques of BSM-foam.

Amidst these advantages of using foamed bitumen, there are disadvantages, including:

- Level of skill required. The mix design and manufacturing process of foamed bitumen mixes requires an advanced level of skill and experience. This is necessary to produce a product of satisfactory quality;
- Mix design methods for foamed bitumen are not as well formulated as for HMA. This makes the process of acquiring experience in mix production and mix specification difficult;
- Anti-foaming agents added to some bitumen in the refining process rule out their suitability for use in foamed bitumen without the addition of foaming agents. This adds to the cost of the bitumen.
- No transfer functions have as yet been developed for the design of foamed bitumen layers in a pavement. This makes accurate design of pavement structures difficult.

The advantages and disadvantages of foamed bitumen are factors that should be taken into account, when deciding whether or not to stabilise with foamed bitumen.

2.2.14 Compaction of foamed bitumen stabilised materials (BSM-foam)

Compaction of BSM-foam was researched by the University of Stellenbosch and CSIR and the results relevant to this report, are presented in this Section.

University of Stellenbosch

Early investigations into the compactability of BSM-foam were carried out at the University of Stellenbosch by Carl Weston (Weston, 1998). The investigation had two main objectives:

- Determining and comparing the influence of different laboratory compaction methods on the volumetric and mechanical properties of BSM-foam;
- Make recommendations regarding the suitability of various laboratory compaction methods for use in mix design of BSM-foam.

To address these objectives, Weston investigated different laboratory compaction methods to produce BSM-foam specimens for testing. He identified four laboratory compaction methods to produce specimen, as follows:

- Marshall hammer;
- Hugo hammer;
- Gyratory compaction;
- Vibratory hammer compaction.

Specimens prepared using the above compaction methods, were then compared with a site specimen produced by means of roller hydrostatic double vibrating roller. The site compaction performed was in fact a simulation of site compaction.

Two types of granular materials were identified to be used for the compaction investigation. They were:

- A G2 quality graded crushed stone;
- A G7 quality gravel material.

These materials were stabilised using foamed bitumen to produce BSM-foam.

The G2 material was stabilised using foamed bitumen made from a 150/200 penetration grade bitumen. The G7 however, was stabilised using two different penetration grade bitumen. One portion was stabilised with an 80/100 penetration grade bitumen and the other portion was stabilised with a 150/200 penetration grade bitumen.

Specimens were prepared from the BSM-foam using the different compaction methods (See method identified by Weston, page 13). These were then subjected to indirect tensile strength (ITS) and semi-circular bending (SCB) tests. These tests are used for obtaining strength and stiffness, and strength, respectively which were used to assess the mechanical properties of the specimens.

The results of Weston's investigation are divided into two sets, namely, volumetric, and compaction effort analysis, and are shown in Table 2-2 and Table 2-3.

TABLE 2-2: VOLUMETRIC PROPERTIES OF THE COMPACTED G2 FBSM (WESTON, 1998)

Compaction method	G2 Material: 150/200 bitumen		G7 Material: 80/100 bitumen		G7 Material: 150/200 bitumen	
	Bulk Relative Density	Voids (%)	Bulk Relative Density	Voids (%)	Bulk Relative Density	Voids (%)
Marshall	2.248	12.7	2.042	17.8	2.080	16.3
Hugo	2.263	12.1	2.017	18.8	2.065	16.9
Kango ®	2.249	12.7	2.036	18.1	2.051	17.5
Gyratory	2.219	13.8	2.073	16.6	2.037	18.0
Site	2.284	11.3	2.010	19.1	1.992	19.7

Based on the results of Table 2-2 Weston made the following conclusions:

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

Table 2-3, shows the compaction effort analysis.

TABLE 2-3: COMPACTION EFFORT OF VARIOUS COMPACTION METHODS (WESTON, 1998)

Compaction Methods	G2 BSM-foam		G7 BSM-foam (both 80/100 and 150/200 specimens)	
	Effort	Energy (kJ)	Effort	Energy (kJ)
Marshall	75 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
Site	20 Passes	2.2	16 Passes	31.7

Based on the results in Table 2-3, Weston made the following conclusions:

- Marshall and Hugo compaction required more energy than the other methods, especially for the crushed stone mix (G2);
- The Kango® and gyratory compaction seemed to be the most effective laboratory compaction methods based on compaction energy.

Based on the results of his investigation, Weston made various recommendations regarding the suitability of the laboratory compaction methods for BSM-foam mix designs as well as for further research work in this regard. The recommendations made are as follows:

- Marshall, Hugo, Kango® and gyratory compaction may be employed in the design of foamed bituminous mixes;
- ITS and ITT testing can be used for foamed mixed design;
- More research is necessary on other aggregates before an appropriate mix design procedure can be formalised;
- A more detailed investigation into the compaction kinematics is needed;
- Energy applied during Kango® compaction needs to be assessed in more detail;
- Kango® 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 could reduce the human factor;
- Air void structure and particle orientation was not covered in Weston's study. More work should be done in this area especially on the permeability of foam mixes;
- The establishment of different compaction levels for different road categories in the mix designs also needs attention.

CSIR

The CSIR also performed an experimental investigation on laboratory compaction methods on BSM-emulsion as well as on BSM-foam. For the purposes of (relevance to) this report, the results for BSM-foam are shown in Table 2-4 below.

TABLE 2-4: CSIR FBSM COMPACTION EXPERIMENT RESULTS (THEYSE, 2004)

Compaction method	Results
Crushed Hornfels	
Vibratory Table compaction	• The use of Cement in combination with foamed bitumen had no effect on the compaction of the material. I.e. no effect on either the Vf or the Vs.
Mod AASHTO compaction	• Where the bitumen content was increased there was a negative effect on the Vs. Here significant reductions took place at the highest bitumen contents.
	• The use of filler in combination with foam resulted in a reduction of the negative effect of increasing the bitumen content mentioned above.
Gyratory compaction	• Increasing the bitumen content resulted in a marginally significant improvement in the Vf but with a significant reduction in the Vs.
	• No significant interaction took place between the filler and foamed bitumen when Cement and Fly-Ash were used in combination with the foam.
Decomposed Granite	
Vibratory Table	• Increasing the bitumen content had a slight negative effect on the compaction in terms of the Vs. I.e. a reduction in the Vs took place.
Mod AASHTO	• Increasing the bitumen content had a negative impact in terms of a decrease in the Vs.
Gyratory	• No significant interaction took place between the Cement filler and the foamed bitumen;
	• Increasing the bitumen content improved the Vf significantly but resulted in a significant reduction in the Vs for the BSM with no filler;
	• The use of Fly-Ash in combination with foamed bitumen had no significant interaction taking place between two. The was however an improvement in the Vf and the Vf during compaction.

Based on the results in Table 2-4, the CSIR made the following conclusions:

- The negative effect on the unconfined compression stress (UCS) of the crushed Hornfels due to increased bitumen content was less for the BSM-foam than for the BSM-emulsion. The BSM-foam on its own or in combination with a small amount of cement produced significantly higher UCS results than the BSM-emulsion produced at the same filler content.
- UCS and ITS requirements of the TG2 document could be achieved using stabiliser such as foamed bitumen in combination with cement.

Viewing the bitumen emulsion and foamed bitumen results together, it was concluded that the following factors affected compaction of both BSM-foam and BSM-emulsion:

- Nature of the aggregate (grading and Atterberg Limits);
- Compaction method;
- Type of stabiliser (foamed or emulsion);
- Filler types used and filler contents.

These factors, state the CSIR, make it very difficult to formulate a set of consistent guidelines that will ensure that the most appropriate laboratory compaction method, stabiliser type, filler type and bitumen content in the stabiliser, and filler content levels, are achieved and used.

The findings of the CSIR support the final points made in Sections 2.2.3 and 2.2.4.

2.2.15 Comparison of Bitumen Emulsion and Foamed Bitumen

Section 2.2.6 to 2.2.14 described BSM-emulsion and BSM-foam. From this information a comparison between the two bitumen stabilizers are summarised in Table 2-5.

TABLE 2-5: COMPARISON OF BITUMEN EMULSION AND FOAMED BITUMEN

Factor	Bitumen Emulsion	Foamed bitumen
Applicable aggregate types	• Crushed rock • Gravel • RAP	• Crushed rock • Gravel • Rap • Marginal (sands) • Contaminated materials
Aggregate temperature during mixing	• Ambient (cold) • Warm (49^0C to 55^0C) • Warm (104^0C to 127^0C)	• Ambient (cold) • Half Warm (40^0C to 99^0C)
Coating of aggregate	• "Painting" or coating of coarse particles and cohesion of mix with fines mortar	• Partial coating of large aggregates with "spot welds" of mix with fines mortar
Rate of initial strength gain	• Slow	• Medium
Important parameters of bitumen	• Emulsion type (anionic, cationic) • Solids content • Breaking time • Curing	• Half-life • Expansion ratio • "Foamability" • Penetration • Softening point
Engineering properties	• Decrease in ITS and UCS with increasing bitumen contents • In combination with Cement may be used to obtain TG2 ITS and UCS requirements	• Decrease in ITS and UCS with increasing bitumen contents but significantly higher than emulsion • In combination with Cement may be used to obtain TG2 ITS and UCS requirements
Compaction	• Low to intermediate bitumen contents allow emulsion to act as a compacting lubricant • Influenced by material properties (grading, Atterberg Limits)	• Influenced by material properties (grading, Atterberg Limits)

2.3 Existing laboratory compaction methods for possible adaptation for the compaction of BSM-foam and BSM-emulsion in South Africa

This section considers literature on existing laboratory compaction methods used internationally. South African laboratories use all these method. Both Theyse (Theyse, 2004) and Weston (Weston, 1998) (See Sections 2.2.9 and 2.2.14, respectively) concluded that laboratory methods using vibratory compaction to produce BSM-foam and BSM-emulsion specimens, are more representative of site compaction than specimens produced using Marshall hammer, Hugo hammer and gyratory compaction methods. This was also the motivation why Weston used vibratory hammer compaction in his research (Weston, 1998);

Therefore, given the objective of identifying appropriate international laboratory refusal density compaction methods (See Section 1.2), it was conclude that vibratory compaction methods should be considered the method of choice for this research study.

International vibratory compaction methods are explored further in the sections below.

The following five countries were identified as having laboratory method for this form of compaction:

- New Zealand;
- The United Kingdom (UK);
- The Netherlands (Specifically the Technical University at Delft);
- The United States of America (USA).

Methods from the above countries were evaluated against the following two criteria:

- To identify the specifications of the compaction methods: this includes hammer specifications, compaction times etc;
- To identify the purpose of each method: this includes what the specimens are used for, are OMC and MDD values determined etc.

2.3.1 New Zealand vibratory hammer compaction method

The New Zealand vibratory hammer compaction method has been in use for a number of years. The information regarding this compaction method was taken from Test 4.1.3 of the New Zealand Standards (NZS) 4402: 1986. This document was supplied by Mr. Thorsten Frobel of Fulton Hogan Ltd. in New Zealand.

The procedure provides specifications for the vibratory hammer that is to be used, the mould and the compaction procedure that is to be followed. These are as follows:

Hammer specifications:

- Frequency of 4.2 to 10Hz (250 to 600 blows per minute);
- Power rating of 60 to 1200W power consumption;
- Mass of loading frame plus hammer and applied downward force of 300N ± 50N (Figure 2-4). The Hammer may also be operated manually by experienced personnel provided the hammer is held in an upright position and that the total downward force is also in the order of 300N ± 50N. For inexperienced personnel the hammer may be placed on a scale and a downward force be applied until the scale records 30 to 40kg. This is done prior to compaction while the machine is switched off;
- Foot piece diameter of 145mm.

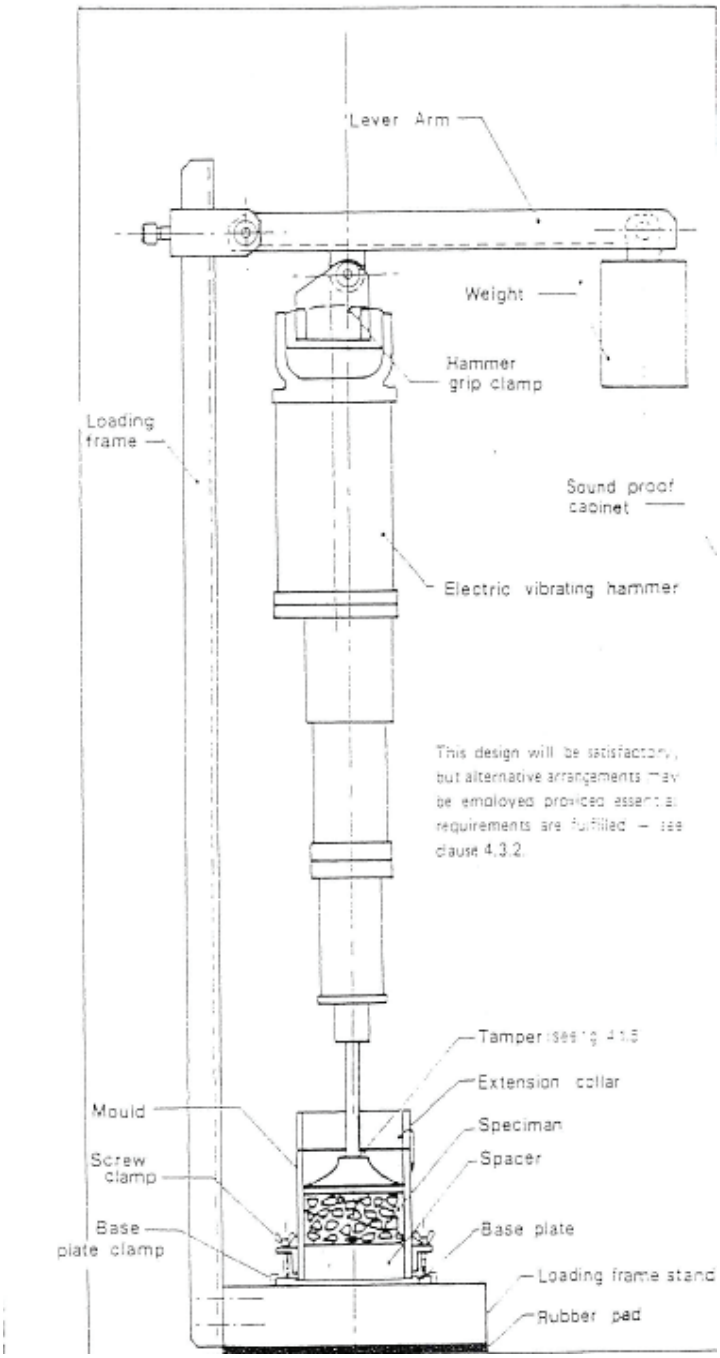


FIGURE 2-4: NEW ZEALAND MOUNTING FOR VIBRATORY HAMMER

Mould specifications:

- Non-corrodible cylindrical metal mould;
- Inside diameter of 152mm ± 0.5mm;
- A metal spacer with diameter of 150mm ± 0.5mm. This is placed inside the mould prior to compaction;
- Final specimen height is 125 to 127mm high.

Compaction procedure:

- Mass of material used for a sample is 5.5 kg;
- Assess the moisture contents required for the compaction. Adjust these contents so that there are different moisture contents across the samples which span the OMC within a required range;
- Compaction time is 180sec ± 10sec per layer;
- Number of layers compacted per sample is 2 layers.

Should there be uncertainty as to the adequacy of a vibratory hammer being used, the following test may be performed:

- A 10kg sample of Leighton Buzzard silica sand is taken, of which at least 75% passes the 600µm test sieve. The coarse fraction is discarded. Sufficient water is mixed with the sand finer than 600µm to raise the moisture content to 25% ± 5%. The material is compacted according to the procedure described above, excluding varying moisture contents, to produce a total of three specimens, the mean Dry Density is then determined. If the mean Dry Density of the sand exceeds 1.74 t/m^3 the hammer may be considered suitable for the compaction procedure.

Purpose of the compaction method:

- Determine the moisture-density relationship of a given material;
- Specify the MDD of a material. MDD is then used to specify the target Dry Density of compaction on site;
- Specimens prepared are also used for UCS testing. This is in the case of stabilised material specimens.

In New Zealand the Mod AASHTO compaction method has been replaced by the Vibratory Hammer compaction method. The reason is that New Zealand has fairly soft aggregates, and the heavy dynamic compaction of the Mod AASHTO compaction method causes a change in the grading. This influences the MDD and OMC significantly. The vibratory hammer compaction method is therefore used to **determine the moisture-density relationship** of the material.

From the moisture-density relationship, the **MDD of the material is determined** and this is used to **specify the target Dry Density of a site**. The target Dry Density of a site undergoes adjustments in the case of stabilised material. Therefore a sample is usually taken and compacted, either in the laboratory or on site, at that moisture content so as to get an idea of the shift. In the case of unbound granular materials however, no adjustment to the MDD needs to be made. The unbound pavement layer specifications of New Zealand call for plateau testing of these materials. This is in addition to vibratory hammer compaction.

Plateau testing is a procedure which makes use of a vibratory roller and a static roller to compact a marked off section of material till the densities achieved begin to remain constant. The vibratory roller is first used and after each pass the density of the compacted material is measured. This continues until the densities become constant. This point is called the "vibratory cut-off" point as no further compaction with vibratory compaction can take place. Following the vibratory roller, a static roller is used and after every 10 passes the density is measured. Once the density becomes constant the so-called the plateau density has been reached.

The target Dry Density is not only specified from vibratory hammer compaction, but the plateau density may also be used. This is subject to the type of site. The New Zealand Specifications (TNZ, 2005) provide target compaction levels for two site types. These levels are expressed as a percentage of the MDD achieved using the vibrating hammer (See Table 2-6). The site types are:

- Greenfield sites: This is a site on which no previous urban development has taken place and may be found on the periphery of existing built up sites. (The target Dry Density is quoted as: "The Maximum Dry Density (MDD) for construction shall be the higher of the maximum laboratory dry density at optimum water content (OWC) and the plateau density at optimum water content (OWC)." The OWC is the content of water at which the Maximum Dry Density of the material can be obtained);
- Overlay sites: These are sites where layers are placed on top of existing layers of a pavement so as to extend the life of the pavement (The target Dry Density is quoted as: "The Maximum Dry Density (MDD) for construction shall be the maximum laboratory dry density at optimum water content (OWC).").

Note: The term OWC used in New Zealand means the same as the term OMC used in South Africa.

TABLE 2-6: MEAN AND MINIMUM LEVEL OF COMPACTION OF PAVEMENT LAYERS

Values	% MDD	
	Sub-base Pavement Layers	**Base Pavement Layer**
Mean Value	≥ 95%	≥ 98%
Minimum Value	≥ 92%	≥ 95%

The compaction levels in Table 2-6 are checked by testing five randomly selected areas on site with a frequency of one MDD per 5000m^3 of material laid. Should the tested areas conform to the criterion in Table 2-6 the compaction levels are accepted (TNZ, 2005).

2.3.2 United Kingdom (UK) vibratory hammer compaction method

The method developed in the UK is for the compaction of HMA, but is also used for "loose plant mixed material". The vibratory hammer compaction method developed and used in the UK is as follows (BSEN12697-32-2003):

Hammer specifications:

- The vibrating hammer is fitted with a circular steel tamper of 146 mm diameter;
- Power consumption of 750W to 1000W;
- Frequency of 20 to 50Hz;
- The hammer is mounted as shown in
- Figure 2-5: UK mounting of vibratory hammer
- ;
- During compaction a firm downward force is applied so that the resulting force (which includes the mass of the hammer) is 350N ± 50N. It is recommended that for inexperienced persons, that the hammer is placed on a scale and a downward force be applied till a reading of 35kg ± 5kg be achieved. This gives an indication of how force is needed to be applied by the person during compaction.

Comment: The tolerance of 50kN allowed for the applied downward force is very lenient. The result is that there is a large variability of the achieved densities (Prof KJ Jenkins).

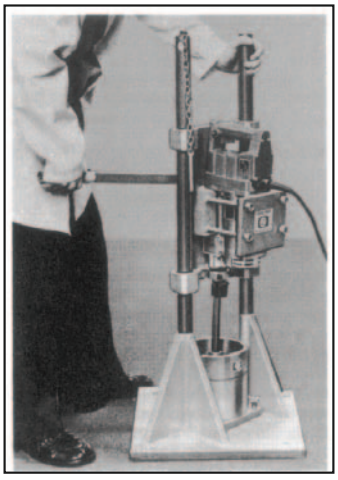


FIGURE 2-5: UK MOUNTING OF VIBRATORY HAMMER

Mould specifications:

- Split core mould is 170mm high (±0.5mm) with internal diameter of 152.45mm;
- Base plate is fitted to a 20mm plywood panel. The operator stands on the panel to keep it steady.

Compaction procedure:

- Silica sands: Specimen compacted in 3 layers;
- Silica sands: Compaction time: 60sec ± 2sec per layer;
- HMA: Specimen compacted is a single layer;
- HMA: Compass sequences N, S, E, W, NW, SE, SW, NE for a total of 120sec.

Purpose of the vibratory hammer compaction procedure:

- Determine reference densities for site;
- Determine the compactability of a material.

2.3.3 The Netherlands (TU Delft) vibratory hammer compaction method

Delft University at Technology (TU Delft) in the Netherlands also developed a compaction method regarding the vibratory hammer, refer PhD student Patrick Muraya. The method followed is long; therefore only a basic description of the procedure followed at TU Delft is provided here:

Hammer specifications:

- No vibratory hammer specifications were provided by TU Delft;
- The hammer is mounted on two guide rods (Figure 2-6).

Mould Specifications:

- Steel split mould: internal diameter 150mm and height of 300mm.

Compaction procedure:

- Target Dry Density is identified;
- The exact mass of material of each layer is calculated and weighed off;
- The thickness to which the layer will be compacted is also determined;
- The mass of material is then poured into the mould, not spilling any material;
- The compacting unit is then set up accordingly. The height adjusting rings are loosened and the compacting bar is lowered till it touches the material. The material is first compacted by hand (8 blows). The height adjusting rings are then fastened X mm down from the nylon rings, X being the calculated thickness of the layer;
- The hammer is then turned on and a small amount of pressure is applied till the nylon rings meet the height adjusting rings, i.e. the height of the layer is achieved;
- The surface is then roughened (scarified) up using a bar with a rounded head and the next layer is added and compacted in the same way. This is done until compaction of the specimen is completed.

FIGURE 2-6: TU DELFT VIBRATORY HAMMER MOUNTING

Purpose of the vibratory hammer compaction procedure:

- Preparation of specimens for triaxial testing.

2.3.4 United States of America (USA) vibratory hammer compaction method

In and paper on hammer compaction test for granular materials (Prochaska, A and Drnevich, V, 2005) it was shown that there is great promise for the use of vibratory hammer compaction for the preparation of specimens in the laboratory. The authors stated that their "One-Point Vibrating Hammer test on an oven dried sample will provide the maximum Dry Density of the material and moisture content range for effective site compaction of granular materials".

The results from their work were found to produce consistent and reproducible compaction results. The test method is also applicable to a broader range of materials than current vibratory table tests. These materials include both free-draining materials and materials that are not free-draining. The vibratory table tests are limited to free-draining materials with a fines content of less than 15%. The test results from the compaction of sandy materials indicated that the values for the Dry Density in the densest condition are representative of that obtained from the vibratory table tests.

In 2007 the America Society for Testing Materials (ASTM) published a standard test method for the vibratory hammer (ASTM D7328-07, 2007). The procedure has two methods, method A using a mould of 152.4mm diameter and method B using a mould of 279.4mm diameter. As the New Zeeland, UK, TU Delft and ASTM method A, all use a circa 152mm diameter mould, for purposes of this research study, method B of the ASTM was ignored. The procedure for method A accounts for hammer specifications, mould specifications and a description of the compaction procedure itself, as described below:

Hammer Specifications:

- Frequency of 3200 to 3500 beats per minute;
- Impact energy (manufacturers rating) of 9.5 to 12 Joule;
- Weight of hammer of 53 to 89N excluding the weight of the tamper. A list of potential hammers and their characteristics are provided by the ASTM and is shown in TABLE 2-7 below:

TABLE 2-7: POTENTIAL VIBRATORY HAMMERS FOR ASTM VIBRATORY HAMMER COMPACTION METHOD

	Bosch 11248EVS	Bosch 11318EVS	Milwaukee 5327-21	Milwaukee 5336-22
Beats/min	1700 to 3300	1300 to 3300	3400	1300 to 3450
Hz	28 to 55	22 to 55	57	22 to 58
Impact Energy (J)	10	12	11	12
Length (cm)	46	45	44	47
Weight (N)	14.4	12.5	12.9	15

Mounting frame specifications:

- The frame (Figure 2-7) shall have a metal clamp assembly to firmly hold the vibrating hammer that moves on guide rods that allows for free vertical movement. The guide rods are fastened to a metal base so as to keep them vertical and parallel;
- The frame is designed to securely hold the vibrating hammer and clamp assembly in a vertical position during the removal and insertion of the mould;
- The total applied surcharge of the clamp assembly plus the vibrating hammer and tamper shall be 19.3kPa ± 0.7 kPa.

FIGURE 2-7: MOUNTING FRAME FOR ASTM VIBRATING HAMMER COMPACTION

Mould Specifications:

- Cylindrical mould made of rigid metal;

- Average inside diameter is 152.4mm ± 0.7mm;
- Height of 116.4mm ± 0.5mm;
- Volume of 2124 ± 25cm^3.

Compaction Procedure:

- Material passing the 19mm sieve shall be used for the preparation of samples;
- Specimens are compacted in three layers;
- A compaction time of 60sec ± 5sec per layer is used to compact each layer.

The ASTM also has a procedure to check the suitability of a vibratory hammer for the compaction process. This procedure is in some ways similar to the New Zealand procedure for confirming the suitability of a vibratory hammer. The procedure is as follows:

- Standard sand shall be tested and is to conform to the requirements for 20-30 sand. These specifications are found in the ASTM specifications C778. Before the test is performed the material should be stored in such a way that freezing and/or contamination does not occur, if the material was previously used it should not be re-used. A required dry specimen mass of 7kg is required and must have a moist mass of at least 9kg. A representative sample meeting this specification is selected using a riffler or splitter or any such method quartering included. The vibratory hammer and mould (152mm diameter mould) are then prepared. The sand is then compacted according to method A described above. After compaction the Dry Density is calculated and should the specimen meet or exceed a dry density of 1.76t/m^3 (17.29kN/m^3) then the vibratory hammer may accepted as having sufficient energy.

2.3.5 One other relevant finding

Teresa Santana of the University of Nova in Lisbon Portugal (Santana, T, 1998) produced similar findings to that of Prochaska and Drnevich (Prochaska, A and Drnevich, V, 2005) in terms of site related compaction using a vibratory hammer. Santana presented a paper on a concise mix design process in order to produce Roller Compacted Concrete (RCC) mixtures for both mass and structural applications. To prepare specimens in the laboratory a drop hammer and a Kango® hammer was used. Samples were prepared using a predetermined combination of aggregates and cementious materials while varying the amount of water in the sample. The tests performed showed that the Kango® produced higher energy. This was concluded because the Dry Density produced by the Kango® was higher than the Dry Density of the impact compaction specimens (drop hammer). It was also found that the drop hammer compaction method was also much more time consuming, especially when a mechanical drop hammer was not available. The benefits of the Kango® hammer were that it uses equipment that is readily available, is not dependent on an operator, and because it simulates site compaction better than the drop hammer.

2.4 Conclusions

Based on the literature study the following conclusions were made:

- Various factors influence compaction. These include compaction method, compaction energy, material type and their properties and moisture contents;
- BSM-emulsion and BSM-foam do not respond the same to compaction;
- Bitumen emulsion acts as an additional compaction lubricant with the water;
- International vibratory hammer compaction methods from New Zealand, UK, TU Delft and the USA, were identified and details of the methods presented;
- Vibratory compaction methods produce specimens that are more representative of site compaction than other compaction methods (Theyse, 2004 and Weston, 1998);
- The finding of Santana shows that densities achieved with the vibratory hammer method are higher than Mod AASHTO densities.
- A vibratory hammer compaction method can be used for refusal density compaction;
- Air voids contents of specimens produced using laboratory vibratory hammer compaction (Kango®) are representative to air voids contents achieved using site compaction (See Table 2-2);
- Vibratory hammer compaction method can produce specimens with densities representative of densities achieved using site compaction methods (See Table 2-2).
- Vibratory hammer compaction is more energy efficient than other laboratory compaction methods (See Table 2-3);
- Vibratory hammer can be used on a broader range of materials than the vibratory table for example (Prochaska, A and Drnevich, V, 2005);
- Vibratory hammer compaction methods are a good alternative to current laboratory compaction methods (Prochaska, A and Drnevich, V, 2005);
- The New Zealand vibratory hammer compaction method shows that vibratory compaction can be used to specify site compaction levels;
- The existing vibratory hammer compaction methods identify potential compaction times and apparatus masses required to obtain necessary compaction energy;
- The laboratory vibratory hammer compaction method used by TU Delft provides good quality control of the densities achieved;
- In line with the objective to "identify appropriate international laboratory refusal density compaction methods, that can possibly be adapted to produce laboratory compaction of specimens of foamed bitumen stabilised materials (BSM-foam) and bitumen emulsion stabilised materials (BSM-emulsion) in South Africa" (See Section 1.2), vibratory hammer compaction method is the method of choice and used in this research study.

3 Experimental work

This section (Section 3) describes the experimental work performed, covering the following elements:

- Material selection, with details of material types and why they were chosen (Section 3.1);
- Samples preparation (Section 3.3);
- Compaction tests (Section 3.4);
- Summary of test work performed (Section 3.5).

The experiment design made initial use of a high quality granular crushed stone to establish vibratory hammer compaction results. This was done for BSM-emulsion and BSM-foam. A procedure was then developed from these results and used to perform further experiments. These experiments entailed: Figure 3-1 below shows a flow chart covering the above activities in more detail.

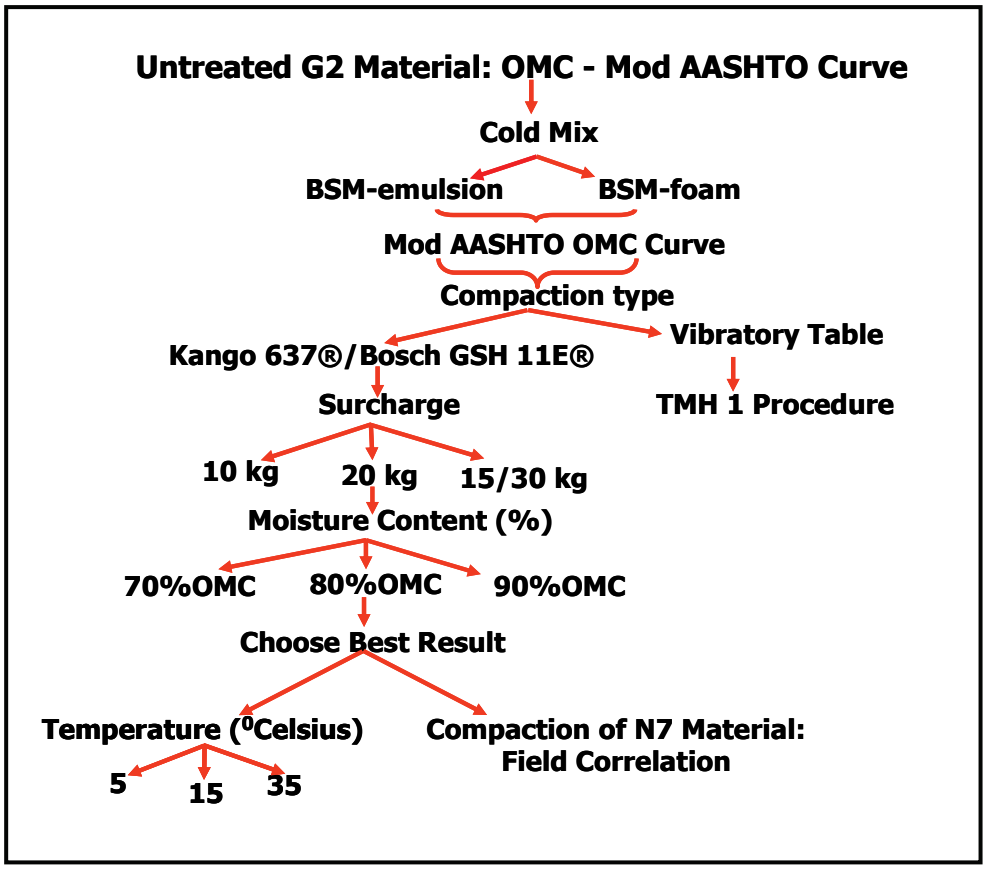


FIGURE 3-1: FLOW CHART OF EXPERIMENT DESIGN

3.1 Material selection

Three types of materials were identified for the compaction experimentation. They were:

- G2 graded crushed stone (G2);
- G5 graded crushed stone (G5);
- N7 recycled base course (N7).

Table 3-1 below lists the motivation for selection of the above material as well as the sources these materials were obtained from.

TABLE 3-1: MOTIVATION AND SOURCE OF VARIOUS MATERIALS SELECTED

Description	Material type		
	G2 graded crushed stone	**G5 graded crushed stone**	**N7 recycled base course**
Motivation	• G2 is a high quality granular material typically used in base course of pavement structures. • G2 would represent material encountered on rehabilitation projects as the base course is typically the structural zone that undergoes rehabilitation.	• G5 is a lower quality granular material than G2 with a different response to compaction and comparison with G2 is required.	• N7 represents in-situ quality site material. • Site compaction data was available (treatment type and compaction levels) • Stabilisation could be simulated in the laboratory
Source	• Lafarge's Tygerberg quarry outside Durbanville, Western Cape Province.	• Lafarge's Tygerberg quarry outside Durbanville, Western Cape Province	• Rehabilitation project along the N7 national road just outside of Cape Town, Western Cape Province.
Parent rock	• Hornfels	• Primarily from Hornfels but containing large amounts of material from other parent rocks.	• G2 quality from initial construction. Due to in-situ weathering and the milling process of rehabilitation, the material underwent physical changes and contained RAP.

3.2 Material characteristics

This section presents the following material characteristics of the various material types:

- Atterberg Limits, OMC and MDD;
- Grading.

3.2.1 Atterberg Limits, OMC and MDD

Material characteristics as determined by the University of Stellenbosch are presented in Table 3-2 and Table 3-3.

Table 3-2: Atterberg Limits of selected material

Description	G2	G5	N7
Linear Shrinkage	Non Plastic	3.3%	2%
Liquid Limit	Non Plastic	24%	20%
Plastic Limit	Non Plastic	20.7%	16.3%
Plasticity Index	Non Plastic	3.3%	3.7%

Table 3-3: OMC and MDD of selected material as per Mod AASHTO compaction

Material Type	G2		G5		N7	
	OMC (%)	**MDD (kg/m^3)**	**OMC (%)**	**MDD (kg/m^3)**	**OMC (%)**	**MDD (kg/m^3)**
Untreated	6.15	2260	6.70	2228	6.70	2228
Bitumen emulsion	4.00	2188	6.80	2217	6.80	2217
Foamed bitumen	4.80	2132	6.95	2149.5	6.95	2149.5

3.2.2 Grading of the various materials

Grading for the G2 material is shown in Figure 3-2. Due to the differences in how the material was transported, the potential for a discrepancy in the grading of the two types of sample material existed. Therefore a series of comparative grading curves were developed. G2 material from the bulk sample was graded as per the TMH 1 method (See Legend "Sample 1 Stock Pile", Figure 3-2), and compared to the grading of samples obtained from two randomly selected bags (See Legend "Random Bag", Figure 3-2). "Sample 1" (See Legend Figure 3-2) also represents the grading of a sample obtained from randomly selected bags, for comparative purposes.

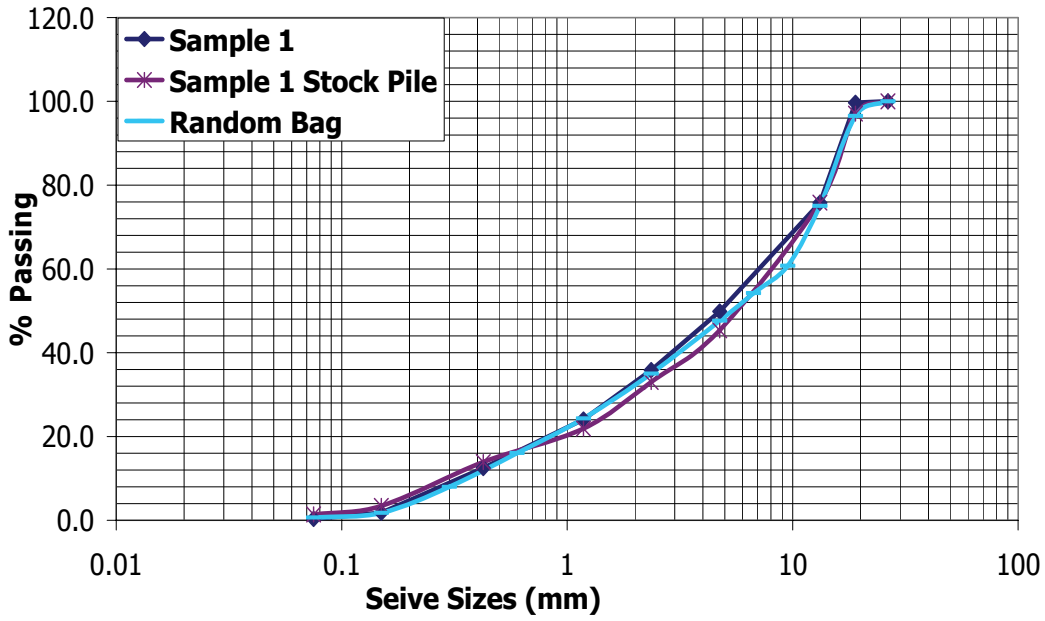


FIGURE 3-2: GRADING OF UNTREATED G2 MATERIAL

The grading for G5 material is shown in Figure 3-3. Grading for this material was available from Lafarge. The aggregate size fraction >19mm were crushed because it was considered to be too large a particle size for the specimen diameter (circa 152mm). The crushed material fraction <19mm was then re-added to the sample before grading took place. This means that this grading curve (See Legend "US Adjusted Grading", Figure 3-3), only accounts for material <19mm as apposed to the Lafarge grading, which accounted for aggregates retained on the 26mm sieve, as well (See Legend "Quarry Grading of G5 Material", Figure 3-3).

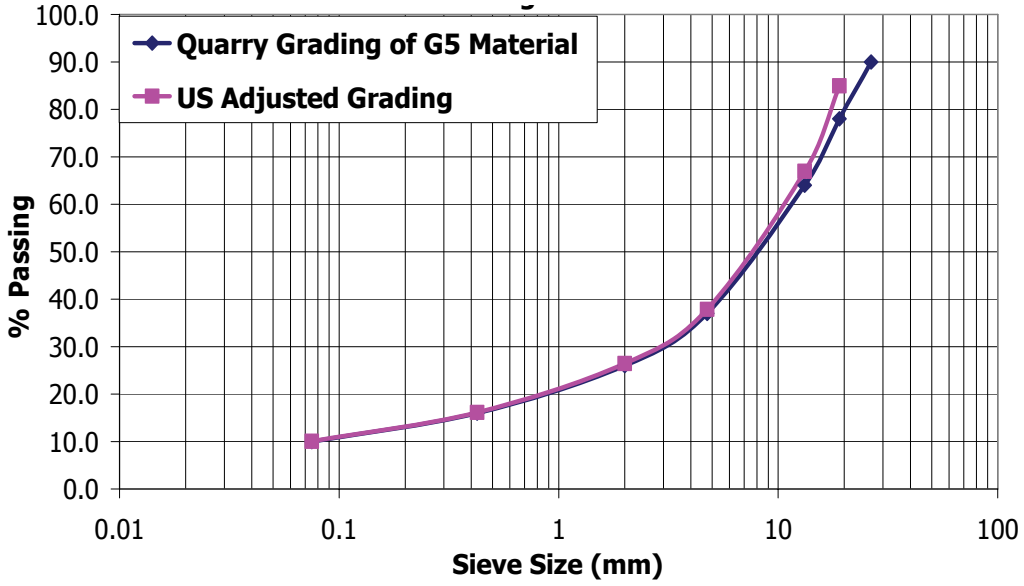


FIGURE 3-3: GRADING OF G5 MATERIAL

The grading for the N7 material is shown in Figure 3-4. This grading was obtained from work done by MSc student, Mr. Percy Moloto. The limits identified for the grading (see legend "Upper Limit", "Lower Limit" and "Ideal", Figure 3-4) are as per the TG2 (2002)

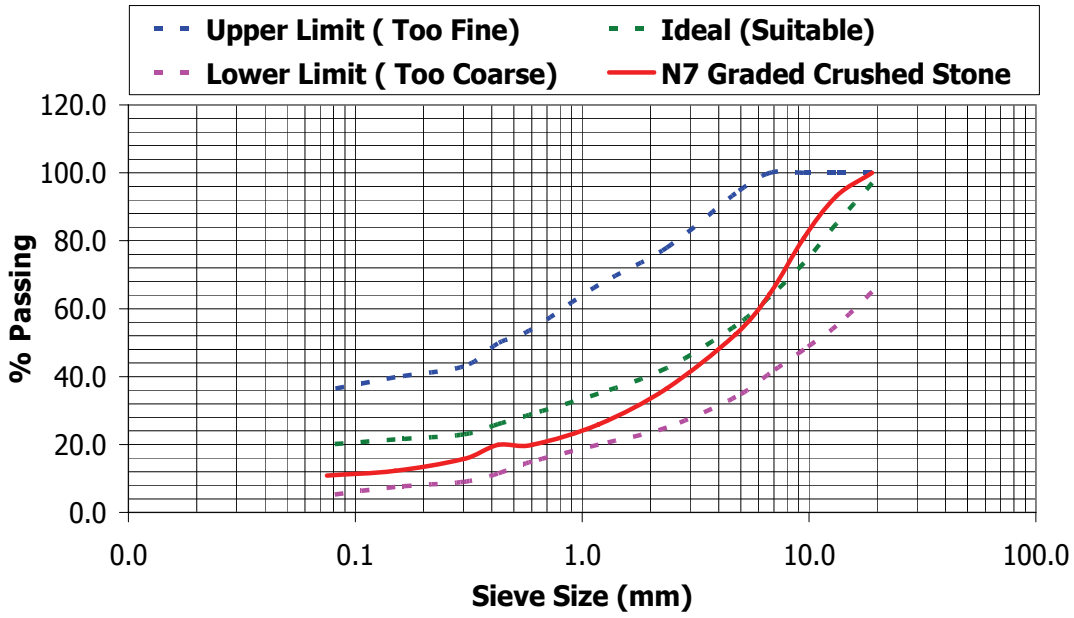


FIGURE 3-4: GRADING OF N7 MATERIAL

3.3 Sample preparation

The sample preparation procedure was as follows:

- A 7kg mass sample for Mod AASHTO compaction;

- A 13 or 14 kg for vibratory hammer and vibratory table compaction. (The mass of material required for vibratory compaction was influenced by the target Dry Density. A higher Dry Density would require 14kg of material per sample and a lower Dry Density would require 13kg of material per sample).
- All acquired material was spread out on the floor of the laboratory and dried out (in the case of the G2 bags, each bag was done individually);
- All acquired material was then passed through a 19mm sieve. The material that was retained on the sieve was crushed and added to the material passing through the sieve (in the case of the G2 bags, each bag was done individually);
- A grading curve for each material type was developed, except for the first set of test for the G2 material that was used as is (directly from the bags). This (G2) material was put through a riffle and weighed off until the target mass of the sample was achieved;
- Samples were sieved into fractions based on their respective grading;
- The target sample mass was determined and from the respective grading, the correct proportions of fraction were weighed off to reconstitute samples (thus a consistent grading across samples of each respective material type was obtained);
- The material to be stabilised with foamed bitumen was reconstituted into two portions, 1) aggregate fraction size <13.2mm, 2) aggregate fraction size ≥13.2mm (This was to account for the pug mill mixer which could not accommodate aggregate sizes ≥13.2mm).

