FURTHER DEVELOPMENT OF TWINLAY POROUS ASPHALT SURFACES

by

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DECLARATION

I the undersigned hereby declare that the work contained in this dissertation is my own original work and has not previously in its entirety or in part been submitted at any Technikon for a degree.

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SUMMARY

Road traffic noise (with tyre/road interaction being the predominating factor to the generation of noise production especially at vehicle speed above 50 km/h) is becoming an escalating problem that poses a threat to the environment. Ways and means of eradicating or at least retarding this problem have led to the development of Porous Asphalt surfaces which has excellent functionality. Porous asphalt has been used mainly for reducing aquaplaning subsequently reducing splash and spray thereby reducing accident rate during wet weather conditions, reducing road traffic noise and improves wet weather skid resistance

Two layered construction so called "Twinlay" is a new development which was initiated in the Netherland with an intention of optimizing reduction to road traffic noise and also to solve the shortfalls (e.g. clogging) associated with the conventional single layer of porous asphalt. Twinlay is made up of a bottom layer of porous asphalt with a coarse single grained aggregate (11/16) and a thin top layer of fine porous asphalt (4/8). Twinlay has many advantages as opposed to the previous practises (single layer of porous asphalt) in South Africa, e.g the fine top layer acts as a sieve preventing sand or dirt from clogging the coarse bottom layer, and also, the fine surface texture of the top layer reduces tyre/road noise and many more.

More research into road/traffic noise reveals that the acoustic properties of a conventional Twinlay porous asphalt surface can be further improved by introducing a thick double layer system (e.g. Superfine Twinlay) with a superfine top single-grained aggregate mixture. The superfine top structure assists in minimising tyre vibration (which will result in subsequent reduction in noise production) and also increases flow resistance which then gives us the desired short-wavelength texture.

The purpose of this research project was to design a wearing course that is durable, provide larger reductions with respect to noise production, which has good sound absorption properties and that has excellent drainage capabilities. A superfine Twinlay was proposed for this study as an improvement from Twinlay. A Superfine Twinlay consisted of a thin superfine top layer with aggregates contained in 2.36 – 4.75 mm sieve and a coarse single grained bottom layer with aggregates passing 13.2 mm sieve and retained in the 9.5 mm sieve (9.5 - 13.2 mm) and with bitumen rubber as a binder. The overall thickness of this layer was 7 cm, the top and bottom layer being 2.5 cm and 4.5 cm thick respectively. The grading of the mix yielded very high porosity and optimal water drainage capabilities.

The research method that was adopted for this research project was an experimental one were a number of laboratory tests were conducted to try and simulate field performance. A double layer porous asphalt construction is still a new concept for South African roads. It was therefore important to evaluate the materials used, mix design, and pavement performance. This was mainly done to try and establish and retrieve as much as possible information about this particular mix for prevailing South African conditions. Porous asphalt is well known for poor performance with time. Therefore the short and long term performance of Superfine Twinlay was monitored under carefully controlled conditions. A number of strategic steps were followed in the research method. This thesis was divided into six different chapters. The first chapter dealt with the introduction to the study, chapter two (literature review), chapter three

(volumetric properties), chapter four (acoustic analysis), chapter five (performance evaluation of Superfine Twinlay) and chapter six (conclusions and recommendations). As mentioned above, the proposed Superfine Twinlay mix was designed in the laboratories and was then subjected to a number of intensive tests to monitor its initial performance and the long-term pavement performance. These tests included the volumetric analysis (e.g. VIM, Bulk relative densities etc), acoustic analysis (sound absorption measurements), accelerated pavement tests using the MMLS Mk3 etc. These tests were conducted under stringent conditions, meaning that all the relevant parameters were monitored closely during testing.

In general, the Superfine Twinlay performed well but the mix displayed poor resistance to the environmental forces such as damage due to moisture. Damage due to moisture caused stripping of the binder with a subsequent loss of aggregates (ravelling). This had an adverse effect on the structural integrity of the mix, rendering Superfine Twinlay less durable than densely graded mixes. High void contents were achieved with this mix. This type of mix also showed a poor resistance to abrasion loss. Superfine Twinlay offered a higher sound absorption coefficient on a broader frequency range as opposed to a single homogeneous porous asphalt layer but the maximum absorption is not yet at the desired frequency (e.g 1000 Hz). The frequency at which maximum absorption occures can be shifted by adjusting relevant factors of the mix materials (e.g. total layer thickness and structural factor). Superfine Twinlay porous asphalt surfaces have an excellent resistance against rutting.

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DEFINITION OF TERMS

TERM	DEFINITION
Air Voids	The pockets of air between the bitumen-coated aggregate particles in a compacted bituminous paving mixture.
Ambient Noise	The total encompassing sound in a given situation at a given time, and usually composed of sound from many sources, both near and far
Asphalt	Is a mixture of aggregate, sand, filler and bitumen
Apparent Bulk Relative Density	The ratio of the mass in air of a given volume of material (excluding the permeable voids but including the impermeable voids normal to the material) at a stated temperature, to the mass in air of an equal volume of distilled water at the same temperature
Apparent Maximum Relative Density	The ratio of the mass of a given volume of HMA to the mass of an equal volume of water, both at the same temperature
Binder	A term used to describe any material that is used in road construction processes to bind together aggregate or soil particles.
Bitumen	(1) a class of amorphous, black or dark-coloured (solid, semi-solid, or viscous) cementitious substances, natural or manufactured, composed principally of high molecular weight hydrocarbons, soluble in carbon disulfide, and found in asphalts, tars, pitches, and asphaltites; (2) a generic term used to denote any material composed principally of bitumen.
Bituminous, *adj.*	Containing or treated with bitumen (also bituminized). Examples: bitumen concrete, bituminized felts and fabrics, bituminous pavements.
Coarse Aggregate	Mineral aggregate greater than 4,75mm in particle size
Dense-Graded Aggregate	An aggregate that has a particle size distribution such that when it is compacted the resulting voids between the aggregate particles expressed as a percentage of the total space occupied by the material are relatively small.

Filler or Dust	Mineral aggregate less than 0,075mm in particle size
Fine Aggregate	Mineral aggregate less than 4,75mm in particle size
Fluff Point Moisture Content	Moisture content at which a material occupies the maximum loose volume in an uncompacted state
Modified Binder	A bitumen or tar, the properties of which have been modified by the addition of compounds so that performance is enhanced. Examples of modifiers are plastic compounds such as PVC and natural or synthetic rubber.
Mortar	Mixture of the sand fraction, filler, bitumen and sometimes water
Open-Graded Aggregate	An aggregate that has a particle size distribution such that when it is compacted, the voids between the aggregate particles, expressed as a percentage of the total space occupied by the material remains relatively large.
Porous Asphalt	Porous asphalt wearing course are bituminous mixes with discontinuous grading whose void content are in excess of 20 percent and in which the nature of the voids is such that rainwater can be conveyed through a system of interconnecting voids to the boundaries of the pavement. This makes it highly suitable for wet weather conditions.
Rating Level	The equivalent continuous A-weighted sound pressure level $L_{Aeq,T}$ during specified adjustments for tonal character and impulsiveness of sound.
Residual Noise	The ambient noise that remains at a given position in a given situation when one or more specific noises are suppressed.
Sand Fraction	Mineral aggregate less than 2,36 mm in particle size, without the filler fraction
Twinlay	Is a double layer porous asphalt construction with a bottom layer of coarse single grained aggregate (11/16) and a thin top layer of fine porous asphalt (4/8) bottom layer contains aggregate

LIST OF SYMBOLS AND ABBREVIATIONS

SYMBOL	DESCRIPTION
PA	Porous Asphalt
OGA	Open Graded Asphalt
L_{pA}	A-weighted sound pressure level (sound level) in decibels
$L_{Aeq,T}$	Equivalent continuous A-weighted sound pressure level
L_{10}	*Sound level which is just exceeding* 10 percent of the measured period
L_r	Rating level
dBA	Measurement of sound expressed as A-weighted decibel
ρ	Density of air = 1.21 kg/m^3
c	Speed of sound in air 343 m/s
HMA	Hot Mix Asphalt
MMLS Mk3	Modal Mobile Load Simulator Mk3
α	Absorption coefficient of a porous media
A	Per cent total aggregate in mix
P	Per cent bitumen by mass in mix
N	Number of observations or tests
G_b	*Apparent bulk relative density of compacted mix*
S	Standard deviation of a sample of observations
VMA	Voids in Mineral Aggregate.
VFB	Voids Filled with Bitumen.
s	Relative density of bitumen (1.025)
VIM or V_m	Voids in Mix = Volume of air voids in mix excluding water/ Total volume of mix including water x 100 (%)
VMA	Voids in Mineral Aggregate = Volume of Voids in Dry Aggregate/ Volume of Dry Aggregate x 100 (%)
D_m	Apparent maximum relative density
ZOAB	Zeer Open Asfalt Beton or Porous Asphalt with a high void content
G_{ag}	Bulk relative density of aggregate
k	Permeability coefficient
Ξ	Specific flow resistance of the porous material
χ	Configuration or structural factor of the porous material
d	Thickness of the layer
US	United States
UK	United Kingdom
RMM	Ready Mix Materials
SPB	Static-Pass-By method of measuring rolling noise
MTRD	Maximum Theoretical Relative Density

CHAPTER 1

INTRODUCTION TO THE STUDY

1 BACKGROUND

Because traffic noise is becoming an ever increasing problem, the question has arisen as to what extent road surfaces contribute to noise production. With a sound-measuring trailor it is possible to measure-under-specific conditions-rolling tyre sound adjacent to the wheel. Under the same speed and tyre conditions, the influence of the road surface on the noise produced can be measured. Among the surface courses, the porous asphalt layers offer advantageous acoustical properties, particularly at high traffic speeds.

But also with conventional surfaces, considerable differences in noise generation have been measured. Thus further examination and optimization of the pavings' acoustical properties are needed. Additional studies on noise generating mechanism should lead to appropriate surface designs. More attention needs to be focused on noise reduction at low vehicle speeds.

> *By definition: Porous asphalt wearing course are bituminous mixes with discontinuous grading whose void content are in excess of 20 percent and in which the nature of the voids is such that rainwater can be conveyed through a system of interconnecting voids to the boundaries of the pavement. This makes it highly suitable for wet weather conditions.*

Twinlay, which is a new concept of porous asphalt was developed by Heijmans Road Construction Company, offered a larger reduction with regards to the disadvantages of conventional single layer porous asphalt as mentioned in Chapter 2. Twinlay consists of a double-layered porous asphalt construction, made up of a bottom layer of coarse porous asphalt (single-grained gradation, aggregate size 11 – 16 mm) and a top layer of fine-graded porous asphalt aggregate size 4 – 8 mm). The binder in both layers consists of rubberized asphalt.

Abbot and Nelson, (1989) once said, "Road related noise has increasingly been identified as a major environmental pollution aspect which needs new and innovative measures to attenuate and control. In the United Kingdom a number of new environmental laws have been passed with the specific purpose of 'putting people first'. Some of these regulations have stiffened considerably to the extent that '...the *regulations specify that when a new road is built or when an existing road* is substantially modified by the addition of an extra lane or carriageway, then it is mandatory for the highway authority to offer sound insulation treatment to the owners of the property whose traffic levels exceeds 68 dBA....' Traffic noise pollution is becoming an increasing problem especially with the significant increase in traffic densities. Immediate and corrective measures need to be taken to protect the environment and most importantly the people."

The significant increase in traffic densities (and speed) especially in urban areas is expected to cause an increase in noise pollution. Noise interferes with work, sleep *and recreation.* It *also causes strain and fatigue,* loss *of appetite and indigestion,* irritation and headache. High intensity noise has adverse cumulative effect on the human hearing mechanism, producing temporary or permanent deafness. This makes the development of a low noise pavement imperative.