3.3.1 Sample stabilisation

BSM-emulsion

To simulate site stabilisation of the material the following type of bitumen emulsion and concentration was used:

- A 60/40 anionic bitumen emulsion (stable grade);
- A concentration of 3.3% (wt/wt) bitumen emulsion by mass of the sample.

FIGURE 3-5: 60/40 ANIONIC BITUMEN EMULSION

The stabilisation of material by means of bitumen emulsion treatment was done as follows:

Step 1: The target moisture content of the sample was chosen (70%, 80% or 90% of OMC);

Step 2: Additional water required to be added to the sample to obtain a target moisture content, was calculated by subtracting the moisture content in the bitumen emulsion from the target moisture content (See Equation 8-3 in Section 8, Appendix A);

Step 3: The additional water was added to the sample and mixed using a flat pan mixer;

Step 4: The bitumen emulsion was added 60min after the additional water, and mixed in a flat pan mixer. The final mixture (in the bag) is now called BSM-emulsion.

BSM-foam

For purposes of testing, an 80/100 type penetration bitumen was used to prepare a BSM-foam with a target bitumen concentration of 1.98% (wt/wt.).The target concentration of 1.98% was chosen similar to that of the bitumen concentration of the BSM-emulsion of the N7 sample. Thus direct comparison between the results of BSM-foam and BSM-emulsion were possible.

Figure 3-6 shows a picture of the foam plant at the University of Stellenbosch, with Figure 3-7, showing the mixer, used.

FIGURE 3-6: FOAM PLANT AT THE UNIVERSITY OF STELLENBOSCH

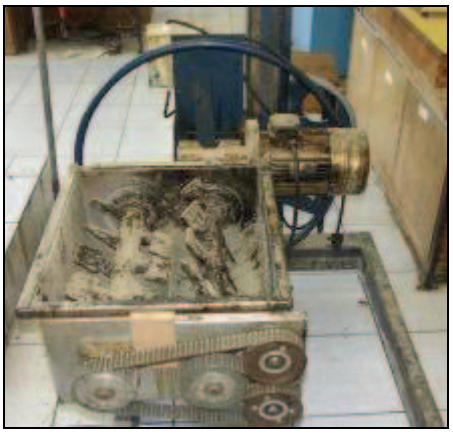


FIGURE 3-7: TWIN SHAFT PUG MILL MIXER

A procedure along the lines of that described in the TG 2 manual was followed to produce BSM-foam, and is as follows:

Step 1: Prepared samples (See Section 3.3) were accurately weighed, mass recorded with the >13.2mm fraction separated from the <13.2mm fraction, and placed in separate buckets;

Step 2: The mass of water required to obtain a target moisture content was then calculated (See
Equation 8-3 Section 8, Appendix A);

Step 3: The calculated mass of water was weighed, recorded and split into two fractions, one 90% (wt/wt) of the original mass, and one 10% (wt/wt);

Step 4: The one 90% water fraction was added to the <13.2mm fraction of sample material (See Step 1) and the other 10% water fraction added to the >13.2mm fraction;

Step 6: Heat bitumen (in oven) to a temperature of 170^0C and place into foam plant kettle;

Step 7: The foam plant was prepared; firstly the flow rate of the bitumen was determined by calculating the average mass flow rate of bitumen flow by recording the total mass of five 5sec bitumen flow intervals, divided by 25sec. This process was then repeated by recording the total mass of three 3sec bitumen flow intervals, divided by 9sec;

Step 8: Set water flow rate. Typically a water flow of 3% of the bitumen flow rate is initially used (TG 2, 2002). The water flow rate, expressed in g/sec and multiplied by 10, then equates to the target mass of water which should be released from the foam plant after 10sec. The water pressure on the foam plant in then set to deliver the target mass of water (determined by recording a mass of water delivered in specific time);

Step 9: Perform foam test, i.e. 500g of foamed bitumen is sprayed into a container (at a temperature of 60^0C), allowed to expand, and followed by measuring foam collapse over time. A target collapse rate should be above 20 to 30sec to the half-life of the foam;

Step 10: Set bitumen concentration, by performing a simple concentration calculation;

Step 11: The plant is now ready to produce foamed bitumen, used for stabilisation of the sample materials;

Step 12: The <13.2mm fraction of the sample material is place into the pug mill mixer, and mixed with foamed bitumen, produce by the foam plant, and mixed, removed and place into a plastic bag;

Step 13: Thereafter >13.2mm fraction of the sample material is added to the bag, and mixed by shaking. The final mixture (in the bag) is now called BSM-foam.

3.4 Compaction tests

Vibratory hammer compaction was chosen as the compaction method by which refusal density compaction of bitumen stabilised materials (BSM-emulsion and BSM-foam) was researched (See final conclusion, Section 2.4). This section provides details on the following:

- Vibratory hammers used and reasons why they were chosen;
- The mounting design with reasons why mounting is required - initial and modified designs are also provided;
- Experiment compaction procedure;
- Experiment using vibratory table compaction.

3.4.1 Vibratory hammers used

The vibratory hammer experimentation was performed using the following two hammers:

- The Kango 637® (Kango®) vibratory hammer;
- The Bosch GSH 11E® (Bosch®) vibratory hammer.

The Kango® vibratory hammer was chosen because the University of Stellenbosch had ownership of one, and experience in using it for compaction tests. During the course of experimentation however, this hammer experienced technical difficulties suffering damage to the gearbox and as a result became unusable. The replacement part for the hammer could not be found in South Africa and hence a new hammer was sought.

The criteria for an adequate replacement vibratory hammer were:

- Readily availability in South Africa – both hammer and replacement parts;
- Mass of hammer – to be similar to that of the Kango®;
- Impact energy – from previous compaction work done at the University of Stellenbosch with the Kango®, it was determined that the point energy of the Kango® is 27J. The replacement needed to have an impact energy similar to this.

The Bosch GSH 11E vibratory hammer was found to meet the criteria and was therefore chosen as the replaced hammer. Figures 8 and 9 provide a visual of the two vibratory hammers, while Table 8 shows how they compare technically.

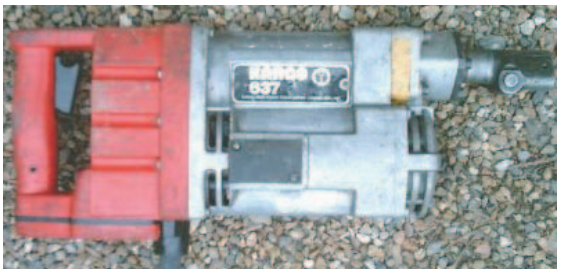


FIGURE 3-8: KANGO 637 ® VIBRATORY HAMMER

FIGURE 3-9: BOSCH GSH 11E® VIBRATORY HAMMER

TABLE 3-4: COMPARISON BETWEEN KANGO 637® AND BOSCH GSH 11E® VIBRATORY HAMMER

Hammer	Rated power input (W)	Impact energy (J)	Impact rate (1/min)	Frequency (Hz)	Mass (kg)
Kango 637®	750	27	2750	45.83	7.5
Bosch GSH 11E®	1500	6 to 25	900 to 1890	15 to 31.5	10.1

Noteworthy from the information in Table 3-4, are the following:

- The Bosch® has a frequency range of 15 to 31.5Hz compared to the fixed frequency of the Kango® hammer;
- The impact energy of the Kango® hammer was not given in the technical specifications. Attempts made to confirm its estimated impact energy, were unsuccessful. As consequence a correlation experiment was performed it was found that Kango® the previously determined impact energy of 27J was not accurate.

3.4.2 Mounting design for the vibratory hammer

A mounting frame for the vibratory hammer was designed for two reasons:

- To reduce the amount of physical labour of the operator during compaction;
- Reduce the influence of human error during compaction i.e. less variability in the applied force of the vibratory hammer.

Initial vibratory hammer mounting design - Kango 637 ®

With the aid from Mr. Johan Muller (technical/mechanical support at the University of Stellenbosch), a mounting system for the Kango® was designed and build. This system (including the mould) was fastened to the floor. Figure 3-10 shows a plan view of the design, and Figure 3-11 shows photograph of the constructed mounting frame.

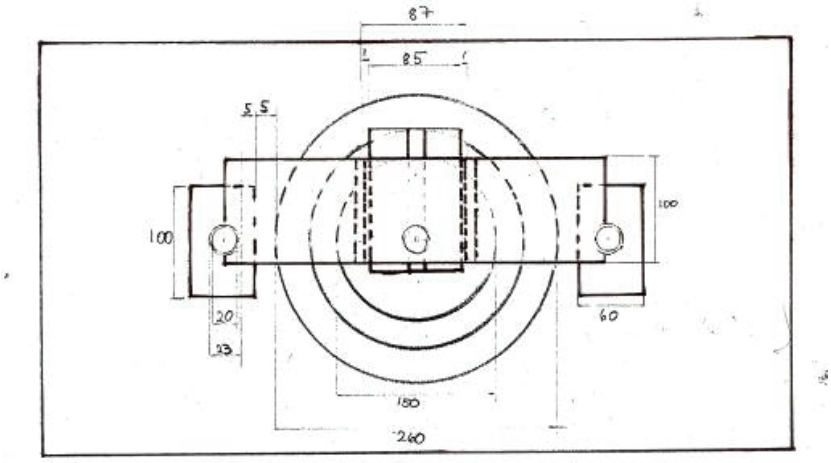


FIGURE 3-10: SCHEMATIC TOP VIEW OF THE MOUNTING FRAME DESIGN FOR THE KANGO®

FIGURE 3-11: TOP VIEW OF THE CONTRUCTED KANGO® MOUNTING FRAME

Figure 3-12 shows the front view of the mounting frame design and Figure 3-13 show a photograph of the final constructed mounting frame.

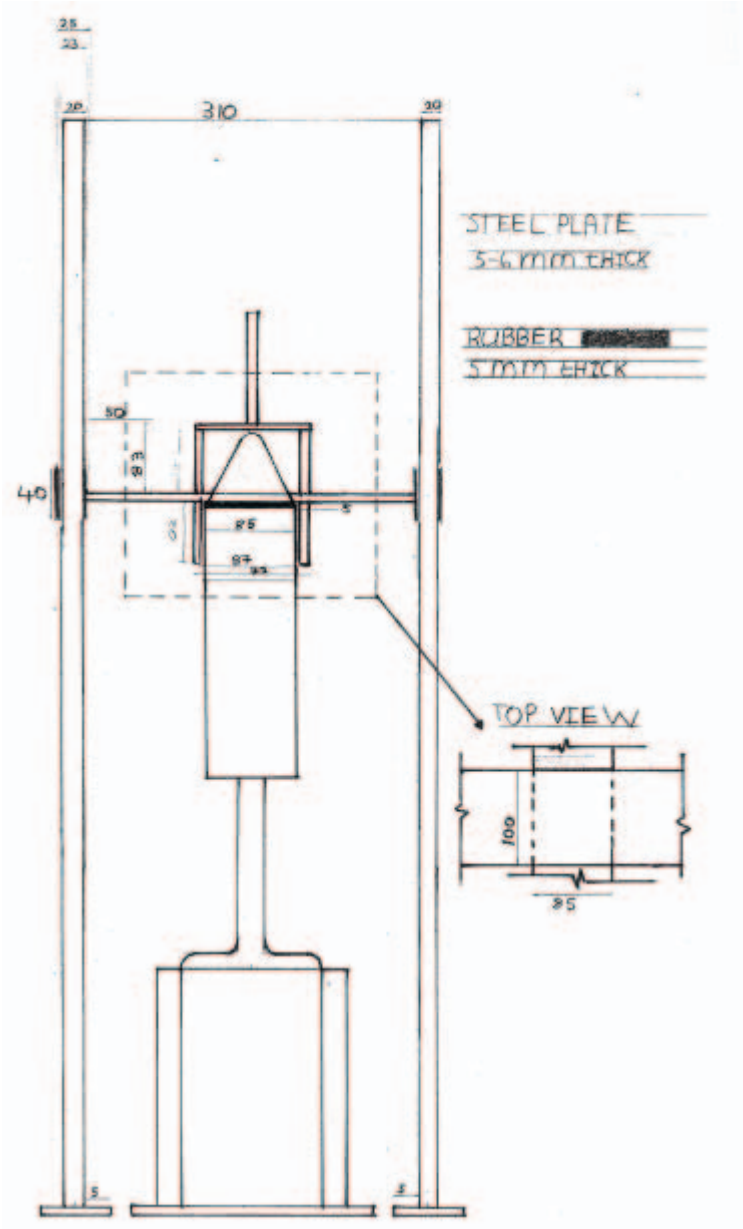


FIGURE 3-12: FRONT VIEW OF THE MOUTING FRAME DESIGN FOR THE KANGO®

FIGURE 3-13: FRONT VIEW OF THE CONSTRUCTED KANGO® MOUNTING FRAME

Modification of the vibratory hammer mounting design - Bosch GSH 11E ®

The mounting frame designed for the Bosch® was effectively a modification of the existing Kango® frame. The mounting head which is attached to the hammer was modified. This modification was designed and constructed by the technical/mechanical support at the University of Stellenbosch Civil Engineering Department. This modification was necessary because the size and shape of the Bosch® differs from that of the Kango®. The design is shown in Figure 3-14

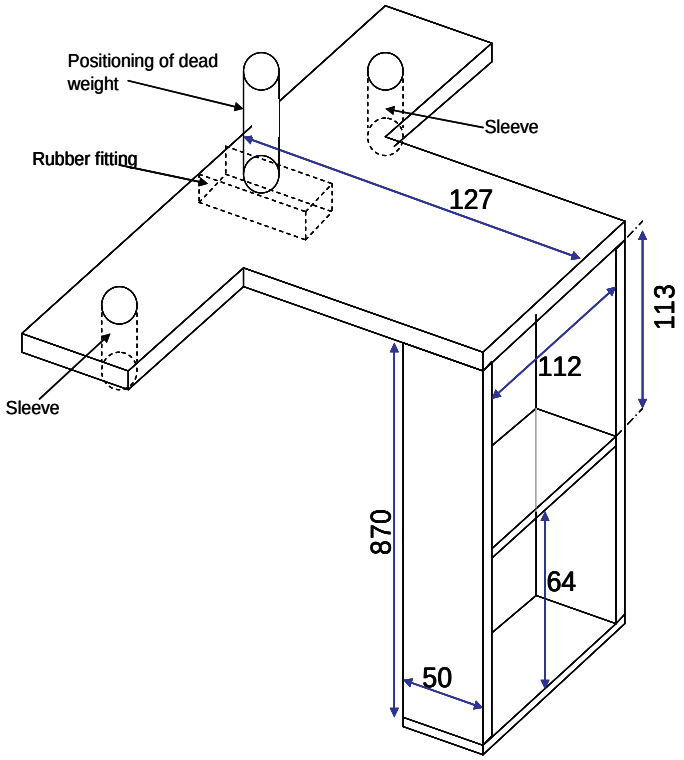


FIGURE 3-14: SCHEMATIC OF THE MOUNTING HEAD FOR THE BOSCH®

In both the original design (for the Kango® and the modified design, rubber sections protect the vibratory hammer from damage by direct contact with the steel plates of the mounting head. The constructed modification is shown from Figure 3-15 to Figure 3-17.

FIGURE 3-15: LEFT VIEW OF THE CONSTRUCTED MONTING HEAD FOR THE BOSCH ® HAMMER.

FIGURE 3-16: FRONT VIEW OF THE CONSTRUCTED MOUNTING HEAD FOR THE BOSCH® HAMMER.

FIGURE 3-17: FULL VIEW OF THE CONSTRUCTED MOUNTING HEAD BOSCH®

Modifications were made to the existing mounting frame by Mr. Dion Viljoen from the technical/mechanical support at the University of Stellenbosch Civil Engineering Department workshop. This was done for the following reasons:

- To better stabilize the entire system – problems were noted with the original mounting design. These included "shaking" of the guide rods, and thus the accuracy with which readings can be taken during operation, how perpendicular the foot piece was to the surface of the material in the mould during compaction;
- To further reduce labour effort – The original design did not make provision to reduce the physical effort required to raise and lower the vibratory hammer (including mounting head and surcharge) of circa 30kg. This could cause injury, specifically to people who suffer from back problems.

Based on the two reasons above, the following modifications were made:

- A supporting frame to stabilise the guide rods was designed (See Figure 3-18). The guide rods were fastened to this frame providing along which the vibratory hammer could move and in total to provide a more stable set-up. This also kept the foot piece more perpendicular to the surface of the material being compacted and improved the accuracy of readings being taken;

- A pulley system was also fixed to the mounting head and the supporting frame (See Figure 3-19). This reduced the labour required to raise and lower the vibratory hammer.

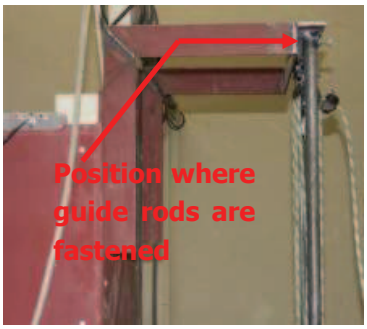


FIGURE 3-18: LEFT VIEW OF THE SUPPOTING FRAME

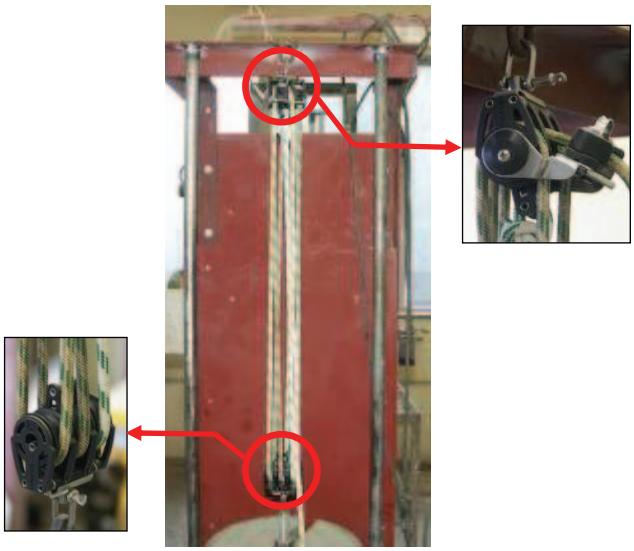


FIGURE 3-19: PULLEY SYSTEM OF VIBRATORY HAMMER

FIGURE 3-20: RAISED VIBRATORY HAMMER

3.4.3 Experiment compaction procedure using the vibratory hammer

To perform the experiment the operator must have the following possessions:

- A stopwatch;
- A 150mm steel rule and tape measure;
- Any marking agent that will be clearly visible on the guide rods, e.g. a permanent marker;

The experimentation procedure followed for the compaction of stabilised G2 material is as follows:

Step 1: The moisture density relationship of the untreated (non-stabilised) sample to be tested was determined according to the THM 1 procedure (TMH1: Method A7).

Step 2: The moisture density relationship of the stabilised material was determined using the OMC, obtained from Step 1 (See Section 4.1 for a typical moisture density relationship);

Step 3: The target moisture content was calculated as a percentage (used 70%, 80% and 90%) of the OMC determined in Step 1.

Step 4: Using the relationship developed in Step 2 and the target moisture content of Step 3, the target dry density of the either the BSM-emulsion or the BSM-foam was determined;

Step 5: From the target moisture content of Step 3, and the target dry density of Step 4, the mass of the final compacted specimen was calculated, using Equation 8-1 (See Section 8, Appendix A);

Step 6: The mass of the final compacted specimen calculated in Step 5, is divided by 5 to obtain that mass of material to be compacted per layer (called the "layer mass"). Using either BSM-emulsion or BSM-foam, 5 layer mass samples were accurately weighed and placed in plastic bags.

Note: Other than what was believed to have achieved better compaction using five layer, the decision to use five layers was based on the ITT Report 18.1-1997 (van de Ven, et al., 1997) where five layers were used during vibratory table compaction. It is possible that less or more layers could be used, but this impact thereof was not investigated, and could be a subject for further research.

Step 7: The extra 2kg BSM-emulsion or BSM-foam of the sample is used to perform a moisture content test (See Section 8 Appendix A). This is done by means of the standard oven drying method (TMH 1).

Step 8: The mounted vibratory hammer is lowered into the empty mould and the hammer foot piece allowed to rest on the base of the mould. The position of the base of the right sleeve (of the mounting head) on the guide rod is clearly marked (called the "zero line") (See Figure 3-21).

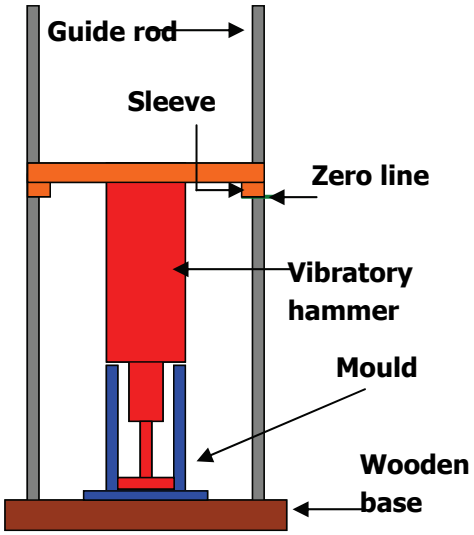


FIGURE 3-21: MARKING OFF OF ZERO LINE

Step 9: The mounted vibratory hammer is then raised, a distance of 60mm measured from the zero line (using a 150mm steel rule) and is clearly marked (using typically a permanent marker pen). This line denotes the target Dry Density.

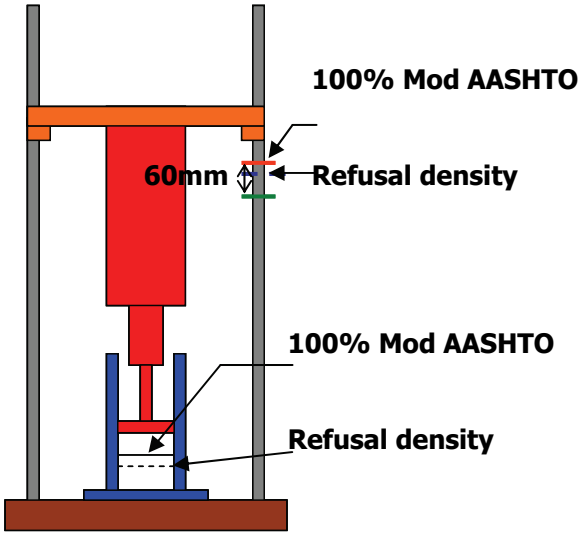


FIGURE 3-22: INDICATING THE TARGET DRY DENSITY LINE (100%MOD AASHTO)

Step 10: One of the five bags from Step 6 is taken and the material into the mould.

Step 11: The mounted vibratory hammer is lowered into the mould until the foot piece rests on the surface of the material.

Step 12: The mounted vibratory hammer is switched on and simultaneously a stop watch is started. The material is compacted until the base of the right sleeve reaches the marked point of Step 9. At this point the vibratory hammer is switched off and simultaneously the stopwatch is stopped. The time is recorded.

Step 13: The mounted vibratory hammer is switched on again and simultaneously the stop watch is started. The material is compacted further, stopping the vibratory hammer at regular time intervals and recording the thickness of the layer at the time interval. The thickness is as the distance from the zero line to the base of the right sleeve. This is done until the recorded height becomes constant (i.e. the same height is recorded 3 times). This height is then refusal density and is clearly marked.

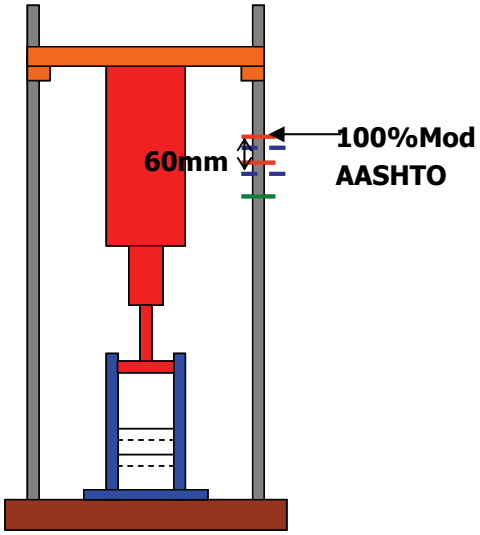


FIGURE 3-23: INDICATING TARGET DRY DENSITY (110% MOD AASHTO) FROM THE REFUSAL DENSITY OF THE PPRVIOUS LAYER

Step 14: The mounted vibratory hammer is raised.

Step 15: 60mm is measured from the clearly marked refusal density height of the previously compacted layer.

Step 16: The surface of the compacted layer of material is scarified to ensure interlocking of layers.

Step 17: A second bag from Step 6 is taken and the material poured into the mould.

Step 18: Step 10 to Step 15 is repeated until the material of all five bags from Step 6 has been compacted. Please note that the "zero line" of each compaction layer, is the refusal density height of the previous layer

Step 19: The compacted material is now called a specimen and is removed from the mould.

Step 20: The specimen is weighed and the mass recorded.

Step 21: The final height of the specimen is measured using a tape measure and recorded.

The above experimental procedure was performed by varying moisture content using a set surcharge load, and the results recorded. This was repeated for 3 set surcharge loads. From these varying conditions, the corresponding compaction times per layer giving the best balance between time, compaction, was then used to assign a fixed compaction time per layer, used in the reset of the experimental work.

Note: Much time is lost during the preparation of specimens once compaction is completed. This is due to having to unscrew the bolts of the split mould and then having to dismantle the entire mould so as to remove the specimen. Once removed the mould may at times be wiped clean, depending on how dirty it has become during compaction, and then re-assembled for the compaction of the next specimen. This dismantling is necessary because the specimen does have a tendency to stick to the walls of the mould, therefore it cannot merely be slid out of the mould. A non-stick spray, this may be purchased at any supermarket, is used to treat the walls of the mould prior to the compaction of a specimen. This reduces the sticking of the specimen to the mould walls.

3.4.4 Experiment compaction procedure using the vibratory table

Research has shown that structurally (i.e. particle orientation), the specimens produced from this laboratory compaction method are more representative of site compacted specimens than other laboratory compaction methods (Theyse, 2004).

The principle on how the vibratory table compaction method compacts material is similar to how a vibratory hammer would. The compaction process involves applying a large impact force while vibrating the material in the mould. The skeletal structure of specimens produced from these respective compaction methods is therefore believed to be similar to each other and more representative of site compaction (See Section 1.1).

Due to this, an assessment on how the vibratory hammer compaction of BSM-emulsion and BSM-FOAM compares to the vibratory table compaction of the same material was done. The two compaction methods were compared in terms of:

- Time of compaction Dry Density;
- Final Dry Density achieved using each method;
- Ease of execution.

The standard procedure for the vibratory table compaction method is found in the TMH 1: Revised Addition (1990). The specifications of the TMH 1 vibratory table compaction method are:

- Amplitude of 0.5mm;
- Frequency of 50Hz;
- Surcharge of 50kg;
- Compaction time of 120sec (2min).

For the purposes of this research compaction was done until the layer being compacted reached a layer thickness of 60mm.

The experiment is performed as follows:

Step 1: The layer mass of material is determined and weighed off as explained in Step 1 to Step 7 in Section 3.4.3.

Step 2: A steel split mould is clamped to the vibratory table (See Figure 3-25)

Step 3: the frequency and amplitude settings are set for the vibratory hammer as per the TMH 1 (1990).

Step 4: A bag of either BSM-emulsion or BSM-FOAM is taken and poured into the mould.

Step 5: The 50kg surcharge is placed in the mould, on top of the material.

Step 6: The vibratory table is turned on and the time is recorded to compact the material to the target Dry Density.

Step 7: The 50kg surcharge is removed and the surface of the compacted material is scarified.

Step 8: The next bag of material is taken and poured into the mould.

Step 9: Step 5 to Step 8 is repeated until all five bags of material are compacted.

Step 9: The compacted material (specimen) is removed from the mould and weighed.

Step 10: The final height of the specimen is recorded for accuracy purposes.

To identify when the layer of material had been compacted to 60mm markings were made on the 50kg surcharge at intervals of 60mm in length (see Figure 3-24).

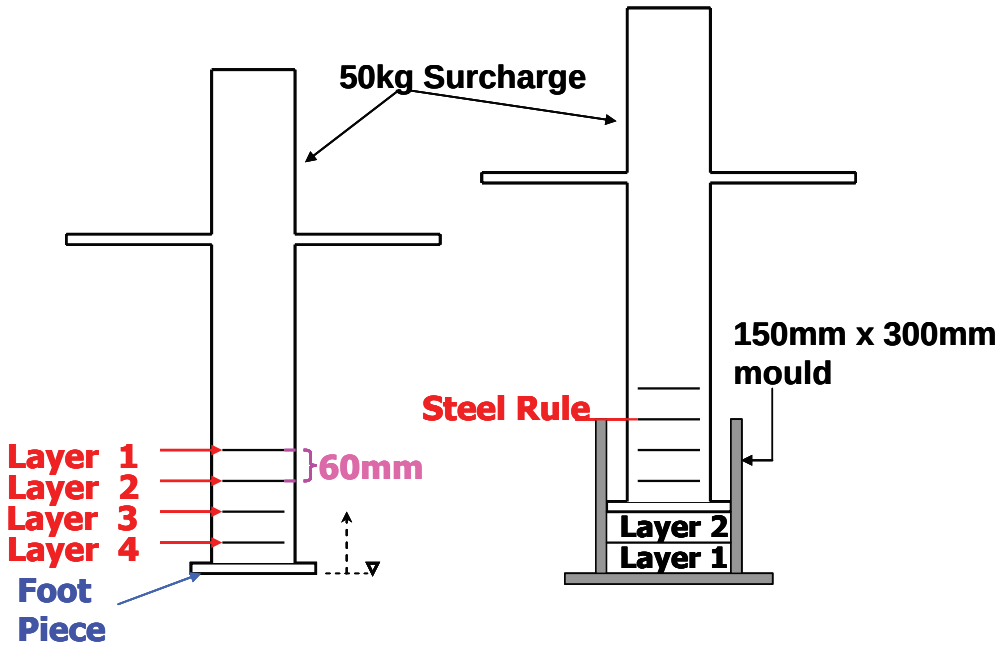


FIGURE 3-24: MARKINGS ON SURCHARGE LOAD FOR LAYER THICKNESS RECORDINGS OF THE VIBRATORY TABLE COMPACTION METHOD

Note: The BSM-FOAM layers were compacted to a thickness of 60mm, the time was recorded and the compaction of the layer commenced until a total compaction time of 2min had been achieved. This position was marked on the 50kg surcharge and became the reference line from which the 60mm mark for the next layer was measured.

FIGURE 3-25: VIBRATORY TABE COMPACTION SET UP

3.5 Summary of test work performed

A summary of the test work performed is presented in Table 3-5.

Table 3-5: List of test performed through out the research

Test №	Name	Description	Method compaction	Stabilisation	Material used
1	G2 Untreated	Test to develop MOD AASTHO moisture density relationship test	MOD AASHTO	None	G2
2	G2 BSM-emulsion	Test to develop MOD AASTHO moisture density relationship test	MOD AASHTO	Bitumen emulsion	G2
3	G2 BSM-foam	Test to develop MOD AASTHO moisture density relationship test	MOD AASHTO	Foamed bitumen	G2
4	G5 Untreated	Test to develop MOD AASTHO moisture density relationship test	MOD AASHTO	None	G5
5	G5 BSM-emulsion	Test to develop MOD AASTHO moisture density relationship test	MOD AASHTO	Bitumen emulsion	G5
6	G5 BSM-foam	Test to develop MOD AASTHO moisture density relationship test	MOD AASHTO	Foamed bitumen	G5
7	N7 Untreated	Test to develop MOD AASTHO moisture density relationship test (test result obtained from Mr. P Moloto, MSc student at the University of Stellenbosch)	MOD AASHTO	None	N7
8	G2 BSM-emulsion	Test to determine the influence of moisture and surcharge load on compaction times and compaction levels	vibratory hammer – Kango®	Bitumen emulsion	G2
9	G2 BSM-emulsion	Test to determine the influence of moisture and surcharge load on compaction times and compaction levels	vibratory hammer – Kango®	Bitumen emulsion	G2
10	G2 BSM-emulsion	Test to determine the influence of moisture and surcharge load on compaction times and compaction levels	vibratory hammer – Kango®	Bitumen emulsion	G2
11	G2 BSM-emulsion	Test to determine the influence of moisture and surcharge load on compaction times and compaction levels	vibratory hammer – Kango®	Bitumen emulsion	G2
12	G2 BSM-emulsion	Test to determine the influence of moisture and surcharge load on compaction times and compaction levels	vibratory hammer – Kango®	Bitumen emulsion	G2
13	G2 BSM-emulsion	Test to determine the influence of moisture and surcharge load on compaction times and	vibratory hammer –	Bitumen emulsion	G2

Test №	Name	Description	Method compaction	Stabilisation	Material used
		compaction levels	Kango®		
14	BSM-foam	Test to determine the influence of moisture and surcharge load on compaction times and compaction levels	Vibratory hammer – Bosch®	Foamed bitumen	G2
15	BSM-foam	Test to determine the influence of moisture and surcharge load on compaction times and compaction levels	Vibratory hammer – Bosch®	Foamed bitumen	G2
16	BSM-foam	Test to determine the influence of moisture and surcharge load on compaction times and compaction levels	Vibratory hammer – Bosch®	Foamed bitumen	G2
17	BSM-foam	Test to determine the influence of moisture and surcharge load on compaction times and compaction levels	Vibratory hammer – Bosch®	Foamed bitumen	G2
18	G2 BSM-emulsion	Test to correlate Kango® vibratory hammer compaction results to Bosch® vibratory hammer	Vibratory hammer – Bosch®	Bitumen emulsion	G2
19	BSM-emulsion	Test to determine how temperature affects compaction	Vibratory hammer-Bosch®	Bitumen emulsion	G2
20	BSM-foam	Test to determine how temperature affects compaction	Vibratory hammer-Bosch®	Foamed bitumen	G2
21	BSM-emulsion	Test to determine whether or not site compaction levels can be reproduced with the developed vibratory hammer compaction method	Vibratory hammer-Bosch®	Bitumen emulsion	N7
22	BSM-emulsion	Test to determine whether or not site compaction levels can be reproduced with the developed vibratory hammer compaction method	Vibratory hammer-Bosch®	Foamed bitumen	N7
23	Untreated	Test to develop the moisture density relationship of the material	Vibratory hammer-Bosch®	None	G2
24	BSM-emulsion	Test to develop the moisture density relationship of the material	Vibratory hammer-Bosch®	Bitumen emulsion	G2
25	BSM-foam	Test to develop the moisture density relationship of the material	Vibratory hammer-Bosch®	Foamed bitumen	G2
26	Untreated	Test to develop the moisture density relationship of the material to determine applicability of the developed vibratory hammer compaction method	Vibratory hammer-Bosch®	None	G5
27	BSM-emulsion	Test to develop the moisture density relationship of the material to determine applicability of the developed vibratory hammer compaction method	Vibratory hammer-Bosch®	Bitumen emulsion	G5
28	BSM-foam	Test to develop the moisture density relationship of the material to determine applicability of the developed vibratory hammer compaction method	Vibratory hammer-Bosch®	Foamed bitumen	G5
29	BSM-emulsion	Test to compare vibratory hammer compaction to vibratory table compaction	Vibratory table	Bitumen emulsion	G2
30	BSM-foam	Test to compare vibratory hammer compaction to vibratory table compaction	Vibratory table	Foamed bitumen	G2
31	BSM-emulsion	Test performed to determine the air voids profile of the compacted specimen	Mod AASHTO	Bitumen emulsion	G2
32	BSM-emulsion	Test performed to determine the air voids profile of the compacted specimen	Vibratory hammer-Bosch®	Bitumen emulsion	G2
33	BSM-foam	Test performed to determine the air voids profile of the compacted specimen	Vibratory hammer-Bosch®	Foamed bitumen	G2

4 Results and Interpretations

This section of the report presents the results of the experiments performed as well as the interpretations there of. For purposes of clarity the following information is important:

- %OMC – Percentage of the Mod AASHTO optimum moisture content from the Mod AASHTO moisture density relationship of the untreated material type (e.g. For an experiment or test performed at a moisture content of 80%OMC on a G2 BSM sample, the moisture content of the BSM is 80% of the Mod AASHTO optimum moisture content);
- %Mod AASHTO – Percentage of the target Mod AASHTO Dry Density from the moisture Density relationship of the specific BSM.

4.1 Mod AASHTO compaction as a reference compaction level

Mod AASHTO compaction is a well known compaction method in industry. Should an engineer speak of 98% Mod AASHTO, the majority of Civil engineers would have an understanding of what the compaction level is. Therefore comparing the vibratory hammer Dry Densities to Mod AASHTO Dry Densities would provide a concept of compaction levels being achieved.

Currently Mod AASHTO compaction is used to specify site compaction levels in South Africa (TRH 4). In this research study, the Mod AASHTO is used as a reference density for expressing vibratory hammer compaction results, providing a direct comparison between vibratory hammer compaction and site compaction levels.

Accordingly, all density results were expressed as a percentage of Mod AASHTO density.

Mod AASHTO moisture density relationships for the material type used (See Figure 4-1) is shown in the figure below.

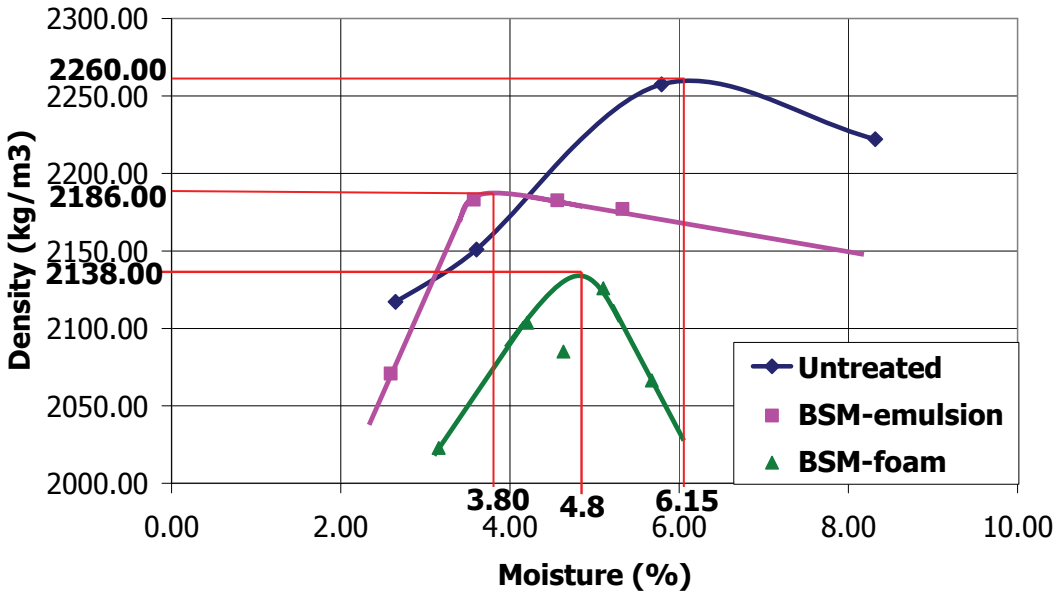


FIGURE 4-1: CONSOLIDATED MOD AASHTO MOISTURE DESINTY RELATION SHIP – G2 MATERIAL

Figure 4-1 is a consolidated Mod AASHTO moisture density relationship of the 3 different type of G2 type materials used, namely untreated, BSM-emulsion and BSM-foam G2 material (See Table 3-5 for more details). The data obtained from Figure 4-1 for the G2 material are indicated in Table 4-1.

Table 4-1: OMC and MDD for G2 material

Test №	Name	Method compaction	OMC %	MDD kg/m^3
1	Untreated	MOD AASHTO	6.15	2260
2	BSM-emulsion	MOD AASHTO	3.8	2186
3	BSM-foam	MOD AASHTO	4.8	2138

Figure 4-1 indicates that for the G2 material both the OMC and MDD, decrease with stabilisation, with a more pronounced effect for BSM-emulsion for the OMC but visa versa for MDD. Knowing that the bitumen concentration of both BSM-emulsion and BSM-FOAM was the same (1.98 % wt/wt), the low OMC, and higher MDD, is like to be a function of the stabilisation type.

With respect to the vibratory hammer experiments performed, information from Figure 4-1 (Table 4-1) supports the fact that it is not preferable to use the untreated material's dry density as the target dry density for stabilised material, because the stabilisation has an impact on the dry densities that can be achieved.

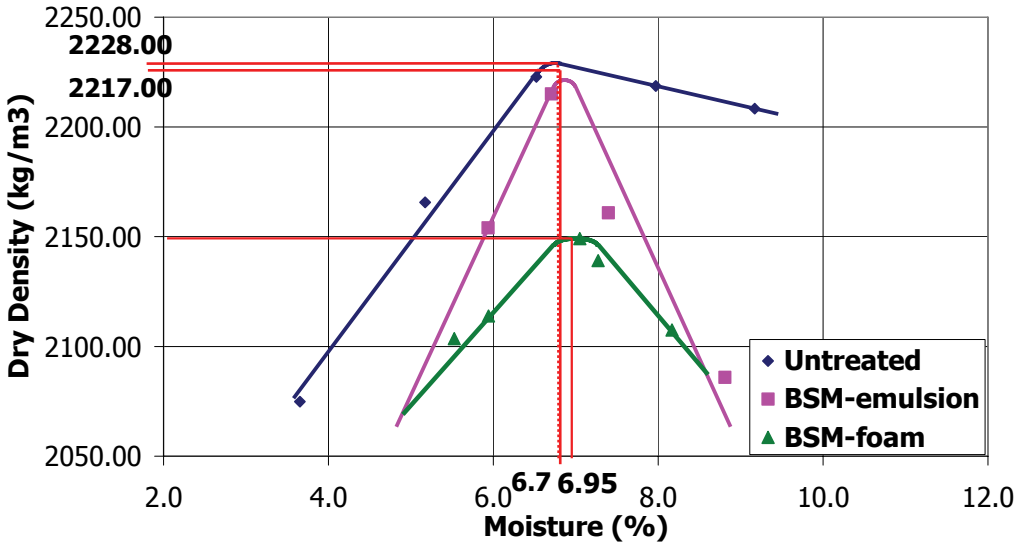


FIGURE 4-2: CONSOLIDATED MOD AASHTO MOISTURE DESINTY RELATION SHIP – G5 MATERIAL

Figure 4-2 is a consolidated Mod AASHTO moisture density relationship of the 3 different type of G5 type materials used, namely untreated, BSM-emulsion and BSM-foam G5 material (See Table 3-5 for more details). The data obtained from Figure 4-2 for the G5 material are indicated in Table 4-2.

TABLE 4-2: OMC AND MDD FOR G5 MATERIAL

Test №	Name	Method compaction	OMC %	MDD kg/m³
4	Untreated	MOD AASHTO	6.7	2228
5	BSM-emulsion	MOD AASHTO	6.8	2217
6	BSM-foam	MOD AASHTO	6.95	2150

Conversely to the G2 material, Figure 4-2 indicates that for the G5 material the OMC, increases with stabilisation, but the MDD decreases with stabilisation (the magnitude of this effect is however, less for the G5 material compared to the G2).

Thus the OMC and MDD characteristic of lower quality granular material (e.g. G5) is less sensitive than high quality granular material (e.g. G2) to the effects of bitumen stabilisation.

With respect to the vibratory hammer experiments performed, information from Figure 4-2 (Table 4-2) supports the fact that it is not preferable to use the untreated material's dry density as the target dry density of stabilised material, because the stabilisation has an impact on the dry densities that can be achieved.

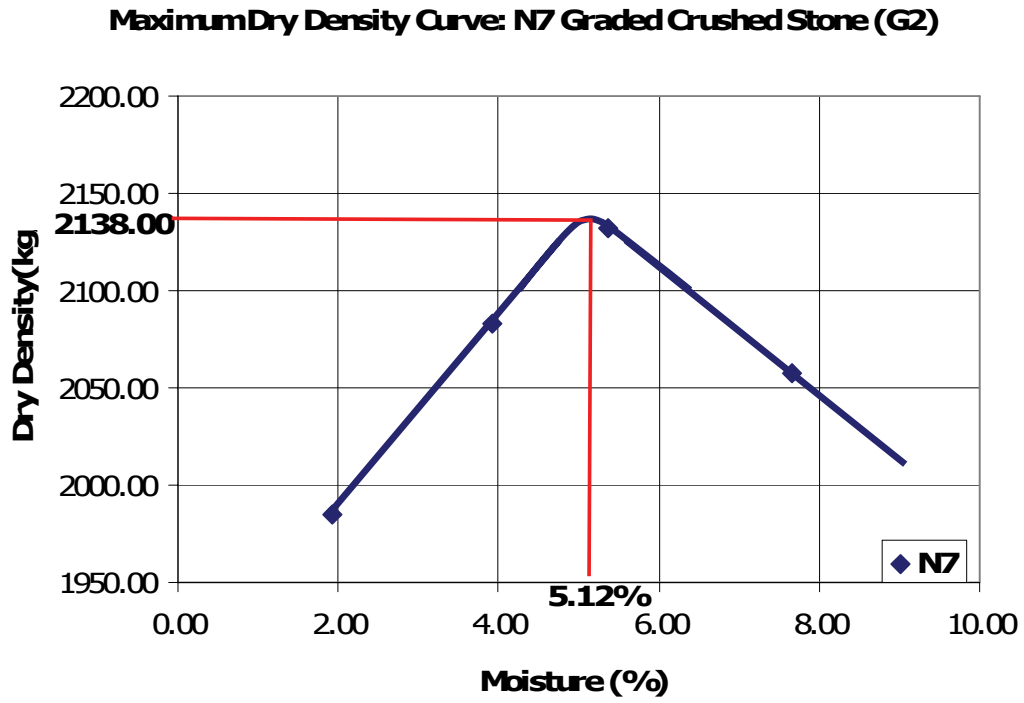


FIGURE 4-3: MOD AASHTO MOISTURE DESINTY RELATION SHIP – N7 MATERIAL

Figure 4-3 is the Mod AASHTO moisture density relationship of the untreated N7 material. (See Table 3-5 for more details). The data obtained from Figure 4-3 for the N7 material are indicated in Table 4-3.

TABLE 4-3: OMC AND MDD FOR N7 MATERIAL

Test №	Name	Method compaction	OMC %	MDD kg/m^3
7	Untreated	MOD AASHTO	5.12	2138

The N7 material is a G2 quality base course aggregate. The OMC and MDD results of Table 4-3 are however significantly lower than the G2 OMC and MDD results in Table 4-1. The N7 material must have undergone in situ weathering to have had such a pronounced difference between it and a material that is of the same quality.

Therefore the N7 material is not expected to have the same characteristics as the G2 material when using vibratory hammer compaction to compact both materials.

4.2 Influence of moisture content and surcharge on compaction time

A factor that affects compaction quite significantly is moisture content. Moisture acts as a lubricant between particles and therefore aids in the shifting and orientation of particles during compaction. In this section the influence of moisture content, and surcharge, on the time it takes to compact a stabilised G2 specimen from each of the stabilisation sample types (BSM-emulsion and BSM-foam), is considered.

Therefore experiments were carried out using varying moisture contents and varying the surcharge, and the outcome of the compaction was accessed. For experiments specific to this section (4.2), the BSM-emulsion G2 material was compacted using the Kango 637® (Kango®), while the FESM G2 material was compacted using the Bosch GSH 11E® (Bosch®) unless otherwise stated.

Table 4-4 lists the tests carried out (See Table 3-5 for more details).

TABLE 4-4: LIST OF TESTS PERFORMED AT VARIOUS MOISTURE CONTENTS AND SURCHARGE LOADS

Test №	Name	Method compaction	Moisture content %OMC of untreated G2 material (Test № 1)	Surcharge kg
8	BSM-emulsion	Vibratory hammer – Kango®	70	10
9	BSM-emulsion	Vibratory hammer – Kango®	70	20
10	BSM-emulsion	Vibratory hammer – Kango®	80	10
11	BSM-emulsion	Vibratory hammer – Kango®	80	15
12	BSM-emulsion	Vibratory hammer – Kango®	80	20
13	BSM-emulsion	Vibratory hammer – Kango®	90	10
14	BSM-foam	Vibratory hammer – Kango®	70	10
15	BSM-foam	Vibratory hammer – Bosch®	80	10
16	BSM-foam	Vibratory hammer – Bosch®	80	15
17	BSM-foam	Vibratory hammer – Bosch®	90	10

4.2.1 *BSM-emulsion using G2 material*

The experiment results of the BSM-emulsion experiment from Table 4-4 are presented in graphical format in Appendix (See Section 9) with the relevant consolidated information extracted and presented below for discussion (See Figure 4-4 and Figure 4-5). Experiments on BSM-emulsion G2 material at the moisture content 70% OMC were performed by final year civil engineering student Mr. Rojean Hannekom, who also supplied the results of the experiments.

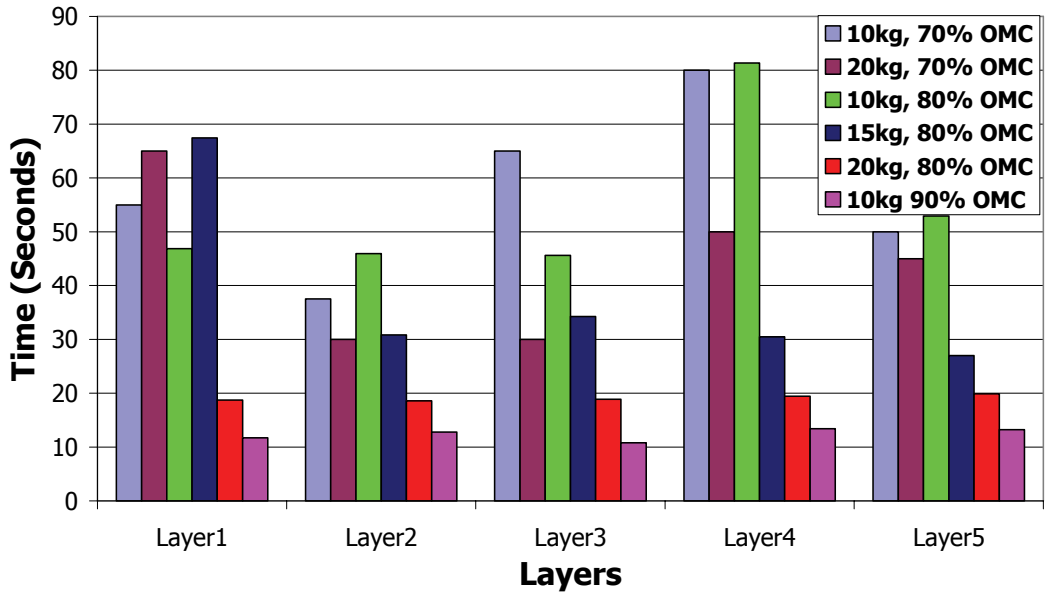


FIGURE 4-4: CONSOLIDATED GRAPH OF COMPACTION TIME TO 100% MOD AASHTO COMPACTION-BSM-EMULSION

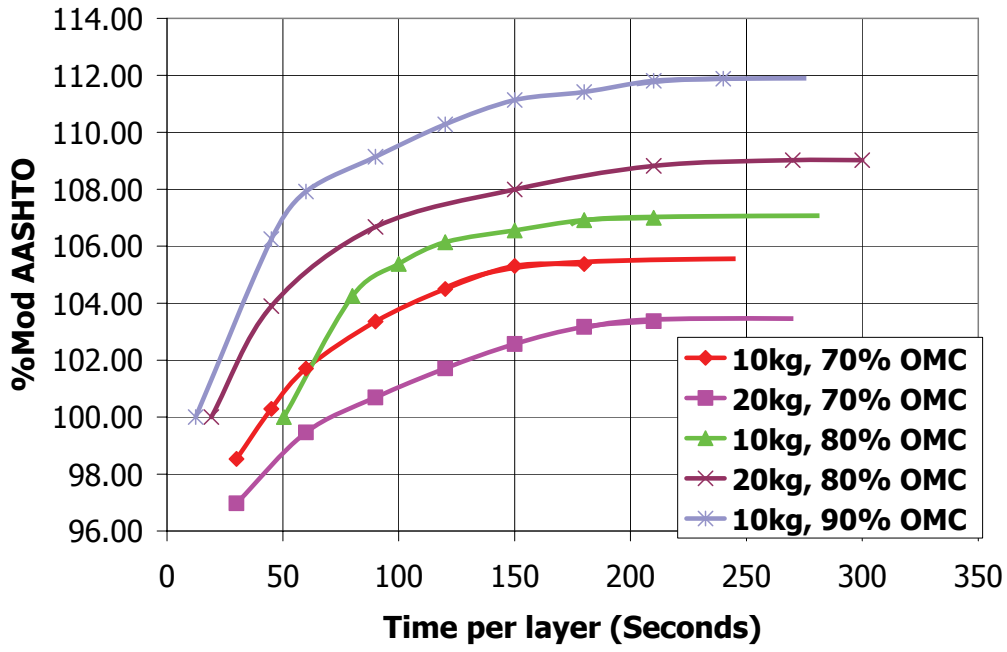


FIGURE 4-5: REFUSAL (DRY) DENSITY PROFILE OF THE SPECIMENS FOR EACH TEST PERFORMED-BSM-EMULSION

Figure 4-4 and Figure 4-5 show the required time to compact each layer of a specimen to an equivalent Mod AASHTO Dry Density (of the specific moisture content) and the refusal density trend for the different BSM-emulsions respectively. The results from Figure 4-4 and Figure 4-5 are discussed as follows:

- Variability in the compaction time of specimen layers at a specific moisture content;
- Constant surcharge load with varying moisture content;
- Constant Moisture content with varying surcharge load.

Variability in the compaction time of specimen layers at a specific moisture content

From Figure 4-4 it is seen that there is a variability in the time it takes to compact the respective layers of a specimen at a given moisture content. This is more pronounced in the 70% OMC experiment results. This variability is reduced as the moisture contents are increased. From 80% OMC to 90% OMC time to compact layers to a target density (100% Mod AASHTO) becomes more consistent. Thus moisture contents of 80% OMC and higher are more favourable for developing compaction times for individual layers of a specimen.

Constant surcharge load with varying moisture content

TABLE 4-5: RESULTS OF CONSTANT SURCHARGE LOAD WITH VARYING MOISTURE CONTENTS-G2 BSM-EMULSION

Surcharge kg	Moisture content (% OMC)	Average time per layer to 100% Mod AASHTO (sec)	Refusal Density (%Mod AASHTO)	Time per layer to refusal Density (sec)	Tendency	Comments
10	70	45	105.5	180	• Initial increase in compaction time as moisture is increased. Then a significant decrease in compaction time with an further increase in the moisture • Achieved refusal density increases as moisture increases • Time to achieved refusal density increases as moisture increases	The increase in compaction time from 70% to 80%OMC is not significant when compared to the decrease in compaction time from 80% to 90% OMC
	80	50.46	107	200		
	90	12.38	112*	225		
15	80	38				No refusal density profile was developed
20	70	60	103.5	200	• Increase in moisture content results in a decrease in the compaction time	

Surcharge kg	Moisture content (% OMC)	Average time per layer to 100% Mod AASHTO (sec)	Refusal Density (%Mod AASHTO)	Time per layer to refusal Density (sec)	Tendency	Comments
	80	19.12	109	250	• Achieved refusal density increases as moisture increases • Time to achieved refusal density increases as moisture increases	

*Due to the excessively wet condition of the material, seepage of the material began to take place during compaction.

From Table 4-5 specimens compacted at 80% OMC with a 10kg surcharge and specimens compacted at 70% OMC with a 20kg surcharge require compaction times (to achieve 100% Mod AASHTO) that are similar to what is specified by the ASTM and UK compaction procedures. These two surcharge/moisture content combinations results are therefore considered candidates from which to develop a preliminary compaction procedure. The 80% OMC 10kg combination is however more favourable, as it achieves a higher refusal density than the 70% OMC 10kg combination. The results also show that by increasing the moisture content (from 70% OMC to 80% OMC), the surcharge load may be reduced, but still obtain the same level of compaction.

Constant Moisture content with varying surcharge load

TABLE 4-6: RESULTS OF CONSTANT MOISTURE CONTENTS WITH VARYING SURCHARG LOADS – G2 BSM-EMULSION

Moisture content (% OMC)	Surcharge (kg)	Average time per layer (sec)	Refusal Density (%Mod AASHTO)	Time to refusal Density (sec)	Tendency	Comments
70	10	45	105.5	180	• Time of compaction is reduced as the surcharge load is increased • Achieved refusal density decreased with an increasing surcharge • Time to refusal density increased with increasing surcharge load	
	20	60	103.5	200		
80	10	50	107	200	• Time of compaction is reduced as the surcharge load is increased • Achieved refusal density increased with an increasing surcharge • Time to refusal density increased with increasing surcharge load	
	15	38	No refusal density profile	No refusal density profile		
	20	19	109	250		
90	10	12.38	112*	225		

From Table 4-6 it is seen that the refusal density of the material at 80% OMC is not significantly influenced by the surcharge load. Owing to the fact that the Kango® suffered damage to the gearbox while using the 20kg surcharge, the decision was made not to consider this surcharge load further. Hence 70% OMC at 20kg surcharge was no longer an option.

Therefore the preliminary vibratory hammer compaction method was developed using the 80% OMC and 10kg surcharge combination.

4.2.2 BSM-foam using G2 material

The experiment results of the BSM-emulsion experiment from Table 4-4 are presented in graphical format in Appendix (See Section 9) with the relevant consolidated information extracted and presented below for discussion (See Figure 4-6 and Figure 4-7). Experiments on BSM-foam G2 material at the moisture content 70% OMC were performed by final year civil engineering student Mr. Rojean Hannekom, who also supplied the results of the experiments.

Figure 4-6 and Figure 4-7 show the required time to compact each layer of a specimen to an equivalent Mod AASHTO density (of the specific moisture content) and the refusal density trend for the different BSM-emulsions respectively. The results from Figure 4-4 and Figure 4-5 are discussed as follows:

- Variability in the compaction time of specimen layers at a specific moisture content;
- Constant surcharge load with varying moisture content;
- Constant Moisture content with varying surcharge load.

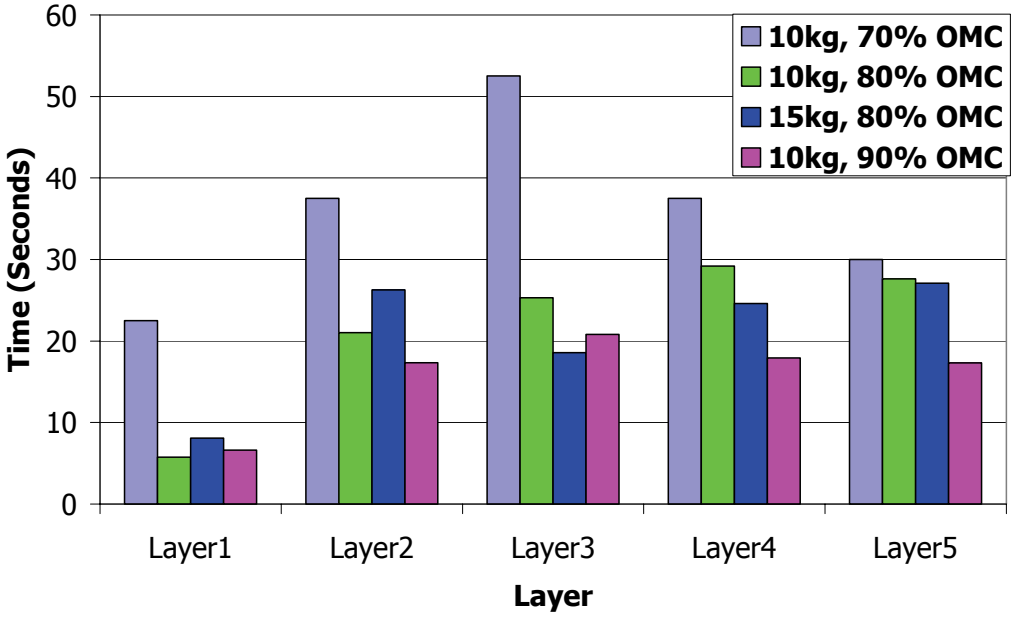


FIGURE 4-6: CONSOLIDATED GRAPH OF COMPACTION TIME TO 100% MOD AASHTO COMPACTION-BSM-FOAM

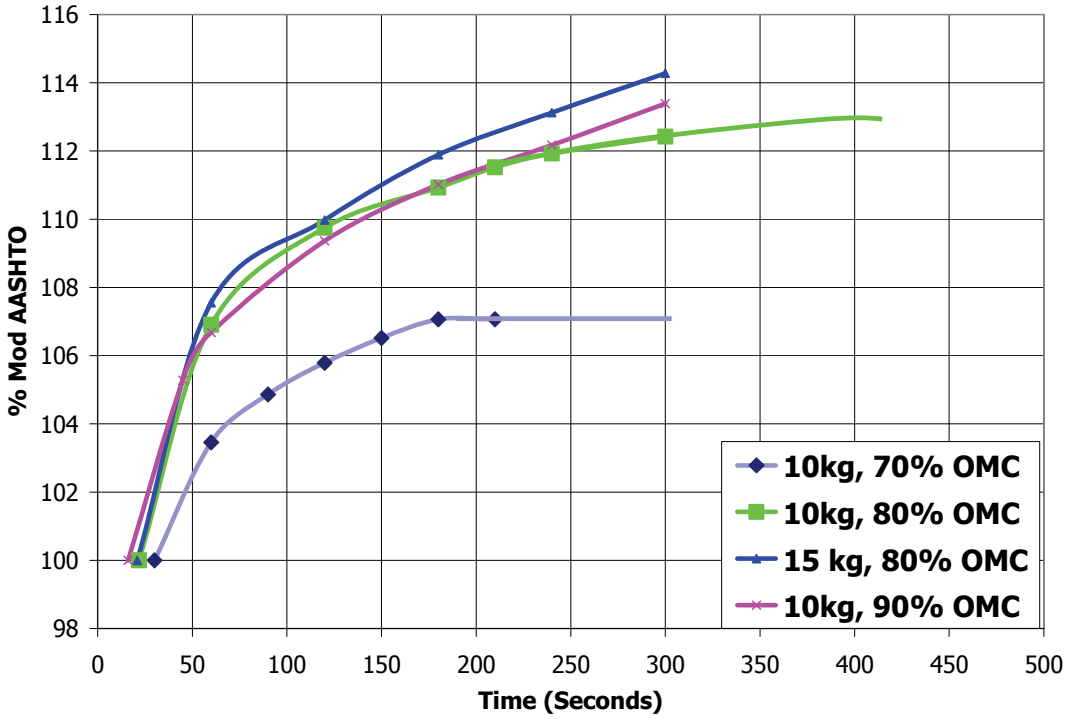


FIGURE 4-7: REFUSAL DENSITY PROFILE OF THE SPECIMEN FOR EACH TEST PERFORMED-BSM-FOAM

Variability in the compaction time of specimen layers at a specific moisture content

Contrary to the BSM-emulsion, the BSM-foam does not become more consistent in the time it takes to compact individual layers to 100% Mod AASHTO (See Figure 4-6). Rather individual layers of the BSM-foam specimens require individual compaction times that differ from each other. The results of the 70% OMC and 80% OMC at 10kg surcharge have a more similar and consistent trend, both increase to a point and then taper off to the final layer. 90% OMC at 10kg is more consistent throughout, but as with the BSM-emulsion, this moisture content resulted in material seeping out of the mould during compaction. Thus the 70% OM and 80% OMC at 10kg surcharge are the favoured moisture content/surcharge combination.

Constant surcharge load with varying moisture content

TABLE 4-7: RESULTS OF CONSTANT SURCHARGE LOAD WITH VARYING MOISTURE CONTENTS – G2 BSM-FOAM

Surcharge kg	Moisture content (% OMC)	Average time per layer to achieve 100% Mod AASHTO (sec)	Refusal Density (%Mod AASHTO)	Time per layer to refusal Density (sec)	Tendency	Comments
10	70	30	107	180	• Increasing the moisture content reduces compaction time to 100% Mod AASHTO per layer	The refusal density profile is still increasing after 5min compaction time per layer. No reason be given
	80	22	113	400		

Surcharge kg	Moisture content (% OMC)	Average time per layer to achieve 100% Mod AASHTO (sec)	Refusal Density (%Mod AASHTO)	Time per layer to refusal Density (sec)	Tendency	Comments
	90	16	>113	+300	• Increased moisture contents require more time to achieve refusal density	
15	80	21	>114	+300		The refusal density profile is still increasing after 5min compaction time per layer. No reason be given.

The 70% OMC experiment was performed using the Kango® hammer. Therefore the result of the 70% OMC 10kg surcharge and 80% OMC 10kg surcharge may not be as comparable as desired. However the Bosch® hammer was chosen to simulate the compaction effort of the Kango® based on the criteria in section 3.4.1, Therefore the BSM-foam results of the Kango® vibratory hammer are compared to the BSM-foam results of the Bosch® vibratory hammer.

From Table 4-7 it is seen that compaction times do reduce as the moisture content of the surcharge/moisture content combination is increased. The time to the target density (100% Mod AASHTO) was well below the compaction times indicated in the literature (See section 2.3 and section 2.4). This however did not impact on the development of a compaction method to produce laboratory specimens of equivalent Mod AASHTO densities.

Constant Moisture content with varying surcharge load

Table 4-8: Results of constant moisture contents with varying surcharge load -G2 BSM-foam

Moisture content (% OMC)	Surcharge (kg)	Average time per layer to 100% Mod AASHTO (sec)	Refusal Density (%Mod AASHTO)	Time per layer to refusal Density (sec)	Tendency	Comments
70	10	30	107	180		
80	10	22	113	400		Surcharge load variation at a given moisture content does not influence the compaction time significantly
	15	21	>114	+300		
90	10	16	>113	+300		

From Table 4-8 the influence of increasing the surcharge load at a given moisture content (80% OMC) is seen to be insignificant. Therefore BSM-foam compacted under a slightly lower surcharge load at the same moisture content will use the same compaction time per layer to achieve the target density.

Note: Varying the surcharge load by more significant amounts was not tested and therefore that influence is not known and as such may be a direction for further research.

Due to the Kango® hammer having been replaced, the lack of influence of the surcharge load on the compaction time to 100% Mod AASHTO and the achievable refusal density as well as the time to achieve refusal density, the choice was made to use the 80% OMC with 10kg surcharge to develop a preliminary compaction procedure for the vibratory hammer.

4.3 Developed vibratory hammer compaction procedure based on G2 tests

This section (4.3) makes use of the results of section 4.2 to develop laboratory compaction methods to produce specimens that are representative of Mod AASHTO compaction. The reasons for this are as follows:

- BSM specimens are to be compacted to realistic site compaction levels. The compacted BSM specimens are then to undergo material testing (triaxial testing) in order to classify the BSM;
- Mod AASHTO compaction levels are realistic levels to which material can be compacted on site. The Mod AASHTO compaction method though does not produce specimens as representative of site compacted specimens as engineers would like;
- Vibratory hammer compaction can compact specimens more representative of site compacted specimens (See Section 1.1 and Section 3.4.4);

Therefore as per the objective "Develop a compaction procedure from the above results, to simulate realistic field compaction levels in order to perform material test (triaxial test) on bitumen stabilised material (BSM), and hence classify it" the following laboratory compaction methods are developed:

- Vibratory hammer compaction method for BSM-emulsion specimens;
- Vibratory hammer compaction method for BSM-foam specimens.

Table 4-9 lists tests that were performed for a correlation test (See Section 4.3.1 details):

TABLE 4-9: LIST OF TESTS PERFORMED FOR CORRELATION EXPERIMENT

Test №	Name	Method compaction	Moisture content %OMC of untreated G2 material (Test № 1)	Surcharge kg
18	BSM-emulsion	Vibratory hammer – Bosch®	80	10

4.3.1 Vibratory hammer compaction method for BSM-emulsion specimens

Based on the choice of surcharge/moisture content combination of Section 4.2.1 the following information was used:

- Average time to 100% Mod AASHTO compaction of 50sec;

- Surcharge load of 10kg;
- Moisture content of 80% OMC of the Mod AASHTO moisture density relationship for the untreated material.

Before compaction times were assigned to individual specimen layers, the accuracy with which the Bosch® vibratory hammer simulated compaction results of the Kango® vibratory hammer was first determined. This was done by means of a correlation experiment. The following criteria were used to perform this experiment:

- BSM-emulsion G2 material;
- Moisture content of 80% OMC;
- 10kg surcharge;
- A Target Dry Density (100% Mod AASHTO at 80%OMC) of 2188 kg/m^3 (See Figure 4-1 Legend "BSM-emulsion").

Specimens for the Bosch® vibratory hammer were compacted in 5 layers to a thickness of 60mm each. The result of the experiment is shown in Figure 4-8.

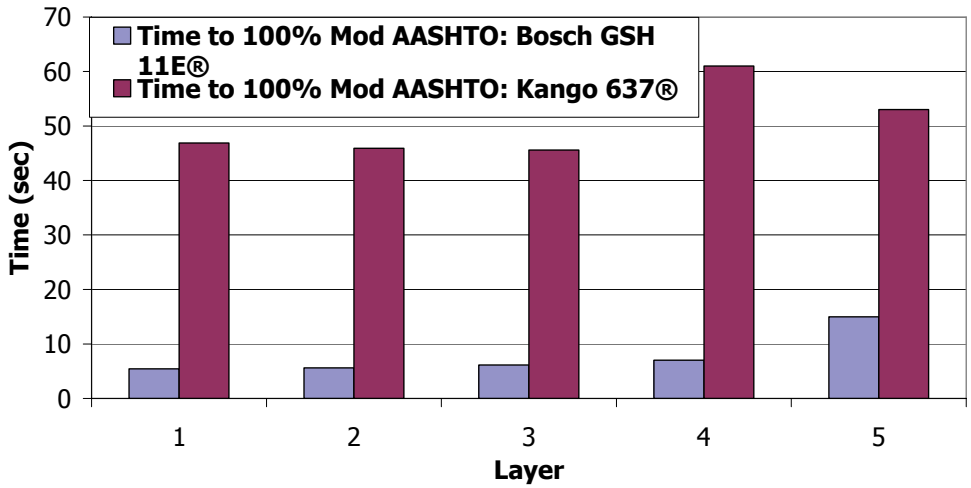


FIGURE 4-8: BOSCH® VIBRATORY HAMMER CORRELATION EXPERIMENT – BSM-EMULSION

Figure 4-8 shows that the Bosch® has a consistent time throughout the specimen layers. The compaction time required is also well below the compaction time of the Kango®.

Therefore the compaction times per layer of the Kango® must first be adjusted according to this result. The Bosch® compaction times were below 10sec, therefore to allow for adequate compaction and to reduce the variability of achieved densities the compaction times of the Bosch® were increased to 15 sec and assigned to the specimen layers.

Compaction times of 15sec per layer assigned from the Bosch® meant that compaction time was increased by 10sec per layer (for layers 1 to 4, layer 5 was not increased). This increased the achieved Dry Density from 100% Mod AASHTO to 102% Mod AASHTO (seen in later results). Viewing the time increase of 10sec for the Kango® in Figure 4-3 (See legend "10kg, 80%OMC"), the same increase in achieved Dry Density is seen. Thus the refusal density profile of a specimen compacted using the Bosch® will be the same as for the Kango®, only the time of compaction to refusal density will be reduced.

Therefore the preliminary laboratory vibratory hammer compaction procedure is as follows:

- Compaction time per layer is 15sec (except Layer 1 which had 10sec allocated. This was due to layer 1 being compacted on a steel base, which did not have the cushioning effect that subsequent layers experienced in previously compacted layers);
- Surcharge load of 10kg
- Moisture content of 80% of OMC of the Mod AASHTO moisture density relationship for the untreated material.

4.3.2 Vibratory hammer compaction method for BSM-foam specimens

Based on the choice of surcharge/moisture content combination of Section 4.2.2 the following information was used:

- Average time to 100% Mod AASHTO compaction of 7sec, 20sec, 25sec,29sec and 28sec for layers 1,2, 3, 4 and 5 respectively;
- Surcharge load of 10kg;
- Moisture content of 80% OMC of the Mod AASHTO moisture density relationship for the untreated material.

The compaction times were increased to reduce the variability of the level of compaction. The times therefore assigned to the respective specimen layers are as follows:

- Layer 1 – 10sec (3sec increase);
- Layer 2 – 25sec (5sec increase);
- Layer 3 – 25sec (0 sec increase);
- Layer 4 – 35sec (6sec increase);
- Layer 5 – 30sec (2sec increase).

Viewing these increases on the refusal density profile for the individual layers (See Section 9, Appendix C, Figure 9-15), the increase in the achieved Dry Density is 2% Mod AASHTO compaction. This increase is not significant enough to produce specimens that are not representative (in terms of Dry Density) of Mod AASHTO compaction. Therefore these times are acceptable.

4.4 Testing the developed laboratory vibratory hammer compaction method

The vibratory hammer compaction method developed in Section 4.3 was performed on four BSMs to test and determine the following:

- Influence of material temperatures on compaction;
- Site correlation tests - Reproducibility of site compaction levels in the laboratory with the developed procedure;
- Development of moisture density relationships of the G2 and G5 BSM-emulsion and BSM-foam using the developed Vibratory hammer compaction method.

Table 4-10: List of tests performed using the developed vibratory hammer compaction method

Test №	Name	Method compaction	Moisture content %OMC	Surcharge kg
19	BSM-emulsion	Vibratory hammer-Bosch®	80	10

Test №	Name	Method compaction	Moisture content %OMC	Surcharge kg
20	BSM-foam	Vibratory hammer-Bosch®	80	10
21	BSM-emulsion	Vibratory hammer-Bosch®	80	10
22	BSM-emulsion	Vibratory hammer-Bosch®	80	10
23	Untreated	Vibratory hammer-Bosch®	Varying	10
24	BSM-emulsion	Vibratory hammer-Bosch®	Varying	10
25	BSM-foam	Vibratory hammer-Bosch®	Varying	10
26	Untreated	Vibratory hammer-Bosch®	Varying	10
27	BSM-emulsion	Vibratory hammer-Bosch®	Varying	10
28	BSM-foam	Vibratory hammer-Bosch®	Varying	10

4.4.1 Influence of material temperatures compaction

Temperature tests were performed on the following BSMs:

- BSM-emulsion – G2 material at temperatures of 5, 15 and 35^{0}C;
- BSM-foam – G2 material at temperatures of 5, 15 and 35^{0}C.

Table 4-11 presents a layout of how the various temperatures were obtained:

TABLE 4-11: TEMPERATURE PREPERATION OF THE G2 MATERIAL

	BSM-emulsion and BSM-foam		
Temperature	**5^{0}C**	**15^{0}C**	**35^{0}C**
Preparation	• Layer mass placed in plastic bag • Plastic bag place in a fridge at 5^{0}C for a few hours • Temperature was recorded until the temperature was at 5^{0}C(±2^{0}C) • Bags removed and material compacted one by one	• Layer mass placed in plastic bag • Plastic bag place in a fridge at 5^{0}C for a few hours • Temperature was recorded until the temperature was at 5^{0}C • Bags were removed and packed out on a table • Temperatures were recorder regularly until the temperature was 15^{0}C (±2^{0}C) • Bags taken and material compacted one by one	• Layer mass placed in two plastic bags • Plastic bag place in an oven at 35^{0}C for a few hours • Temperature was recorded until the temperature was at 35^{0}C (±2^{0}C) • Bags removed and compacted one by one

BSM-emulsion – material temperatures of 5, 15 and 35^{0}C

Figure 4-9 shows graphically the results of the test.

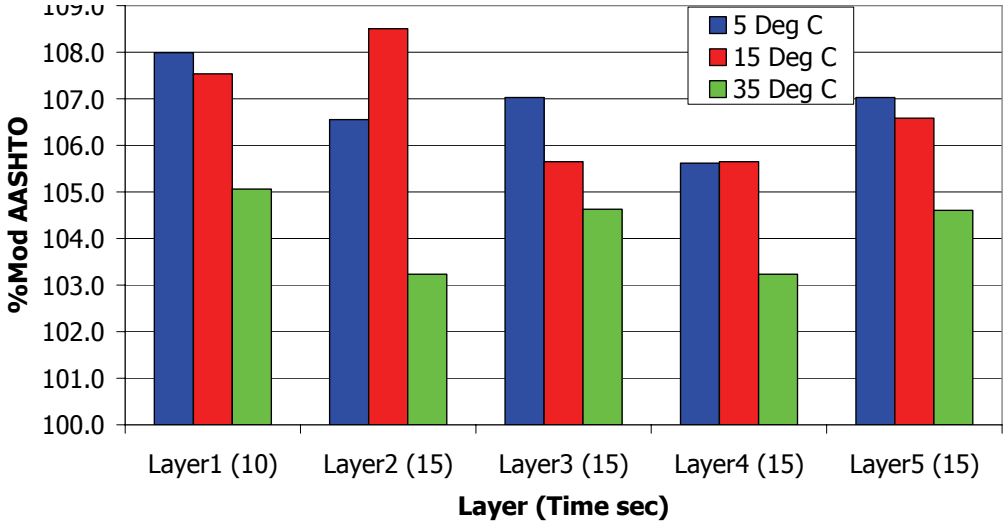


FIGURE 4-9: TEMPERATURE TEST OF DEVELOPED VIBRATORY HAMMER COMPACTION METHOD – BSM-EMULSION

It is intuitive that at lower temperatures the material would not compact as well as it would at higher temperatures. The converse of this is seen in Figure 4-9. The 5^0C and 15^0C result produce Dry Densities that may not be realistically achievable site compaction levels. The 35^0C result does produce compaction levels that are more realistic of site compaction levels for a G2 material. Therefore when compacting BSM-emulsion specimens, compaction should be done with the material temperature in the order of 35^0C.

BSM-emulsion – material temperatures of 5, 15 and 35^0C

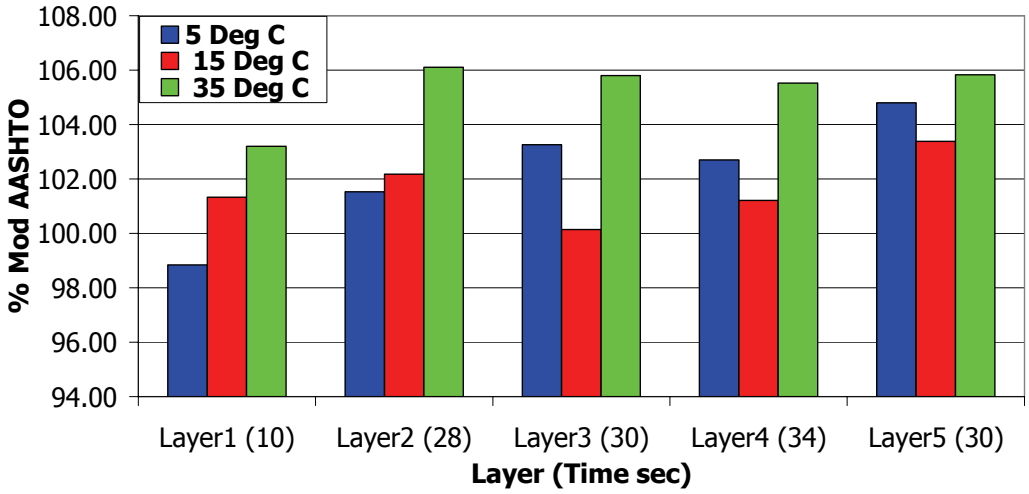


FIGURE 4-10: TEMPERATURE TEST OF DEVELOPED VIBRATORY HAMMER COMPACTION METHOD – BSM-FOAM

The intuitive trend expect in Figure 4-9 is seen in Figure 4-10. The 5^0C and 15^0C result produce compaction levels that are realistically achievable site compaction levels. The 35^0C result does not however produce compaction levels that are realistically achievable on site for a G2 material. Therefore when compacting BSM-emulsion specimens, compaction should be done with the material temperature between 5^0C and 15^0C.

4.4.2 Site correlation tests - Reproducibility of site compaction levels in the laboratory with the developed procedure

Material acquired from a rehabilitation project taking place along the N7 national road just outside of Cape Town was used for these tests. The N7 material was used to prepare the following:

- BSM-emulsion;
- BSM-foam.

The target Dry Densities for these tests was determined from site compaction data obtained from the rehabilitation project (BSM-emulsion) and from the CSIR report CR-2003/23 (BSM-foam). Statistical analysis was performed on the data to determine what the target Dry Density will be. The results of the statistical analysis are shown below for the respective BSMs.