Due to clogging and ageing of the high void content of porous asphalt surfaces both the absorption and the texture degrades. This leads to a significant loss of noise reduction capacity. This research focuses as part of the investigation on eradicating or at least retarding the clogging and ageing problem.

The *eventual failure of porous* asphalt is often related to the *oxidation (ageing)* of the binder. As porous asphalt has a high voids content, a much greater surface is exposed to air than that in normal surface. The consequence of this is that the binder hardens (or ages) more rapidly. Age hardening renders bitumen less cohesive and more liable to brittle fracture and aggregate loss.

2 PROBLEM STATEMENT

Road Traffic Noise

Traffic noise is the most important source of environmental noise pollution. Noise emission from road vehicles is composed of several different noise producing mechanisms and these can be divided into the following three main categories (Jongens, 1995):

- Power-train – being engine, air intake, fan, exhaust, gearbox and transmission.
- Tyre/road interaction.
- Aerodynamic noise – due to air turbulence around the vehicle.

Research into road traffic noise show that the interaction of tyre with the road surface is the main contributor, especially at high vehicle speeds. Thus further examination and optimisation of the road surfaces' acoustical properties is needed.

The rapid increase in traffic density and the growing concern for the environment in densely populated areas have increased the importance of minimising noise pollution (Verhaeghe, 1992).

Road related noise has increasingly been identified as a major environmental pollution aspect which needs new and innovative measures to attenuate and control. In the United Kingdom a number of new environmental laws have been passed with the specific purpose of 'putting people first'. Some of these regulations have stiffened considerably to the extent that "...the regulations specify that when a new road is build or when an existing road is substantially modified by the addition of an extra lane or carriageway, then it is mandatory for the highway authority to offer sound insulation treatment to the owners of the property whose traffic levels exceeds 68 dBA..."(Abbot and Nelson, 1989), (Horak et al, 1994)

Road traffic is the most important single source of community noise, which may be because traffic noise is the most difficult noise to eradicate. The optimal way to express noise exposure is to describe it as a number of events over a certain noise level (70 dBA) and the maximum noise level that occurs three to five times per 24-hour period.

2.1 The sub-problems

2.1.1 Durability of porous asphalt surface

- Porous asphalt has excellent functionalities with respect to sound absorption, skid resistance etc., but it also has a short structural life meaning that it is less durable. A number of factors contribute to this, mainly because of the high air void contents in the final mix, just to mention a few: 1. Ageing of the binder, causing raveling, and 2. Perturbation of the adhesion between binder and mineral aggregate by moisture intrusion, causing stripping and many more.

"The structural properties of porous asphalt mixes, by comparison with those of conventional dense-graded mixes, are such that shorter maintenance cycles are required, thus increasing the costs during the intended service life of the layer. Also, porous asphalt mixes do not distribute traffic stresses as well as dense mixes, and may therefore not be used as strengthening courses. Because of their high void contents, durability of these mixes may also be a problem in the long term. High porosity causes the binder system to be exposed to oxidation, moisture damage and attacks by fuels and oils. Care should therefore be taken when selecting the binder." (Verhaeghe, 1992)

2.1.2 Permeability

Owing to the increased contact of the coated aggregate in porous asphalt with water, stripping of the bitumen from the stones can also be a problem, especially where high rainfall and high humidity occurs.

2.1.3 Clogging

Experience has shown that the high air voids content (in excess of 20 percent) may become partially filled with dust, reducing the effectiveness of the mix in the long-term. This is known as void clogging and is a very commonly report problem of porous asphalt. Porous asphalt can be blocked very quickly with detritus such as tyre rubber, leaves, dust, soil, crashed, aggregate and other road debris.

Many observers consider that, on highly trafficked roads, the pumping action of tyres assists in keeping the voids free from debris and the asphalt free draining.

"The most important aspect in the practical wide spread application of porous asphalt surfaces however, is the expected performance after several years. It is known that due to clogging and ageing of the surface, both the absorption and the texture degrades which will lead to a significant loss of reduction capacity" (Van Blokland, 1997)

Preventative and curative measures have to be found to eliminate, or at least to retard the clogging effect, subsequently optimizing the resistance against clogging of a porous asphalt pavement.

The main cause for not acting as a porous layer is clogging. It primarily occurs in (relatively) less trafficked parts of roads (e.g. hard shoulders, emergency lanes). Preventative and curative measures have to be found to eliminate, or at least to retard the clogging effect." (Van Gorkum, 1991)

3 OBJECTIVES AND SCOPE OF STUDY

The primary objective of the research is the development of an improvement Twinlay surface design (for low noise porous asphalt pavements) that will provide the long-term pavement performance. To try and optimise the pavement acoustic properties and also to optimise resistance against clogging.

In summary, the objectives of the research project are:

- Design of a pavement wearing coarse using a porous asphalt mixture with a high void content that will provide a larger reduction in traffic noise. It has been proven that by a careful control of factors such as aggregate size, surface texture and porosity the acoustical performance of a conventional porous road surface can be optimised to produce a large reduction in the road traffic noise. The design of such road surface materials is such as to try and obtain maximum sound absorbing properties under the constraints of rather stringent demands of good road engineering practice.

- *Determination of a specific surface design that will improve the long-term* pavement performance of porous asphalt surfaces and resistance to abrasion due to the loss of aggregate by traffic attrition. Consequently improving durability.

- Development of a surface wearing coarse that will provide larger drainage or permeability performance of rainwater to the side drains of a porous asphalt pavement structure subsequently improving the skid resistance, improving day and night time wet weather visibility and to reduce splash and spray during wet weather conditions.

NB, *a number of studies have been conducted all over the world (especially in* Europe using European aggregates) with an attempt to reduce rolling noise. For the purpose of this study only South African materials were used.

3.1 Engineering data required

The following engineering data was obtained during the study and is reported upon in this project report (it is important to note that, briquettes and slab samples were compacted using a Kango hammer, Marshall hammer and SUPERPAVE gyratory compactor only):

- Volumetric properties - these are: apparent bulk relative density, apparent maximum relative density, voids-in-mix (obtained by performing Rice's test),
- The amount of binder run-off taking place during transportation and laying operations. The Basket drainage test and Schellenberger drainage test simulate and quantify this very well,
- Determination of abrasion loss (obtained by performing a Cantabro abrasion test),
- The long-term performance of the pavement {performed by using the Model Mobile Load Simulator MMLS Mk3 (MMLS3)},
- Determination of the permeability coefficient (k) of the pavement (using the LCS Drainometer)
- Rutting measurements (obtained by profilometer measurements on the test samples) and
- *Sound absorption measurements performed* by *using the Standing Wave Tube* Apparatus on a freshly compacted Marshall briquette in the laboratory or from cores cored from slabs compacted using a Kango hammer.

3.2 Delimitations of the research

The study will not attempt to evaluate the design mix engineering properties with regards to flexibility, skid resistance, stiffness (elastic modulus) and workability.

This study will not attempt to perform the Indirect tensile strength (ITS) and Strain at maximum strength and Resilient *modulus* or Indirect tensile test (ITT).

The selection of the materials and relevant test methods are based on the objective of the research.

4 LAYOUT OF THE THESIS

This study was divided into six different chapters, starting from Chapter 1 and ending with Chapter 6. A flow chart showing different chapters followed in the research method are as follows:

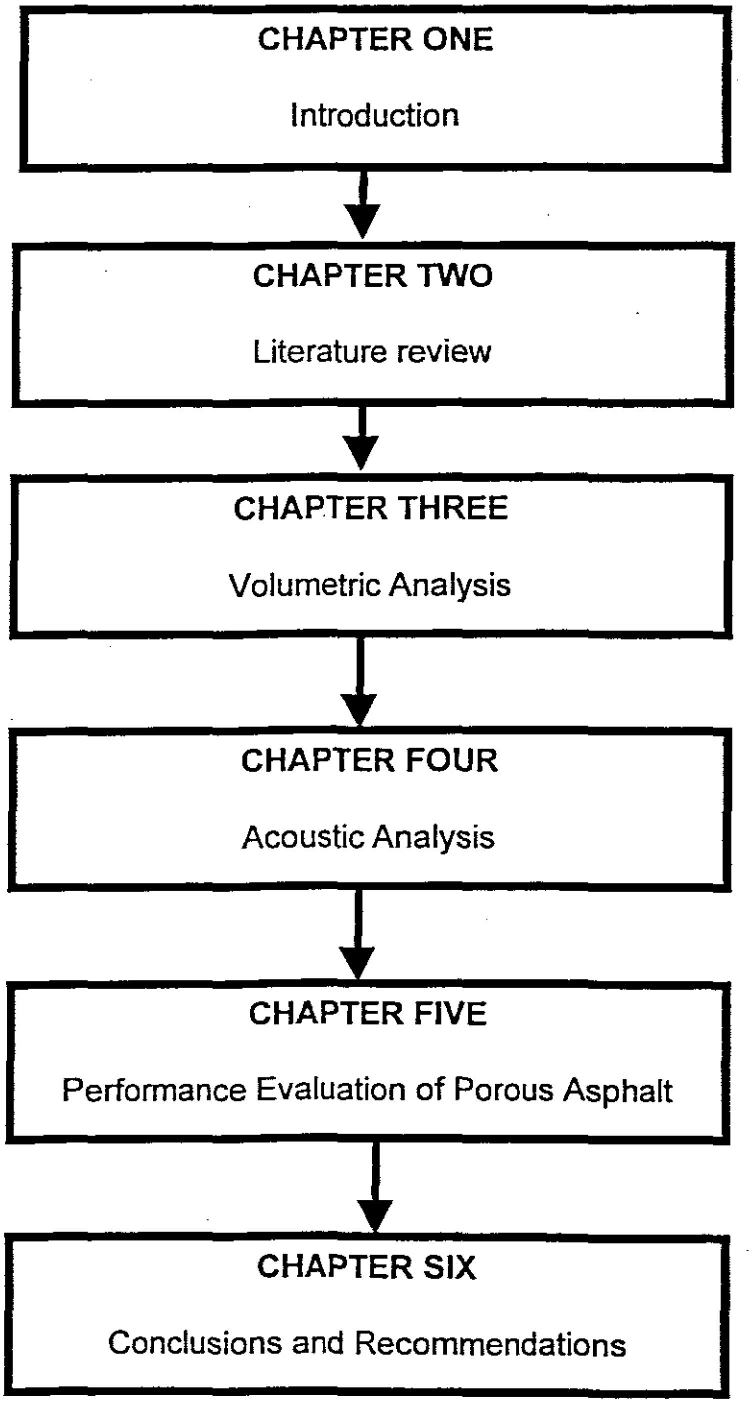

FIGURE 1: Flow chart showing different stages of the research

In a research, it is important to establish and follow a research method that will cover a broad spectrum ensuring that the objectives set out for the research are met without losing track of the scope of the research. The research identified the different stages as displayed if Figure 1 as these were important steps to follow in analysing such a mix (Superfine Twinlay). This is still a new thing for South African roads. Twinlay system has been tried and tested in other countries around the world e.g. Europe.

Superfine Twinlay was subjected to a number of tests in the laboratory which yielded interesting results which are reported upon in this report. The majority of the tests were covered mainly in Chapter three to Chapter five.

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CHAPTER 2

LITERATURE REVIEW OF POROUS ASPHALT MIXES

1 INTRODUCTION

The effects of road traffic noise on the community in South Africa have been highly underrated. Nevertheless, the promulgated Environmental Conservation Act of 1989 further enhances the awareness of noise pollution in South Africa (Rossouw, 1992). It is very difficult to sleep or concentrate, when there is a continuous noise emanating from the traffic outside. Exposure to road traffic noise with noise originating from different forms of traffic also has an adverse effect on the living standards especially in urban areas located in close proximity to high traffic roads.