BSM-emulsion: statistical results of site data

Table 4-12 presents the statistical results of the N7 site compaction data for BSM-emulsion. Φ is taken as 15% (CSRA, 1987).Therefore the 85th percentile is used to determine the target Dry Density (See Section 10, Appendix C for full statistical analysis).

TABLE 4-12: STATISTICAL RESULTS OF N7 SITE DATA – BSM-EMULSION

	Mean	Standard deviation	COV (%)	85th Percentile
%Mod AASHTO	106.72	2.38	2.65	103.99
Dry Density (kg/m^3)	2292.6	56.76	2.48	2245.2

From Table 4-12 the target Dry Density for the BSM-emulsion was calculated as the MDD of the Mod AASHTO Dry Density which is 2158.9 kg/m^3.

BSM-foam: statistical results of site data

Table 4-13 presents the statistical results of the N7 site compaction data for BSM-foam (See Section 10, Appendix C for full statistical analysis).

TABLE 4-13: STATISTICAL RESULTS OF N7 SITE COMPACTION DATA- BSM-EMULSION

	Mean	Standard deviation	COV (%)
Dry Density (kg/m^3)	2177.33	49.15	2.26

From the statistical analysis, the mean Dry Density was taken as the target Dry Density for the test.

Site correlation test results

Figure 4-11 and Figure 4-12 show the results of the site correlation test for the BSM-emulsion and BSM-foam. The reference in the legend of each figure indicating "N7" is the reference to the site correlation experiment. Table 4-14 summarises the compaction levels obtained with developed vibratory hammer compaction method.

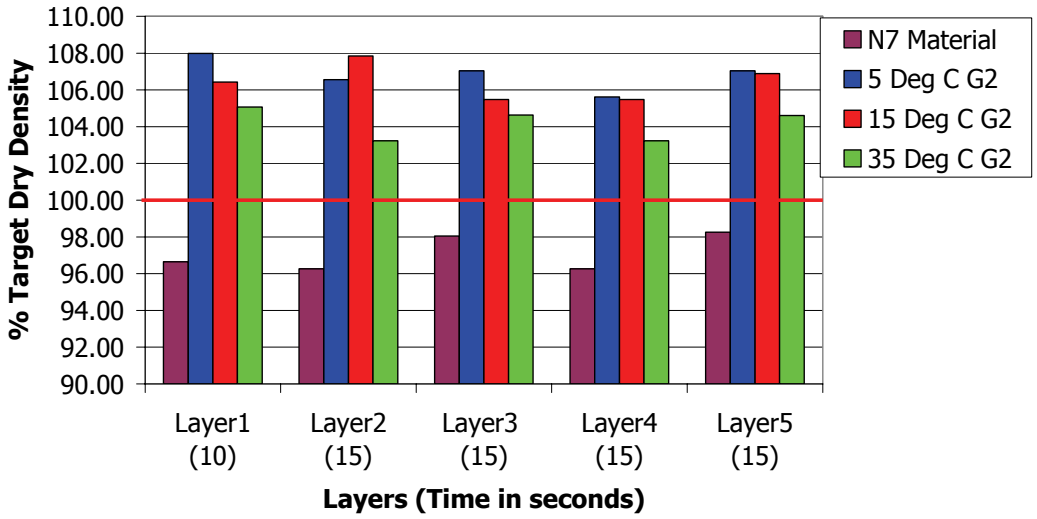


FIGURE 4-11: SITE CORRELATION TEST OF N7 MATERIAL – BSM-EMULSION

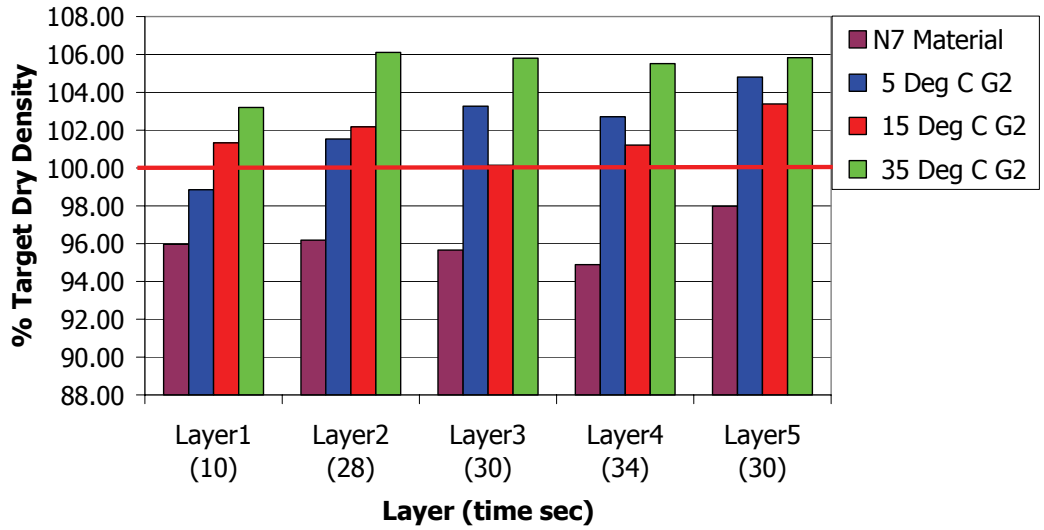


FIGURE 4-12: SITE CORRELATION TEST OF N7 MATERIAL – BSM FOAM

TABLE 4-14: COMPACTION LEVELS OBTAINEDON N7 SITE MATERIAL USING THE DEVELOPED VIBRATORY HAMMER COMPACTION METHOD.

Material	Level of compaction achieved (% of the target Dry Density)				
	Layer 1	Layer 2	Layer 3	Layer 4	Layer 5
N7 BSM-emulsion	96.5	96	98	96	98
N7 BSM-foam	96	96	95.8	95	98

Table 4-14 shows that the developed vibratory hammer compaction method was unsuccessful in reproducing the site compaction levels for both BSM-emulsion and BSM-foam. This may be due to two reasons:

- The material properties of the N7 material were more of a G5 quality material in terms of their Atterberg Limits (see Table 3-2);
- The presence of RAP in the recycled material may have hindered the compaction of the material.

The N7 material did not respond as the G2 material did, this was expected (See Section 4.1, Table 4-3), although the N7 itself is classified as a G2 quality material.

4.4.3 Developed of the moisture density relationship of the G2 and G5 BSM-emulsion and BSM-FOAM using the Vibratory hammer compaction method

Moisture density relationships were developed for various material types and compared to the moisture density relationships developed for that specific material in Section 4.1. These material types are:

- G2 Untreated material;
- G2 BSM-emulsion;
- G2 BSM-foam;
- G5 Untreated material;
- G5 BSM-emulsion;
- G5 BSM-foam.

The moisture density relationship for the G5 material was developed in order to determine the applicability of the developed vibratory hammer compaction method on lower quality granular material.

The vibratory hammer compaction method applied to the untreated material was the same method applied to the BSM-emulsion. This was done because bitumen emulsion acts as a compacting lubricant during compaction, and water is the compacting lubricant in the untreated material, therefore the same vibratory hammer compaction method was applied to both materials.

The results of this test are presented in Figure 4-13 to Figure 4-15 for the G2 material and from Figure 4-16 to Figure 4-18 for the G5 material. The results are tabulated in Table 4-15 and Table 4-16 for the G2 and G5 respectively.

G2 Moisture density relationships developed using the vibratory hammer compaction method

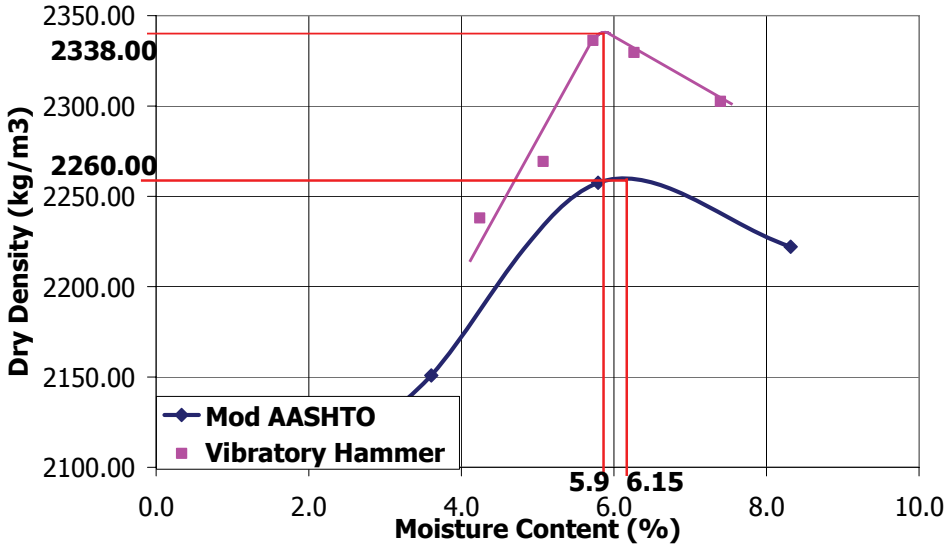


FIGURE 4-13: MOISTURE DENSITY RELATIONSHIP - UNTREATED G2 MATERIAL, VIBRATORY HAMMER COMPACTION METHOD VS. MOD AASHTO COMPACTION

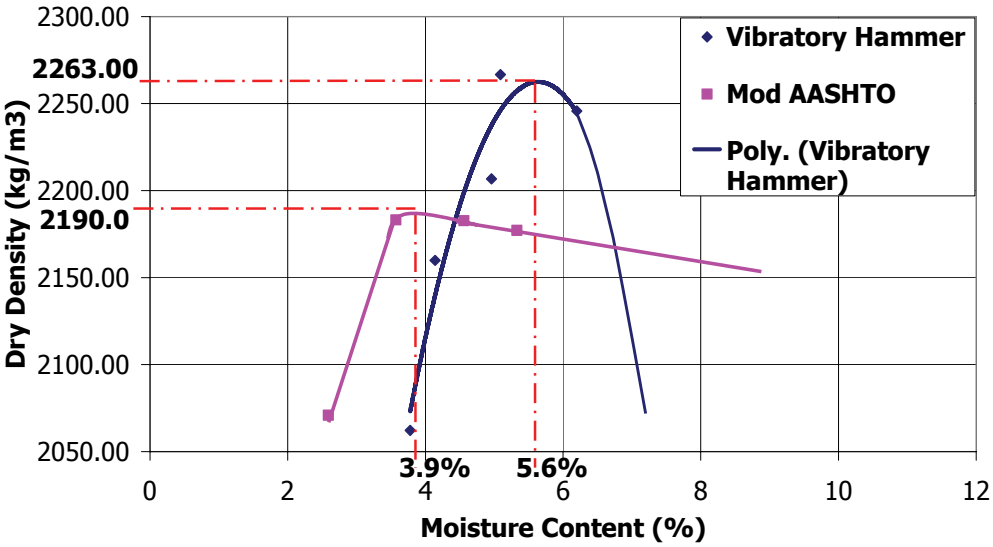


FIGURE 4-14: MOISTURE DENSITY RELATIONSHIP – BSM-EMULSON G2 MATERIAL, VIBRATORY HAMMER COMPACTION METHOD VS. MOD AASHTO COMPACTION

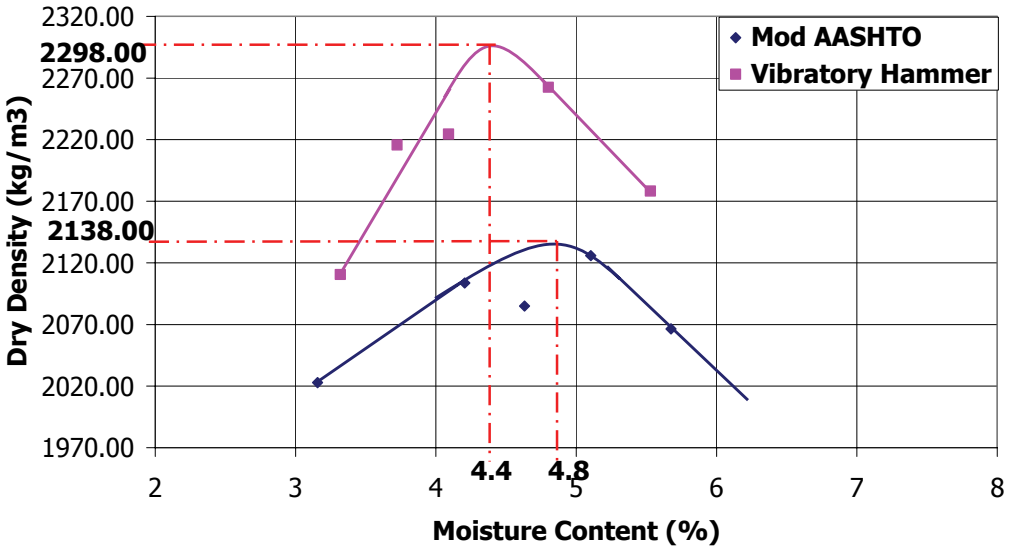


FIGURE 4-15: MOISTURE DENSITY RELATIONSHIP – BSM-FOAM G2 MATERIAL, VIBRATORY HAMMER COMPACTION METHOD VS. MOD AASHTO COMPACTION

Table 4-15 shows the tabulated results of the moisture density relationships of the G2 BSM.

TABLE 4-15: TABULATED RESULTS OF VIBRATORY HAMMER MOISTUR DENSITY RELAIONSHIP-G2 MATERIAL

	Untreated G2 material		G2 BSM-emulsion		G2 BSM-foam	
	Mod AASHTO	**Vibratory hammer**	**Mod AASHTO**	**Vibratory hammer**	**Mod AASHTO**	**Vibratory hammer**
OMC	6.15	5.9	3.9	5.6	4.8	4.4
MDD	2260	2338	2190	2263	2138	2298
Compaction level of vibratory hammer MDD (%Mod AASHTO MDD)	103.45		103.33		107.5	

Table 4-15 shows that except for the BSM-emulsion the OMC of the material reduced for the vibratory hammer. The MDDs of the vibratory hammer for all three G2 material types were well in excess of their respective Mod AASHTO compaction MDDs.

This result shows that for an untreated G2 material and a G2 BSM-foam less moisture is required to achieve higher levels of compaction. The result also shows that should vibratory hammer compaction levels be used to specify compaction moisture for site compaction, a Mod AASHTO moisture density will be required when compacting BSM-emulsion, so as to specify the lower OMC of the two compaction methods.

Specifications for site compaction levels of a G2 quality material require 100 to 102% Mod AASHTO compaction. The vibratory hammer compaction method exceeds this, especially in the case of BSM-foam. The BSM-emulsion and untreated material show that realistic site compaction levels can be obtained in the laboratory on a good quality granular material using the vibratory hammer as their MDD compaction levels are not excessively higher than the specifications. The BSM-foam however achieves an MDD compaction level that is significantly higher than the specifications for site compaction levels. Therefore BSM-foam may not necessarily achieve realistic site compaction levels in the laboratory using vibratory hammer compaction.

G5 Moisture density relationships developed using the vibratory hammer compaction method

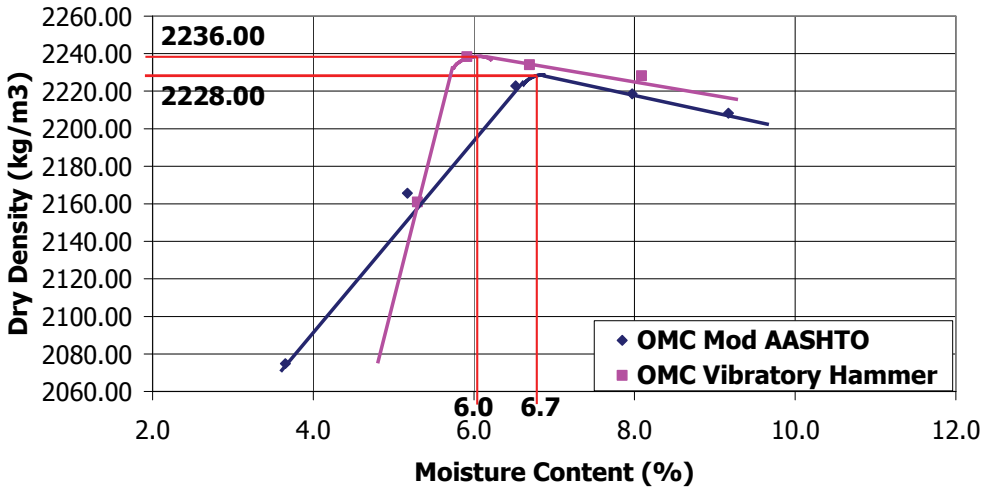


FIGURE 4-16: MOISTURE DENSITY RELATIONSHIP - UNTREATED G5 MATERIAL, VIBRATORY HAMMER COMPACTION METHOD VS. MOD AASHTO COMPACTION

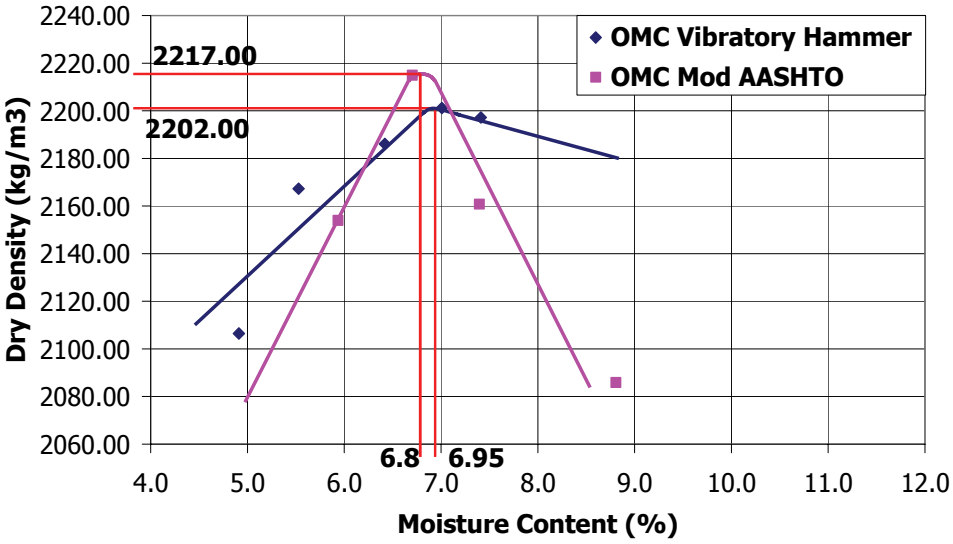


FIGURE 4-17: MOISTURE DENSITY RELATIONSHIP – BSM-EMULSION G5 MATERIAL, VIBRATORY HAMMER COMPACTION METHOD VS. MOD AASHTO COMPACTION

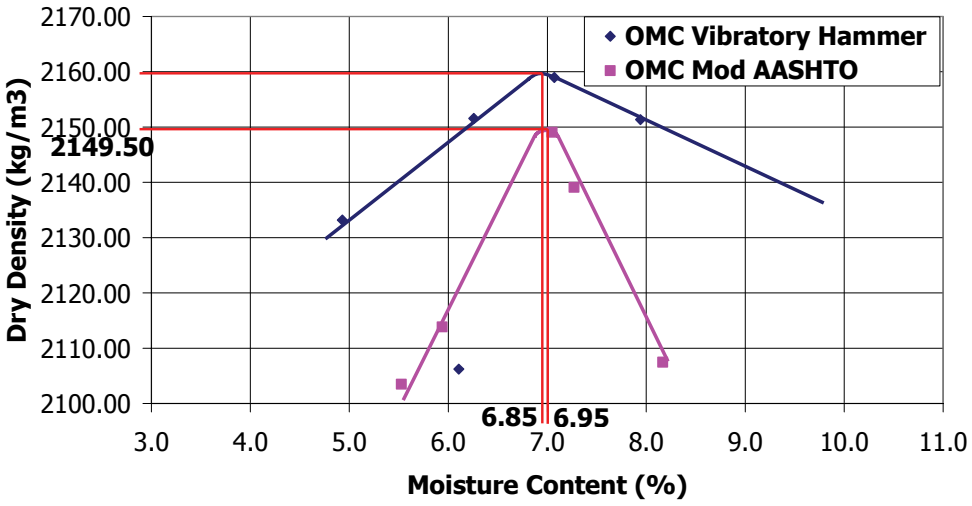


FIGURE 4-18: MOISTURE DENSITY RELATIONSHIP – BSM-FOAM G5 MATERIAL, VIBRATORY HAMMER COMPACTION METHOD VS. MOD AASHTO COMPACTION

Table 4-16shows the tabulated results of the moisture density relationships of the G5 BSM.

TABLE 4-16: TABULATED RESULTS OF VIBRATORY HAMMER MOISTUR DENSITY RELAIONSHIP-G5 MATERIAL

	Untreated G5 material		G5 BSM-emulsion		G5 BSM-foam	
	Mod AASHTO	Vibratory hammer	Mod AASHTO	Vibratory hammer	Mod AASHTO	Vibratory hammer
OMC	6.7	6	6.8	6.95	6.85	6.95
MDD	2228	2236	2217	2202	2149.5	2160
Compaction level of vibratory hammer MDD (%Mod AASHTO MDD)	100.36		99.32		100.5	

Table 4-16 shows very little variation in the OMC of the BSM-emulsion and BSM-foam. The untreated material however had a more pronounced difference in the OMC, with the vibratory hammer having the lower value. The achieved MDD compaction levels of the lower quality granular material are consistently in the order of 100% Mod AASHTO MDD. This is a good indication that the vibratory hammer compaction procedure is able to be applied successfully to lower quality granular materials. Considering that site specifications require a minimum of 95% Mod AASHTO (TRH 4, 1996), the vibratory hammer well exceeds this specification providing confirmation that realistic site compaction levels can be obtained in the laboratory on a low quality granular material using vibratory hammer compaction.

4.5 Comparing the vibratory hammer compaction method to existing compaction methods

CSIR findings state that vibratory table compaction produces specimens with a skeletal structure more representative of site compaction than other compaction methods (Theyse, 2004). Due to the principle by which vibratory compaction takes place (vibrating material while applying an impacting force at the same time) it is believed that the skeletal structure of a specimen produced from vibratory table compaction will be similar to the skeletal structure of a specimen produced using vibratory hammer compaction.

Therefore Tests were performed on G2 material (BSM-emulsion and BSM-foam) using vibratory table compaction to determine the following:

- The time it takes vibratory table compaction to achieve the same Dry Density at a given moisture content as the vibratory hammer;
- How the final Dry Density of the vibratory table compares to that of the vibratory hammer.

Table 4-17 presents the tests performed for this section.

TABLE 4-17: TESTS PERFORMED FOR COMPARING VIBRATORY TABLE COMPACTION TO THE DEVELOPED VIBRATORY HAMMER COMPACTION METHOD

Test №	Name	Method compaction	Moisture content %OMC	Surcharge kg
29	BSM-emulsion	Vibratory table	80	50
30	BSM-foam	Vibratory table	80	50

4.5.1 Vibratory Table

The criteria used for the vibratory table was taken from the TMH1 Revised Addition (1990) and is as follows:

- Frequency of 50Hz;
- Surcharge of 50kg;
- Amplitude of 0.5mm;
- Compaction time of 120sec per layer (specifically for BSM-foam).

Tests were performed as follows:

- Specimens were compacted in 5 layers until 100% Mod AASHTO density was achieved;
- BSM-foam specimens were compacted for 120sec per layer;
- The experiment was conducted using two specimens for the BSM-emulsion and three specimens for the BSM-foam. The average result between the specimens of a specific stabilised material was used to develop the figures.

The results of the tests are present in graphical form.

BSM-emulsion vibratory table test

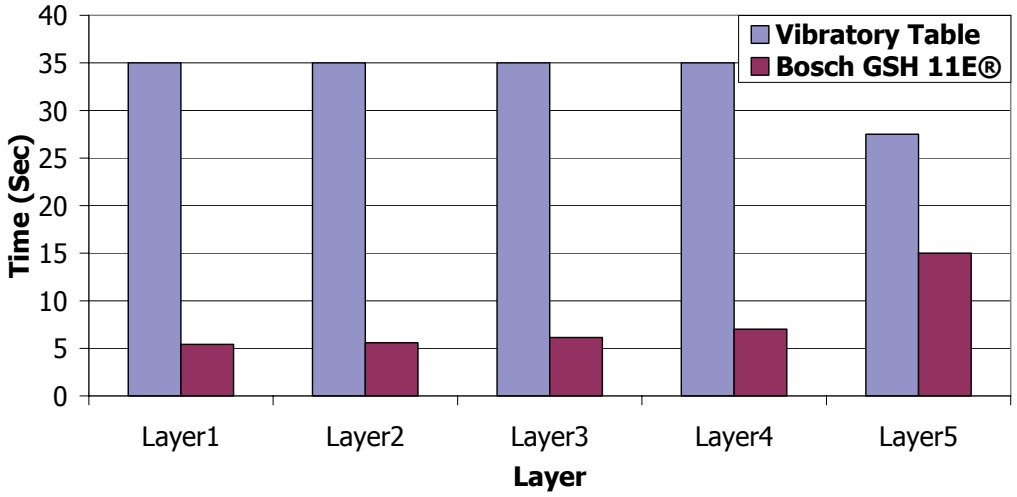


FIGURE 4-19: COMPARISON OF VIBRAORY TABLE COMPACTION TO THE DEVELOPED VIBRATORY HAMMER METHOD- BSM-EMULSION, COMPACTION TIME TO TARGET DRY DENSITY

Figure 4-19 shows the result of the Bosch® hammer compared to the vibratory table for time to 100% Mod AASHTO compaction at 80%OMC. The time it takes the vibratory table to achieve the target Dry Density is much longer than for the vibratory hammer.

This result shows that the same target Dry Density can be achieved faster by using the vibrating hammer.

BSM-foam vibratory table test

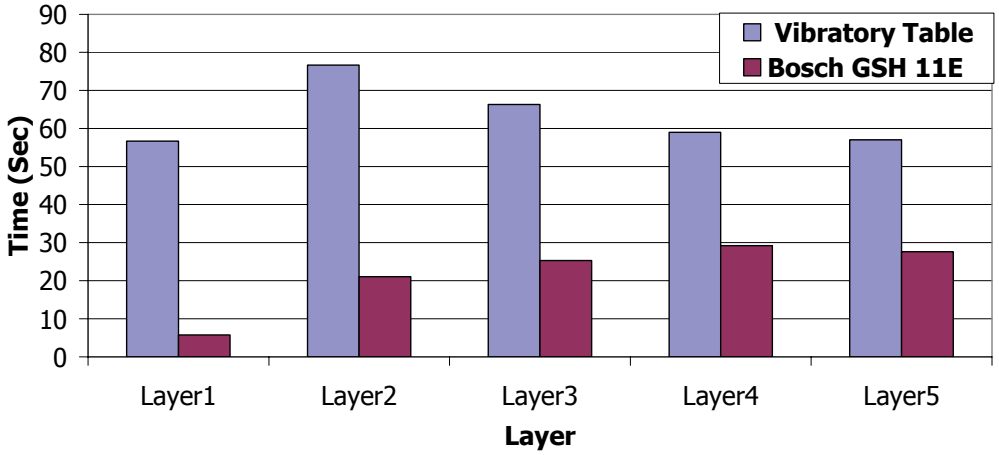


FIGURE 4-20: COMPARISON OF VIBRAORY TABLE COMPACTION TO THE DEVELOPED VIBRATORY HAMMER METHOD- BSM – FOAM, COMPACTION TIME TO TARGET DRY DENSITY

Figure 4-20 shows the result of the comparison test of the vibratory table to the vibratory hammer at the same moisture content (80% OMC) compacted to the same Dry Density. The results of the vibratory table show a similar trend in compaction times for the individual layers. Each layer requires its own time to achieve the target Dry Density. The vibratory hammer is however, as with the BSM-emulsion, the faster compaction method to obtain the target Dry Density.

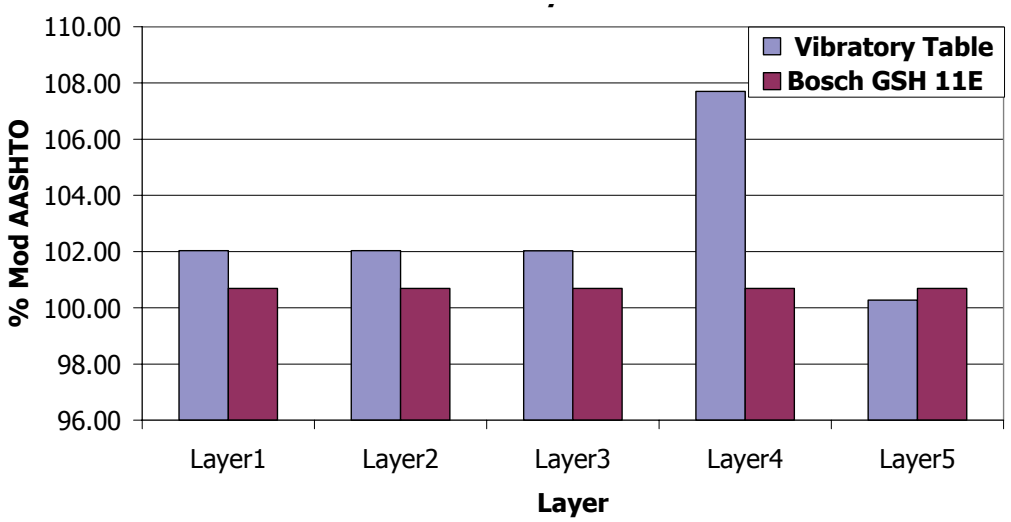


FIGURE 4-21: COMPARISON OF VIBRAORY TABLE COMPACTION TO THE DEVELOPED VIBRATORY HAMMER METHOD- BSM – FOAM, FINAL ACHIEVED DRY DENSITIES

Figure 4-21 shows the final Dry Density achieved using the vibratory table compaction method (compaction time is 120sec). The final Dry Densities achieved with the vibratory table do not differ extensively from the final Dry Densities achieved using the developed vibratory compaction method (except for Layer 4). Thus the developed vibratory hammer compaction method is capable of producing specimens with final Dry Densities that are similar to specimens produced using vibratory table compaction.

Note: The vibratory table is very labour intensive, specifically with regard to the raising and lowering of the 50kg surcharge into and out of the mould. The vibratory hammer however is a much less labour intensive compaction method.

4.6 Further analysis of vibratory hammer compacted specimens

This section presents the results of further analysis performed on the following:

- Specimens produced using the vibratory hammer compaction method – CT Scanning;
- Developed vibratory hammer compaction method – Compaction energy comparisons;
- Statistics – level of variability of the vibratory hammer compaction method.

Table 4-18 provides a list of all tests performed for the further analysis of vibratory hammer compacted specimens

Table 4-18: List of tests performed for further analysis of vibratory hammer compacted specimens

Test №	Name	Method compaction	Moisture content %OMC	Surcharge kg
31	BSM-emulsion	Mod AASHTO	80	NA
32	BSM-emulsion	Vibratory hammer	80	10
33	BSM-foam	Vibratory hammer	80	10

4.6.1 CT Scanning (Computer Tomography scanning)

Computer Tomography scanning (CT-scanning) was performed on the following specimens:

- Mod AASHTO compacted G2 BSM-emulsion;
- Vibratory hammer compacted G2 BSM-emulsion;
- Vibratory hammer compacted G2 BSM-foam;

The above specimens were sent to TU Delft in the Netherlands who performed the CT-scanning. Due to weight restriction on the aeroplane the specimens were resized in order to be sent. The purpose of the CT-scanning was to determine what the voids profile of the compacted specimens is like. The results are as follows:

TABLE 4-19: CT-SCANNING RESULTS

Specimen	Specimen section	Voids Profile
Mod AASHTO G2 BSM-emulsion	S2	• Consistently low • Slight increase at the beginning but drops off
Vibratory hammer G2 BSM-emulsion	S1B	• Slight increase at the beginning but tapers off • Large increase at the end
	S1A	• Starts low, then a large increase tii half way before decreasing toward the end
Vibratory hammer G2 BSM-foam	S3B	• Consistently low
	S3A	• Consistently low

Table 4-19 presents the summarised results of the CT-scanning analysis. The full view of these results may be seen in Section 15, Appendix H.

The increases in the voids content of S1A and S1B (See Figure 15-1 and Figure 15-2 in Section 15, Appendix H) is explained by the position of the increases on the sample. This is done by means of Figure 4-22. The locations of the increase were found to lie directly on the scarified area. This indicates that the compaction time was insufficient to allow for proper compaction at these points. A possible reason for this:

- Excessive scarifying of the surface of the compacted layer

The G2 BSM-foam specimen was compacted to near refusal density (See Figure 15-4 and Figure 15-5 of Section 15, Appendix H). Therefore there was sufficient compaction time per layer to allow for the particles in the scarified area to be properly orientated and fill any remaining voids; hence the voids content was more consistent and lower.

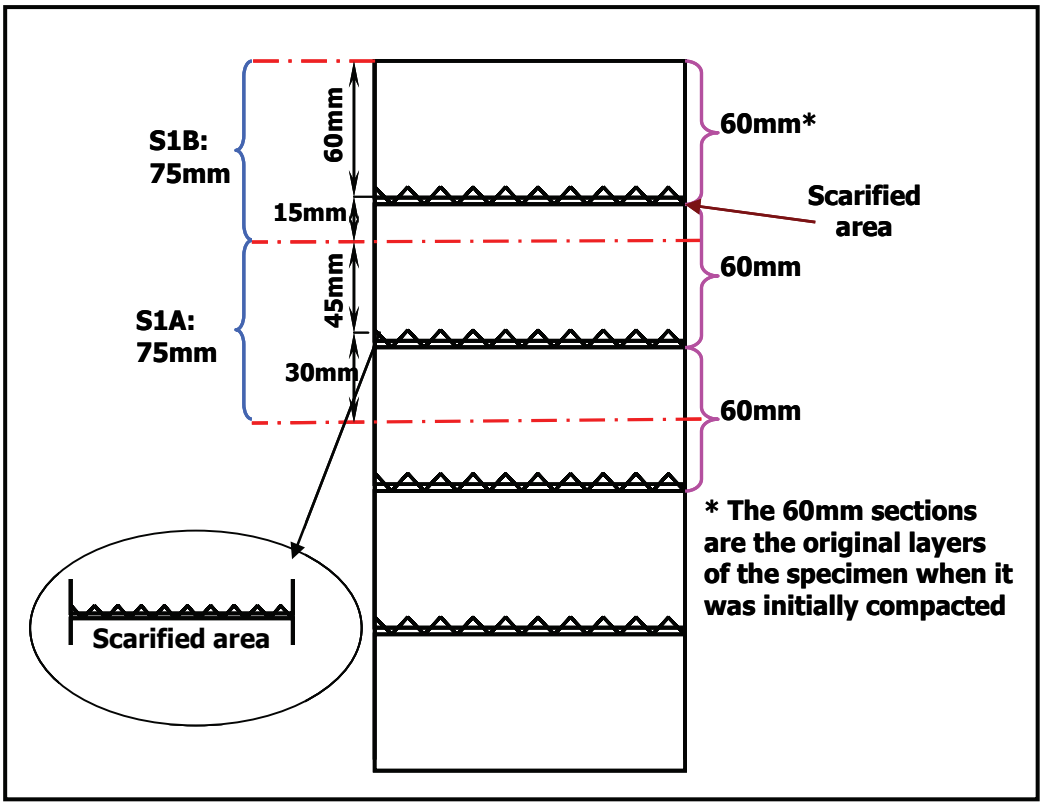


FIGURE 4-22: SECTIONAL VIEW OF VIBRATORY HAMMER COMPACTED SPECIMENS SENT FOR CT-SCANNING

The void profiles shown in Section 15, Appendix H, shows no significant drop in the voids content for any of the specimens. This identifies that aggregate in the already compacted layers are not under going crushing during the compaction of the subsequent layers.

Based on this, sufficient compaction times are necessary to allow voids to be filled, else the specimen will not be a fair structural representation of site or Mod AASHTO compacted specimens.

4.6.2 Compaction energy of compaction methods

This section (4.6.2) presents a comparison of the compaction energy of the following compaction methods:

- ASTM vibratory hammer compaction method (ASTM);
- UK vibratory hammer compaction method (UK);
- New Zealand vibratory hammer compaction method (New Zealand);
- US vibratory hammer compaction method (US);
- Vibratory table compaction method;
- Mod AASHTO compaction method.

Calculation of the compaction energy of the vibratory compaction methods was performed as follows:

$$E = \frac{Wh \times Freq \times Amp \times CompTime \times NoLayers}{1000}$$ **EQUATION 4-1**

Where

E = energy (KJ);

Wh = weight of the vibratory hammer during compaction or the weight of the surcharge in the case of the vibratory table (N);

Freq = frequency (Hz)

Amp = amplitude (m)

CompTime = Compaction time per layer (sec)

NoLayers = No of layers compacted

Calculation of the compaction energy of the Mod AASHTO compaction is performed as follows (See Section 2.2.4 for details on the necessary information):

$$E = \frac{Wmh \times No.blows/layer \times dh \times NoLayers}{1000}$$ **EQUATION 4-2**

With

E = energy (KJ)

Wmh = Weight of the drop hammer (N)

No.blows/layer = Number of blows per layer

dh = Drop height of the hammer (m)

NoLayers = No of layers compacted

In order to perform this energy comparison, the following assumptions were made:

- Vibratory hammer amplitude = 5mm;
- Compaction of a specimen 300mm high;
- The mass of the New Zealand hammer was Taken as 35kg;
- The maximum frequency of the vibratory hammer was used;
- The US BSM-foam CompTime was taken as the average compaction time across all five layers;
- For the ASTM (USA) calculation the Bosch 11248 EVS® hammer was chosen, because this vibratory hammer met the technical criteria of the ASTM vibratory hammer compaction method;

The results are presented in the table below.

TABLE 4-20: COMPACTION ENERGY OF VARIOUS COMPACTION METHODS

Compaction method	Wh	Freq	Amp	CompTime	NoLayers	E (kJ)
ASTM (USA)	343.35	55	0.005	60	8	45.32
UK	343.35	50	0.005	60	8	41.20
New Zealand	343.35	60	0.005	180	5	92.70
US-BSM-emulsion	294.3	31	0.005	15	5	3.42
US BSM-foam	294.3	31	0.005	25	5	5.70
Vibratory table	490.5	50	0.0005	120	5	7.36
Impact compaction	**Wmh**	**No.blows/layer**	**dh**		**NoLayers**	**E (kJ)**
Mod AASHTO	44.145	55	0.475		8	8.88

The results are presented in the table below.

Table 4-20 shows that the New Zealand vibratory hammer method makes use of the highest compaction energy. This is an indication that the compaction levels achieved in New Zealand may approach refusal density.

The compaction times assigned at the University of Stellenbosch resulted in the lowest compaction energy of all the compaction methods (including Mod AASHTO compaction). This is not consistent as the relationship between the zero air voids and moisture density relationship (See Section 13, Appendix F) for details on the Zero air voids with moisture density relationship) show an increase in the compaction effort when compacting with the vibratory hammer. This indicates that there is room to increase the compaction times. Increasing the compaction time per layer will increase the compaction energy, thereby producing specimens with Dry Densities closer to refusal density.

Based on the literature, both the UK and the ASTM indicate compaction times of 60sec per layer. This was concluded to indicate a potential compaction time to achieve refusal density. Substituting the compaction times assigned to the US (both BSM-emulsion and BSM-foam) with the ASTM and UK time of 60sec the compaction energy for the US vibratory hammer is as follows:

- Compaction energy at 60sec per layer = 13.68 kJ.

A compaction time of 60sec per layer still does not place the compaction method in line with the international standings. Increasing the compaction time to 180sec had the following result:

- Compaction energy at 180sec per layer = 41 kJ.

At 180sec the Stellenbosch vibratory hammer compaction method meets the standard of the internationally developed vibratory hammer compaction procedures (ASTM and UK).

Therefore to make use of refusal density as a reference density for site, a compaction time of 180sec should be considered.

4.6.3 Statistics developed from the experiments and test performed

Statistical analysis was performed on the vibratory hammer compacted specimens to determine the extent of their variability (further statistical analysis performed may be seen in Section 11 Appendix D). The variability is indicated by the coefficient of variation (COV). The following statistics are included in this section:

- COV of both BSM-emulsion and BSM-foam at temperatures 5, 15 and 35^0C;
- COV of Mod AASHTO compaction.

Table 4-21: presents a list of tests performed for this section (4.6.3).

TABLE 4-21: LIST OF TESTS PERFORMED FOR SECTION 4.6.3

Test Nº	Name	Method compaction	Moisture content %OMC	Surcharge kg
34	Untreated	Mod AASHTO	constant	NA

The results of the temperature experiment (Section 4.4.1) were used to perform a statistical analysis to determine the extent of variation of specimen compacted using vibratory hammer compaction. The results of this analysis are shown in Table 4-22.

TABLE 4-22: COV OF THE VIBRATORY HAMMER

Temperature	COV* of BSM	
	Emulsion	Foam
5^0C	0.13	0.24
15^0C	0.39	0.42
35^0C	0.84	2.34

Table 4-22 shows that the BSM-emulsion is less variable that BSM-foam for all temperatures. The level of variability of the BSM-emulsion is not significantly increased as temperatures increase, foam on the other hand is. This means that the specimens produced from BSM-emulsion will be less variable than the specimens produced from BSM-foam.