Unlike industrial noise, road traffic noise is rarely loud enough to cause hearing loss. Its principal effects are annoyance, the loss of sounds, which would otherwise be audible, such as birds and vegetation, and effects such as fatigue through sleep deprivation. The disturbance caused by road traffic noise is one of the most important environmental health consequences. Over a number of years, investigations in different countries have shown that noise affects different activities and causes sleep disturbance and poorer life quality. There is thus a great need to control noise caused by transport. This can be achieved by controlling noise from the source, that is road/tyre interaction or rolling noise.

In the past years different countries over the world have been involved in an ongoing attempt to develop a low-noise pavement. This has led to the development of porous asphalt, which besides its excellent sound absorption properties, offers different advantages, e.g. improved drainage abilities which results in reduced splash and spray, improved skid resistance, etc.

The clogging of the pores (due to road debris) subsequently affecting permeability soon dissipated the excellent acoustic properties of this material. This is due to the open structure of the layer, which also causes oxidation of the bitumen. This renders porous asphalt less durable.

Due to the European experience, "Twinlay" porous asphalt surface was developed. This wearing coarse offered solutions to the problem of premature failure of the functions of porous asphalt as mentioned before. Nevertheless, the problem of road traffic noise posing a threat to the environment has not been solved as yet.

Road traffic noise is the most important single source of community noise, which may be because traffic noise is the most difficult noise to eradicate. Concern into the alleviation of this problem has led the author to undertake this research project "Further development of Twinlay porous asphalt surfaces".

2 HISTORY OF POROUS ASPHALT

Open-Graded Asphalt (OGA) wearing courses have been used world-wide for more than 40 years. Over the last 40 years, the later issue promoted the use of open graded asphalt to improve skid resistance world-wide (Visser et al, 1974). Initially it was used to improve skid resistance on roads which became too smooth. Open graded asphalt surfacings normally use a maximum stone size of 9 mm or 13 mm with an average void content of 15 percent. OGA abilities were however limited by the following (Horak et al, 1994):

- Relatively low resistance to permanent deformation
- Loss of porosity (void contents related) over time (clogging up with detritus)
- Low recycling potential (a maintenance aspect specifically related to the use of bitumen rubber)
- Stone loss due to binder ageing and brittleness (raveling)
- Maintenance related problems (pothole patching, etc)

Over the years, due to its attributes it OGA has developed into porous asphalt. Porous asphalt has become a useful tool to improve road safety and functionality. This generation of OGA, in general also uses a maximum stone size of 9 mm or 13 mm but with a minimum void content of 20 percent (Verhaeghe, 1992)

Porous asphalt originates from friction courses developed in the US in the 1950s for the use of airfield runways to reduce aquaplaning subsequently improving wet skid resistance. The Erstwhile Property Service Agency was the first British organisation to import the technology from the US and adopt it on UK military airfields.

It was later transferred to highway pavements to reduce splash and spray on high speed roads following performance monitoring in pilot-scale trial projects in the 1960s under the auspices of the Transport Research Laboratory.

In South Africa, the National Institute of Road Research (NIRR) conducted experiments in 1953 on the road linking Pretoria and Germiston to investigate the durability of the bituminous binders. Open graded asphalt was one of the mixes evaluated which performed well over a period of 11 years. Since 1970, open graded wearing courses have been used by all major road authorities in South Africa and have also been used successfully on the runways of major airports (e.g. Windhoek and Johannesburg). These mixes were paved in a relatively thin layer and seldom had void content in excess of 18 percent. They also tendered to ravel at an early age. Its functional properties were lost due to premature clogging of the voids with sand, dust and detritus (Sabita Manual, 1995).

By 1984, porous asphalt technology had reached the stage at which it could become commercialised in Europe, to the extent that by 1991, 50 million square metres of porous asphalt had been laid (Sabita Manual, 1995).

3 WHAT IS POROUS ASPHALT?

Porous asphalt formerly known as open graded asphalt (OGA) has been used all over the world since 1950. As the name says "Porous Asphalt" simply means that it allows liquid or water to flow through.

Porous asphalt is made up of a combination of a bituminous binder, a high proportion of course aggregate and limited amount of fines and filler. It is manufactured in a conventional hot mix asphalt plant (at temperatures lesser than 160°C), transported to site, laid and compacted on a sound impermeable underlying layer. The interconnected voids allow rainwater falling on the surface to percolate down through the asphalt layer and to drain away on the underlying impervious subgrade, thereby reducing substantially traffic induced spray, Figure 1 shows a schematic overview of a typical porous asphalt layer and how it works.

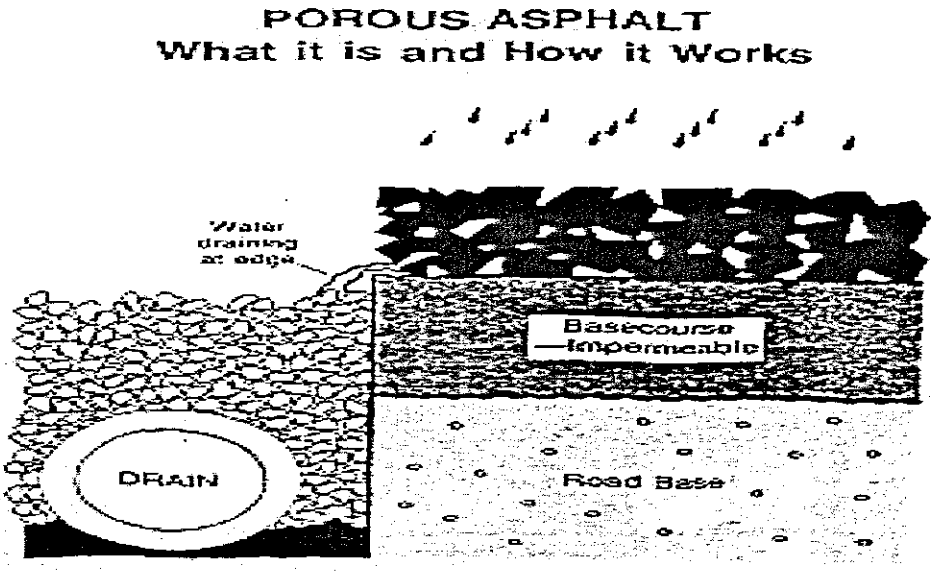


FIGURE 1: Typical porous asphalt layer (after Fabb, 1993)

Porous asphalt surfaces have proven to be an effective and reliable way to reduce rolling noise from road vehicles. The primary properties of porous asphalt is it's high porosity; its capacity for reducing traffic noise pollution, and reduction in splash and spray from vehicles in wet weather thereby improving the skid resistance at high and low vehicle speeds.

However, as a result of the relatively open structure of porous asphalt, the binder is likely to undergo accelerated ageing due to oxidation, which in turn will increase the stiffness of the material and decrease the ductility of the binder system. This in turn may lead to early fatigue failure and to ravelling. Also porous asphalt has relatively low structural strength (low stiffness, indirect tensile strength, and shear strength) by comparison with that of dense-graded asphalt mixes and the relatively thin films holding the aggregate structure together may be insufficient to counter the loss of aggregate particles as a result of moisture attack and of the abrasive force of traffic.

With the introduction of polymer-modified or bitumen-rubber binder or cellulose –fibre additives to porous asphalt mixes with high void content, the binder content can be increased without the risk of binder run-off and the mixture's initial level of serviceability can be maintained with improved durability.

Research conducted since the 1970's on porous asphalt has demonstrated that the pavement/tyre noise can be reduced on main roads by 3 to 5 dBA and on motorways by up to 7 dBA.

Compared with dense-graded asphalt or concrete surfacings, porous asphalt can reduce noise levels of vehicle tyres by as much as 8 dBA in wet weather (a 3 dBA reduction in noise level is comparable with a 50 percent reduction in noise pollution) and by 4 dBA in dry weather.

3.1 Advantages of using porous asphalt

"The structural properties of porous asphalt mixes, by comparison with those of conventional dense-graded mixes, are such that shorter maintenance cycles are required, thus increasing the costs during the intended service life of the layer. Also, porous asphalt mixes do not distribute traffic stresses as well as dense mixes, and may therefore not be used as strengthening courses. Because of their high void contents, durability of these mixes may also be a problem in the long term. High porosity causes the binder system to be exposed to oxidation, moisture damage and attacks by fuels and oils. Care should therefore be taken when selecting the binder." (Verhaeghe, 1992)

The overall properties of porous asphalt can be categorised as follows (Verhaeghe, 1992):

- Functional properties of porous asphalt

Road safety aspects with regards to accidents
Capacity effects - increase in traffic densities
Environmental aspects with regards to noise pollution and
Economical aspects, which refer to fuel consumption and tyre wear.

- Structural properties of porous asphalt

1. Properties of unconditioned porous asphalt (resistance to deformation, resistance to fatigue, indirect tensile strength and stiffness modulus (E-modulus from dynamic bending tests)
2. Ageing and stripping characteristics
3. Effects of temperature

4. Overall effect on structural design and service life
5. Effect of binder modification

As mentioned before the functional properties of porous asphalt can be subdivided into the following categories:

- Environmental aspects;
- Road safety aspects;
- *Road economics, and*
- Traffic volume capacity.

3.1.1 Environmental considerations

Tyre noise

The texture is almost completely "negative", that is to say beneath the motional plane of the surface. Thus there are practically no asperities to deform the tyres and to create noise. Compared with continuously graded asphalt, porous asphalt is quieter by about 4 decibels in dry conditions and up to 8 decibels in wet conditions (Fabb, 1993).

A reduction of 4 decibels is very significant. It is equivalent to either halving the volume of traffic or doubling the distance to the observer from the road. To a certain extent the reduction in tyre noise is retained even when the material has become clogged. This gives support to the view that porous asphalt reduces the generation of noise rather than absorb noise. Road traffic noise poses an escalating threat to the environment as Verhaeghe, (1992) once said:

> *"The rapid increase in traffic density and the growing concern for the environment in densely populated areas have increased the importance of minimising noise pollution."*

Noise reduction in tyre/road interaction is comprised of two elements. The noise caused by the rolling tyre is reduced. The second is that most of the downward noise from the car itself is absorbed to a certain extent, contrary to traditional road surfaces where it is reflected back (Khalid and Perez Jimenez, 1996).

The control of traffic noise at the source has in recent years been focussed on tyre/road noise, since this noise component appears to be the major contributor to traffic noise at traffic speeds above 50 km/h. An approach followed by researchers and engineers in many countries is the application of porous road surfaces, which offer a certain degree of sound absorption.

The design of such road surface materials is such as to try and obtain maximum sound absorbing properties under the constraints of rather stringent demands of good road engineering practice.

The use of bitumen rubber as opposed to conventional bitumen as a binder for any acoustically optimised material offers a higher absorption coefficient especially at frequencies below 1000Hz. This is expected to result in a significantly higher A-level reduction of traffic noise (Von Meier, '88). Jongens (1995), also said that the use of an elastic binder will further reduce the noise production.

There are two different effects that seem to be directly responsible for the reduction in the road traffic noise.

1. Since air can penetrate into the pavement, no closed air volumes with high pressure are formed in the tread of the tyre or the road, so that aerodynamic noise source in the tyre tread are partly suppressed.
2. Furthermore, porous asphalt pavement surfaces are able to absorb noise energy, which is emitted from the engine or the tyre directly to the road surface or via reflection at the car body.

This topic will be dealt with in more detail in chapter two of this report.

Noise barriers

Experience with noise barriers has been very disappointing, they do very little to protect properties further than about 300 m from the road (Fabb, 1993). Noise barriers are normally very expensive and less effective. It is good practise to reduce noise from the source rather than to contain it.

The alternative use of porous asphalt has a clear positive cost/benefit ratio in direct economic terms. Noise reduction, in general, is the main "selling point" of porous asphalt. This automatically limits its use to high speed rural roads as the noise reduction is highly dependent upon speed (Khalid and Perez Jimenez, 1996).

Driver comfort

The reduction in tyre noise from the use of porous asphalt is manifested inside as well as outside vehicles, making driving far more pleasant and less tiring. Improvement is quite dramatic but it seems to have been overlooked in previous debates.

Use of waste rubber

Waste rubber from old car tyres is a major environmental problem in many countries. Using granulated waste rubber in asphalt roads is a way of disposing it. Experience showed, however, that this application was often more than waste disposal, where many characteristics of asphalt roads improved by using granulated rubber.

The most important improvements are the noise reduction as mentioned above and the increase in life. Increases in life from some 9 to 12 years have been reported (Lefebvre, 1993)

3.1.2 Safety

Aquaplaning

Porous asphalt allows rainwater to flow through the pores into the side drains leaving the pavement surface free from standing water. Even if it becomes saturated, as could happen after a prolonged period of very heavy rain, aquaplaning will not occur as the pressure under the tyre is dissipated through the pores of the material. (Fabb, 1993). *He also added by saying that aquaplaning* could be greatly retarded by not using very fine tyres and road surfaces. In practise both tyre and road surfaces are quite heavily textured as shown in Figure 2. This has the effect of delaying the build-up of a hydraulic wedge by dissipating the water as it is compressed between the surface and the tyre.

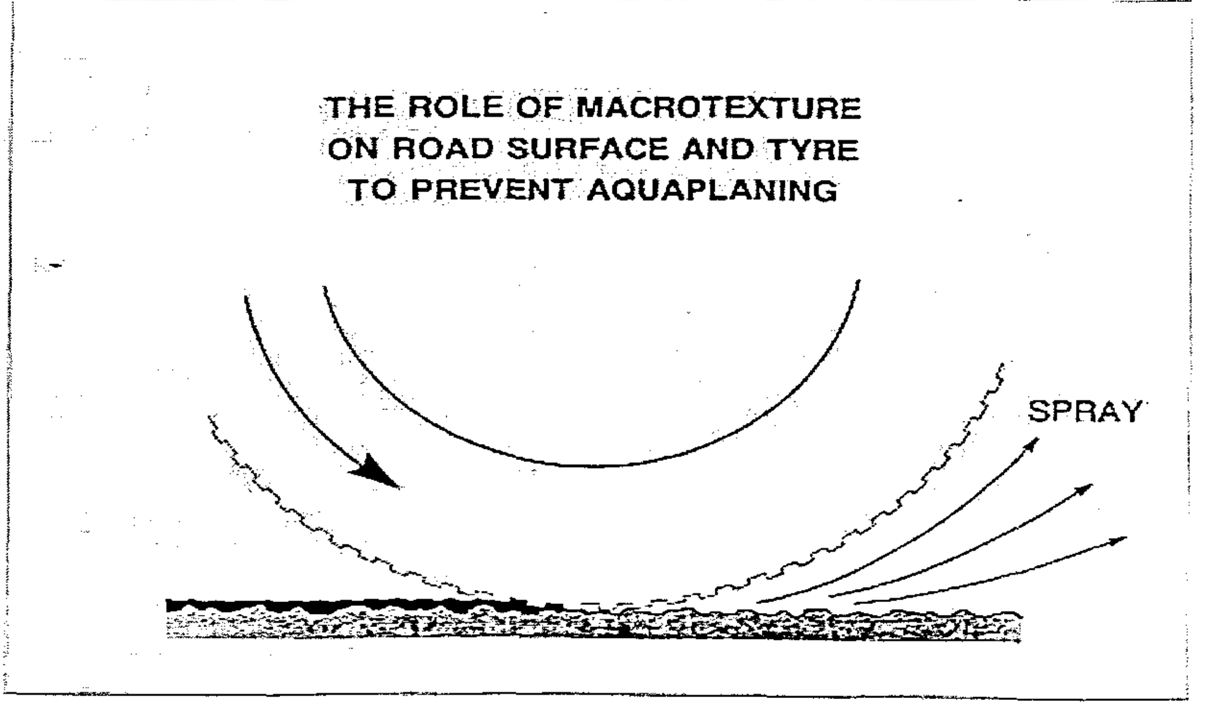


FIGURE 2: The role of macrotexture on road surface and the tyre to prevent aquaplaning (after Fabb, 1993)

Spray

The spray thrown up by the vehicle tyre is very much a function of speed (Fabb, 1993). Poor visibility caused by spray can be directly associated with the cause of accidents. The use of porous asphalt greatly reduces spray, in fact it almost eliminates it when newly laid depending on the void content. Even when it has become significantly clogged, it still gives considerable reductions in spray.

The use of porous asphalt drastically reduces the accident rate in wet weather.

Glare reduction

Users of motor vehicles have to observe the road ahead in order for them to reach their destination safely. During wet weather conditions, at normal driving speed, the road user must be able to view the road from a considerable distance of e.g. 50 to 100 metres ahead of the vehicle. When viewed, most surfaces reflect the incident light very strongly because when the surface is smooth, it usually looks like a mirror. There are no statistics available to quantify the reduction of glare from headlights in wet weather conditions offered by porous asphalt, but there can be no doubt that any contribution to better visibility and reduced driver fatigue is a contribution to safety.

Skid resistance

Rain may reduce skid resistance of road surfaces considerably even when no aquaplaning takes place. Porous asphalt may counteract this effect, even when the *surface stays humid. The skid resistance of a wet porous asphalt at high vehicle* speeds will be higher than that of a wet traditional asphalt, but not equal to that of a dry road. At low speeds, the skid resistance of wet porous asphalt is not higher than that of a wet traditional asphalt (Khalid and Perez Jimenez, 1996).

There are two components that affect stopping distance: the friction and the macrotexture.

FRICTION Good friction is associated with good microtexture. Good dry friction means that you can stop in dry conditions (Pprune, 1999):

- a dry skid pan often has good dry friction, because it is very smooth so there is maximum tyre/surfacing contact area, and the stones in the surfacing have not been polished by lots and lots of traffic.
- of course a wet skid pan is slippery because it is so smooth.
- cobble stones have poor dry friction because there is only limited tyre/surfacing contact and the cobble stones have poor microtexture (they are smooth). To make matters worse, cobble stones are not just smooth, they are often polished by centuries of traffic as well, which makes them even more slippery.

Good wet friction means that you can stop in wet conditions. This has two parts - the microtexture and the macrotexture.

- The microtexture (and polishing) are relevant for very thin films of water (say less than 0.1 mm).
- For highways, with high traffic volumes and lower speeds, it is an issue.
- Macrotexture is relevant for thicker films of water. Anytime someone reports standing water on the runway, or you see a plane throwing gusts of spray, I believe that there are thick films of water present, and macrotexture is the more important. This is the main problem in aviation (particularly for commercial jets), and will be deal with in a separate section below.

MACROTEXTURE Good macrotexture means that the surface is rough enough, or has enough holes or grooves in it, that water can be easily pushed away by the tyre at low to medium speeds, and then the tyre can contact the surface and can be braked. Poor macrotexture means that the surface is smooth, and above slow speeds, the tyre easily rides up onto the water and aquaplanes.

- Concrete or rigid roads and runways inherently have poor macrotexture, and grooving is used extensively on concrete runways to provide macrotexture.
- Bitumen or bituminous or flexible or asphalt or asphalt concrete or sealed roads and runways often have fair macrotexture. Grooving is often used on flexible runways for large commercial jets, which have asphalt surfacings.
- Macrotexture is gradually lost with time due to stone wear. Grooving wears out in time.
- Macrotexture is rapidly lost with rubber build-up in the touchdown areas. Grooving fills up in time.
- A very few authorities use special bitumen surfacings (known as porous asphalt) to give good macrotexture without grooving.
- A sealed road surface (which is typically only found in Australia, New Zealand and South Africa, common on roads) has good macrotexture.

A summarised relationship between of microtexture and macrotexture of porous asphalt surfaces is shown in Figure 3:

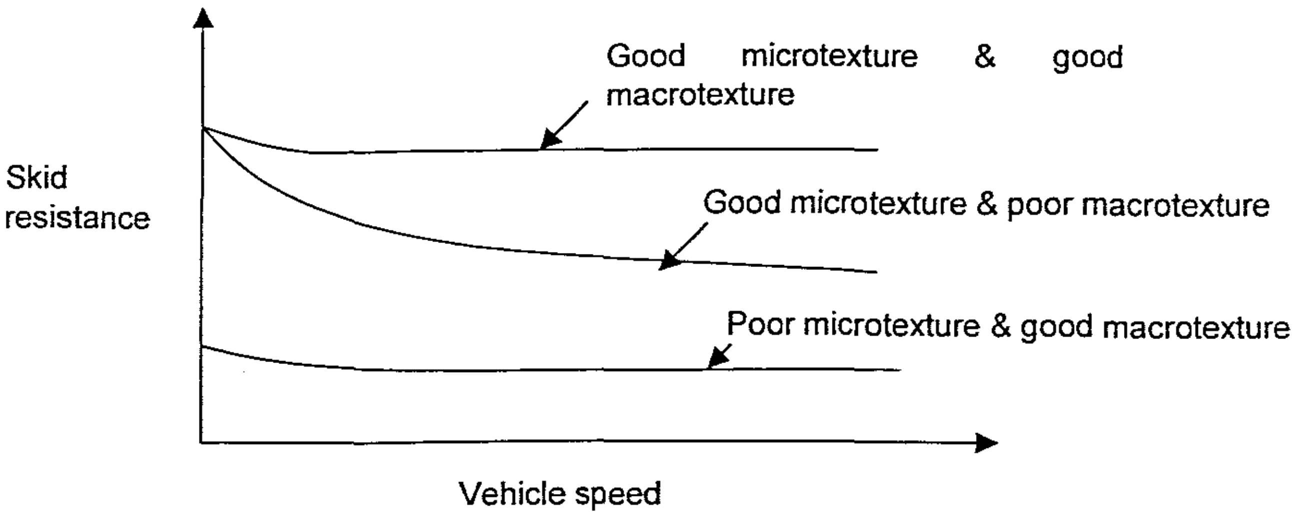


FIGURE 3: The role of macrotexture on road surface and the tyre to prevent aquaplaning

3.1.3 Economics

Fuel consumption

The vibrations in tyres, which create the noise, increase the rolling resistance of the vehicle and therefore increase fuel consumption (Fabb, 1993). The smoother the road surface used, the higher the potential for fuel saving.

Tyre wear

It is clear that the use of porous asphalt stresses tyres much less than conventional surfaces do, quantification of this benefit is of course virtually impossible, but general consideration of the factors affecting tyre wear suggest that significant savings must follow from the reduction of stresses which reduce fuel consumption (Fabb, 1993).

3.1.4 Capacity effects

Traffic congestion builds up more rapidly in wet weather. The major contributing factor affecting congestion is the significant reduction in traffic capacity brought on by changes in driving behaviour. The drivers' perception of the reduced skid resistance of the wearing course and the disturbing effects of splash and spray normally result in an overall reduction of speed (assuming good driving behaviour). The improved safety of porous asphalt will reduce congestion, resulting in considerable financial benefits to road users in terms of decrease in user delay.