The COV of the Mod AASHTO compaction method was determined by compacting 4 G5 specimens at the same moisture content.. This was done to determine the repeatability of the Mod AASHTO compaction method. The G5 material was not treated with stabiliser, only water was added. The COV of the Mod AASHTO is shown below:

$COV_{ModAASHTO}$ = 0.45%

When this COV is compared to the vibratory hammer COV values, it is found that generally the vibratory hammer COV is less than the Mod AASHTO COV. This is however not the case when the vibratory hammer was used to compact material warmer than room temperature (25^0C).

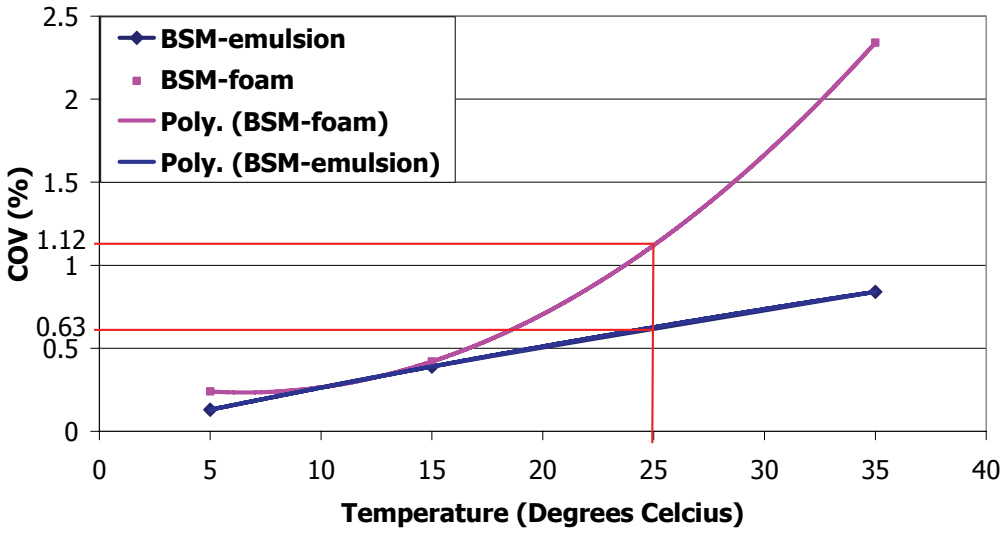


FIGURE 4-23: PROJECTION OF COV VALUES OF THE VIBRATORY HAMMER AT ROOM TEMPERATURE

From Figure 4-23 the COV of the vibratory hammer at room temperature is determined for both BSM-emulsion and BSM-foam. The results are:

- COV of BSM-emulsion vibratory hammer compaction = 0.63%;
- COV of BSM-foam vibratory hammer compaction = 1.12%.

Comparing these COV values to the Mod AASHTO COV and it is found that the vibratory hammer is more variable than the Mod AASHTO compaction method.

4.7 Development of site compaction specifications

This section presents the development of site compaction specifications. The development is performed as follows:

- Allocation of an adequate compaction times and moisture contents;
- Determination and allocation of site compaction levels.

4.7.1 Allocation of an adequate compaction time and moisture content

Based on Section 4.2 and Section 4.3 the surcharge load and moisture content for compaction of BSM-emulsion and BSM-foam were taken. These are as follows for both BSM-emulsion and BSM-foam:

- Surcharge of 10kg;
- Moisture content of 80% OMC (Mod AASHTO OMC) of the untreated material.

In order to allocate adequate compaction times to compact specimens from which site compaction levels may be assigned, the refusal density profile of the BSM-emulsion and BSM-foam for the surcharge load and moisture content indicated previously is used. Each profile is analysed separately below.

BSM-emulsion refusal density profile

Compaction times per layer

Figure 4-24 shows the refusal density profile of the BSM-emulsion at 80%OMC with a 10kg surcharge. This profile is the profile determined from the Kango® vibratory hammer but has bee adjusted (time axis) according to the results of the correlation experiment of Section 4.3.1.

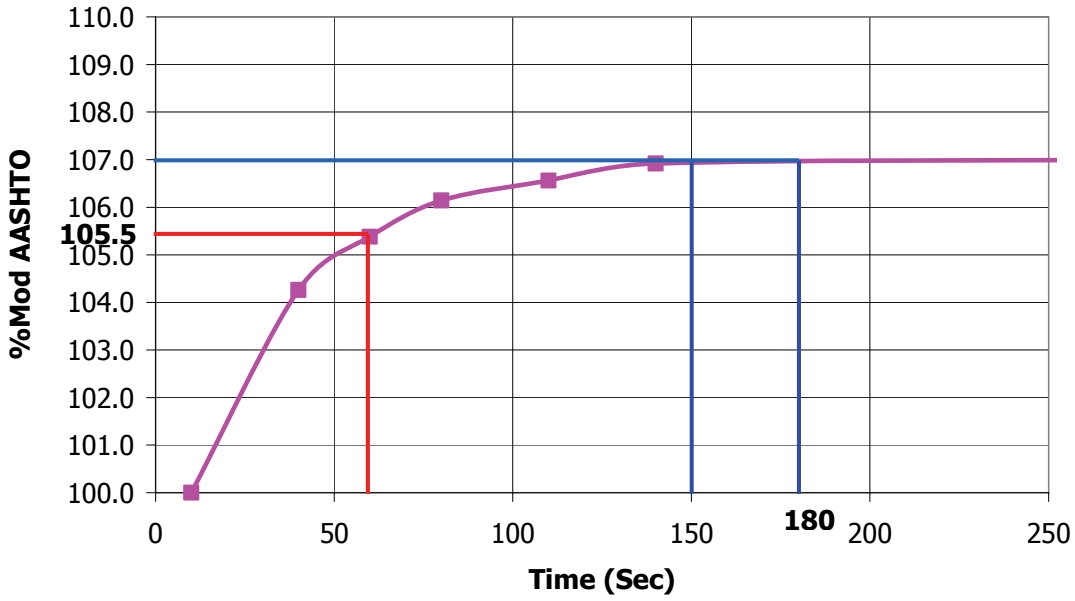


FIGURE 4-24: REFUSAL DENSITY PROFILE OF G2 BSM-EMULSION AT 80%OMC WITH 10KG SURCHARGE

Assigning the compaction times assigned by the UK, USA and New Zealand to the US vibratory hammer compaction method as well as taking the results of Section 4.6.2 into account, Table 4-23 is developed.

Table 4-23: Result of assigned UK, USA and New Zealand compaction times to US vibratory hammer compaction method for G2 BSM-emulsion

Country times assigned to US vibratory hammer compaction method	Compaction time (sec)	Compaction energy of country (kJ)	US compaction energy (kJ)	US Compaction level (%Mod AASHTO)	US % of refusal density
UK	60	41.2	13.68	105.5	98.6%
USA	60	45.32	13.68	105.5	98.6
New Zealand	180	92.7	41.00	107.0	100%

Table 4-23 shows that at 60sec per layer compaction time, the compaction energy of the US vibratory hammer compaction method does not produce enough compaction energy to achieve refusal density. Assigning the New Zealand compaction time to the US vibratory hammer compaction method however produces sufficient energy to achieve refusal density. However at 150sec (reduction in compaction time of 30sec) the same level of compaction is achieved by the US (See Figure 4-24Figure 4-24: Refusal density profile of G2 BSM-emuslion at 80%OMC with 10kg surcharge), but the effect of reducing the compaction time to this extent (30sec) on lower quality granular materials is not known.

Therefore a compaction time of 180sec per layer should be assigned for the compaction of BSM-emulsion specimens.

BSM-foam refusal density profile

Compaction times per layer

Figure 4-25 shows the refusal density profile of the BSM-foam at 80%OMC with a 10kg surcharge.

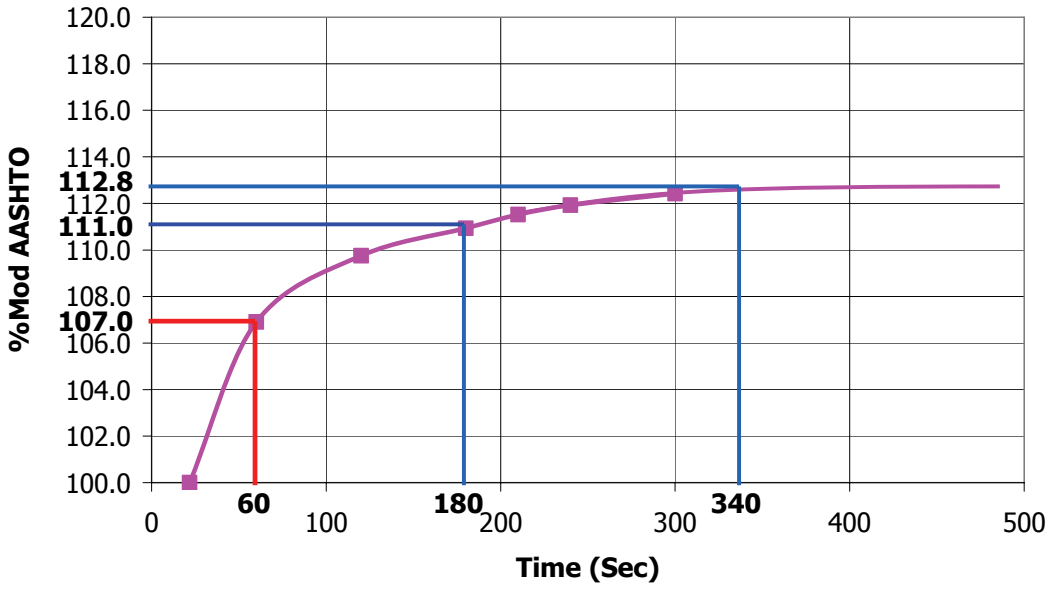


FIGURE 4-25: REFUSAL DENSITY PROFILE OF G2 BSM-FOAM AT 80%OMC WITH 10KG SURCHARGE

Assigning the compaction times assigned by the UK, USA and New Zealand to the US vibratory hammer compaction method as well as taking the results of Section 4.6.2 into account, Table 4-24 is developed.

Table 4-24: Result of assigned UK, USA and New Zealand compaction times to US vibratory hammer compaction method for G2 BSM-foam

Country times assigned to US vibratory hammer compaction method	Compaction time (sec)	Compaction energy of country (kJ)	US compaction energy (kJ)	US Compaction level (%Mod AASHTO)	US % of refusal density
UK	60	41.2	13.68	107.0	94.9%
USA	60	45.32	13.68	107.0	94.9%
New Zealand	180	92.7	41	111.0	98.4%

Table 4-24 shows that at 60sec compaction time per layer, the compaction energy of the US vibratory hammer compaction method does not produce enough compaction energy to achieve refusal density. Assigning the New Zealand compaction time to the US vibratory hammer compaction method also does not produce sufficient compaction energy to achieve refusal density. To achieve refusal density the New Zealand compaction time must virtually be doubled (See Figure 4-25, x-axis "Time (Sec), 340"). This is problematic for the following reasons:

- Compaction times of >180sec per layer may influence grading – "muddy" material has been found to seep out between the foot piece and the walls of the mould during prolonged periods of compaction. This may contain fine material and the loss of it will produce a specimen with an inconsistent grading;
- Time efficiency – compaction times of >180sec per layer may not be time efficient when preparing specimens.

A compaction time of 180sec per layer does produce a final Dry Density of 98.4% of refusal density. This is close enough to refusal density to be used as a reference density for site specifications and looking at international specifications a compaction time of 180sec per layer should be assigned for the compaction of BSM-foam specimens.

Compaction moisture

The $OMC_{vibratoryhammer}$ results of Section 4.4.3 when compared to the specified moisture content of 80% OMC are as follows:

Table 4-25: Proportion of Mod AASHTO OMC to vibratory hammer OMC of G2 BSM-emulsion

BSM	80%OMC	$OMC_{vibratoryhammer}$	80%OMC:$OMC_{vibratoryhammer}$
Untreated	4.92%	5.9	83.4%
Emulsion	4.92%	5.6%	87.8%
Foam	4.92%	4.8%	102.5%

The vibratory hammer compaction method developed in Section 4.3.1 provides a method by which the vibratory hammer OMC of the BSM may be determined. The moisture content of 80%OMC specified in Section 4.2 is typically lower than that of the vibratory hammer. The BSM-foam however had an $OMC_{vibratoryhammer}$ less than the 80%OMC. Therefore the compaction moisture for vibratory hammer compaction of BSM-foam should be taken at 100% $OMC_{vibratoryhammer}$. The moisture contents used for vibratory hammer compaction to specify both site compaction levels and moisture content are shown in Table 4-26.

Table 4-26: Moisture contents for site compaction specifications of G2 BSM-emulsion by means of vibratory hammer compaction

BSM	Compaction moisture: % of vibratory hammer OMC
Untreated	83.4%
Emulsion	87.8%
Foam	100%

Therefore the vibratory hammer compaction method developed in Section 4.3.1 should be used to develop the moisture density relationship from which the OMC of the vibratory hammer compaction method is determined. This OMC is adjusted as per Table 4-26; samples are then prepared and compacted at this moisture content for 180sec per layer.

4.7.2 Determination and allocation of site compaction levels

The vibratory hammer compaction method is to be used to provide specifications for compaction levels on site. In order to develop the specifications the vibratory hammer results were equated to the current specifications. This was done as follows:

TABLE 4-27: CURRENT SITE COMPACTION LEVEL SPECIFICATION

Material Type	Currents specification (%Mod AASHTO)
G2	100 to 102%
G5	95%

Based on the results of Section 4.7.1 the following data is obtained for both BSM-emulsion and BSM-foam:

- Compaction time of 180sec per layer;
- Achieved level of compaction after 180sec compaction time;

The determination of the specification is then as follows:

New specification = Current specification ÷ Achieved level of compaction after 180sec × 100

The results are presented in Table 4-28.

Table 4-28: New Specification for site compaction level of G2 material

Material type	Compaction level after 180sec per layer (%Mod AASHTO)	New Specification (% refusal density)
G2 BSM-emulsion	107	93.5 to 95.3
G2 BSM-foam	111	90.1 to 91.9

Specifications for G5 material were not calculated, due to no refusal density profile being available.

4.8 Outline of the proposed protocols

This section identifies and provides a brief layout of the proposed compaction procedure developed from the results of this research study.

From the results two potential compaction protocols may be identified. They are:

- Production of specimens to indicate achievable densities;
- Compact specimens based on site results.

A full, detailed description of the compaction protocols is provided in the recommendation section of this report. A brief outline is described below.

4.8.1 Compaction Protocol 1: Moisture density relationship by means of vibratory hammer compaction

For compaction protocol 1 the following information is needed:

- Target Bitumen content if material is to be stabilized;
- Type BSM i.e. BSM-emulsion or BSM- foam;

The following tools and temperature information is also needed:

- Bosch GSH 11E® with a surcharge of 10kg;
- Compaction is done at room temperature;
- Chisel 300mm long or a Drill with a drill bit longer than or equal to 300mm with a point marked off 10mm from the tip of the drill bit;
- Extension piece for the mould so as to compact layer 5;
- Material scoop.

The procedure to be followed is as such:

- Develop a moisture density relationship for either the BSM-emulsion or the BSM-foam using the vibratory hammer compaction method developed in Section 4.3 as follows:
- Moisture is added to the samples, varying the contents from 2% moisture to 10% moisture;
- The samples are stabilised, should that be required. BSM-foam is prepared as per the TG manual (TG2, 2002), and BSM-emulsion as per the GEMS manual (Sabita, 1993);

- The specimen is then compacted in 5 layers in a mould 300mm high with a diameter of 150mm. Material is placed into the mould using a material scoop. Each individual layer receives three scoops of material for the respective mix. Each layer is compacted for a set period of time until all five layers have been compacted. Times for the respective layers are provided in the recommendations section of this research study;
- After a layer has been compacted, the surface of the layer is scarified using the drill;
- Three scoops of material are then added using the material scoop and the layer is compacted, this process continues until all five layers have been compacted;
- The specimen is removed and the final height and final mass of the specimen is taken;
- A Moisture sample from the remaining material is taken to determine the moisture content of the specimen by means of the standard oven drying method;
- The Dry Density is determined. The Dry Density for each of the specimens is determined at their respective moisture contents;
- The moisture density relationship is determined;
- The OMC of the vibratory hammer is obtained from the moisture density relationship.

4.8.2 Compaction Protocol 2: Analysis of refusal density for specification purposes using the vibratory hammer

For compaction protocol 2 the following information is needed:

- Target Bitumen content if material is to be stabilized;
- Type BSM i.e. BSM-emulsion or BSM- foam;
- OMC of vibratory hammer compaction (See Section 4.8.1)

The following tools and temperature information is also needed:

- Bosch GSH 11E® with a surcharge of 10kg;
- Compaction is done at room temperature;
- Chisel 300mm long or a Drill with a drill bit longer than or equal to 300mm with a point marked off 10mm from the tip of the drill bit;
- Extension piece for the mould so as to compact layer 5;
- Material scoop.

The procedure to be followed is as such:

- Three samples of the material type are prepared;
- Moisture is added to the samples at the following fractions:
    - Untreated: 83.4% $OMC_{vibratory\ hammer}$ of untreated material;
    - BSM-emulsion : 87.8% $OMC_{vibratory\ hammer}$ BSM-emulsion;
    - BSM-foam : 100% $OMC_{vibratory\ hammer}$ BSM-foam.
- The samples are stabilised, should that be required. BSM-foam is prepared as per the TG manual (TG2, 2002), and BSM-emulsion as per the GEMS manual (Sabita, 1993);
- The specimen is then compacted in 5 layers in a mould 300mm high with a diameter of 150mm. Material is placed into the mould using a material scoop. Each individual layer receives three scoops of material for the respective mix.

- Each layer is compacted for 180sec.
- After a layer has been compacted, the surface of the layer is scarified using the drill;
- Three scoops of material are then added using the material scoop and the layer is compacted, this process continues until all five layers have been compacted;
- The specimen is removed and the final height and final mass of the specimen is taken;
- A Moisture sample from the remaining material is taken to determine the moisture content of the specimen by means of the standard oven drying method;
- This procedure is followed until all three samples are compacted
- The Dry Densities of the three samples is determined;
- The average Dry Density of the three is then calculated;

Site compaction specifications are then determined using

- Table 4-28 and the average Dry Density previously calculated.

4.8.3 Compaction Protocol 3: Standard vibratory hammer laboratory compaction for specimen procurement

When compacting specimens based on the site compaction results, the following information is needed:

- Mod AASHTO OMC of the untreated material;
- Target Dry Density Bitumen content;
- Type of BSM i.e. BSM-emulsion or BSM- foam.

The following tools and temperature information is also needed

- Bosch GSH 11E® with a surcharge of 10kg;
- Compaction is done at room temperature (25^0C);
- Chisel 300mm long or a Drill with a drill bit longer than or equal to 300mm with a point marked off 10mm from the tip of the drill bit;
- Extension piece for the mould so as to compact layer 5.

A target moisture content of 80% OMC (Mod AASHTO OMC of the untreated material) is used to compact the specimen. The procedure is as follows:

- Moisture is added to the material. The amount of moisture added will depend on the type of cold mix treatment. For the BSM-foam, the moisture content is 80%OMC (wt/wt). For the BSM-emulsion the moisture in the emulsion must first be calculated out of the 80% OMC (wt/wt) and then this moisture content is used to determine the mass of water per bulk mass to be added;
- Target Dry Density is obtained from data obtained from site. From the target dry density information, the mass of material required per 60mm layer thickness is determined. The sample is prepared using the appropriate cold mix treatment and the mass for each layer is weighed off and stored in a small plastic bag;

- The specimen is compacted in 5 layers in a mould 300mm high with a diameter of 150mm;
- The material for the layer to be compacted is then added into the mould and compacted till a height of 60mm, time is not a factor as the specimen is compacted to a pre-determined height;
- The surface of the compacted layer is soured using either the chisel or the drill. This ensures bonding between the separate layers;
- The next layer is added and compacted as the previous layer was. This process is continued until all five layers have been compacted. Prior to the compaction of the fifth layer the extension piece must first be fitted to the mould. This is to ensure that no material is lost when the material for layer 5 is added into the mould;
- The procedure outlined above is a good procedure in preparing representative specimens of the base layer in the road so as to identify where the engineering properties of the in situ base course.

5 Conclusions

Based on the results of the experiments the following conclusions were made.

5.1 Influence of time on compaction with varying moisture content of G2 material

The results of the experiments showed that as the moisture content increased the compaction time to 100% Mod AASHTO decreased. However, for BSM-emulsion, it was observed that once the moisture content was at about 90% OMC, compaction time reduced. The extent of time reduction was however, so significant that it may be assumed that the fluid-like behaviour, does not allow the material particles to become sufficiently orientated (compacted). Hence the prepared specimen is not representative of the site compaction.

At 80% OMC in both the BSM-foam and BSM-emulsion mixes the compaction time to reach 100% Mod AASHTO was sufficient to allow for proper orientation of the material particles, but also short enough that preparation of the specimen does not necessarily become a very time consuming procedure.

The influence of the surcharge weight is also evident in the results of the experiments. The 20kg load at 80% OMC showed a compaction time effect similar to that of the 10kg load at 90% OMC. The Kango 637® however suffered damages to the gear box at a 20kg surcharge load and this damage is believed to be as a result of this load. Based on the short time the 20kg load gives and the fact that the Kango 637® suffered damages at this load the 10kg load became the safest and best option. The 15kg surcharge showed compaction times in between the 10kg and 20kg surcharge mass, it could therefore be considered as an option for the surcharge weight used during compaction, however these results are all based on the Kango 637® results and when the correlation experiment between the Kango and Bosch hammer is taken into account, the 10kg surcharge proves to be the best option.

In terms of the refusal density, it was generally seen that throughout the compaction of the emulsion mixes the time required to achieve refusal density was between 2 and 5 minutes of compaction time depending on the layer being compacted. The effect of moisture on this seems minimal, as there are cases where at 80% OMC it took roughly 3.5 minutes to reach refusal density and then at 90% OMC the layers all fall into a bracket of between 3.5 and 4 minutes. The surcharges also had little effect, with the layers across the various specimens again taking 3.5, 4 minutes to reach refusal density. What is clear is that the achieved refusal densities are influenced by the moisture content and surcharge load. The higher the moisture content, the higher the bracket of the refusal density and the higher the surcharge load in combination with the moisture content the higher the bracket in which the refusal density falls.

The foam mixes exhibited a similar trait to that of the emulsion mixes with regard to the refusal density compaction. Once again as the moisture content increased so to does the bracket in which the refusal density falls, and with the surcharge mass, the same trend was seen. A difference was seen in the compaction of the foamed mix to refusal density, the density of this mix continued to climb after 5 minutes of compaction. This results shows that the foamed mix requires longer compaction time to reach refusal density than does the emulsion mix.

5.2 Comparison of vibratory hammer to vibratory table

The conclusion from this correlation experiment is that the vibratory hammer is a faster procedure with less physical labour required (if no pulley system is available for the vibratory table). Also the vibratory hammer gives more control and accuracy over both the target densities and the final level of the surface of the specimen (a more perpendicular surface face is achieved with the vibratory hammer).

5.3 Correlation of N7 material to G2 material

Parameters used for the compaction of the clean G2 material i.e. time per layer etc. were not applicable to the N7 G2 material. This is because, although the N7 material is a G2 quality, the milling process of the recycling process changes the grading and quality of the material from its original state when initially used in construction. The presence of RAP in the N7 material is believed to have had an influence on the compaction of the material. More time is required to reach the targeted site densities for the N7 material than for the clean bitumen treated G2 material to reach its 100% Mod AASHTO dry density. Simply because it takes 30 seconds to compact the G2 material to its 100% Mod AASHTO does not mean it will take the same time to compact the N7 material to its 100% Mod AASHTO density or the targeted site density. The material properties, i.e. grading and the presence of other elements such as RAP or cement from the initial construction influence the compaction time.

The correlation experiment shows an important conclusion. Time cannot be taken as a fixed unit. Material properties influence the compaction time. Therefore compaction using the vibratory hammer to produce site related specimens should be performed as a function of the layer thickness and not as a function of time.

5.4 CT Scanning

From the CT scanning results the first conclusion that can be drawn is that the vibratory hammer produces specimens with very low voids contents. The extent to which the surface of various layers is scarified has an influence on the level of voids at the intersection of two layers. This indicates that when compacting, care must be taken that the surface of a compacted layer is not scarified to extensively as this allows for higher voids contents in those areas, this is because the compaction time assigned to compact a single layer (specifically for emulsion mixes) is relatively short, this does not allow the loose material to necessarily arrange itself properly even though the target Dry Densities are achieved. These points will inevitably be week spots in the prepared specimen.

The CT Scanning showed a consistency in the air voids across the two specimens per mix that were sent to the Netherlands. There is no sudden drop in the voids content in the lower layer of the specimen, this indicates that no subsequent compaction of the underlying layers takes place nor does crushing of the material occur.

5.5 Applicability of the developed vibratory hammer compaction method to G5 Material

The vibratory hammer compaction method can be used for the compaction of lower quality granular materials. The compaction times assigned to the original compaction method produced specimens with densities that are achievable on site. This is known because the specifications for the compaction of G5 material on site are a minimum of 95% Mod AASHTO. The vibratory hammer achieved in the order of 100% for both types of stabilisation which is higher than the site specifications.

5.6 Variability

The variability results of Subsection 4.7 show that the vibratory hammer does have a low variability in terms of specimen production. Therefore the vibratory hammer is capable of consistently producing laboratory specimens. The results also show in Subsection 4.7.6 that the Mod AASHTO compaction (at room temperature) is slightly less variable than the vibratory hammer compaction. The difference is only slight. The largest difference came from the BSM-foam which showed a difference of 0.67 from the Mod AASHTO COV at room temperature. The conclusion drawn from such a small difference is that the variability of vibratory hammer is very similar to the Mod AASHTO compaction.

The low variability of the vibratory hammer compaction method allows for the production of three specimens and the average of the three to be used for specifying site compaction levels.

5.7 Mod AASHTO curves

An interesting conclusion may be drawn when viewing the Mod AASHTO curves of the untreated material against the BSM. The maximum Dry Densities produced for the BSM were lower than the untreated material. This shows that the bitumen emulsion and foamed bitumen influence the level of compaction that may be achieved.

5.8 Conclusions drawn from the vibratory hammer moisture curves

The moisture density relationships developed showed that vibratory hammer compaction can produce realistically achievable site compaction levels. Therefore the preparation of specimens with Dry Densities achievable on site may be done by means of vibratory hammer compaction.

5.9 Development of a refusal density compaction procedure

A refusal density compaction procedure can be developed. Compaction times to obtain refusal density would be as follows:

- BSM-emulsion – 180sec per layer;
- BSM-foam – 180sec per layer.

5.10 Overall conclusions and observations

A procedure using time to produce specimens may be developed. This procedure should not be used to compact a specimen after a pavement has been constructed with the intention to produced site representative specimens. When the procedure using time to compact is compared to the procedure followed by the USA (ASTM D 7382 – 07) and New Zealand it is evident that the compaction time allocated from the experiment results is far less than what these two countries have specified in their compaction methods. The reason for this is the compaction energy of the hammer. The compaction energy assigned by the USA is around 10 Joule, The Bosch GSH 11E® used by Stellenbosch University has a point energy during compaction of 27 Joule, this is 2.7 times higher than specified by the USA, and will influence the compaction time of the various layers.

The refusal densities of the various layers are variable. As was stated in the results, this is believed to be as a result of the variability of the grading of the individual layers. Although the final grading of a specimen may be correct in relation to the grading curve of the material, the material of the individual layers may in fact have variability in relation to the grading curve.

During the compaction of the G5 material at higher moisture contents (90%OMC to 110%OMC) it was noted that there was no seepage of water out from the bottom of the mould. Where in the case of the G2 material there was clearly water seeping out. The G5 material when wet had a very clayey appearance where the G2 did not. This clayey appearance may account for the water retention of the G5 material, as clay materials do have a high level of water retention, which may be the reason for the lack of seepage of water through the bottom of the mould.

6 Recommendations

Based on the results obtained from the experiments and the conclusions drawn, the following recommendations may be made.

6.1 Further development of the vibratory hammer compaction method

Compaction of other aggregate types by means of vibratory hammer compaction needs to be researched further. These aggregate types include:

- G1, G3, G4, G5, G6, G7 etc.

Further more, data obtained from the use of the compaction method should be fed into a data base so that further development and improvement of the vibratory hammer compaction method can take place. This data includes:

- Compaction levels being obtained on site;
- Refusal density levels obtained in the laboratory etc.
-

6.2 Improving mould assembly

The dismantling and re-assembling of the mould takes up a significant part of the specimen preparation time. The removing and replacing of the bolts in particular consumes time. Therefore the mechanism of loosening and fastening the split mould and fastening the mould onto its steel base should be reviewed. As apposed to using nuts and bolts to fasten the mould, a type of clasp should rather be used. i.e. instead of having to unfasten the bolts, the clasps may merely be opened and the mould disassembled.

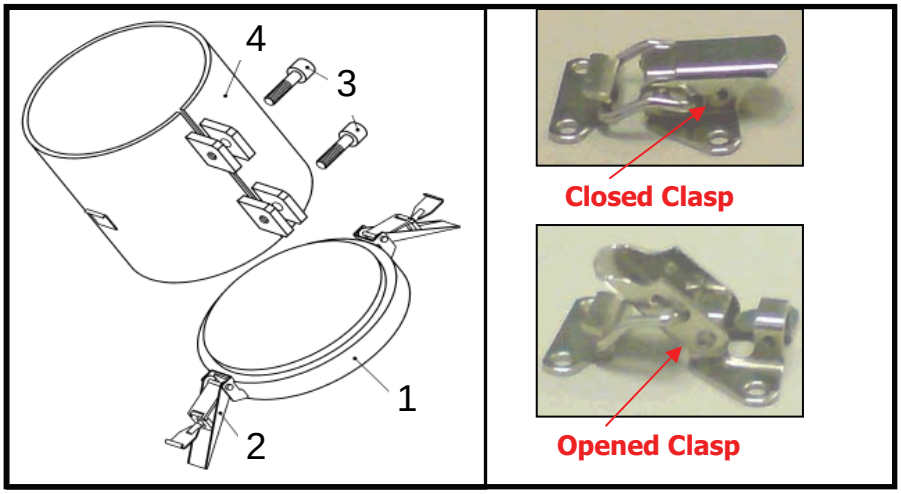


FIGURE 6-1: SPLIT MOULD ST UP WITH CLASPS

Figure 6-1 shows the Mould (4) set-up taken from the British Standards. A similar clasp system to this is proposed to mount the mould to the base. These clasps are shown by number 2 in the figure and the base by number 1. The bolts used in the British Standards (number 3) should be replaced by clasps similar to those shown on the right of the mould set up; a total of four clasps would be need, two clasps on either side of the mould. It is also recommended that as apposed to two clasps being mounted to the base, that two more clasps be mounted; a clasp at the point marked 1 on the mould set up and a clasp directly across from it. This would bring the total number of clasps used to fasten the mould to the base to four which would provide enough support for the mould during compaction. It is believed that a clasp system similar to the one proposed would greatly speed up the process of producing specimens.

6.3 Reducing loss of material

The extension piece used to extend the split mould height so as to accommodate the final layer of material just prior to compaction was taken from the moulds used for Mod AASHTO compaction. This piece does not fit tightly around the split mould used for the vibratory hammer compaction; instead there is a small surface space between the mould and the extension's inner circumference. This is where material gathers while compacting Layer 5. An extension piece that fits exactly on the circumference of the split mould's opening should be made. This will therefore reduce the amount of material lost in Layer 5.

6.4 Vibratory hammer specifications

The following vibratory hammer specifications are proposed for laboratory compaction:

TABLE 6-1: VIBRATORY HAMMER SPECIFICATIONS PROPOSED FOR LABORATORY COMPACTION

Hammer	Rated power input (W)	Impact energy (J)	Impact rate (1/min)	Frequency (Hz)	Mass (kg)
Bosch GSH 11E®	1500	25	900 to 1890	15 to 31.5	10.1

- The vibratory Hammer should be mounted on two guide rods; one on either side of the hammer;
- The total mass of vibratory hammer, surcharge and mounting head should be 30kg ± 1.5kg.

6.5 Procedures to be followed for compaction using vibratory hammer

Based on the findings of this report the following compaction procedure is recommended when using the vibratory hammer.

The compaction of a 150mm X 300mm specimen of bitumen stabilized granular material will be performed using a vibratory hammer, e.g. the Bosch GSH 11E®, with a surcharge of 10kg mounted in a frame. Compaction of the material will take place with the aggregate at room temperature i.e. 25ºC. The layout of the procedure is similar to the layouts provided in the TG 2 manual.

Compaction Protocol 1: Development of the moisture-density relationship of a material using vibratory hammer compaction

1 APPARATUS

1.1 A steel split mould 152mm in diameter and 300mm in height with an extension piece and clasps to fix the mould to the base of the frame.

1.2 Three circular papers with diameter of 152mm.

1.3 Non-stick spray e.g. non stick cooking spray purchased at any supermarket.

1.4 A Vibratory Hammer with the following Specifications (see note 4.3):

TABLE 6-2: SPECIFICATIONS OF VIBRATORY HAMMER FOR COMPACTION

Specification	Criteria
Power rating	1500 W
Frequency	900 to 1890 beats/min (15 – 31.5Hz)
Point Energy	25 J

The vibratory Hammer should be mounted on two guide rods; one on either side of the hammer. A mounting head should be fitted to the vibratory hammer to allow a surcharge of 10kg to be mounted to the vibratory hammer. There should be a pulley system connecting the frame and mounting head. This allows for easy lifting and lowering of the vibratory hammer.

The total mass of vibratory hammer, surcharge and mounting head should be 30kg ± 1.5kg.

1.5 A 150mm tamping foot

1.6 Material Scoop (90mm Φ x 85mm h)

1.7 Specimens are compacted in 5 Layers.

1.8 Suitable marker e.g. permanent marker

1.9 Adjustable spanner to fasten and loosen surcharge load to the vibratory hammer.

1.10 Steel ruler of length >300mm

1.11 Chisel for tamping layers

1.12 Drill with drill bit of 300mm with a point marked off 10mm from the tip of the bit.

2 PROCEDURE

2.1 Preparation of the material

Preparing the sample of material for initial Moisture Curve

Determine the grading curve of the aggregate (TMH 1) and reconstitute the material to produce samples that will be used to obtain the OMC of the natural (untreated), BSM-emulsion or BSM-foam material; which ever one is to be prepared.

Preparing the sample of material for vibratory hammer compaction

From the grading curve reconstitute the material to the produce a sample of 14kg (see note 4.1) of aggregate with a maximum particle size of 19mm. A total of 6 samples of 14kg each are needed for a moisture-density relationship.

The aggregate is prepared as follows:

1. Moisture is added to the aggregate (untreated or stabilised) using a range of moisture contents, from 2% moisture to 12% moisture; increasing in increments of 2%.
2. Should cement or lime need to be added to a specific mix, add these first to the sample:
3. For Untreated material i.e. no bitumen stabilization, add the fractions of water to each of the individual sample masses.
4. For BSM-emulsion, the moisture content of the bitumen emulsion needs to be calculated out of the physical mass of water that is added by hand. An example of this calculation is as follows:

   Assumptions made for the example:

   - A mix is to have a target moisture content of 6% moisture;
   - The bitumen emulsion content of the mix is 3%;
   - The bitumen emulsion is a 60/40 emulsion;

   For a 60/40 emulsion, 40% of the emulsion is water. Therefore of the 3% bitumen emulsion to be added to the mix, 40% of it is water. Therefore the fraction of water being added to the mix from the emulsion is 40% x 3%÷100 = 1.2%

The fraction of water that is to be added to the mix in order to obtain a moisture content of 6% is now 6%-1.2% = 4.8%. The physical mass of water to be added to the mix in order to give a target moisture content of 6% when the bitumen emulsion is added is now 4.8% of the mass of the sample.

First add the physical mass of water to the material and allow to stand for 40 – 60 minutes. After this time add the bitumen emulsion to the mix and also allow to stand for 40-60 minutes to allow breaking of the bitumen emulsion.

5. For the BSM-foam add the fractions of moisture to the material checking the ratio of the water relative to the OMC of the moisture curve developed for the untreated material from the TMH 1. When the moisture to be added reaches around 70-80% of the OMC of the untreated material, add this same moisture to the remaining samples and calculate the amount of moisture to be added to the sample to achieve the targeted moisture content. Prepare the BSM-foam in accordance with the procedure outlined in the TG (2) manual. After the foaming procedure add the remaining moisture to the samples mixed with moistures of 70-80% of OMC of the untreated material.

2.2 Compaction Procedure

2.2.1 Prepare the mould and vibratory hammer

Preparing the vibratory hammer

Fix the Mounting Head to the vibratory hammer and fit hammer onto the guide rods. Place the 10kg surcharge load onto the mounting head and fasten tightly – see separate drawing for Mounting Head, Subsection 5 (Kelfkens, 2008). Using the pulley system raise the vibratory hammer to the maximum height it can be raised or to an adequate height that will allow the operator to work beneath the vibratory hammer.

Preparing the Mould

Make sure the mould is clean and then spray the interior of the mould with the non-stick spray. After a specimen has been compacted and removed from the mould, the mould should be cleaned by wiping of excess material from the mould walls (This should be done prior to the compaction of the subsequent specimens). Fix the mould to the base of the frame directly below the foot piece of the vibratory hammer using the clasps. Place two of the circular paper sheets at the base of the mould.

Lower the vibratory hammer into the mould, checking that the vibratory hammer is perpendicular to the base of the mould i.e. the tamping foot is flat on the base with no point of the foot slightly raised. Allow the vibratory hammer to rest in the mould with no material present. Where the lower end of sleeve of the mounting head rests on the guide rod mark that position clearly on the vertical guide using the suitable marker. Raise the vibratory hammer and measure up from the initial mark 300mm and mark this clearly (non-erasable).

2.2.2 Compaction of the specimen

Addition of material to mould

Material is placed in the mould using a material scoop. Fill the scoop with the prepared material and level off the scoop and place it in the mould. Add three scoops of material to provide a starting layer thickness of 92mm. Using the chisel, work the material around in order to evenly distribute it in the mould; try to distribute the particles evenly as well i.e. not too much fine material on top or to much coarse material on top, but rather a fair distribution of each i.e. unsegregated. Make sure the material is as level as possible before lowering the vibratory hammer till the foot piece comes to rest on the material.

Compaction of individual layers

Specimens are compacted according to set times for each layer. This is to produce specimens that have densities that can be realistically achieved on site. The compaction times for the individual layers of a specimen according to the type of Bitumen Stabilized Material is provided in Table 6-3:

TABLE 6-3: COMPACTION TIMES OF INDIVIDUAL LAYERS FOR VARIOUS BSMS

	Compaction Time of Individual layers in Seconds				
Mix type	Layer 1	Layer 2	Layer 3	Layer 4	Layer 5*
Untreated	10	15	15	15	15
BSM-emulsion	10	15	15	15	15
BSM-foam	10	25	25	35	25

After the material of a layer has been compacted for the allocated time, raise the vibratory hammer. Using the drill, scarify the entire surface area of the top of the compacted layer to a depth of ± 10mm (see Note 4.2).

After the surface of a respective layer has been scarified, add the material for the next layer and compact accordingly.

*After Layer four has been compacted and scarified, the extension piece (collar) must first be fitted to the mould before adding the material for layer 5. After adding the material for layer 5 place a circular sheet of paper on top of the material and then lower the vibratory hammer into position; the paper helps prevent material of the final layer from sticking to the tamping foot. Before raising the vibratory hammer the final height of the specimen must be measured, once this is done the vibratory hammer may be raised and the specimen removed.

Measuring the final height of the specimen

After Layer 5 has been compacted and prior to raising the vibratory hammer take the steel rule and measure the distance from the zero line to the bottom end of the sleeve. This distance is taken as the final height of the specimen.

Removing and handling the compacted specimen

Raise the vibratory hammer and remove the extension piece (collar). Disassemble the mould entirely. Place a plastic bag over the specimen and remove it taking care to pick the specimen up from the bottom end. Weigh the specimen after compaction to check the final mass of the specimen.

Checking the moisture content of the specimen

Take a small amount (750-950 gm) of aggregate either just prior to, during or after compaction and using the standard oven drying method determine the moisture content.

Determining the final Dry Density

From the moisture content determined, the final mass of the compacted specimen and the final height measured the final Dry Density of the specimen may be determined.

2.3 Moisture sensitivity curve

For the moisture sensitivity curve a total of 6 specimens need to be compacted at various moisture contents. This is described in Subsection 2.1. The curve is developed by plotting the final Dry Density of each of the specimens against their respective final moisture contents. The peak (point at which the curve turns) is the OMC (on the horizontal axis) of the vibratory hammer and the Maximum Dry Density (on the vertical axis).

3 CALCULATIONS

3.1 Addition of lime or cement

Cement or lime content (C/L)

$$C/L\ (gm) = C/L\ (\%) \times 14000 \div 100$$

3.2 Addition of water for untreated material

$$Water\ (gm) = (target\ moisture\ content\ (\%))/100 \times mass\ of\ sample\ (gm)$$

3.3 Addition of stabilizer and water to Bitumen Stabilized Material (BSM)

BSM-emulsion

Mass of bitumen emulsion

$$Emulsion\ mass\ (gm) = Emulsion\ content\ (\%)/100 \times aggregate\ dry\ mass\ (gm)$$

Moisture contents

MC in BSM from emulsion (%) = (MC_e (%))/100 × emulsion content (%)

Mass of water added to BSM = (ΔMC) × mass of sample (gm)) ÷100

MC_e = Moisture content of the bitumen emulsion

ΔMC = X (%) - MC in BSM from emulsion (%)

X = target moisture content of the mix

BSM-foam

The bitumen stabilizer is added according to the method provided in the TG 2 manual for preparing BSM-foam.