In summary, the advantages of using porous asphalt are as follows (Verhaeghe, 1992):

1. Reduces the possibility of aquaplaning.
2. Reduces splash and spray behind vehicles.
3. Avoids reflections by the surface of the wet pavement and this enhances the visibility of the pavement markings
4. Reduces noise emission (exterior noise)
5. Reduces noise inside the vehicles.
6. Reduces the vibrations inside the vehicles, which can induce better comfort for the users and electronic devices.
7. Improves wet skid resistance through improved adhesion in high-speed domain.
8. Reduces traffic congestion therefore less rutting and

3.2 Disadvantages of using porous asphalt

Structural properties which are often used to characterise porous asphalt mixes are resistance to deformation, resistance to fatigue, indirect tensile strength, and stiffness modulus (E-modulus from dynamic bending tests). The disadvantages of using porous asphalt can therefore be summarised as follows:

3.2.1 Reduced pavement strength

Traditionally porous asphalt has not been considered as a contributing layer to the overall structural integrity of the pavement (Khalid and Perez Jimenez, 1996). This leads to having to provide more support in the structural layers of the pavement. The reduced strength of porous asphalt surfaces can also limit its application only to areas which are not susceptible to high stresses which might subsequently lead to aggregate fretting (Prof. A. Woodside et al, 1999). Since porous asphalt mixes do not distribute traffic stresses as well as dense mixes, it is therefore recommended that these mixes should never be used as strengthening courses.

In general porous asphalt wearing courses have a low structural strength compared to conventional surfacings. This is due to its high void content; it is relatively weak in shear and is particularly vulnerable on road sections with high traffic stresses.

3.2.2 Less durable

This is due to the open structure of the layer therefore environmental forces such as moisture and binder oxidation (due to the ingress of water, heat and ultra-violet radiation) have an adverse effect on durability.

The service life of porous asphalt has been generally considered to be shorter than that of traditional dense graded asphalt. This is possibly caused by the clogging of the pores and drainage paths while under construction and also during the service life of the road.

3.2.3 Maintenance needs: Clogging

Maintenance

Porous pavement requires extensive maintenance compared with other practices. In addition to owners not being aware of porous pavement on a site, not performing these maintenance activities is the chief reason for failure of this practice. Typical requirements follow in Table 1 below:

TABLE 1. Typical Maintenance Activities for Porous Pavement (Source: WMI, 1997)

Activity	Schedule
• Avoid sealing or repaving with non-materials porous	N/A
• Ensure that paving area is clean of debris • Ensure that paving dewaters between storms • Ensure that the area is clean of sediments	Monthly
• Mow upland and adjacent areas, and seed • Vacuum Sweep frequently to keep the surface free of sediment bare areas • (Typically three to four times per year)	As needed
• Inspect the surface for deterioration or spalling	Annual

Cleaning

Roads are exposed to pollution. When it concerns an open road surface like Twinlay, pollution will penetrate and block the pores. With this the specific advantages of an open surface are lost. To prevent this, maintenance is required.

From porous asphalt it is known that dirt forms itself through the total thickness of the layer. With the Twinlay-construction the pollution stays limited to the top layer. The filter action of the top layer prevents dirt from reaching the bottom layer. The sieve-effect of the top layer also retains coarse dirt or temporary a large amount of dirt, which will run off the surface with the water. Visual observation proved dirt doesn't enter the top layer for more than 1 to 1.5 cm. The dirt concentration in the top layer can easily be removed with a special cleaning technique. There are a number of methods that can be used but for the purpose of this research only one is reported upon, which is the Hydrovac-method (available from the Heijmans Company, Netherlands), by which water under pressure (up to 170 bar) is sprayed onto the surface. The rotating movement of the spray nozzles makes sure that water enters the top layer from all directions. Directly behind the spray nozzles, the water, containing dirt, is sucked up. Cleaning Twinlay is much more effective compared to conventional porous asphalt, because the dirt is concentrated in the top layer (Van Bochove, 1995 and 1995)

Tests have shown a totally clogged Twinlay-surface can be cleaned completely (Van Bochove, 1993 and 1995). Depending on the severity of pollution cleaning is only required once or twice a year. After cleaning, the functional properties of Twinlay are almost the same as in the zero situation. In order to determine the severity of pollution, a permeability test can be performed with the LCS Drainometer (ref. Appendix C). The required time for the discharge of a certain amount of water is a measure for the openness of the structure (a lower discharge value means a cleaner porous asphalt).

4 DOUBLE LAYERED POROUS ASPHALT CONSTRUCTION

In comparison with densely graded asphalt, porous asphalt offers a host of advantages. Traffic safety and capacity of roads during rainfall are considerably improved and the noise level is considerably reduced. As the disadvantages are revealed, the question arises with regard to the technical life span, the risk of clogging and that of functional life span. Another problem is the upholding of skid resistance of porous asphalt. It was then that, those years of research and experience, a new of generation of porous asphalt surfaces, Twinlay was developed by Heijmans Civil engineering at Rosmalen (in the Netherlands).

Test sections of this construction have been in use since 1990. These test sections took part in a large-scale research project aimed at optimising noise reduction of porous asphalt. Acoustic measurements (Van Bochove, 1996) showed Twinlay offers possibilities for even more noise reduction near roads, even at lower vehicle speeds. Experience has shown pollution and consequently cleaning of Twinlay can be easily manageable (cleaning assist in keeping the voids open with optimum absorption maintained at all time). This partly attributed to the noise reduction in the long term, which has been acknowledged by measurements (Van Bochove, 1996).

4.1 Twinlay construction

Two layered construction so called "Twinlay" is made up of a bottom layer of porous asphalt with a coarse of single grained aggregate (11/16) and a thin top layer of fine porous asphalt (4/8). Figure 4 shows the structure of Twinlay. Because the stone particles of the top layer can "settle" into the course texture of the bottom layer, a relatively thin top layer can be applied.

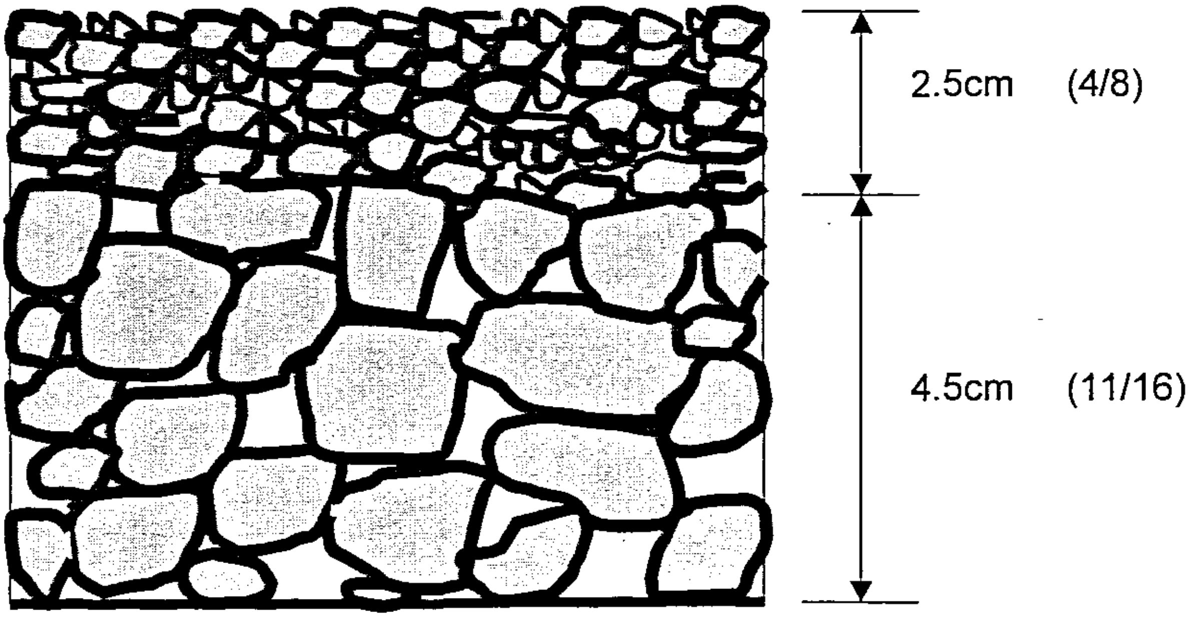


FIGURE 4: Structure of Twinlay: a course single-grained bottom layer and fine top layer.

As opposed to the conventional porous asphalt wearing course, Twinlay offers the following advantages (Van Bochove, 1996):

- The fine top layer acts as a sieve preventing sand or dirt from clogging the coarse bottom layer consequently leaving the asphalt free draining.
- Twinlay is a new product, therefore the service life cannot be specified accurately. The top layer can be easily replaced, depending on the intensity of use (situation, traffic load) an estimate of 7 to 10 years can be given before replacing it.
- The fine surface texture of the top layer reduces tyre/road noise and the coarse bottom layer combined with the fine top layer provides a good sound absorption, this is also caused by the thickness of the overall layer. A thicker layer has a higher sound absorption coefficient.

- The dirt that penetrates the fine top layer can be easily removed by using certain cleaning techniques.

- The difference in airflow resistance between the top layer and bottom layer has a positive effect on the self-cleaning capacity caused by traffic.

The coarse bottom layer has a good discharge of rainwater to the side drains.

Given the fine grain size of the top layer mixture, it is important to keep porosity as high as possible and the flow resistance as low as possible. This can be reached by leaving the sand fraction from the mixture. It is then however necessary to use a binder with – in the warm phase – a very high viscosity (rubber bitumen). The high viscosity allows the use of a high bitumen percentage (6.5 percent) without causing demixing in the warm phase. This higher bitumen percentage is essential for durability. In order to conform to the service life of both layers, rubber bitumen is also *used as a binder in the bottom layer (Van Bochove, 1996).*
From the acoustic point of view Figure 5 shows typical sound absorption measurements carried out by M+P Consulting Engineers and Heijmans Civil Engineering in 1995. The following mixes were investigated:

1. dense asphalt concrete 0/16 (reference section), thickness 4cm;
2. porous asphalt concrete 0/16 (conventional), with aggregate 6/16, thickness 4 cm;
3. porous asphalt concrete 0/8, with aggregate 4/8, thickness 4 cm;
4. Twinlay (2 variations), total thickness respectively 5 and 7 cm.

The acoustic measurements were conducted with 20 cars at different speeds. Indicative measurements were also performed with three (light) trucks. The total average noise production measurements on several test sections are described in Figure 5. In Figure 5, only the results for the thick Twinlay construction (7 cm) are presented. At 60 km/h the Twinlay produces 64 dBA which is the lowest as compared to 67 dBA from porous asphalt concrete 0/8, 68 dBA dense asphalt concrete 0/16 and 68.5 dBA from porous asphalt concrete 0/16.