Ratio of Moisture contents

MC_{mix} : OMC = X/ (OMC (untreated material))

MC_{mix} : OMC = Ratio of the targeted moisture content of the mix to the OMC (untreated material)

X = target moisture content of the mix

For MC_{mix} : OMC > 0.8 (80%)

$MF = X - (MC_{mix} : OMC)_{previous\ mix} \times$ (OMC (untreated material))

MF = Moisture added after foaming

X = target moisture content of the mix

$(MC_{mix} : OMC)_{previous\ mix}$= Final sample with a ratio ≤ 0.8

3.4 Dry Density

Volume of the specimen = π × 0.005625 × Fh

Fh = Final height of the specimen

Dry Density = (Fm (kg)/(1+(MC(%)/100)) ÷ Volume of the specimen

Fm = Final Mass of the specimen

MC = Moisture Content

4 NOTES

4.1 For a final specimen of 300mm high a sample mass of 14kg is recommended when preparing the BSM.

4.2 Layers should not be scarified deeper than 10mm. Scarifying deeper than 10mm results in inadequate bonding on the layers during compaction. There is therefore an increase in voids at this interface.

4.3 Should the vibratory hammer not meet the specifications provided and where no suitable alternative compaction hammers can be sourced, then a vibratory hammer with a point energy of 25 Joule ± 2 Joule should be used. If the weight of the hammer deviates from the specifications by more than 5%, then calibration tests need to be made.

4.4 After a specimen has been compacted and removed from the mould, the mould should be cleaned by wiping off excess material from the mould walls. This should be done prior to the compaction of the next specimen.

4.5 When preparing the moisture curve, the material should be looked at carefully. It must be noted at which moisture content the material becomes muddy. This is because material that is muddy may not produce specimens that are representative of the site compaction (in terms of particle orientation). The specimens should then be compacted at the moisture content immediately below the moisture content at which the material became muddy. Should specimens be prepared in the laboratory for testing without first preparing a moisture curve, then low levels of moisture should be added to the specimen and slowly increased until the operator is satisfied that the material is not muddy but adequately wet.

4.6 When the specimen prepared is to be used in the laboratory and the first four layers have been compacted, add sufficient material to layer five so that that the final height of the specimen is 300mm or slightly higher. This is checked by viewing the final position of the sleeve relative to the 300mm marked of point on the guide rod, a tolerance of 2mm either side of 300mm is allowed. The sleeve may finish either on the mark, slightly above the mark or blow the mark. For each of the finishing positions a description of the procedure to be followed is given in a), b) and c).

a) If the sleeve finishes on the 300mm mark after compacting layer 5, the specimen is removed as previously described.

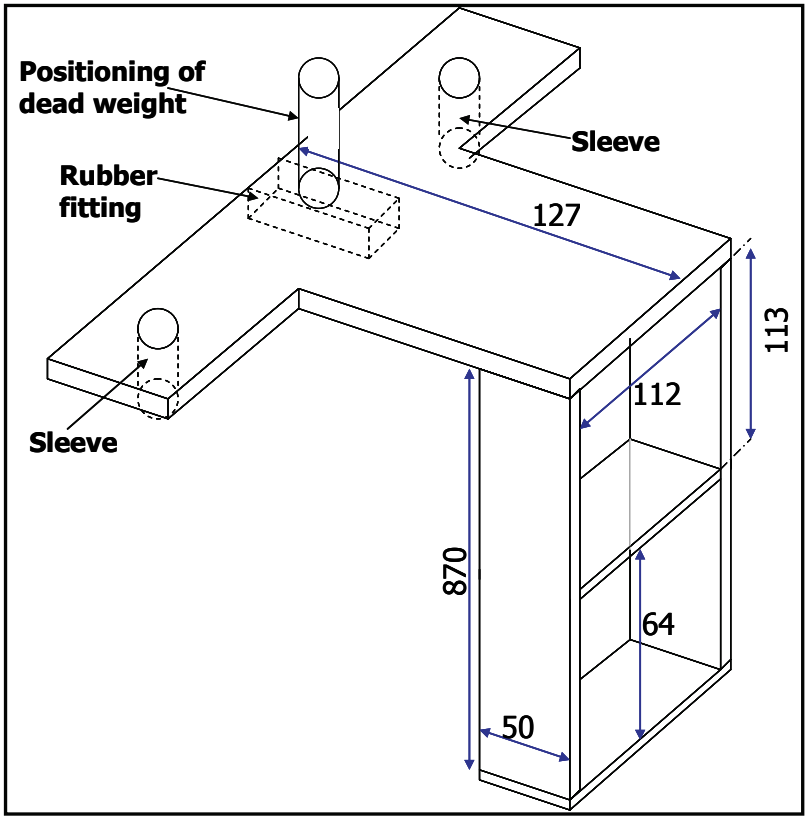
b) If the sleeve finishes above the 300mm mark after compacting layer 5 a steel straight edge is used to cut of the piece of the specimen extending out of the mould. Material is then sieved through a 4.75mm sieve on top of the specimen. The vibratory hammer is the lowered and the sieved material is compacted till the sleeve reached the 300mm mark. The specimen is then removed as previously described.

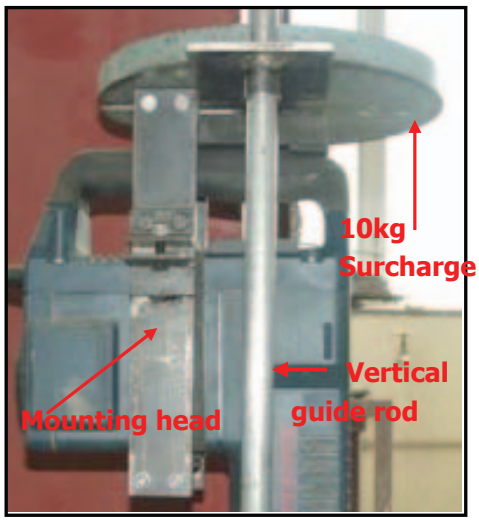
c) If the sleeve finishes below the 300mm mark after compacting layer 5, the surface is scarified and three scoops of material are added. The added material is then compacted for the same duration as layer five and checked using a) and b) of note 4.6.

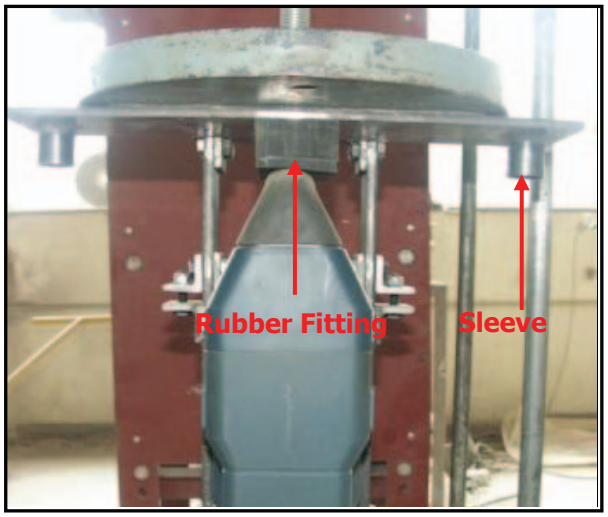
4.7 Should 7 ply shutter board not be obtainable then a wooden base with material properties as close to those of the 7 ply shutter board should be used.

5 DRAWINGS AND PHOTOGRAPHS

The drawings and photographs shown in the images below are of the mounting head used for the Bosch GSH 11E® vibratory hammer







Compaction Protocol 2: Analysis of refusal density using the vibratory hammer, for specification purposes

1 APPARATUS

1.1 A steel split mould 152mm in diameter and 300mm in height with an extension piece and clasps to fix the mould to the base of the frame.

1.2 Three circular papers with diameter of 152mm.

1.3 Non-stick spray e.g. non stick cooking spray purchased at any supermarket.

1.4 A Vibratory Hammer with the following Specifications (see note 4.3):

Table 6-4: Specifications of vibratory hammer for compaction

Specification	Criteria
Power rating	1500 W
Frequency	900 to 1890 beats/min (15 – 31.5Hz)
Point Energy	25 J

The vibratory Hammer should be mounted on two guide rods; one on either side of the hammer. A mounting head should be fitted to the vibratory hammer to allow a surcharge of 10kg to be mounted to the vibratory hammer. There should be a pulley system connecting the frame and mounting head. This allows for easy lifting and lowering of the vibratory hammer.

The total mass of vibratory hammer, surcharge and mounting head should be 30kg ± 1.5kg.

1.5 A 150mm tamping foot

1.6 Material Scoop (90mm Φ x 85mm h)

1.7 Specimens are compacted in 5 Layers.

1.8 Suitable marker e.g. permanent marker

1.9 Adjustable spanner to fasten and loosen surcharge load to the vibratory hammer.

1.10 Steel ruler of length >300mm

1.11 Chisel for tamping layers

1.12 Drill with drill bit of 300mm with a point marked off 10mm from the tip of the bit.

2 PROCEDURE

2.1 Preparation of the material

Preparing the sample of material for initial Moisture Curve

Determine the grading curve of the aggregate (TMH 1) and reconstitute the material to produce samples that will be used for refusal density analysis for the specification of site compaction levels.

Preparing the sample of material for vibratory hammer compaction

From the grading curve reconstitute the material to the produce a sample of 14kg (see note 4.1) of aggregate with a maximum particle size of 19mm. A total of 3 samples of 14kg each required.

The aggregate is prepared as follows:

1. From the moisture-density relationship of the untreated material of Compaction protocol 1, the OMC is used to specify the moisture content of the BSM. A moisture content of 84% of the OMC of the untreated material is added to the sample (see Section 3 for calculations)
2. Should cement or lime need to be added to a specific mix, add these first (before the moisture) to the sample:

4. For BSM-emulsion, the moisture content of the bitumen emulsion needs to be calculated out of the physical mass of water that is added. An example of this calculation is as follows:

   Assumptions made for the example:

   - OMC of untreated material from Compaction protocol 1 = 6.15%.
   - Target moisture content = 85% of 6.15% =5.23%;
   - The bitumen emulsion content of the mix is 3%;
   - The bitumen emulsion is a 60/40 emulsion;

   For a 60/40 emulsion, 40% of the emulsion is water. Therefore of the 3% bitumen emulsion to be added to the mix, 40% of it is water. Therefore the fraction of water being added to the mix from the emulsion is 40% x 3%÷100 = 1.2%

   The fraction of water that is to be added to the mix in order to obtain a moisture content of 5.166% is now 5.23%-1.2% = 4.03%. The physical mass of water to be added to the mix in order to give a target moisture content of 5.23% when the bitumen emulsion is added is now 4.03% of the mass of the sample.

   First add the physical mass of water to the material and allow to stand for 40 – 60 minutes. After this time add the bitumen emulsion to the mix and also allow to stand for 40-60 minutes to allow breaking of the bitumen emulsion.

5. For the BSM-foam, the fraction of moisture added is equivalent to the target moisture content, e.g. Target moisture content is 5.166%, then moisture added to the material prior to stabilisation is 5.166%.

2.2 Compaction Procedure

2.2.1 Prepare the mould and vibratory hammer

Preparing the vibratory hammer

Fix the Mounting Head to the vibratory hammer and fit hammer onto the guide rods. Place the 10kg surcharge load onto the mounting head and fasten tightly – see separate drawing for Mounting Head, Subsection 5 (Kelfkens, 2008). Using the pulley system raise the vibratory hammer to the maximum height it can be raised or to an adequate height that will allow the operator to work beneath the vibratory hammer.

Preparing the Mould

Make sure the mould is clean and then spray the interior of the mould with the non-stick spray. After a specimen has been compacted and removed from the mould, the mould should be cleaned by wiping of excess material from the mould walls (this should be done prior to the compaction of subsequent specimens). Fix the mould to the base of the frame directly below the foot piece of the vibratory hammer using the clasps. Place two of the circular paper sheets at the base of the mould.

Lower the vibratory hammer into the mould, checking that the vibratory hammer is perpendicular to the base of the mould i.e. the tamping foot is flat on the base with no point of the foot slightly raised. Allow the vibratory hammer to rest in the mould with no material present. Where the lower end of sleeve of the mounting head rests on the guide rod mark that position clearly on the vertical guide using the suitable marker. Raise the vibratory hammer and measure up from the initial mark 300mm and mark this clearly (non-erasable).

2.2.2 Compaction of the specimen

Addition of material to mould

Material is placed in the mould using the material scoop. Fill the scoop with the prepared material and level off the scoop and place it in the mould. Add three scoops of material to provide a starting layer thickness of 92mm. Using the chisel, work the material around in order to evenly distribute it in the mould; try to distribute the particles evenly as well i.e. not too much fine material on top or to much coarse material on top, but rather a fair distribution of each i.e. unsegregated. Make sure the material is as level as possible before lowering the vibratory hammer till the foot piece comes to rest on the material.

Compaction of individual layers

Specimens are compacted according to set times for each layer. This is to produce specimens that have densities close to or at refusal density. The compaction times for the individual layers of a specimen according to the type of Bitumen Stabilized Material is provided in Table 6-5:

TABLE 6-5: COMPACTION TIMES PER LAYER TO ACHIEVE REFUSAL DENSITY

Mix type	Compaction Time per layers of specimens (Sec)
Untreated	180
BSM-emulsion	180
BSM-foam	180

After the material of a layer has been compacted for the allocated time, raise the vibratory hammer. Using the drill, scarify the entire surface area of the top of the compacted layer to a depth of ± 10mm (see Note 4.2).

After the surface of a respective layer has been scarified, add the material for the next layer and compact accordingly.

*After Layer four has been compacted and scarified, the extension piece (collar) must first be fitted to the mould before adding the material for layer 5. After adding the material for layer 5 place a circular sheet of paper on top of the material and then lower the vibratory hammer into position; the paper helps prevent material of the final layer from sticking to the tamping foot. Before raising the vibratory hammer the final height of the specimen must be measured, once this is done the vibratory hammer may be raised and the specimen removed.

Measuring the final height of the specimen

After Layer 5 has been compacted and prior to raising the vibratory hammer take the steel rule and measure the distance from the zero line to the bottom end of the sleeve. This distance is taken as the final height of the specimen.

Removing and handling the compacted specimen

Raise the vibratory hammer and remove the extension piece (collar). Disassemble the mould entirely. Place a plastic bag over the specimen and remove it taking care to pick the specimen up from the bottom end. Weigh the specimen after compaction to check the final mass of the specimen.

Checking the moisture content of the specimen

Take a small amount (750-950 gm) of BSM either just prior to, during or after compaction and using the standard oven drying method determine the moisture content.

Determining the final Dry Density

From the moisture content determined, the final mass of the compacted specimen and the final height measured, the final Dry Density of the specimen may be determined. This Dry Density is determined for all three specimens and is averaged out. This average Dry Density is used to specify compaction levels for site.

2.3 Compaction specifications for site compaction

The average Dry Density obtained from the refusal density compaction is used to specify site compaction levels (See Note 4.8). The table below provides the compaction levels:

Table 6-4: Specifications for the level of site compaction

Material Type/Quality	Level of Site Compaction (% Refusal Density)		
	Untreated	BSM-emulsion	BSM-foam
G2 (High Quality)	93.5 to 95.3	93.5 to 95.3	90.1 to 91.1

3 CALCULATIONS

3.1 Addition of lime or cement

Cement or lime content (C/L)

C/L (gm) = C/L (%) × 14000 ÷ 100

3.2 Addition of water for untreated material

Water (gm) = (target moisture content (%))/100× mass of sample (gm)

3.3 Addition of stabilizer and water to Bitumen Stabilized Material (BSM)

BSM-emulsion

Mass of bitumen emulsion

Emulsion mass (gm) = Emulsion content (%)/100 × aggregate dry mass (gm)

Moisture contents

MC in BSM from emulsion (%) = (MC_e (%))/100 × emulsion content (%)

Mass of water added to BSM = (ΔMC) × mass of sample (gm)) ÷100

MC_e = Moisture content of the bitumen emulsion

ΔMC = X (%) - MC in BSM from emulsion (%)

X = target moisture content of the mix

BSM-foam

The bitumen stabilizer is added according to the method provided in the TG 2 manual for preparing BSM-foam.

Moisture added = target moisture content of the mix

3.4 Dry Density

Volume of the specimen = $\pi \times 0.005625 \times$ Fh

Fh = Final height of the specimen

Dry Density = (Fm ÷ (1+ (MC/100)) ÷ Volume of the specimen

Fm = Final Mass of the specimen (kg)

MC = Moisture Content (%)

4 NOTES

4.1 For a final specimen of 300mm high a sample mass of 14kg is recommended when preparing the BSM.

4.2 Layers should not be scarified deeper than 10mm. The result of scarifying deeper than10mm is that the layer being compacted does not bond adequately well to the previous layer and hence there is an increase in voids at this interface.

4.3 Should the vibratory hammer not meet the specifications provided and where no suitable alternative compaction hammers can be sourced, then a vibratory hammer with a point energy of 25 Joule ± 2 Joule should be used. If the weight of the hammer deviates from the specifications by more than 5%, then calibration tests need to be made.

4.4 After a specimen has been compacted and removed from the mould, the mould should be cleaned by wiping off excess material from the mould walls. This should be done prior to the compaction of the next specimen.

4.7 Should 7 ply shutter board not be obtainable then a wooden base with material properties as close to those of the 7 ply shutter board should be used.

4.8 The compaction specifications for site compaction need to be revisited as compaction data from sites become available.

Compaction Protocol 3: Specimen compaction to a known target density

This procedure is used for investigative purposes. Specimens are compacted to densities equivalent to known site densities to simulate the in situ density of a pavement layer. These specimens are used for material testing in the laboratory to determine the in situ engineering properties of the pavement layer.

1 APPARATUS

1.1 A steel split mould 152mm in diameter and 300mm in height with an extension piece and clasps to fix the mould to the base of the frame.

1.2 Three circular papers with diameter of 152mm.

1.3 Non-stick spray e.g. non stick cooking spray purchased at any supermarket.

1.4 A Vibratory Hammer with the following Specifications (see note 4.3):

Table 6-6: Specifications of vibratory hammer for compaction

Specification	Criteria
Power rating	1500 W
Frequency	900 to 1890 beats/min (15 – 31.5Hz)
Point Energy	25 J

The vibratory Hammer should be mounted on two guide rods; one on either side of the hammer. A mounting head should be fitted to the vibratory hammer to allow a surcharge of 10kg to be mounted to the vibratory hammer. There should be a pulley system connecting the frame and mounting head. This allows for easy lifting and lowering of the vibratory hammer.

The total mass of vibratory hammer, surcharge and mounting head should be 30kg ± 1.5kg.

1.5 A 150mm tamping foot

1.6 6 clear plastic bags per specimen to be compacted.

1.7 Specimens are compacted in 5 Layers at 80% of OMC of the untreated material (see Note 4.5).

1.8 Suitable marker e.g. permanent marker

1.9 Adjustable spanner to fasten and loosen surcharge load to the vibratory hammer.

1.10 Steel ruler of length >300mm

1.11 Chisel of at least 300mm long for tamping layers

1.12 Drill with drill bit of 300mm with a point marked off 10mm from the tip of the bit.

2 PROCEDURE

2.1 Preparation of the material

Preparing the sample of material for initial Moisture Curve

Determine the grading curve of the aggregate and reconstitute the material to produce samples that will be used to obtain the OMC of the natural (untreated) material using compaction protocol 1.

Compaction protocol 1 is performed for the specific material type and BSM. The OMC is obtained from the moisture-density relationship, and this is used to specify the target moisture content of the BSM.

Preparing the sample of material for vibratory hammer compaction

From the field compaction data the target Dry Density is decided on. Back calculations are done to determine the final target bulk mass of the sample (see 3.2). This bulk mass is then divided by 5 to obtain the required mass of material that is needed to be compacted for each layer. An extra 2kg is added to the final bulk mass and this is the mass of material that is to be prepared for compaction (see Note 4.1).

From the grading curve reconstitute the material to the produce the required sample with a maximum particle size of 19mm.

The aggregate is prepared as follows:

- Compaction is done at a target moisture content of 85% of OMC (Compaction protocol 1)
- Should cement or lime need to be added to a specific mix, add these first to the sample.

For Untreated material i.e. no bitumen stabilization, add the fractions of water to each of the individual sample masses (see Note 4.5).

For BSM-emulsion, the moisture content of the bitumen emulsion needs to be calculated out of the physical mass of water that is added by hand. First add the physical mass of water to the material and allow to stand for 40 – 60 minutes (see Note 4.5). After this time add the bitumen emulsion to the mix and also allow to stand for 40-60 minutes to allow breaking of the bitumen emulsion.

Prepare the BSM-foam in accordance with the procedure outlined in the TG (2) manual (see Note 4.5).

After the BSM has been prepared the required mass of material for each layer is weighed off and placed in its own separate clear plastic bag. 5 bags for each specimen are required. The extra material is then used to determine the moisture content of the specimen and any material remaining after that is placed in its own clear plastic bag and marked clearly as "Excess Material of Specimen No. " This bag is placed to one side.

2.2 Compaction Procedure

2.2.1 Prepare the mould and vibratory hammer

Preparing the vibratory hammer

Fix the Mounting Head to the vibratory hammer and fit hammer onto the guide rods. Place the 10kg surcharge load onto the mounting head and fasten tightly – see separate drawing for Mounting Head, Subsection 5 of compaction protocol 1 (Kelfkens, 2008). Using the pulley system raise the vibratory hammer to the maximum height it can be raised or to an adequate height that will allow the operator to work beneath the vibratory hammer.

Preparing the Mould

Make sure the mould is clean and then spray the interior of the mould with the non-stick spray. After a specimen has been compacted and removed from the mould, the mould should be cleaned by wiping of excess material from the mould walls (see Note 4.4). This should be done prior to the compaction of the next specimen. Fix the mould to the base of the frame directly below the foot piece of the vibratory hammer using the clasps. Place two of the circular paper sheets at the base of the mould.

Lower the vibratory hammer into the mould, checking that the vibratory hammer is perpendicular to the base of the mould i.e. the tamping foot is flat on the base with no point of the foot slightly raised. Allow the vibratory hammer to rest in the mould with no material present. Where the lower end of sleeve of the mounting head rests on the guide rod mark that position clearly on the vertical guide using the suitable marker. This is the zero line. Raise the vibratory hammer and measure up from the initial mark 300mm marking off clearly at every 60mm interval points (non-erasable) (see Note 4.6).

2.2.2 Compaction of the specimen

Addition of material to mould

Take one of the 5 clear plastic bags that has the weighed off mass of material in it. Pour this material from the bag into the mould, taking care not to mess a drop. After the compaction and scarification of a layer, another clear plastic bag having the weighed off mass of material is taken and the material is poured into the mould and compacted. This continues until all five layers have been compacted.

Compaction of individual layers

After the addition of material for a specific layer, the vibratory hammer is lowered into position. The hammer is switched on and the material is compacted until the bottom end of the sleeve reaches the 60mm marker of that specific layer (see Subsection 4). After the layer is compacted to the target height, the vibratory hammer is switched off and raised to its maximum height. The surface of the compacted specimen is then scarified to a depth of ±10mm (see note 4.2) using either the drill or chisel. The next layer is added after the scarification and compacted as previously described. The specimen is compacted until all 5 layers have been compacted.

After Layer 4 has been compacted and scarified, the extension piece (collar) must first be fitted to the mould before adding the material for layer 5. After adding the material for layer 5 place a circular sheet of paper on top of the material and then lower the vibratory hammer into position. The paper helps prevent material of the final layer from sticking to the tamping foot. Before raising the vibratory hammer the final height of the specimen must be measured, once this is done the vibratory hammer may be raised and the specimen removed.

Measuring the final height of the specimen

After Layer 5 has been compacted and prior to raising the vibratory hammer take the steel rule and measure the distance from the zero line to the bottom end of the sleeve. This distance is taken as the final height of the specimen.

Removing and handling the compacted specimen

Raise the vibratory hammer and remove the extension piece (collar). Disassemble the mould entirely. Place a plastic bag over the specimen and remove it taking care to pick the specimen up from the bottom end. Weigh the specimen after compaction to check the final mass of the specimen.

Checking the moisture content of the specimen

From the excess material left after the weighing off of the layers, take a small amount (750-950 gm) of this material and using the standard oven drying method determine the moisture content.

Determining the final Dry Density

From the moisture content determined, the final mass of the compacted specimen and the final height measured the final Dry Density of the specimen may be determined.

3 CALCULATIONS

3.1 Target moisture content of mix

Target moisture content (%) (TMC) = 0.8 × OMC (%) (Mod-U)

3.2 Bulk dry mass of material

TDD = Target Dry Density obtained from field compaction data in kg/m^3

a) Bulk density and Bulk mass which accounts for the binder

BDD (kg) = TDD ÷ (1 + (TMC (%) × 0.01))

Bdm = BDD × V_m × 1000

Sm = Bdm + 2000gm

BDD = Bulk Dry Density (kg/m^3)

Bdm = Bulk dry mass (gm)

V_m = Volume of the mould = πr^2 × height

Sm = Sample mass from which compacted specimen is prepared

b) Bulk Dry Density and Bulk dry mass which does not account for the binder

BDD = TDD ÷ (1 + (TMC (%) × 0.01)) × (1+ (BindC (%) × 0.01))

Bdm = BDD × V_m

Sm = Bdm + 2000gm

BindC = Binder Content

3.3 Mass of material per layer to be compacted (M/l)

M/l = Bdm ÷ 5

3.4 Addition of lime or cement

Cement or lime content (C/L)

C/L (gm) = C/L (%) × Sm ÷ 100

3.5 Addition of water for untreated material

Water (gm) = (TMC (%))/100× Sm (gm)

3.6 Addition of stabilizer and water to Bitumen Stabilized Material (BSM)

BSM-emulsion

Mass of bitumen emulsion

Emulsion mass (gm) = Emulsion content (%)/100 × Sm (gm)

Moisture contents

MC in BSM from emulsion (%) = (MC of emulsion (%))/100 × emulsion content (%)

Mass of water added to BSM = (ΔMC) × Sm (gm)) ÷100

ΔMC = TMC (%) - MC in BSM from emulsion (%)

BSM-foam

The bitumen stabilizer is added as per the TG 2 manual for preparing BSM-foam.

Moisture content

Water (gm) = (TMC (%))/100× Sm (gm)

3.7 Dry Density

Volume of the specimen = $\pi \times r^2 \times Fh$

r = radius of the specimen (m^2)

Fh = Final height of the specimen (m)

Dry Density = Fm ÷ ((1+ (MC /100)) ×Volume of the specimen)

Fm = Final Mass of the specimen (kg)

MC = Moisture Content of the specimen (%)

4 NOTES

4.1 It is recommended that an extra 2kg of material be added to the Bulk dry mass when preparing the material for compaction. This allows for extra material so as to take moisture contents,

4.2 Layers should not be scarified deeper than 10mm. The result of scarifying deeper than 10mm is that the layer being compacted does not bond adequately well to the previous layer and hence there is an increase in voids at this interface.

4.3 Should the vibratory hammer not meet the specifications provided and where no suitable alternative compaction hammers can be sourced, then a vibratory hammer with a point energy of 25 Joule ± 2 Joule should be used. If the weight of the hammer deviates from the specifications by more than 5%, then calibration tests need to be made.

4.4 After a specimen has been compacted and removed from the mould, the mould should be cleaned by wiping off excess material from the mould walls. This should be done prior to the compaction of the next specimen.

4.5 Specimen compaction is performed at a moisture content of 80% OMC (Mod-U). Should the operator deem the mix excessively wet for this moisture content, then the moisture content may be to lowered until the operator deems the mix adequate i.e. moist enough for compaction but not excessively wet. It is important to note that an excessively wet mix may result in the loss of binder during compaction specifically in the case of BSM-emulsion. This is due the fine material squeezing out between the walls of the mould and the tamping foot.

7 Reference

ASTM Standard D7382, 2007, "Standard Test Methods for Determination of Maximum Dry Unit Weight and Water Content Range for Effective Compaction of Granular Soils Using a Vibrating Hammer," ASTM International, West Conshohocken, PA, www.astm.org.

BS EN 12697-32:2003, 2004, Bituminous mixtures-Test methods for hot mix asphalt Part 32: Laboratory compaction of bituminous mixtures by vibratory compactor, University of Nottingham, Uncontrolled Copy, © British Standards

Carson, 2004, Soil Compaction Handbook, Multiquip Inc, California, USA

CSRA, 1987, Standard Specifications for Road and Bridge Works 1987, pg 8200-8, table 8206/1, Committee of State Road Authorities, Pretoria

Hanekom, R, 2007, University of Stellenbosch, Thesis V08, Compaction of Cold Mixes using the Kango Hammer Method

Jönsson, M, Partl, MN, Flisch, A, 2002, Report Nr. 113/12, Comparison of Different Compaction Methods Using X-ray Computer Tomography, EMPA

Muthen, KM, 1998, Contract Report CR-98/077, CSIR

NZS 4402, 1986,"Test 4.3.1 New Zealand vibrating hammer compaction test", New Zealand Standards, Wellington,

Prochaska, A.B., and Drnevich, V.P., (2005), "One-Point Vibrating Hammer Compaction Test for Granular Soils," Proceedings, GeoFrontiers Conference, ASCE, Austin, TX, January, 25 p.

Read, J, Whiteoak, D, Shell Bitumen, 2003, The Shell Bitumen Handbook Fifth eddition, Thomas Telford

Sabita, 1993, GEMS-The design and use of granular emulsion mixes, Sabita, Roggebaai, South Africa

Santana, T, 1998, A Geotechnical Methodology for Roller Compacted Concrete Mixture Design, 8th International Symposium on Concrete Roads. Lisboa

Scott, R.A, Pearce, R.W, 1976, "Ground Treatment by Deep Compaction: Soil compaction by impact", Thomas Telford Ltd, The institute of Civil Engineers, London

Thenoux, G, Jamet, A, Encina, C, 2004, A Study and Recommendations of a Mix Design Procedure Using gyratory Compactor for Foamed Asphalt Recycled Material, School of Engineering Universidad Católica de Chile

Theyse, HL, 2003, Confidential CSIR Contract Report CR-2003/23 First Level Analysis Report: HVS Testing of the Foamed-treated crushed stone base on the N7/1 near Cape Town,

Theyse, HL, 2004, Restricted CSIR Contract Report CR-2004/38 The Compaction Potential of Foamed- and Emulsified Bitumen Treated Material, Pretoria

TMH 1, 1986, "STANDARD METHODS OF TESTING ROAD CONSTRUCTION MATERIAL", National Institute for Transport and Road Research, Pretoria, South Africa

TNZ B/02, 2005, "Specifications for Construction of Unbound Granular Pavement Layers", Transit New Zealand

TRH 4 Draft, 1996, "Structural Design of Flexible Pavements for Interurban and Rural Roads", Pretoria, South Africa

Van de Ven, M, et al, , Gautrans, 1997, ITT Report 18.1-1997 Investigation into the Feasibility of Scaling Granular Materials for use with the MMLS Trial Tests on G1, Waterbound and ETB, Institute for Transport Technology

Weston, C.T, 2001, Cape Peninsula University of Technology, A STUDY INTO THE MECHANICAL ROPERTIES OF FOAMED BITUMINOUS STABILISED MATERIALS

Web Sites

Miller group & Associate authors, 2004,

http://www.millergroup.ca/pavement/emulsion_mixes.html, 22 July 2008 (11:28 AM)

Patent Storm, http://www.patentstorm.us/patents/6451885-description.html, 22 July 2008, 11:29 AM

Grading and Excavation Contractor, http://www.forester.net/gx_0409_soils.html, 22 August 2008, 11:20AM

Landpac®, http://www.landpac.com/Theory/basic_princ_factors_compaction.htm, 22 August 2008, 11:23AM

Wikipedia, http://en.wikipedia.org/wiki/Proctor_compaction_test, 22 August 2008, 11:58 AM

European Environment Agency, http://glossary.eea.europa.eu/EEAGlossary/G/greenfield_site, 9 September 2008, 11:09AM

8 Appendix A

8.1 Calculations for vibratory hammer compacted materials

The sample mass for preparation of a specimen, is calculated as follows:

$$Sp_m = Sc_m + 2kg = \frac{\rho \times V}{1 + MC_t} + 2$$

EQUATION 8-1

With

$$MC_t = x \times 0.01 \times OMC$$

Equation 8-2

Where:

Sp_m = Sample mass [kg]

Sc_m = Specimen mass [kg]

ρ = Target Dry Density [kg/m^3]

V = Volume of the mould [m^3]

MC_t = Target moisture content [%]

x = 0.7, 0.8, and 0.9

OMC = Optimum moisture content as per Mod AASHTO for the material being used [%]

The amount of water to be added to a sample to obtain a target moisture content of a specimen is calculated as follows:

$$W_{ad} = MC_t - MC_{BE}$$

EQUATION 8-3

Where:

W_{ad} = Water added [% wt/wt]

MC_t = Moisture content [%], obtained from Equation 8-2.

MC_{BE} = Water content of bitumen emulsion [%]

9 Appendix B

This section presents the results of the individual experiments of a varying surcharge mass and varying moisture content, performed on the BSM-emulsion (9.1.1) and BSM-foam (9.1.2) G2 material.