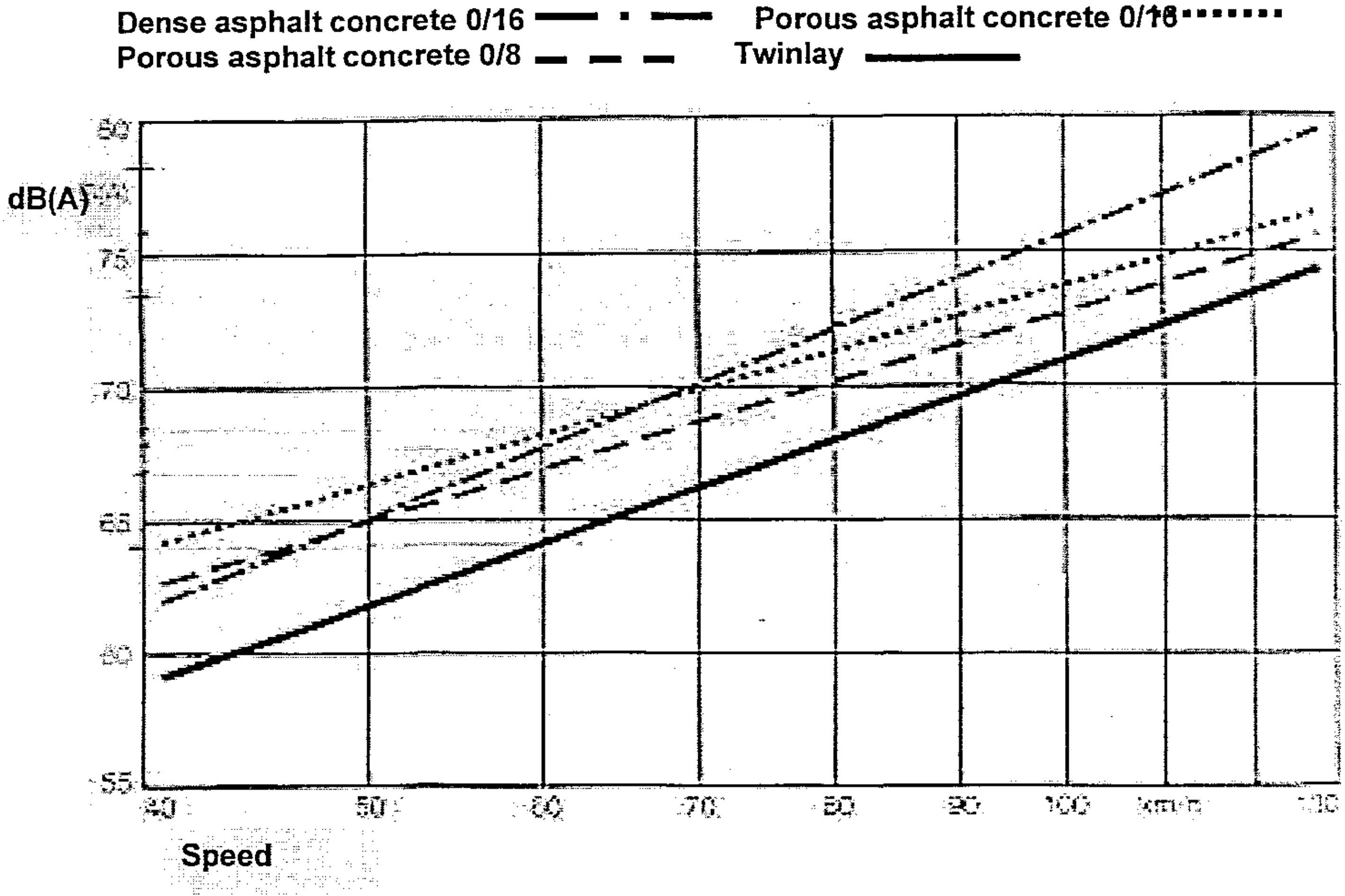


FIGURE 5: noise production as a function of vehicle speed for different road surfaces (after Heijmans, 1995)

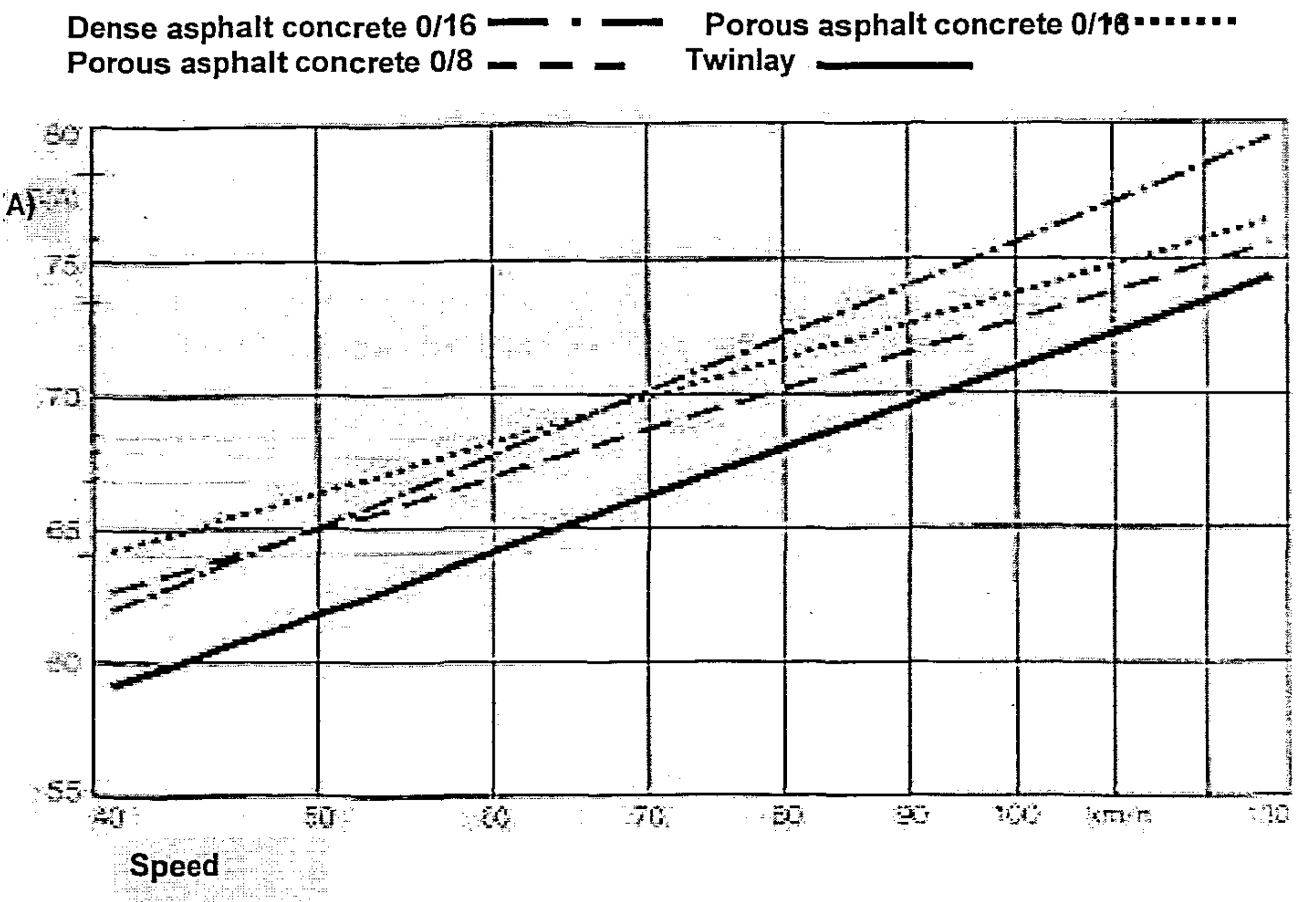
From the graph it is obvious that conventional porous asphalt (0/16) offers at lower vehicle speed no acoustic advantage. At vehicle speeds below 60 km/h, this mixture showed a higher noise production compared to the reference mixture of dense asphalt concrete. The fine porous asphalt 0/8 mixture (with aggregate 4/8) is on the whole approximately 1 dBA quieter compared to porous asphalt 0/16. The lines in the graph are more or less parallel. For the Twinlay construction it can be noted that the slope of line in the graph tends to be like the one for dense asphalt concrete 0/16, while the noise production is significantly less compared to the other porous asphalt constructions. Not only at low vehicle speeds but also at high speeds, the noise reduction Twinlay is considerable better. The results given are only valid for small cars. Sound measurements conducted with trucks gave identical results.

4.1.1 Basic assumptions

The design of Twinlay porous asphalt surfaces is based on the following assumptions (Van Bochove, 1996):

Acoustic

- The improvement of acoustic properties of conventional asphalt requires in general a finer and more single-grained mixture. The use of aggregate 8/11,



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4.1.1 Basic assumptions

The design of Twinlay porous asphalt surfaces is based on the following assumptions (Van Bochove, 1996):

Acoustic

- The improvement of acoustic properties of conventional asphalt requires in general a finer and more single-grained mixture. The use of aggregate 8/11, instead of 6/16 used in conventional porous asphalt, leads to a higher sound absorption around 1000 Hz.

- 1000 Hz is the dominating frequency for vehicle speeds above 70km/h.

- At lower vehicle speeds, for instance in urban situations, it is advisable to use an even finer aggregate (for instance 4/8) and for South African conditions a 2.36 – 4.75 mm can be used.

- Next to absorption, vibration of the tyres, caused by interaction between the tyre and the road surface, is of importance. As the size of the stone in the road surface becomes smaller, the vibration of the tyres – and with that the sound production – decreases. With this aggregate size less than 10 mm is an important parameter, if noise created by the tyre is to be reduced. This effect will only concern the texture of the road surface. The thickness of the fine porous asphalt mixture is not important with this and can therefore stay restricted to a minimum.

Clogging

- Aiming for the finer mixture seems to be in contradiction with the problems of pollution. This requires on the other hand single-grained mixture, because a bigger stone will result into bigger water carrying voids, by which the discharge resistance will reduce. Water will run off more quickly and dirt will erode sooner. On the other hand with a coarse mixture, with large voids on the surface, more dirt will penetrate into the surface.

From these assumptions it is quite imperative to strike a balance between sound production reduction and permeability keeping in mind that permeability plays an important role in improving safety in roads.

4.2 The significance of using porous asphalt

There is an escalating demand to have roads or pavements that will provide larger environmental and structural benefits. An emphasis exists to provide a road surface that will cause the threat of road traffic noise to subside. With the continuous increase of traffic density in urban areas, noise pollution is expected to get correspondingly worse (Sabita Manual, 1995). To date porous asphalt has been proven to offer excellent environmental benefits as well as safe and comfortable riding quality.

Road traffic noise is the most important single source of community noise, which maybe because traffic noise is the most difficult noise to eradicate. As mentioned before the significant increase in traffic densities (and speed) especially in urban areas are expected to cause an increase in noise pollution. "The rapid increase in traffic density and the growing concern for the environment in densely populated areas have increased the importance of minimising noise pollution." (Verhaeghe, 1992)

The Environmental Act of 1989 promulgated regulations with respect to noise, since then not much work has been done to enforce noise level limits produced by road traffic noise. Road related noise is addressed by various regulations in South Africa, which are currently being updated (Rossouw, 1987 and 1992). Various municipalities have adopted the noise control regulations. Road noise, as an environmental issue is however increasingly becoming a problem that needs to be resolved along ethical and cost effective avenues (Horak et al).

There is thus a great need to control noise caused by transport. This can be achieved by controlling noise from the source, that is road/tyre interaction. In the past years different countries over the world have been involved in an ongoing attempt to develop a low-noise pavement. This has led to the development of porous asphalt, which besides its excellent sound absorption properties, offers different advantages, e.g. improved drainage abilities which results in reduced splash and spray, improved skid resistance etc. Advantages of using porous asphalt are covered in greater detail in Chapter 2, Section 3.1. Porous asphalt is a cost effective alternative to noise barriers, offers both the road users and urban residents a highly competitive means of addressing the growing concern for the environment in densely populated areas (Sabita Manual 17, 1995).

A recent study by the Directorate Roads and Health, Housing and Urbanisation Directorate aimed at attenuating road related noise levels was conducted in Johannesburg on experimental test sections on Rifle Range Road with the CSIR. Three different types of attenuation measures were investigated namely: traffic calming measures, noise barriers and noise absorbing surface (open graded asphalt with an average void content of 15 percent). The study yielded the following conclusions:

1. Traffic calming measures: the banning of heavy vehicles and using various geometric and physical road features to reduce "rat-running" usage and general traffic operating speeds on residential roads showed a measured significant reductions in road noise levels.

2. Noise barriers: Modelling studies based on measured noise level measurements on a section of Barry Hertzog Avenue showed that a noise barrier or wall will attenuate noise significantly. Various cost and practical aspects associated with noise barriers in general have up to yet precluded their implementation on any significant scale in Johannesburg. The screening off of road traffic may in some cases have higher perceived benefits than what was achieved due to the lack of visibility of the noise source.

3. Noise absorbent road surfaces: Open graded asphalt surfacings with air void contents on average of 15 percent, generally proved to attenuate road noise levels in South Africa and elsewhere in the world. On average, 3 to 5 dBA reductions were attained compared to various other impervious road surface types. A new technology porous asphalt with minimum voids content of 20 percent was used for the first time in South Africa in Johannesburg on a 3 km stretch of the M2 West Motorway. Experimental sections on Rifle Range Road with various types of porous asphalt proved that significant reduction in noise levels are achievable, 3 to 5 dBA. It was also proposed that whisper course

porous asphalt should be used on major arterials and motorways to achieve maximum benefit.

4. A pricing technique was discussed to compare the viability of various road noise attenuation measures. In Australia, studies with Open Graded Asphalt surfacings were found to have the best Net Present Value compared with other noise attenuation measures having marginal benefits in addition (Reynolds, 1992). It was anticipated that porous asphalt will have even better benefits than Open Graded Asphalt surfacings. The added benefit of good skid resistance (particularly in wet weather) of porous asphalt and its drainage ability (reducing splash and spray and mist) has shown reductions in wet weather accidents.

   The impact of road noise on property values next to roads and highways in the Johannesburg area showed to have a reduction of as high as 22.5 percent on values. It was shown that any noise attenuation measure can be justified based on the increase in rates on property value next to such roads through the normal municipal capital funding mechanism.

In general, this study proved without reasonable doubt that porous asphalt is a cost effective alternative to noise barriers.

5 PAVEMENT DESIGN CONSIDERATIONS

A minimum layer thickness of 40 mm is suitable for adequate water drainage capacity for normal rainfall conditions. Appropriate application of porous asphalt entails good design practices.

5.1 Application of porous asphalt

Porous asphalt is recommended in area where water tends to accumulate or where a water hazard could reduce traffic capacity or impair traffic safety. Typical areas are at change of super elevation, busy motorways or wide pavements (motorways), limited-access roads and highway roads with recognised noise pollution problems, particularly on noisy arterials in urban areas, cross-town freeways or motorway links.

5.2 Relevant engineering properties

Engineering properties that are used to characterise asphalt mixes, in general are: resistance to permanent deformation, resistance to fatigue cracking, indirect tensile strength and stiffness modulus. On account of its composition, other relevant engineering properties of porous asphalt should be considered. These include those which have a direct bearing on the expected life of a porous asphalt wearing course, such as binder durability and short-term resistance to stone loss.

5.3 Environmental considerations

5.3.1 Improvement in road safety

One of the major advantages of using porous asphalt is that it improves wet weather road safety considerably. The drainage ability of porous asphalt allows vehicle tyres to remain in continuous contact with the surface of the pavement under all conditions, and thus reduces the possibility of aquaplaning. A significant reduction in wet-weather accidents may be expected after the application of porous asphalt on wide pavements, such as three-lane highways or major arterials.

5.3.2 Reduction in noise pollution

As mentioned earlier porous asphalt is highly effective in reducing rolling noise both inside and outside the vehicle. It is however, recognised that noise reduction effects are generally more pronounced in wet weather. The reduction in noise level has been as much as 8 dBA under these conditions.

5.3.2.1 Introduction to sound and noise

Noise, music and speech are the three basic categories of sound.

Sound consists of fluctuations in the air pressure which are detected by the ear. The human ear is able to detect these fluctuations with great sensitivity and over a considerable range of both intensity and frequency. It translates acoustic pressure fluctuations into pulses in the auditory nerve, these pulses are carried into the brain which interprets and identifies them, and converts them into sensations (the perception of sound).

As the response of the human ear is a purely subjective quantity, it cannot be measured directly like other physical quantities. The response of the human ear varies with both frequency (20 - 20,000 cycles/sec) and sound intensity (10^{-12} - 1 watt/m^2) at all values. However, the human ear is more sensitive to changes in frequency than to changes in sound intensity and more sensitive to sounds of low intensity than to those of high intensity.

Sound is normally measured using a sound level meter. Sound is measured against a range of octave frequency bands. An octave frequency band is a frequency range for which the highest frequency is twice that of the lowest. The centre frequency is 1.4 times the lowest frequency. The 1/3 octave band filters divide each octave by three.

Sound is measured in decibel dBA. The "A" curve was found to best fit for quiet to moderate loud sounds. It signifies that we are dealing with humans' subjective response to sounds.

Noise is simply unwanted sound. Community noise is unwanted noise which occurs in the community, such as barking dogs, traffic noise, and lawn-mower noise. Its effect should be reduced if our living environment is to become more pleasant. The community has made it clear in no uncertain terms that it wishes this to occur.

5.3.2.2 Road traffic noise

Road traffic noise is the predominating factor to the overall environmental noise pollution. Research into road traffic noise show that the interaction of tyre with the road surface is the main contributor, especially at high vehicle speeds. Thus further examination and optimisation of the road surfaces' acoustical properties are needed. The level of noise generated by traffic depends on factors such as traffic flow rate, smoothness of traffic flow, the percentage of trucks in the traffic, the average speed, the gradient and the type of road surface (Reeves, 1987).

Road noise is a sound which is perceived by the ear as a series of pressure fluctuations. These pressure fluctuation range between 1 to 5 million which is normally expressed in the logarithmic decibel scale (dBA). The loudness is determined by the sound pressure level and its frequency or pitch characteristic. Sound measuring equipment use filtering system to simulate the behaviour of the human ear. This is expressed as A-weighted decibel (dBA).

Traffic noise levels fluctuate due to the factors listed above and therefore a single measurement cannot adequately describe the noise output. In order to express noise climate a time element is introduced typically as L_{Aeq}.

When the porous material is subjected to the action of acoustic pressure, the porous material not only undergoes elastic compression but there is also movement of the fluid (air) back and forth in the voids within the material. The process of "absorption" is the conversion of acoustic energy into heat which takes place as a result of:

- Friction between air particles and flow constrictions in the material,
- Internal friction of the material depending on the degree of elastic deformation.

The effectiveness of porous absorbers in absorbing sound depends on the following physical characteristics:

1. Porosity – which is the ratio of the interconnecting voids within the material to the total volume of the material.
2. Structural factor – which relates to the shape of the air voids and how they are interconnected.
3. Specific flow resistance – which is the resistance to airflow through the material and
4. Thickness of the porous material – which is simply what it means, how thick the material is.

Noise emission from road vehicles is composed of several different noise producing mechanisms and these can be sub-divided into the following three main categories:

1. Power-train – being engine, air intake, fan, exhaust, gearbox and transmission. This is an predominating factor at low vehicle speeds e.g. below 50 km/h and is not considered as having an adverse effect on the overall noise produced from road vehicles.
2. Tyre/road interaction – which refers to the rolling noise.
3. Aerodynamic noise – due to air turbulence around the vehicle. This is only a problem or a major contributing factor to the noise production at vehicle speeds above 200 km/h.

For the purpose of this research we won't dwell too much on the power-train and aerodynamic noise since we are mainly concerned with tyre/road interaction, since it is the predominating factor at vehicle speeds above 50 km/h (Von Meier, 1988 and Jongens, 1995).

5.3.2.3 The generation of tyre noise by the macrotexture of conventional road surfacings

It is generally assumed that the size of the aggregates play an important role in the generation or reduction of tyre noise with porosity gaining prominence in absorbing noise for porous asphalt surfaces. Conventional road surfacing is known for the production of higher noise levels. Fabb, (1993) explains the phenomenon of noise generation by conventional road surfacings as follows:

The rolling noise tyre is slightly compressed as it meets the asperities on the road surface which give it its texture. As the point of contact of the tyre moves on past the asperity, it relaxes as another point on the tyre meets the next asperity. It is this alternating compression and relaxation (i.e. vibration) of the tyre which generates the noise – as well as causing the tyre to heat up (see Figure 6).

It is common experience that the tyre noise on concrete roads is both louder and more unpleasant in character than that generated on asphalt roads. The subject is very complicated, but the main reason is that the closely spaced ridges on concrete cause greater deformations of the tyres at higher frequencies and narrower frequency band than do the randomly spaced bumps on conventional asphalt surfaces.

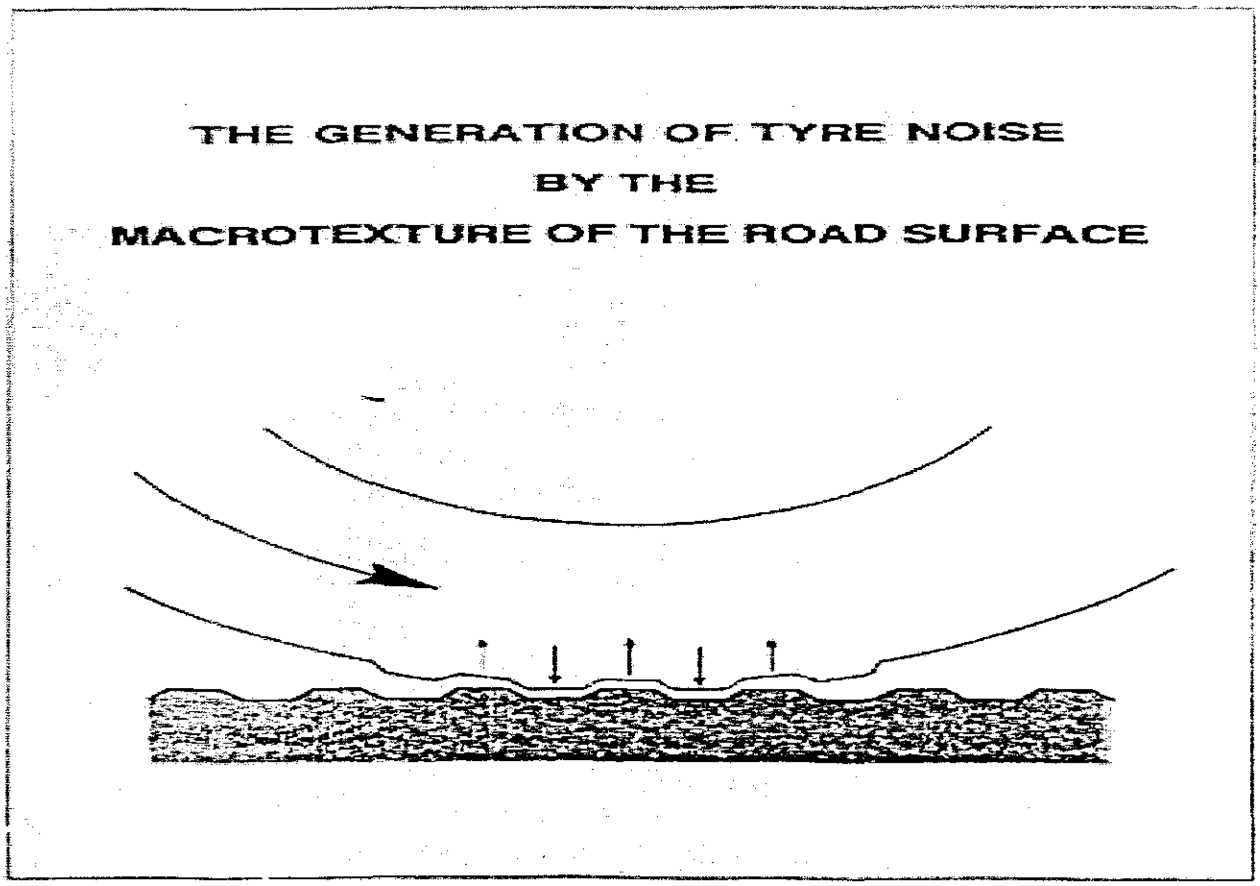

FIGURE 6: The generation of tyre noise by macrotexture of the road surface (after Fabb, 1993)

5.3.2.4 Tyre/road noise generation of porous asphalt surfaces

In the attempt of reducing road traffic noise with regard to rolling noise it is important to understand the tyre/road noise generation mechanism. The macrotexture of porous asphalt road surfaces plays an important role in the prevention of aquaplaning and noise reduction.