9.1.1 BSM-emulsion using G2 material

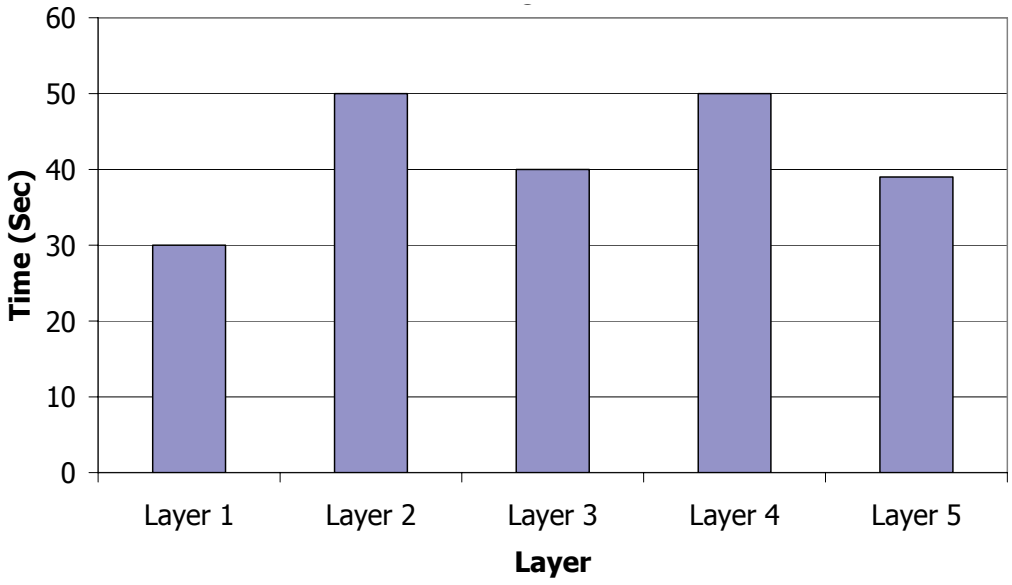


FIGURE 9-1: TIME TO 100% MOD AASHTO COMPACTION AT 70% OMC (MOD-U) – 10KG SURCHARGE BSM-EMULSION G2 MATERIAL, KANGO 637®

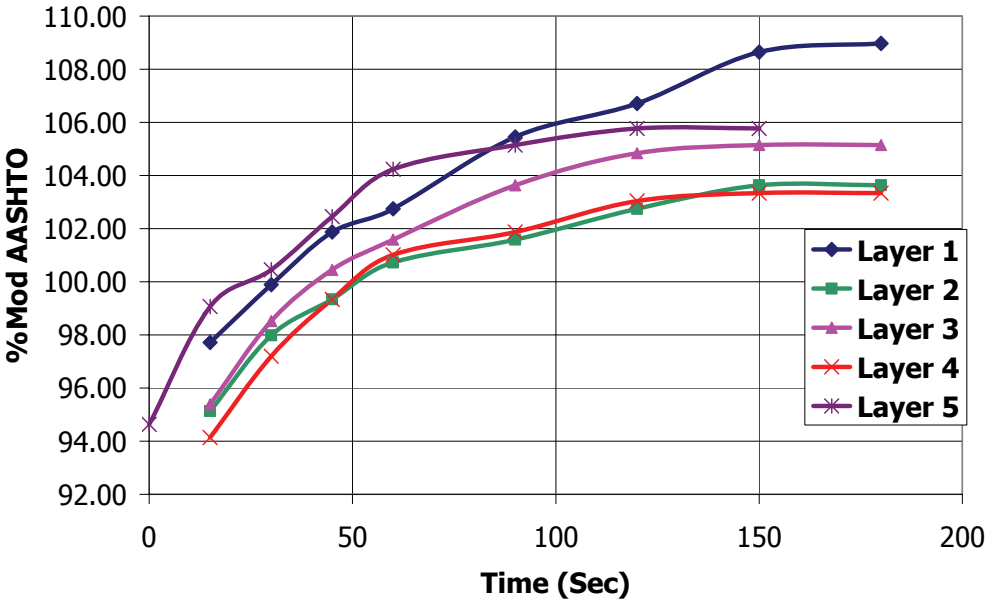


FIGURE 9-2: MOD AASHTO DENSITY OVER TIME OF 70% OMC (MOD-U) BSM-EMULSION G2 MATERIAL – 10KG KANGO 637®

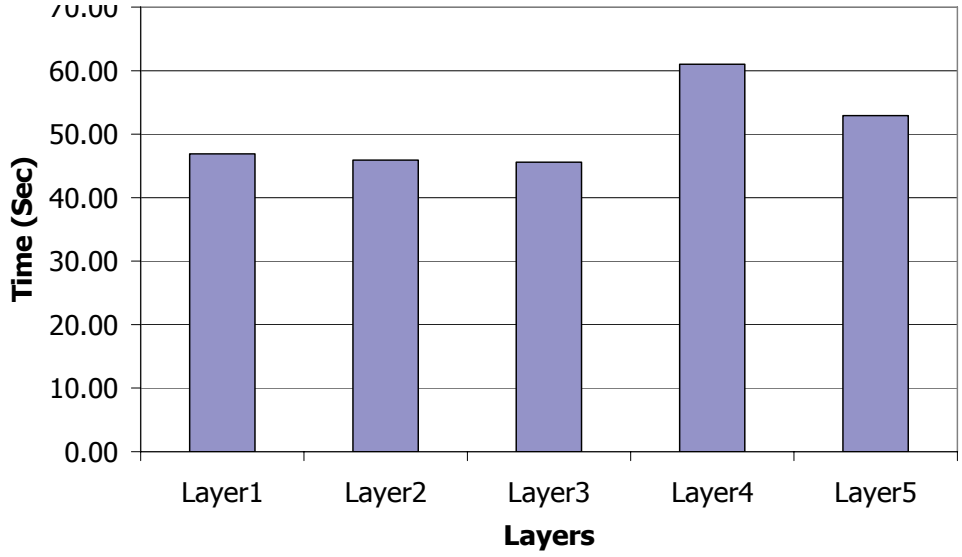


FIGURE 9-3: TIME TO 100% MOD AASHTO COMPACTION AT 80% OMC (MOD-U) – 10KG SURCHARGE BSM-EMULSION, KANGO 637®

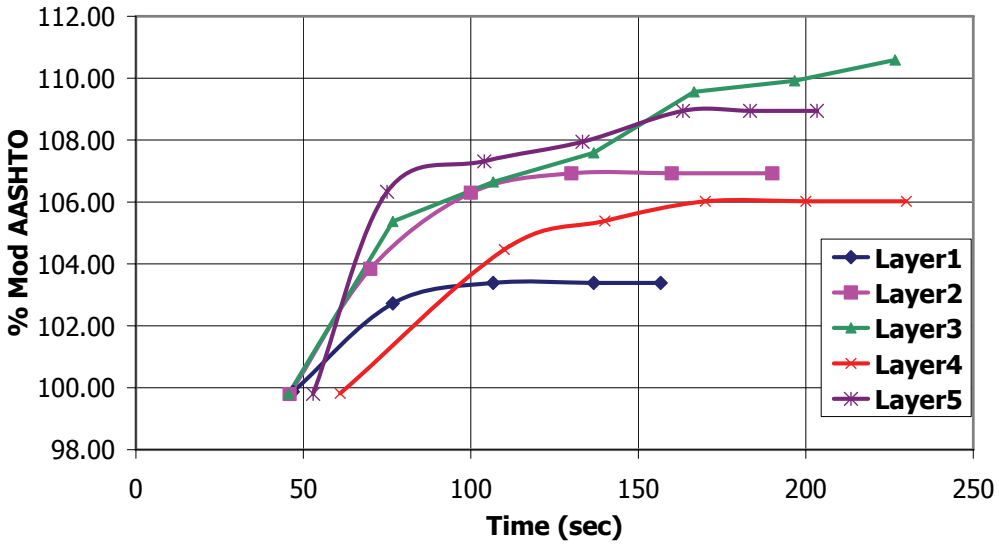


FIGURE 9-4: MOD AASHTO DENSITY OVER TIME OF 80% OMC (MOD-U) BSM-EMULSION– 10KG SURCHARGE BSM-EMULSION, KANGO 637®

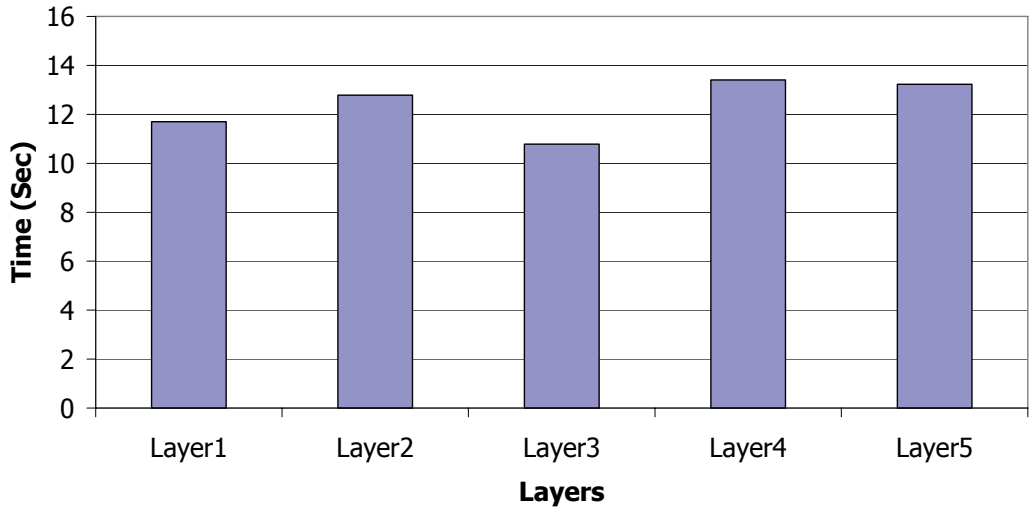


FIGURE 9-5: TIME TO 100% MOD AASHTO COMPACTION AT 90% OMC (MOD-U) – 10KG SURCHARGE BSM-EMULSION, KANGO 637®

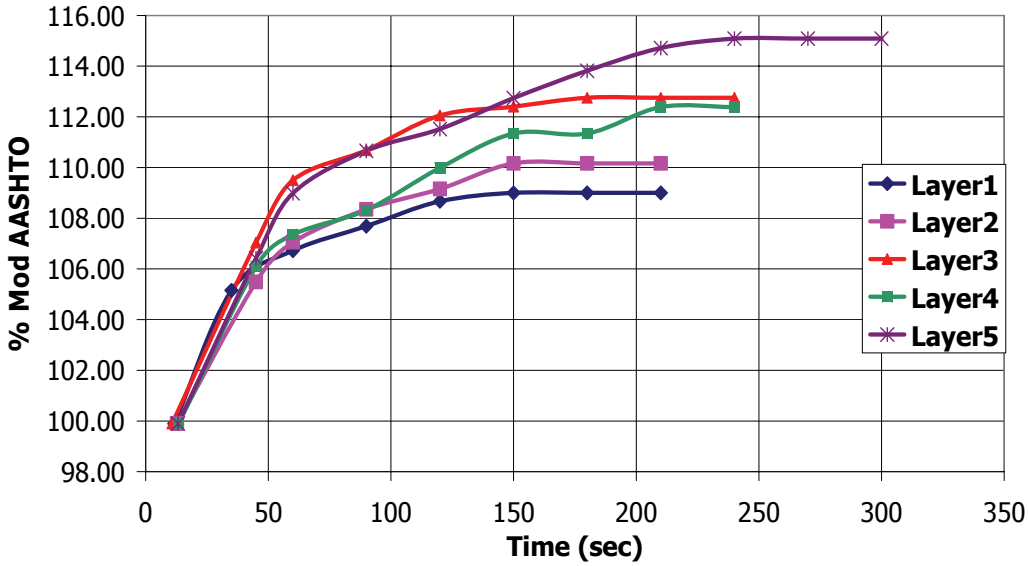


FIGURE 9-6: %MOD AASHTO DENSITY OVER TIME OF 90% OMC (MOD-U) BSM-EMULSION G2 MATERIAL – 10KG SURCHARGE, KANGO 637®

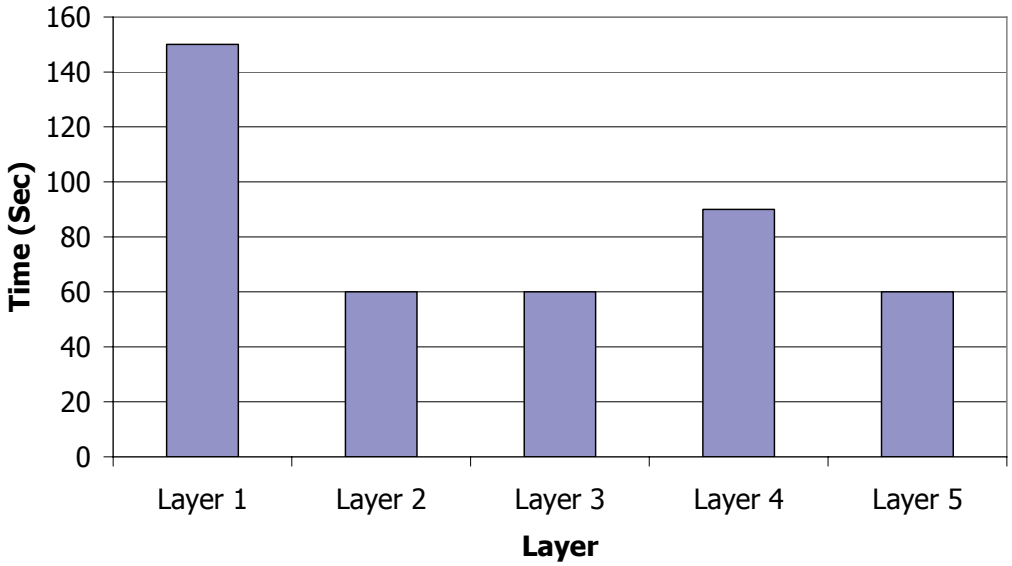


FIGURE 9-7: TIME TO 100% MOD AASHTO COMPACTION AT 70% OMC (MOD-U) – 20KG SURCHARGE BSM-EMULSION G2 MATERIAL, KANGO 637®

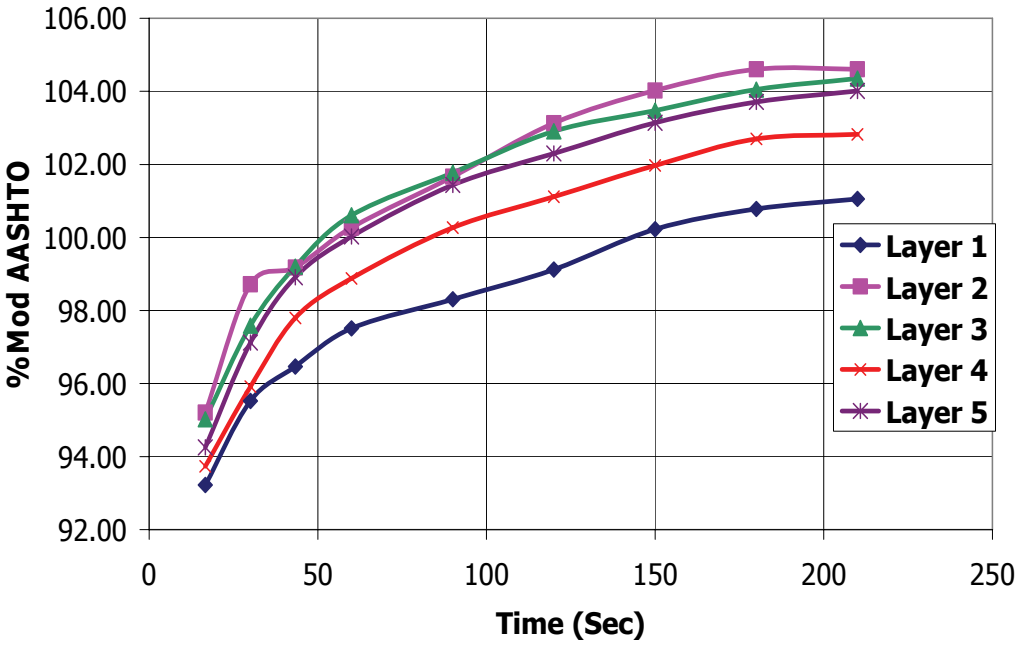


FIGURE 9-8: MOD AASHTO DENSITY OVER TIME OF 70% OMC (MOD-U) BSM-EMULSION– 20KG SURCHARGE BSM-EMULSION G2 MATERIAL, KANGO 637®

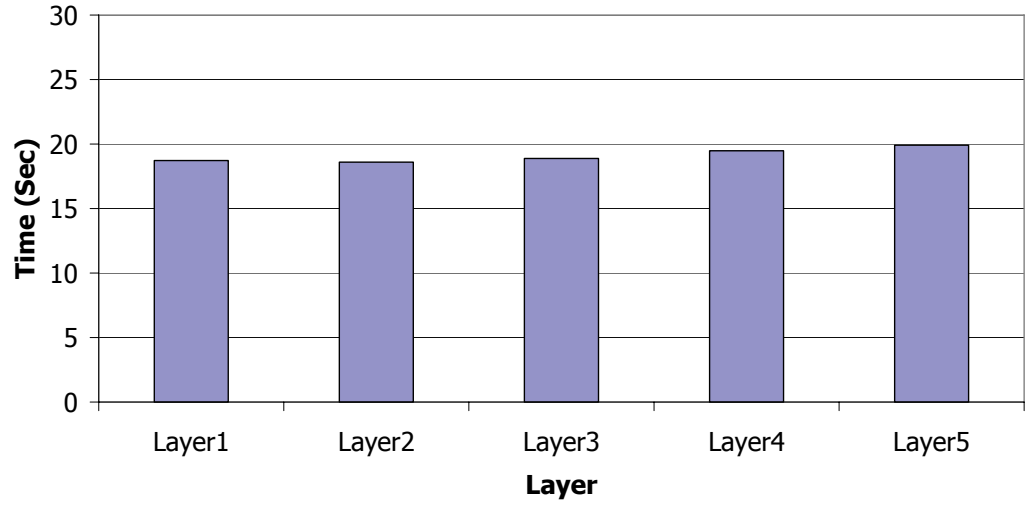


FIGURE 9-9: TIME TO 100% MOD AASHTO COMPACTION AT 80% OMC (MOD-U) – 20KG SURCHARGE BSM-EMULSION G2 MATERIAL, KANGO 637®

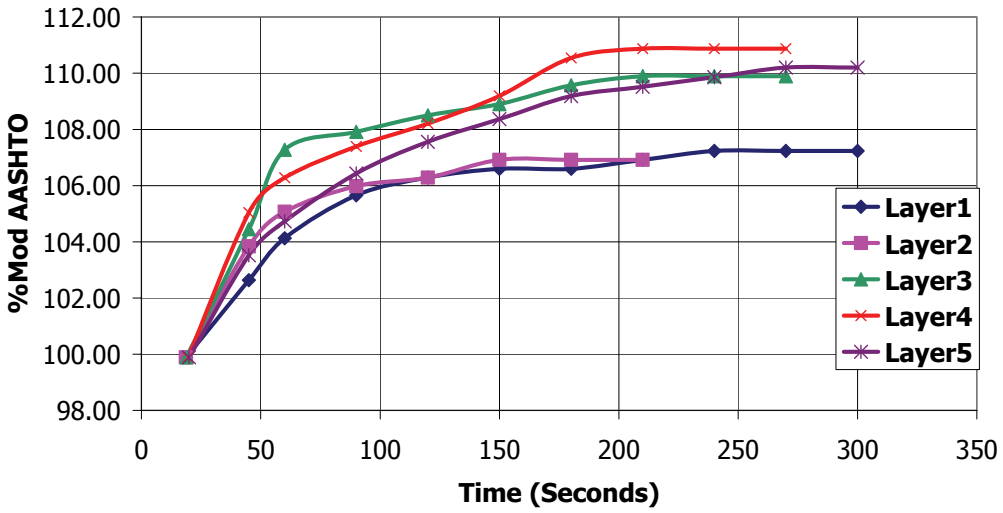


FIGURE 9-10: MOD AASHTO DENSITY OVER TIME OF 80% OMC (MOD-U) BSM-EMULSION G2 MATERIAL – 20KG SURCHARGE, KANGO 637®

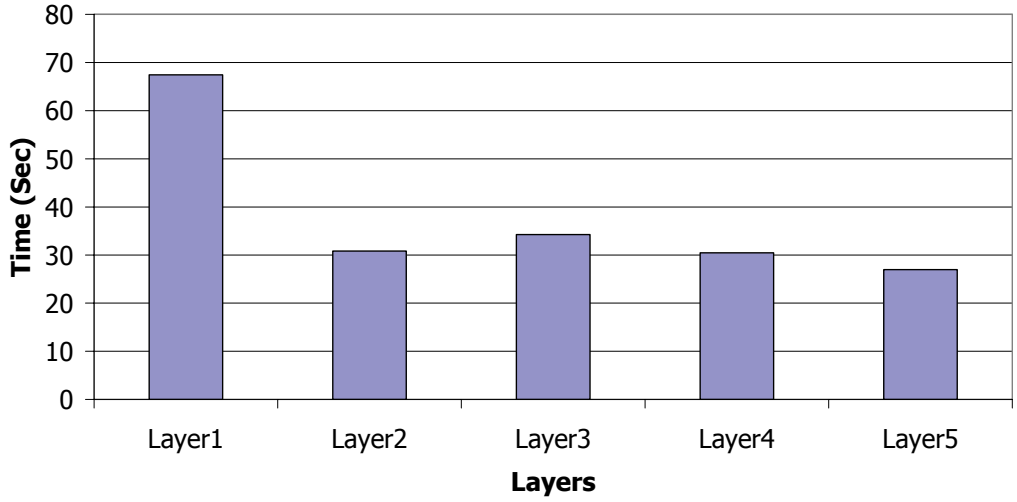


FIGURE 9-11: TIME TO 100% MOD AASHTO COMPACTION AT 80% OMC (MOD-U) – 15KG SURCHARGE BSM-EMULSION G2 MATERIAL, KANGO 637®

9.1.2 BSM-FOAM using G2 material

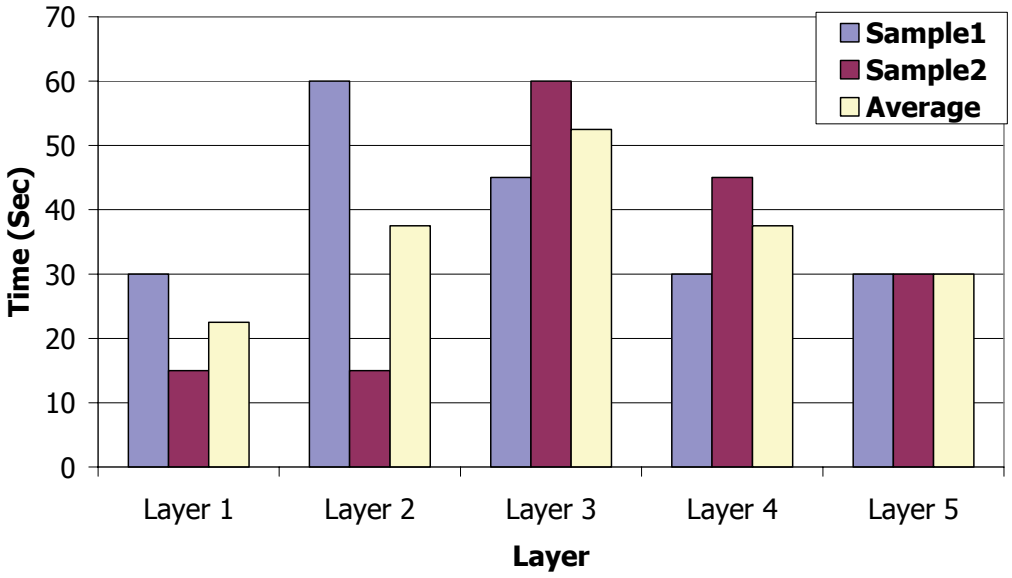


FIGURE 9-12: TIME TO 100% MOD AASHTO COMPACTION AT 70% OMC (MOD-U) 10KG SURCHARGE, BSM-FOAM G2 MATERIAL, KANGO 637®

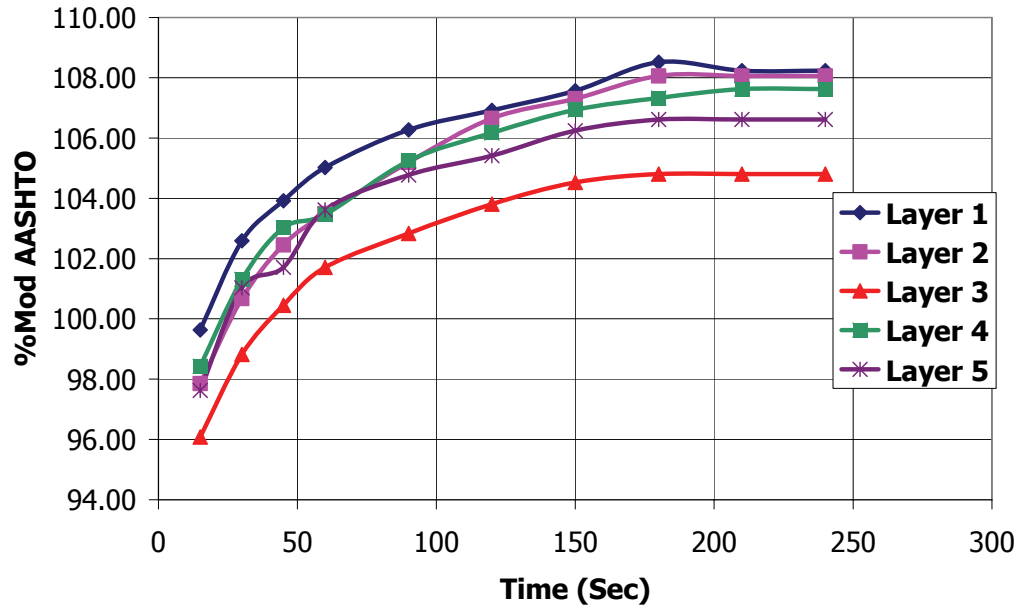


FIGURE 9-13: MOD AASHTO DENSITY OVER TIME OF 70% OMC (MOD-U) 10KG SURCHARGE, BSM- FOAM G2 MATERIAL, KANGO 637®

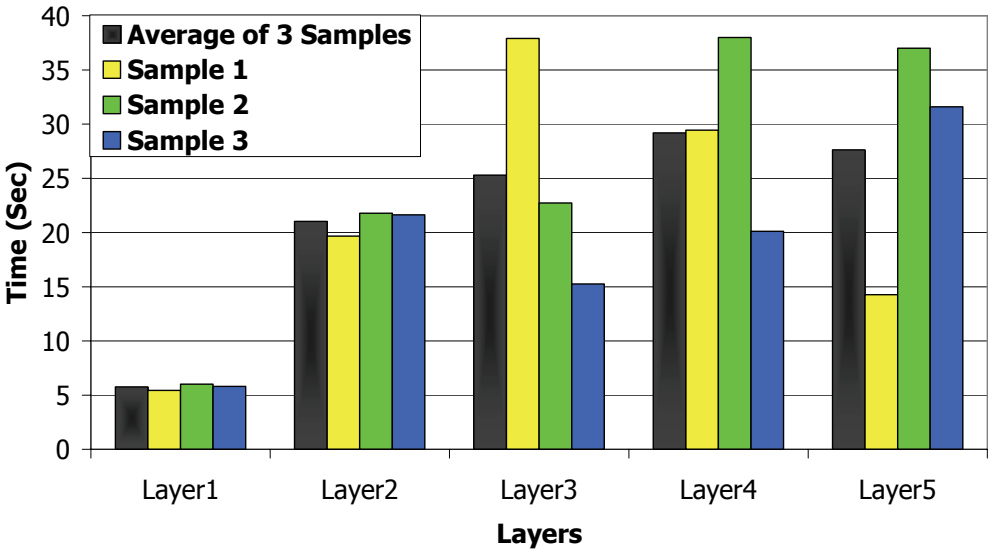


FIGURE 9-14: TIME TO 100% MOD AASHTO COMPACTION AT 80% OMC (MOD-U) 10KG SURCHARGE, BSM-FOAM BOSCH GSH 11E®

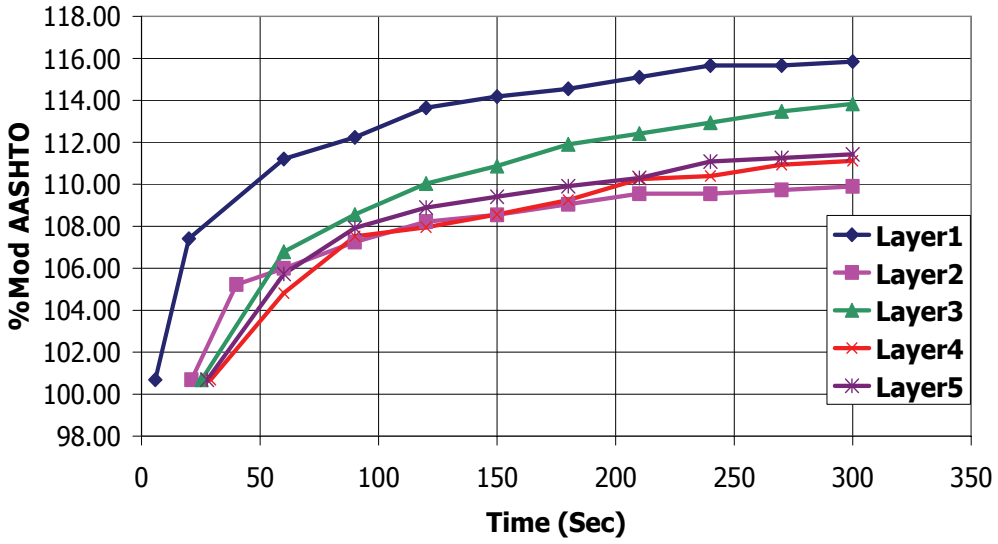


FIGURE 9-15: MOD AASHTO DENSITY OVER TIME OF 80% OMC (MOD-U) 10KG SURCHARGE, BSM-FOAM BOSCH GSH 11E®

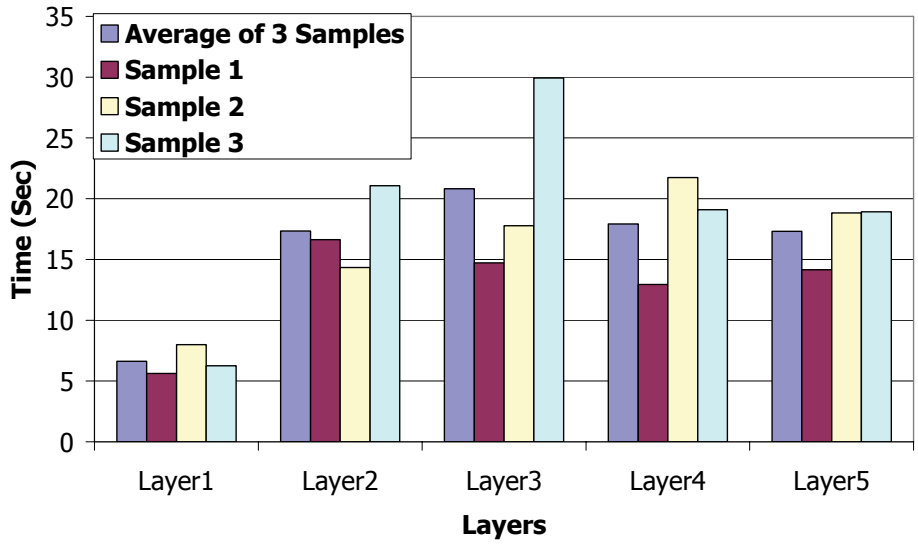


FIGURE 9-16: TIME TO 100% MOD AASHTO COMPACTION AT 90% OMC (MOD-U) 10KG SURCHARGE, BSM-FOAM BOSCH GSH 11E®

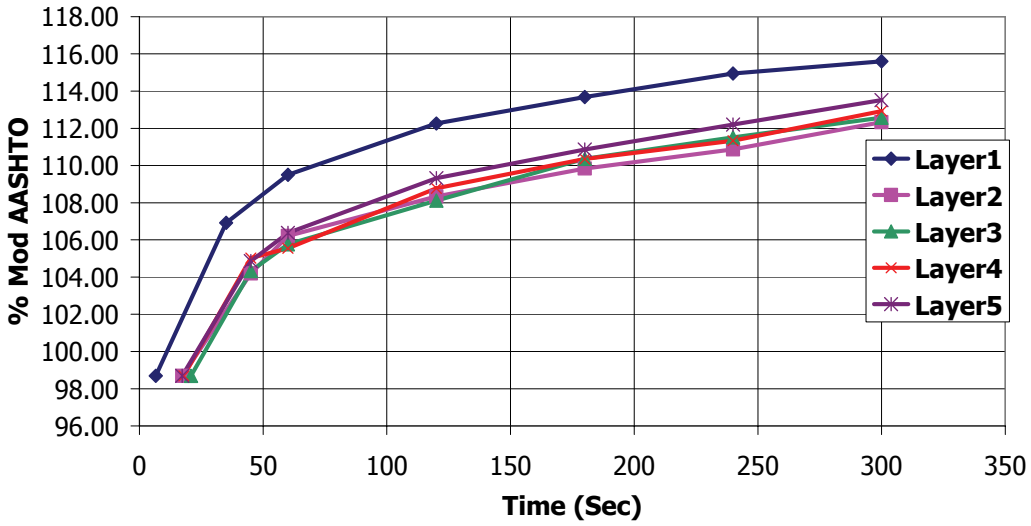


FIGURE 9-17: MOD AASHTO DENSITY OVER TIME OF 90% OMC (MOD-U) 10KG SURCHARGE, BSM-FOAM BOSCH GSH 11E®

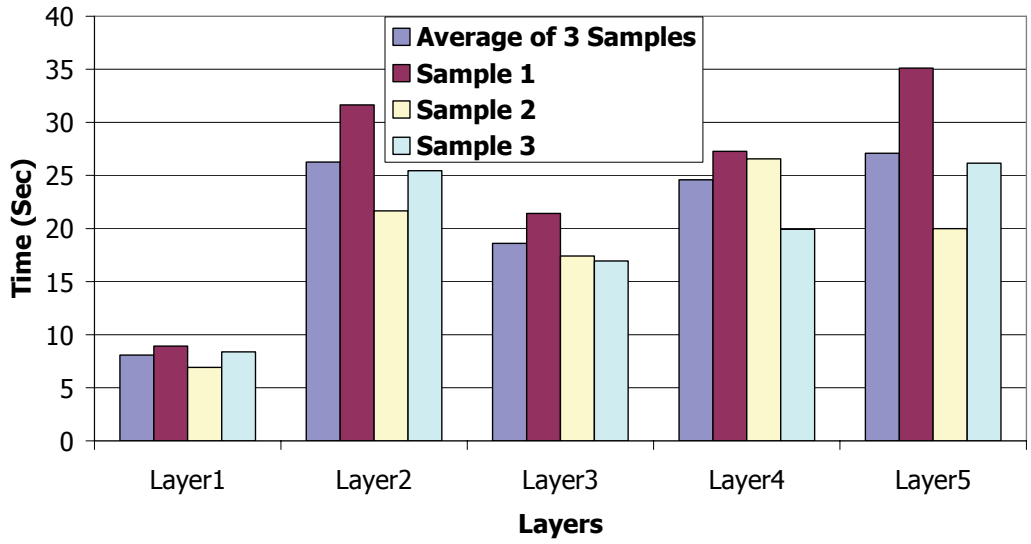


FIGURE 9-18: TIME TO 100% MOD AASHTO COMPACTION AT 80% OMC (MOD-U) 15KG SURCHARGE, BSM-FOAM BOSCH GSH 11E®

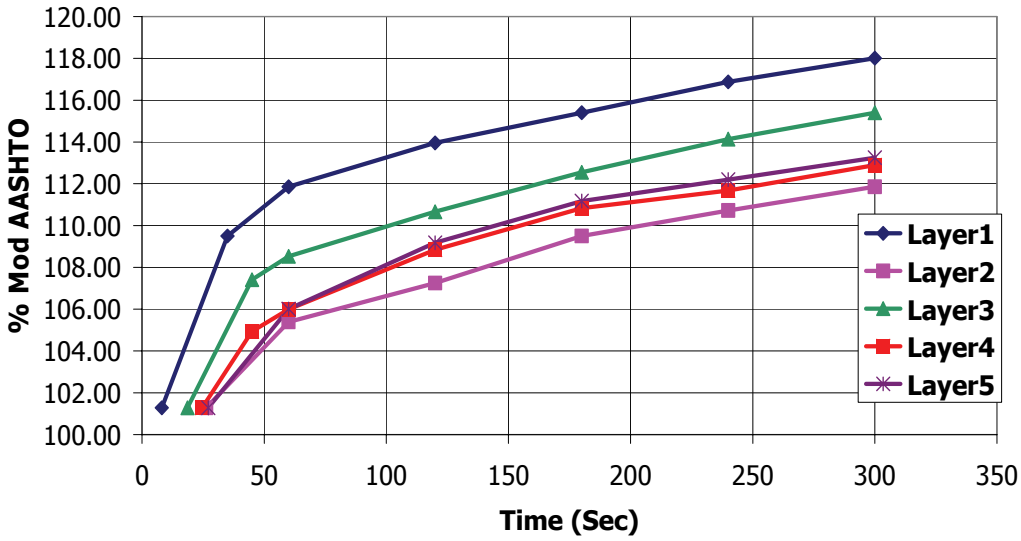


FIGURE 9-19: MOD AASHTO DENSITY OVER TIME OF 80% OMC (MOD-U) 15KG SURCHARGE, BSM-FOAM BOSCH GSH 11E®

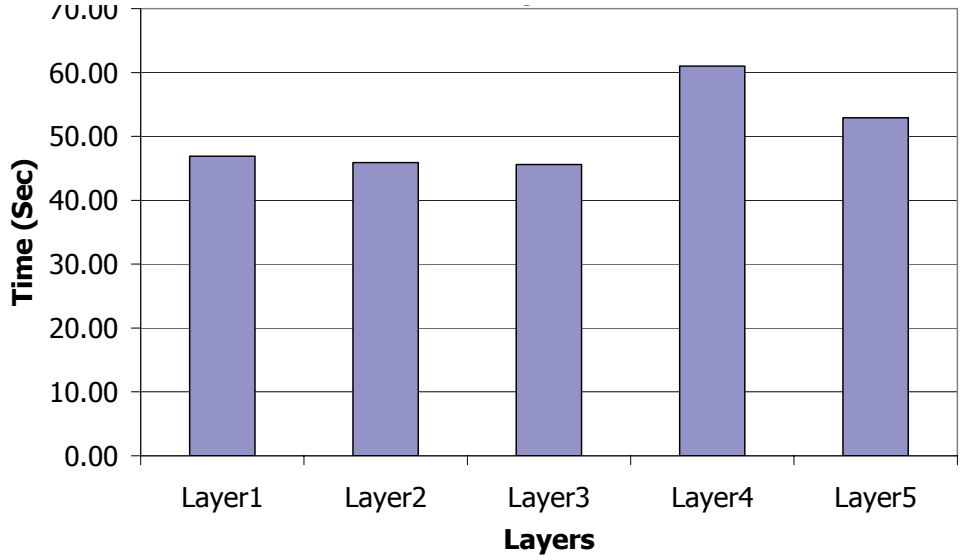


FIGURE 9-20: TIME TO 100% MOD AASHTO COMPACTION AT 80% OMC (MOD-U) – 10KG SURCHARGE BSM-EMULSION, KANGO 637®

10 Appendix C

This section presents a statistical analysis of the site compaction data for BSM-emulsion and BSM-foam.

10.1 BSM-emulsion

Table 10-1 to Table 10-4 show the data and statistical analysis results of the site compaction data for the N7 rehabilitation project using bitumen emulsion stabilisation.

TABLE 10-1: N7 SITE COMPACTION DATA – BSM-EMULSION

n	Dry Density (kg/m^3)	% Mod AASHTO
1	2181	101.6
2	2227	103.6
3	2255	104.2
4	2255	104.7
5	2272	106.1
6	2287	106.2
7	2305	107.4
8	2323	107.5
9	2345	108.9
10	2345	109.6
11	2350	110.1
12	2367	110.7

TABLE 10-2: STATISTICAL ANALYSIS TABLE 10-1 – % MOD AASHTO BSM-EMULSION

Statistic	%Mod AASHTO
Mean	106.72%
Standard deviation	2.83%
COV	2.65%
75th Percentile	104.61%
85th Percentile	103.99%
95th Percentile	102.71%

TABLE 10-3: STATISTICAL ANALYSIS TABLE 10-1 – % MOD AASHTO BSM-FOAM

Statistic	Dry Density
Mean	2292.6 kg/m^3
Standard deviation	56.76 kg/m^3
COV	2.48%
75th Percentile	2255 kg/m^3

Statistic	Dry Density
85th Percentile	2245.2 kg/m^3
95th Percentile	2206.3 kg/m^3

TABLE 10-4: TEST FOR OUTLIERS ON N7 SITE COMPACTION DATA – BSM-EMULSION

n	12
X_0	101.6%
$\|T_0\|$	1.81
T	2.29
|T0| < T therefore there are no outliers	

10.2 BSM-foam

Table 10-5 and Table 10-6 show the data and statistical analysis results of the site compaction data of the N7 rehabilitation project using foamed bitumen stabilisation.

TABLE 10-5: N7 SITE COMPACTION DATA – BSM-FOAM

Distance (km)	Site Dry Density (kg/m^3)
17.7	2109
16	2148
14	2146
11.99	2224
10	2218
7.8	2219

TABLE 10-6: STATISTICAL RESULTS OF TABLE 10-5

Statistic	Site Dry Density (kg/m^3)
Mean	2177
Standard deviation	49.15
COV	2.26%

11 Appendix D

This section provides all statistical analysis performed on the vibratory hammer compacted specimens.

Laboratory Compaction of BSM-emulsion G2 Material

TABLE 11-1: STATISTICAL ANALYSIS OF BSM-EMULSION, 70% OMC, 10KG SURCHARGE KANGO 637®

	Specimen1	Specimen2				
Layer	**Time to 100% Mod AASHTO (sec)**	**Time to 100% Mod AASHTO (sec)**		**Mean**	**STD Dev**	**C.O.V (%)**
Layer1	30	15		22.50	10.61	47.14
Layer2	60	15		37.50	31.82	84.85
Layer3	45	60		52.50	10.61	20.20
Layer4	30	45		37.50	10.61	28.28
Layer5	30	30		30.00	0.00	0.00
Mean	39.00	33.00		36.00		
STD Dev	13.42	19.56		16.49		
C.O.V (%)	34.40	59.27		46.83		

TABLE 11-2: STATISTICAL ANALYSIS OF BSM-EMULSION, 80% OMC, 10KG SURCHARGE KANGO 637®

	Specimen1	Specimen2	Specimen3			
Layer	**Time to 100% Mod AASHTO (sec)**	**Time to 100% Mod AASHTO (sec)**	**Time to 100% Mod AASHTO (sec)**	**Mean**	**STD Dev**	**C.O.V (%)**
Layer1	35	55.37	50.28	46.88	10.60	22.61
Layer2	41	60.73	36	45.91	13.08	28.48
Layer3	51.1	55.82	29.86	45.59	13.83	30.33
Layer4	60	62.01	122	81.34	35.23	43.31
Layer5	25	58.41	75.37	52.93	25.63	48.42
Mean	42.42	58.47	62.70	54.53		
STD Dev	13.65	2.93	37.49	18.02		
C.O.V (%)	32.17	5.01	59.79	32.32		

TABLE 11-3: STATISTICAL ANALYSIS OF BSM-EMULSION, 90% OMC, 10KG SURCHARGE KANGO 637®

	Specimen1	Specimen2	Specimen3			
Layer	**Time to 100% Mod AASHTO (sec)**	**Time to 100% Mod AASHTO (sec)**	**Time to 100% Mod AASHTO (sec)**	**Mean**	**STD Dev**	**C.O.V (%)**
Layer1	12.52	11.65	10.93	11.70	0.80	6.80
Layer2	15.77	12.77	9.81	12.78	2.98	23.31
Layer3	9.47	13.29	9.6	10.79	2.17	20.11
Layer4	10.45	17.19	12.57	13.40	3.45	25.71
Layer5	11.72	14.9	13.07	13.23	1.60	12.06
Mean	11.99	13.96	11.20	12.38		
STD Dev	2.42	2.15	1.58	2.05		
C.O.V (%)	20.16	15.41	14.08	16.55		

TABLE 11-4: STATISTICAL ANALYSIS OF BSM-EMULSION, 80% OMC, 15KG SURCHARGE KANGO 637®

	Specimen1	Specimen2	Specimen3			
Layer	**Time to 100% Mod AASHTO (sec)**	**Time to 100% Mod AASHTO (sec)**	**Time to 100% Mod AASHTO (sec)**	**Mean**	**STD Dev**	**C.O.V (%)**
Layer1	67.44	53	81.85	67.43	14.43	21.39
Layer2	28.68	23.47	40.37	30.84	8.65	28.06
Layer3	35.74	24.59	42.42	34.25	9.01	26.30
Layer4	25.89	26	39.57	30.49	7.87	25.80
Layer5	18.24	25.33	37.4	26.99	9.69	35.89
Mean	35.20	30.48	48.32	38.00		
STD Dev	19.08	12.63	18.83	16.85		
C.O.V (%)	54.21	41.42	38.97	44.87		

TABLE 11-5: STATISTICAL ANALYSIS OF BSM-EMULSION, 70% OMC, 20KG SURCHARGE KANGO 637®

	Specimen1	Specimen2	Specimen3			
Layer	**Time to 100% Mod AASHTO (sec)**	**Time to 100% Mod AASHTO (sec)**	**Time to 100% Mod AASHTO (sec)**	**Mean**	**STD Dev**	**C.O.V (%)**
Layer1	130	210	110	150.00	52.92	35.28
Layer2	25	90	86	67.00	36.43	54.37
Layer3	25	46	165	78.67	75.50	95.98
Layer4	63	45	170	92.67	67.57	72.92
Layer5	32	60	145	79.00	58.85	74.49
Mean	55.00	90.20	135.20	93.47		
STD Dev	44.77	69.39	36.23	50.13		
C.O.V (%)	81.40	76.93	26.80	61.71		

TABLE 11-6: STATISTICAL ANALYSIS OF BSM-EMULSION, 80% OMC, 20KG SURCHARGE KANGO 637®

	Specimen1	Specimen2	Specimen3			
Layer	**Time to 100% Mod AASHTO (sec)**	**Time to 100% Mod AASHTO (sec)**	**Time to 100% Mod AASHTO (sec)**	**Mean**	**STD Dev**	**C.O.V (%)**
Layer1	17.3	18.87	20	18.72	1.36	7.24
Layer2	12.8	22	20.99	18.60	5.05	27.13
Layer3	16.32	28.03	12.28	18.88	8.18	43.34
Layer4	13	22.3	23.13	19.48	5.62	28.88
Layer5	24.91	18.37	16.44	19.91	4.44	22.30
Mean	16.87	21.91	18.57	19.12		
STD Dev	4.92	3.85	4.27	4.35		
C.O.V (%)	29.15	17.58	22.98	23.24		

Statistical analysis of temperature variation tests performed on BSM-emulsion G2 material

TABLE 11-7: STATISTICAL ANALYSIS OF BSM-EMULSION, 80% OMC, 10KG SURCHARGE BOSCH GSH 11E® AT 5^0C

	Specimen1	Specimen2			
Layer	**% Mod AASHTO Achieved**	**% Mod AASHTO Achieved**	**Mean**	**STD Dev**	**C.O.V (%)**
Layer1 (10s)	108.59	107.39	107.99	0.84	0.78
Layer2 (15s)	106.66	106.44	106.55	0.16	0.15
Layer3 (15s)	107.62	106.44	107.03	0.83	0.77
Layer4 (15s)	105.73	105.51	105.62	0.15	0.15
Layer5 (15s)	107.62	106.44	107.03	0.83	0.77
Mean	107.24	106.45	106.84		
STD Dev	1.09	0.67	0.88		
C.O.V (%)	1.01	0.63	0.82		

TABLE 11-8: STATISTICAL ANALYSIS OF BSM-EMULSION, 80% OMC, 10KG SURCHARGE BOSCH GSH 11E® AT 15^0C

	Specimen1	Specimen2			
Layer	**% Mod AASHTO Achieved**	**% Mod AASHTO Achieved**	**Mean**	**STD Dev**	**C.O.V (%)**
Layer1 (10s)	105.30	107.54	106.42	1.58	1.48
Layer2 (15s)	107.18	108.50	107.84	0.93	0.87
Layer3 (15s)	105.30	105.65	105.48	0.25	0.23
Layer4 (15s)	105.30	105.65	105.48	0.25	0.23
Layer5 (15s)	107.18	106.58	106.88	0.42	0.40
Mean	106.05	106.78	106.42		
STD Dev	1.03	1.24	1.13		
C.O.V (%)	0.97	1.16	1.07		

TABLE 11-9: STATISTICAL ANALYSIS OF BSM-EMULSION, 80% OMC, 10KG SURCHARGE BOSCH GSH 11E® AT 35^{0}C

	Specimen1	Specimen2			
Layer	% Mod AASHTO Achieved	% Mod AASHTO Achieved	Mean	STD Dev	C.O.V (%)
Layer1 (10s)	105.13	104.99	105.06	0.10	0.09
Layer2 (15s)	103.32	103.15	103.23	0.12	0.11
Layer3 (15s)	107.01	102.25	104.63	3.36	3.21
Layer4 (15s)	103.32	103.15	103.23	0.12	0.11
Layer5 (15s)	106.06	103.15	104.61	2.06	1.97
Mean	104.97	103.34	104.15		
STD Dev	1.65	1.00	1.32		
C.O.V (%)	1.57	0.97	1.27		

Laboratory Compaction of BSM-foam G2 Material

TABLE 11-10: STATISTICAL ANALYSIS OF BSM-FOAM, 70% OMC, 10KG SURCHARGE BOSCH GSH 11E®

	Specimen1	Specimen2	Specimen3			
Layer	Time to 100% Mod AASHTO (sec)	Time to 100% Mod AASHTO (sec)	Time to 100% Mod AASHTO (sec)	Mean	STD Dev	C.O.V (%)
Layer1	150	150	180	160.00	17.32	10.83
Layer2	180	150	180	170.00	17.32	10.19
Layer3	180	180	210	190.00	17.32	9.12
Layer4	180	180	150	170.00	17.32	10.19
Layer5	180	180	150	170.00	17.32	10.19
Mean	174.00	168.00	174.00	172.00		
STD Dev	13.42	16.43	25.10	18.32		
C.O.V (%)	7.71	9.78	14.43	10.64		

TABLE 11-11: STATISTICAL ANALYSIS OF BSM-FOAM, 80% OMC, 10KG SURCHARGE BOSCH GSH 11E®

	Specimen1	Specimen2	Specimen3			
Layer	Time to 100% Mod AASHTO (sec)	Time to 100% Mod AASHTO (sec)	Time to 100% Mod AASHTO (sec)	Mean	STD Dev	C.O.V (%)
Layer1	5.44	6.02	5.81	5.76	0.29	5.10
Layer2	19.67	21.78	21.64	21.03	1.18	5.61
Layer3	37.92	22.73	15.26	25.30	11.55	45.63
Layer4	29.46	38	20.12	29.19	8.94	30.63
Layer5	14.26	37	31.61	27.62	11.88	43.02
Mean	21.35	25.11	18.89	21.78		
STD Dev	12.71	13.12	9.42	11.75		
C.O.V (%)	59.55	52.26	49.89	53.90		

TABLE 11-12: STATISTICAL ANALYSIS OF BSM-FOAM, 90% OMC, 10KG SURCHARGE BOSCH GSH 11E®

	Specimen1	Specimen2	Specimen3			
Layer	**Time to 100% Mod AASHTO (sec)**	**Time to 100% Mod AASHTO (sec)**	**Time to 100% Mod AASHTO (sec)**	**Mean**	**STD Dev**	**C.O.V (%)**
Layer1	5.62	8	6.25	6.62	1.23	18.62
Layer2	16.63	14.33	21.07	17.34	3.43	19.75
Layer3	14.71	17.77	29.93	20.80	8.05	38.70
Layer4	12.94	21.73	19.1	17.92	4.51	25.17
Layer5	14.15	18.83	18.93	17.30	2.73	15.78
Mean	12.81	16.13	19.06	16.00		
STD Dev	4.23	5.26	8.46	5.98		
C.O.V (%)	33.05	32.61	44.40	36.69		

TABLE 11-13: STATISTICAL ANALYSIS OF BSM-FOAM, 80% OMC, 15KG SURCHARGE BOSCH GSH 11E®

	Specimen1	Specimen2	Specimen3			
Layer	**Time to 100% Mod AASHTO (sec)**	**Time to 100% Mod AASHTO (sec)**	**Time to 100% Mod AASHTO (sec)**	**Mean**	**STD Dev**	**C.O.V (%)**
Layer1	8.93	6.92	8.38	8.08	1.04	12.86
Layer2	31.65	21.67	25.45	26.26	5.04	19.19
Layer3	21.42	17.41	16.94	18.59	2.46	13.24
Layer4	27.27	26.57	19.92	24.59	4.06	16.50
Layer5	35.11	19.99	26.16	27.09	7.60	28.07
Mean	24.88	18.51	19.37	20.92		
STD Dev	10.28	7.29	7.25	8.27		
C.O.V (%)	41.32	39.39	37.41	39.37		

Statistical anallysis of temperature variation tests performed on BSM-foam G2 material

TABLE 11-14: STATISTICAL ANALYSIS OF BSM-FOAM, 80% OMC, 10KG SURCHARGE BOSCH GSH 11E® AT 5^0C

	Specimen1	Specimen2	Specimen3			
Layer	**% Mod AASHTO Achieved**	**% Mod AASHTO Achieved**	**% Mod AASHTO Achieved**	**Mean**	**STD Dev**	**C.O.V (%)**
Layer1 (10s)	96.36	96.98	103.19	98.84	3.78	3.82
Layer2 (28s)	101.18	100.21	103.19	101.53	1.52	1.50
Layer3 (30s)	104.67	103.67	101.46	103.26	1.64	1.59
Layer4 (34s)	105.58	100.21	102.32	102.70	2.70	2.63
Layer5 (30s)	108.41	101.91	104.08	104.80	3.31	3.16
Mean	103.24	100.60	102.85	102.23		
STD Dev	4.63	2.48	1.00	2.70		
C.O.V (%)	4.49	2.46	0.97	2.64		

TABLE 11-15: STATISTICAL ANALYSIS OF BSM-FOAM, 80% OMC, 10KG SURCHARGE BOSCH GSH 11E® AT 15^{0}C

Layer	Specimen1 % Mod AASHTO Achieved	Specimen2 % Mod AASHTO Achieved	Specimen3 % Mod AASHTO Achieved	Mean	STD Dev	C.O.V (%)
Layer1 (10s)		100.96	105.67	103.32	3.33	3.22
Layer2 (28s)		105.39	102.96	104.18	1.72	1.65
Layer3 (30s)		104.47	102.09	103.28	1.69	1.63
Layer4 (34s)		101.82	102.09	101.95	0.19	0.19
Layer5 (30s)		102.69	104.75	103.72	1.46	1.41
Mean		103.07	103.51	103.29		
STD Dev		1.84	1.62	1.73		
C.O.V (%)		1.78	1.57	1.68		

TABLE 11-16: STATISTICAL ANALYSIS OF BSM-FOAM MULSION, 80% OMC, 10KG SURCHARGE BOSCH GSH 11E® AT 35^{0}C

Layer	Specimen1 % Mod AASHTO Achieved	Specimen2 % Mod AASHTO Achieved	Specimen3 % Mod AASHTO Achieved	Mean	STD Dev	C.O.V (%)
Layer1 (10s)	101.20	100.55	107.85	103.20	4.04	3.92
Layer2 (28s)	106.53	105.84	105.96	106.11	0.37	0.34
Layer3 (30s)	105.60	105.84	105.96	105.80	0.18	0.17
Layer4 (34s)	105.97	104.63	105.96	105.52	0.77	0.73
Layer5 (30s)	103.80	107.73	105.96	105.83	1.97	1.86
Mean	104.62	104.92	106.34	105.29		
STD Dev	2.17	2.68	0.85	1.90		
C.O.V (%)	2.07	2.56	0.80	1.81		

12 Appendix E

12.1 Compaction of Site treated Material – BSM-emulsion: Kango 637

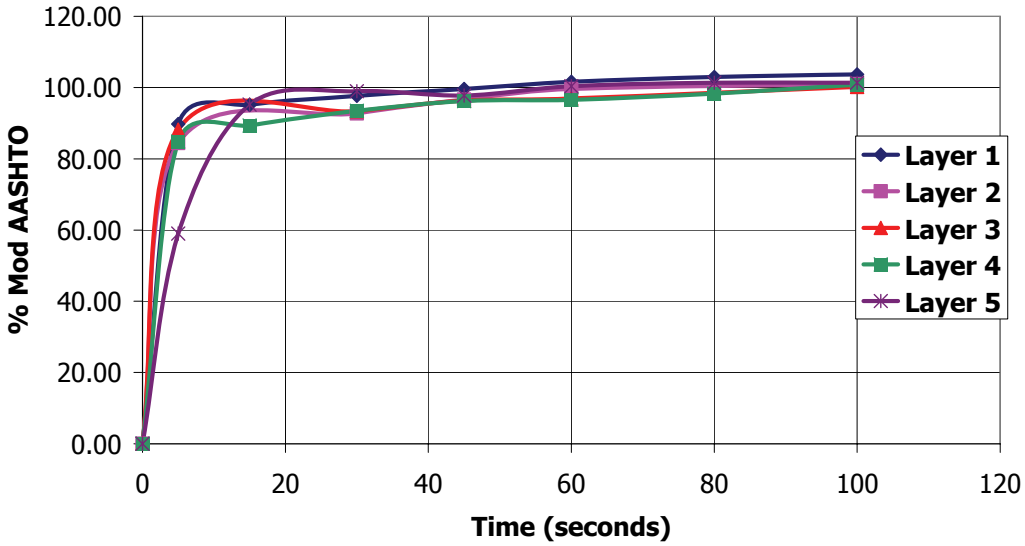


FIGURE 12-1: 0KG SURCHARGE - %MOD AASHTO VS. TIME OF INDIVIDUAL SPECIMEN LAYERS OF SITE TREATED MATERIAL, KANGO 637®

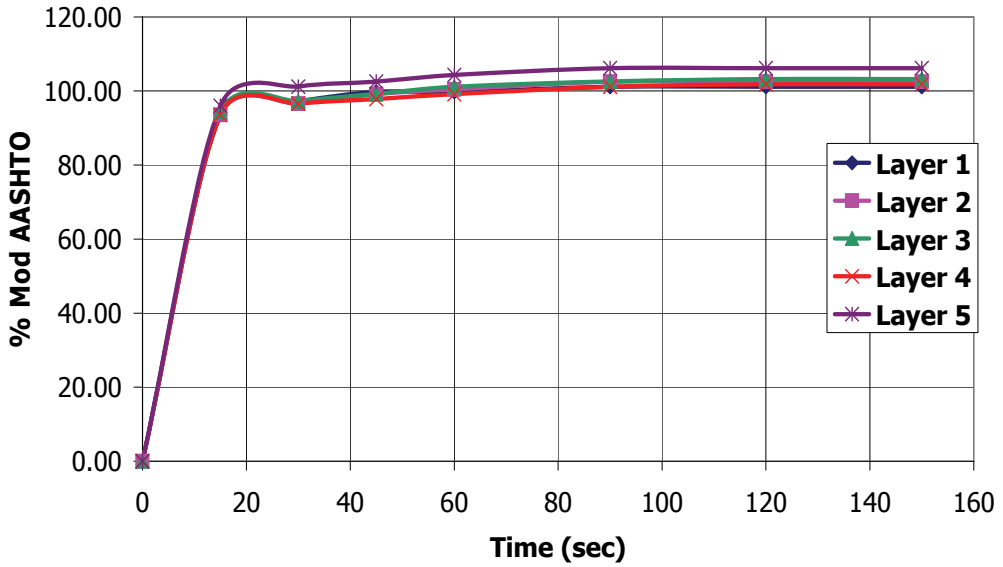


FIGURE 12-2: 10KG SURCHARGE - %MOD AASHTO VS. TIME OF INDIVIDUAL SPECIMEN LAYERS OF SITE TREATED MATERIAL, KANGO 637®.

13 Appendix F

This section presents the comparative grading of the G5 material with the purpose to show that there is a level of variability in the produced specimens.

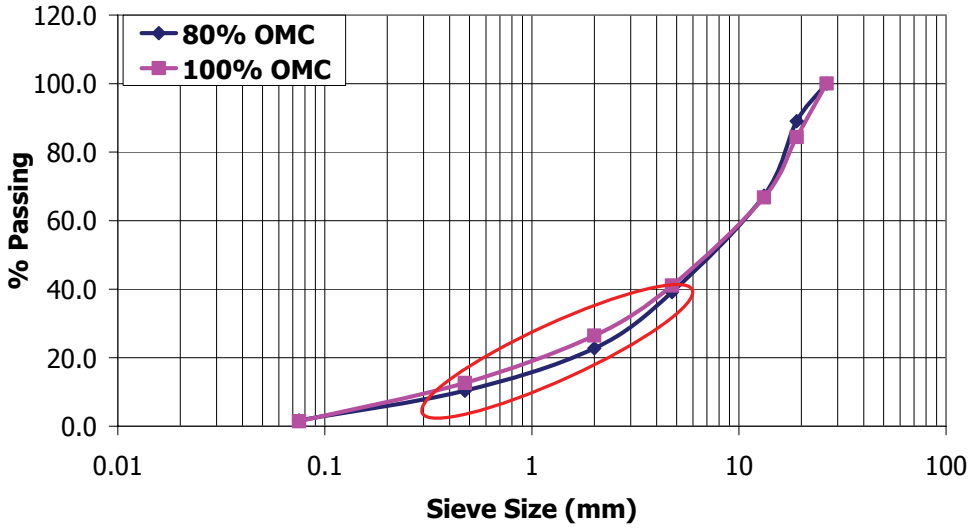


FIGURE 13-1: GRADING OF COMPACTED G5 BSM-FOAM SPECIMENS

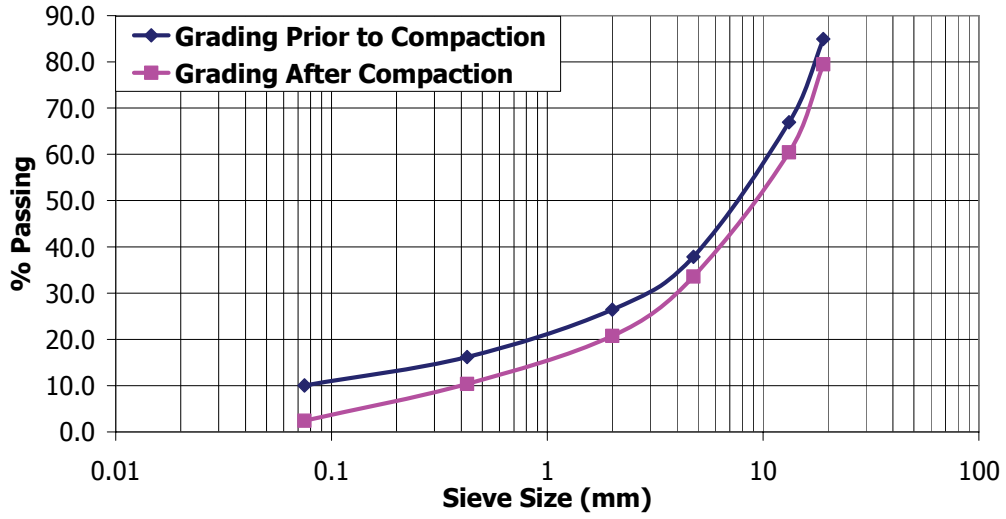


FIGURE 13-2: COMPARATIVE GRADING OF UNTREATED G5 MATERIAL BEFORE AND AFTER VIBRATORY HAMMER COMPACTION

14 Appendix G

This section presents the moisture density relationship of the Mod AASHTO compaction method and the vibratory hammer compaction method and where these to relationships lie relative to the zero air voids line. . The specific gravity (Gs) values use to determine the zero air voids lines are as follows:

- Gs of the Untreated G2 = 2.873
- Gs of BSM (both emulsion and foam) G2 = 2.836
- Gs of the Untreated G5 = 2.788
- Gs of BSM G5 (both emulsion and foam) = 2.733
-

14.1 Zero Air voids line of G2 material

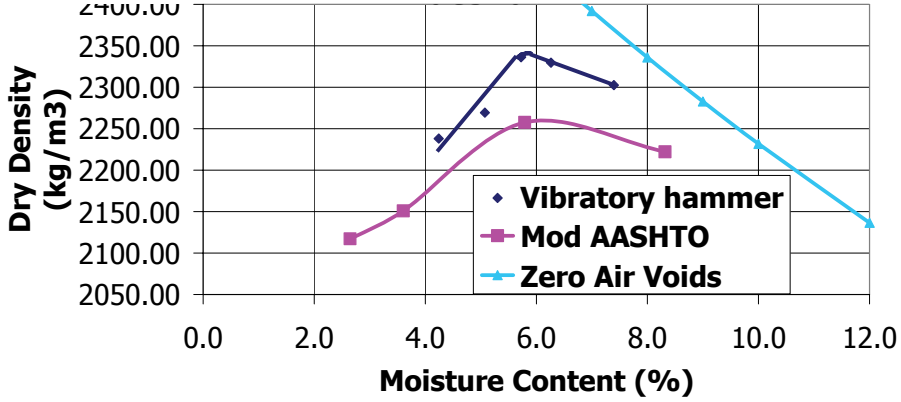


FIGURE 14-1:-14-2: ZERO AIR VOIDS LINE VS. MOISTURE CURVE – UNTREATED G2 MATERIAL

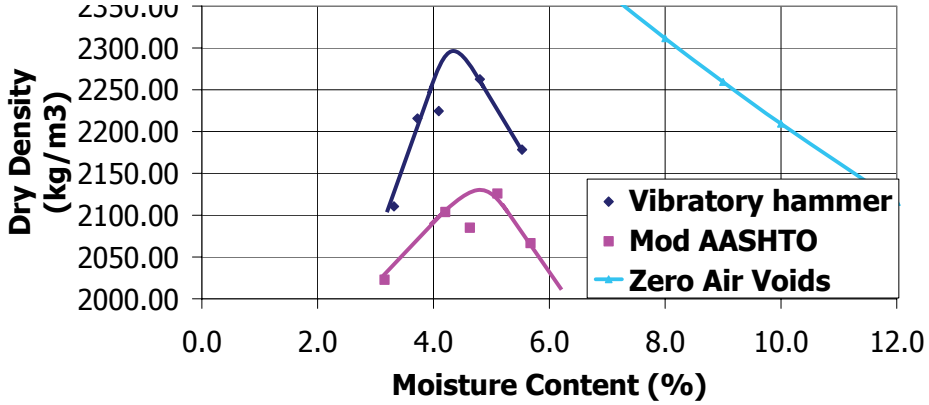


FIGURE 14-3: ZERO AIR VOIDS LINE VS. MOISTURE CURVE – BSM-FOAM G2 MATERIAL

14.2 Zero air voids vs. Moisture curve of the G5 Material

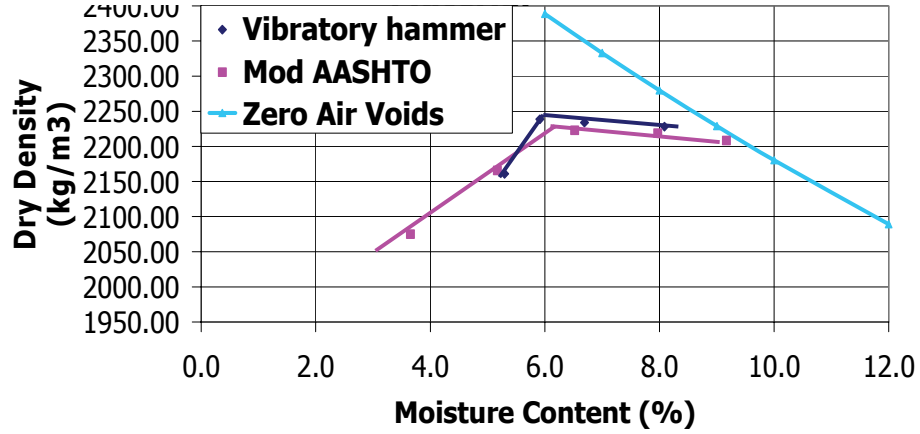


FIGURE 14-4: ZERO AIR VOIDS LINE VS. MOISTURE CURVE – UNTREATED G5 MATERIAL

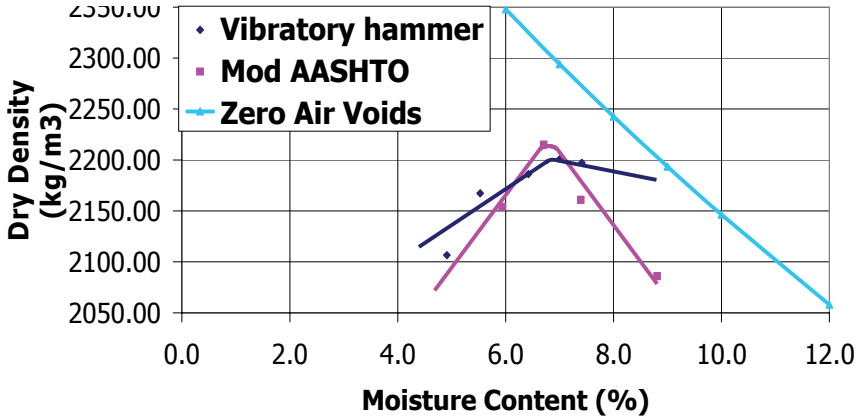


FIGURE 14-5: ZERO AIR VOIDS LINE VS. MOISTURE CURVE – BSM-EMULSION G5 MATERIAL

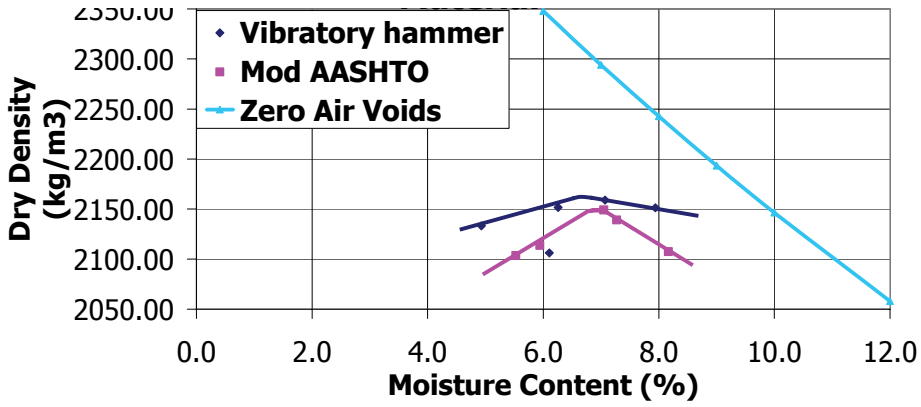


FIGURE 14-6: ZERO AIR VOIDS LINE VS. MOISTURE CURVE – BSM-FOAM G5 MATERIAL

15 Appendix H

This section presents the raw data results of the CT-scanning analysis performed at TU Delft in the Netherlands. Upon viewing the figures the following information is necessary:

- Mortar – Bitumen and the fine material together;
- Stone - the larger aggregate not part of the mortar;
- Voids – air spaces between the particles of the compacted specimen.

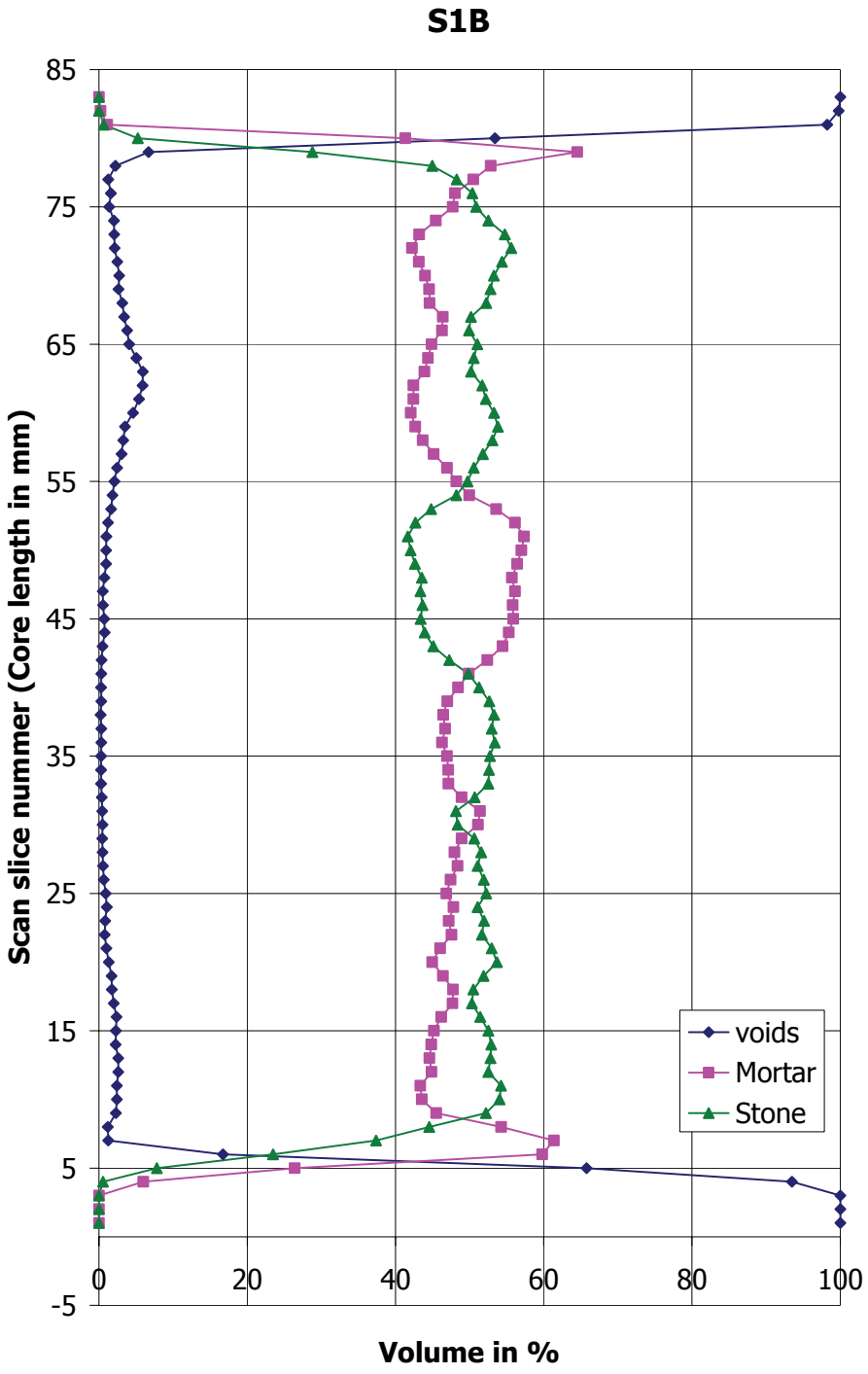


FIGURE 15-1: CT-SCAN OF S1B-VIBRATORY HAMMER COMPACTED BSM-EMULSION

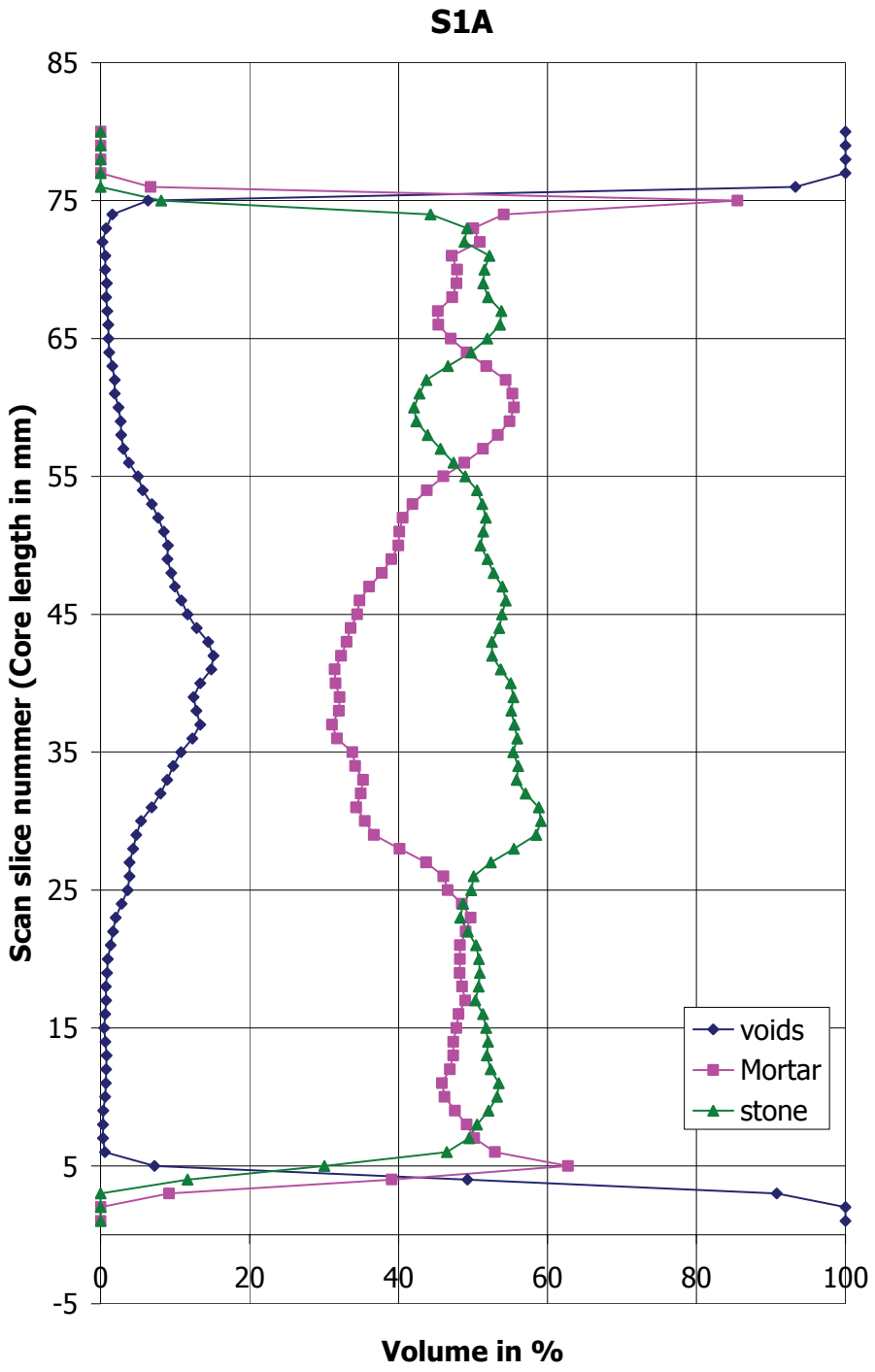


FIGURE 15-2: CT-SCAN OF S1A-VIBRATORY HAMMER COMPACTED BSM-EMULSION

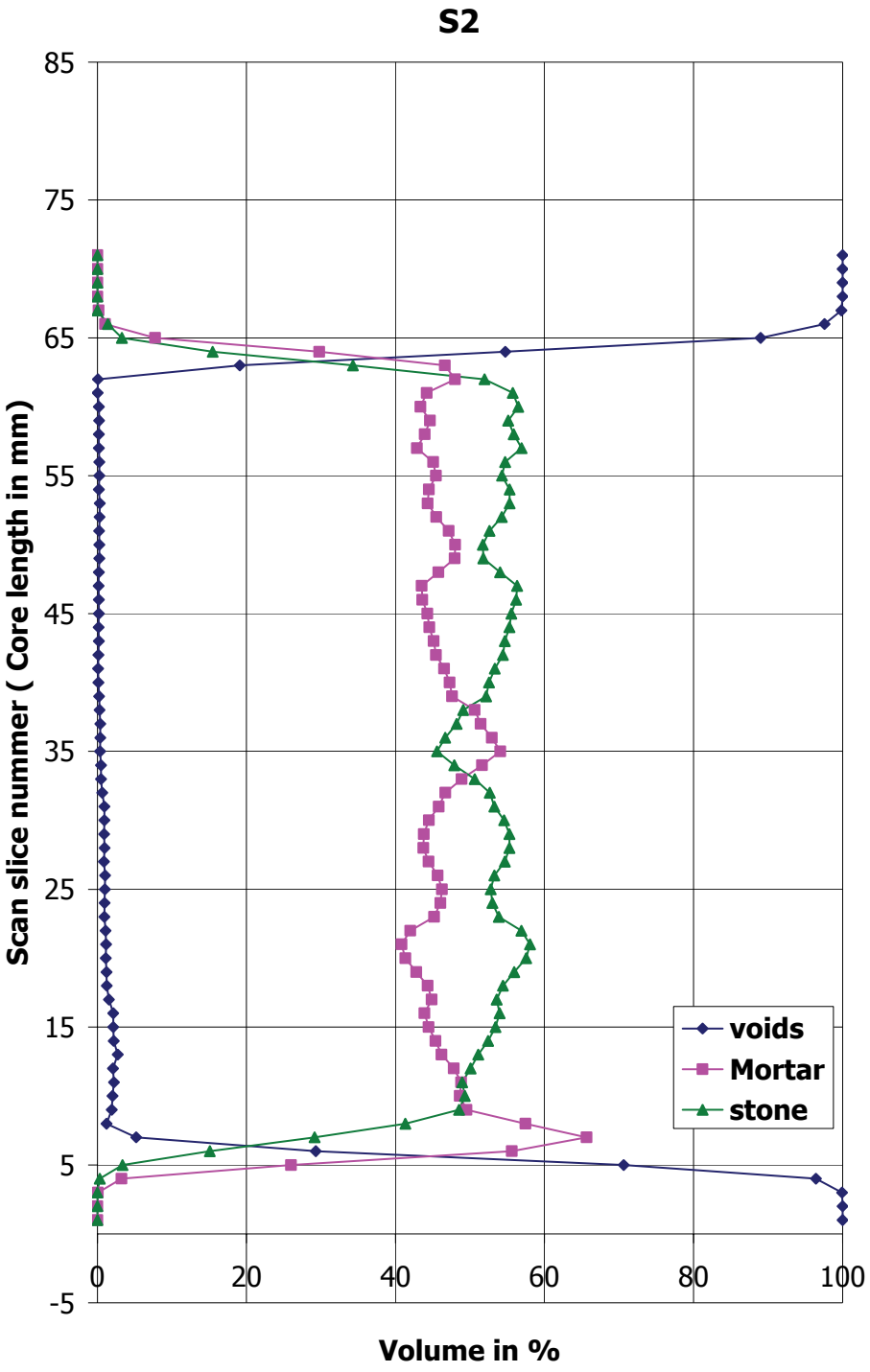


FIGURE 15-3: CT-SCAN OF S2-MOD AASHTO COMPACTED BSM-EMULSION

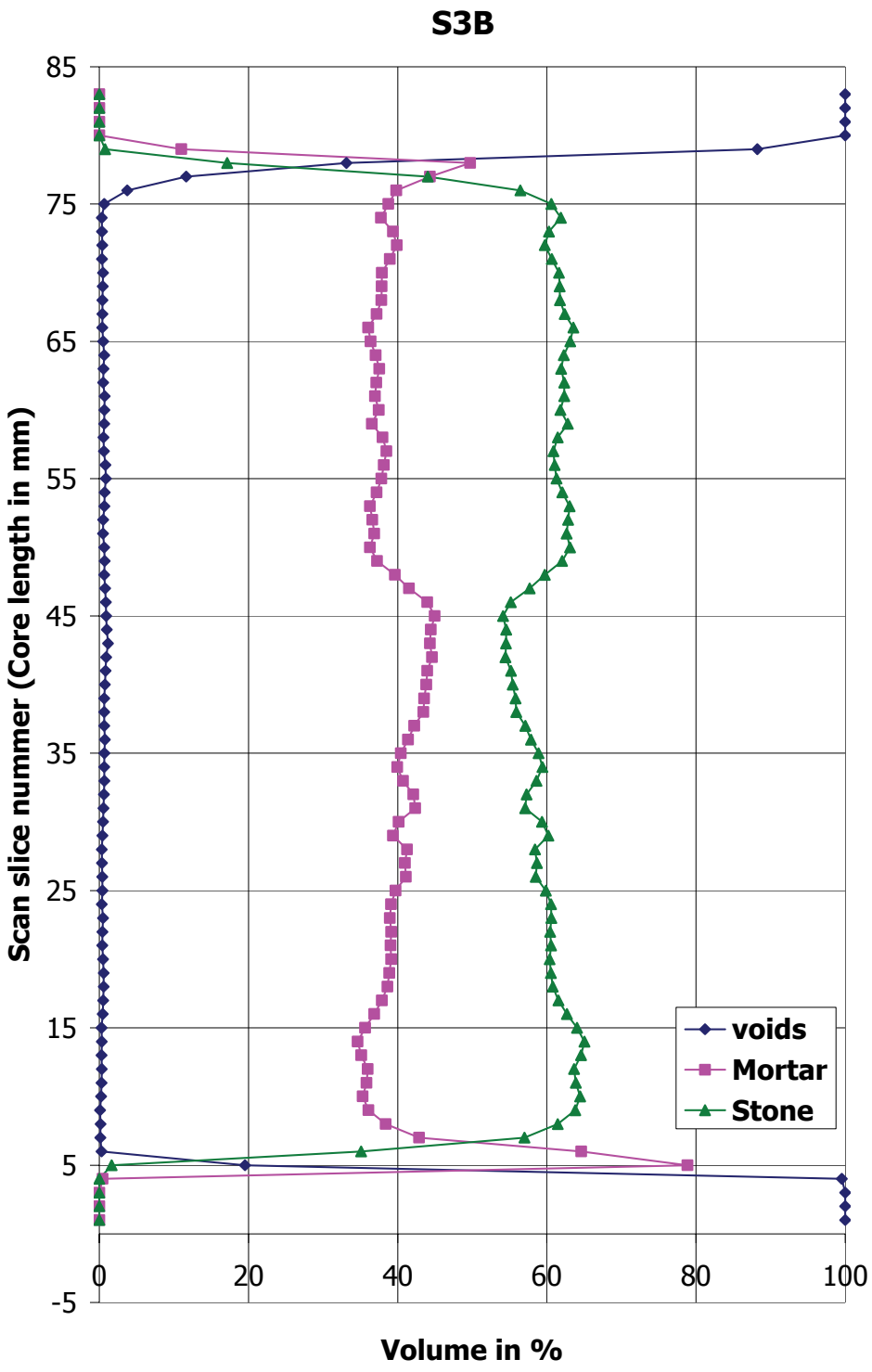


FIGURE 15-4: CT-SCAN OF S3B-VIBRATORY HAMMER COMPACTED BSM-FOAM

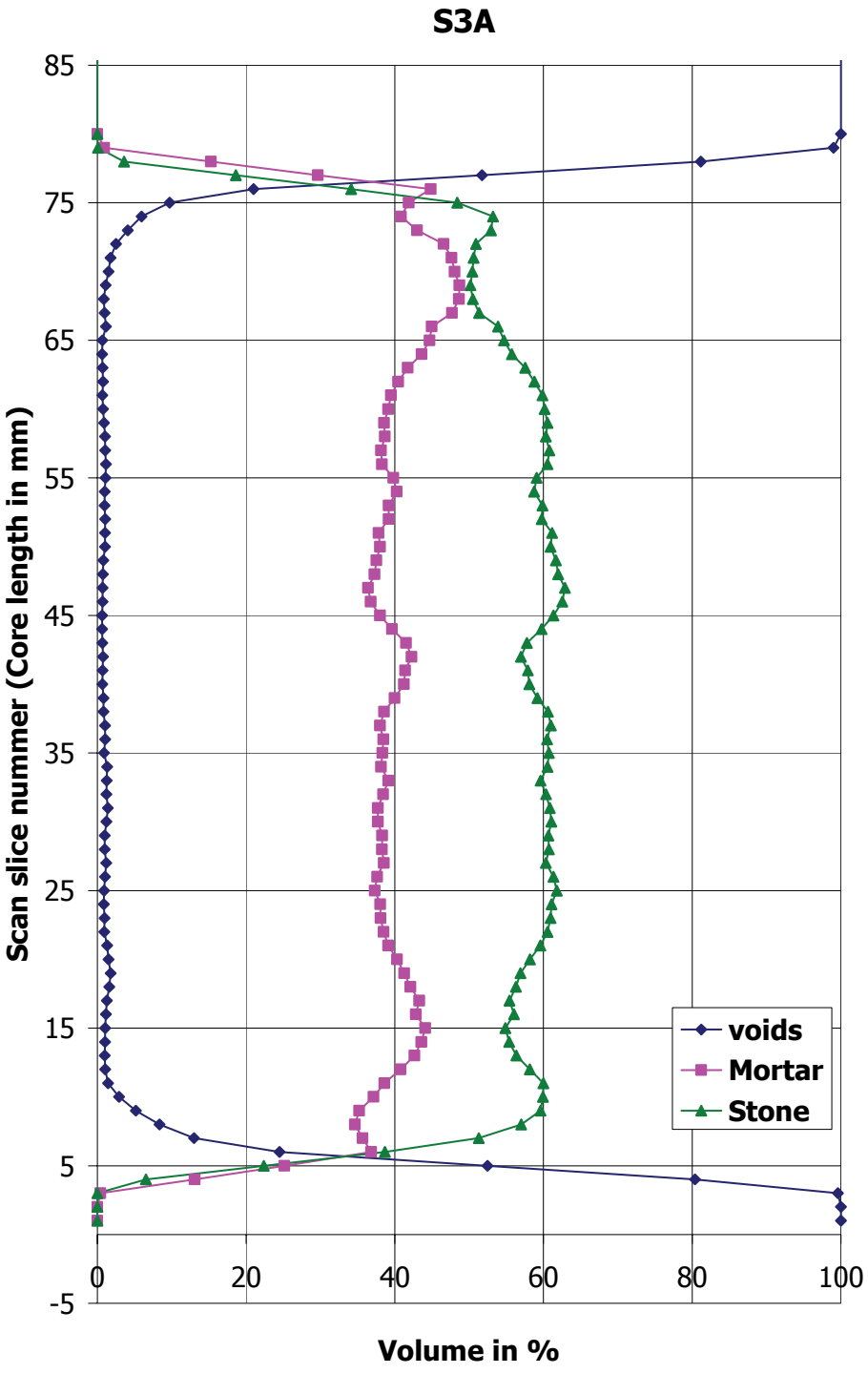


FIGURE 15-5: CT-SCAN OF S3A-VIBRATORY HAMMER COMPACTED BSM-FOAM