In general, road traffic noise is generated by tyre vibration and resonance. Nelson and Underwood (1984), studied tyre vibration by attaching accelerometers to the side wall, shoulder and in a tread groove of a tyre fitted to a lorry when the vehicle was travelling at 64 km/hr. An examination of the third octave frequency spectra showed that the maximum vibration acceleration amplitudes occurred between 400 Hz and 1000 Hz for both tread and side wall. Furthermore, the shape of the vibration frequency spectra correlated closely with that of sound spectra obtained from a microphone located at the side of the test track. This tends to indicate and prove that a large component of the overall sound is produced by the tyre vibration.

The beneficial effects of porous asphalt surfaces on tyre/road noise are twofold:

- The open structure of the surface reduces the compression and expansion of air in the tyre tread profile;

- The acoustic absorption suppresses mechanical and aerodynamic (due to air turbulence around the vehicle) noise generated by the rolling tyre on the road.

The reduction in noise level results from:

- sound absorption in the voids of the layer;
- the elimination of air pumping at the tyre/pavement interface, and
- the excellent surface evenness of this type of wearing course.

Van Blokland (1997) explains the tyre/road noise generation of porous asphalt surfaces mechanism as follows:

The acoustic absorption effect is not restricted to tyre/road noise only but is also effective in reducing mechanical noise, radiated from the underside of the vehicle where the oil pan and gearbox housing form the main sources of engine noise. This was found to be the case not only for passenger cars but also for heavy trucks.

The acoustic effect of most existing porous asphalt road surfaces, however, is limited by the high macro/mega texture level of these surfaces, that causes extensive vibrations of the mechanical system of the tyre. Therefore, progress can only be made by optimising all relevant properties of the porous layer and carefully adjusting noise suppressing mechanisms to noise generating characteristics.

In Figure 7, a schematic overview is displayed of the acoustical processes relevant to the generation and suppression of rolling noise on absorbing surfaces and the surface properties that influence these processes.

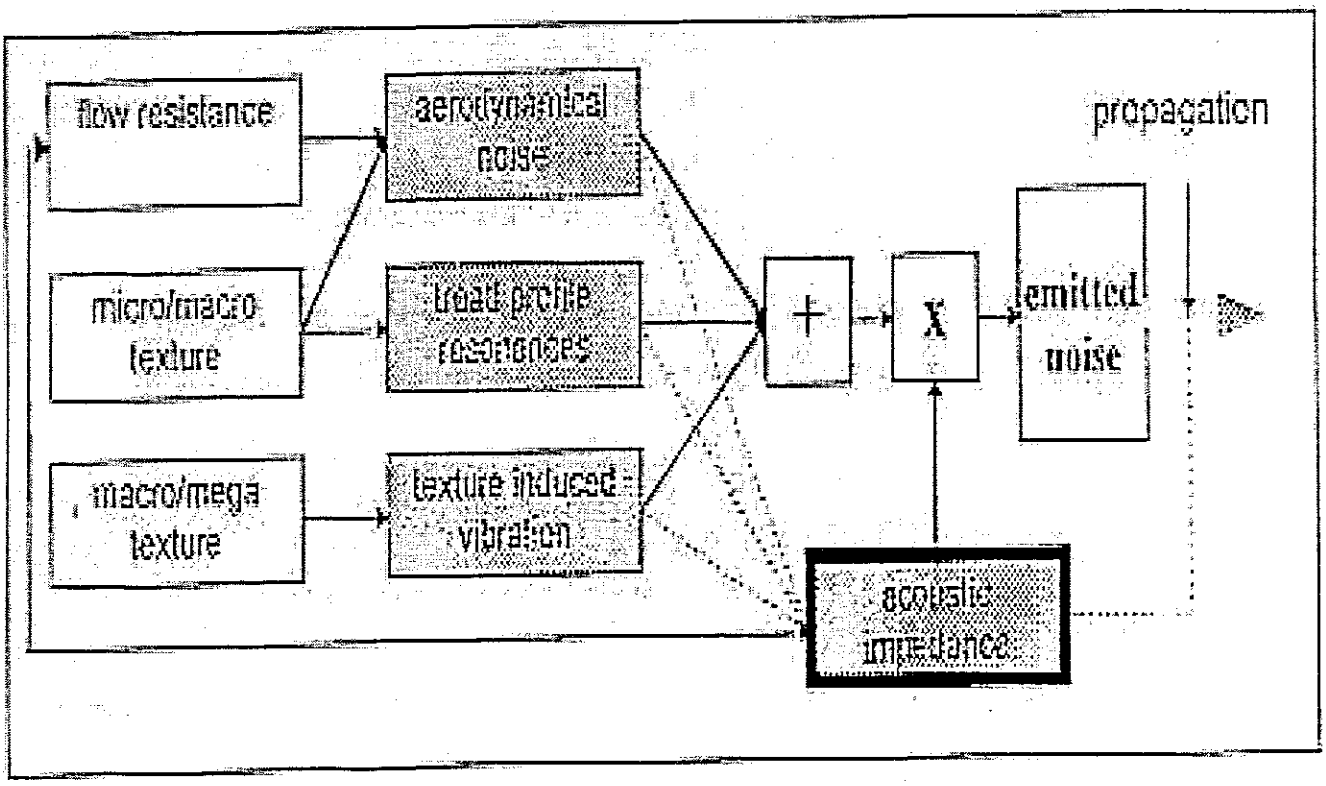

FIGURE 7: schematic overview of the generating and suppressing mechanisms of tyre/road noise on porous surfacing (after Van Blokland, 1997).

The gray blocks in Figure 7 represent the major noise generating processes. Each of these processes exhibit specific frequency and speed characteristics. For instance the aerodynamical and profile resonance effects emit noise at higher frequencies and with a higher speed index than the texture induced vibration component. The surface properties, relevant for the excitation of the different processes are given at the left column. However, much more study is needed to define these surface related parameters. The indications are therefore only tentative.

In this model, the acoustic impedance of the surface, primarily acts as an absorber of noise. An important side effect is the suppression of aerodynamic noise because of the low flow resistance in the surface. Some slight effect may be expected from the change in boundary conditions in the content patch.

The effect of the acoustic absorption is modeled by the total noise emission multiplied by the acoustic transmission of the surface.

5.3.2.5 Measurement and evaluation of community noise

Most community sounds are characterised by fairly steady "residual" or "background" sound levels produced by distant, unidentified sources such as that due to many road vehicles and other city noises. On this are superimposed discrete sound events - normally nearby - of identifiable origin(s) such as individual cars or motorbikes, disco, or a pool pump motor, etc. The Sound Level Meter is used to measure sound. It displays a linear relationship with sound pressure. A-weighted sound levels, measured using a Sound Level Meter during two different time periods in a typical suburban environment are shown in the Figure 8 below.

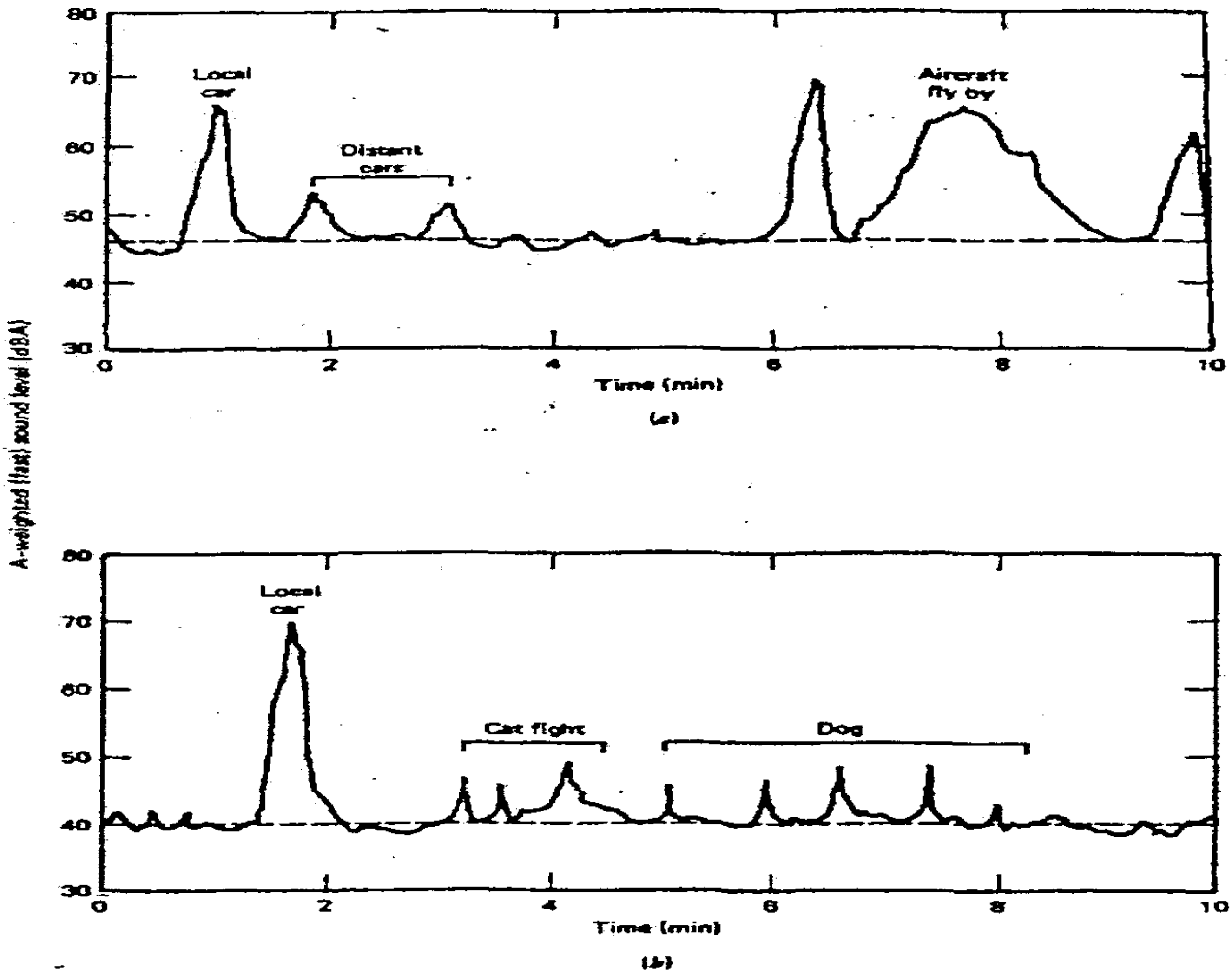

FIGURE 8: Typical community A-weighted sound levels during (a) daytime and (b) night-time (after Jongens, 2000).

5.3.2.5.1 Measurement and evaluation of sound and noise

The response to noise exposure is perceived differently by different people. People respond to noise in a subjective manner rather than in an objective manner. As discussed earlier, the sound level meter is normally used to measure sound and it displays a linear relationship with sound pressure.

The tyre/road noise interaction generates running noise which can be heard, to a varying degree, inside and outside the vehicle. In this document, we shall concentrate mainly on the nuisance caused outside the vehicle. The discomfort caused to the environment by the vehicle rolling noise can be evaluated either by a global index or the measurement of the rolling noise of a single vehicle. The most representative global index is called L_{Aeq}.

Four categories of traffic are likely to cause adverse noise impacts from road projects and these are:

- High volume traffic flows along major roads impacting on quiet residential areas.
- Night-time movement of heavy vehicles along major roads affecting quiet residential areas. (The lower background noise at night appears to enhance the noise source.)
- Increasing traffic flows on local roads in quiet residential areas due to road upgrading or traffic management.
- Increased traffic flows on main roads with existing high traffic noise levels.

Again, people respond to noise in a subjective, rather than objective manner but the relative strength of a person's response can depend as much on factors such as the actual noise levels to which they are exposed.

The environmental impacts of noise on humans depend on several factors. These are the total sound energy received, the rate of occurrence of noise event, the time of day of such occurrence, the magnitude of the noisier events and the frequency spectrum of the noise.

In order to assess the effects of community noise on individuals, and to compare the effects of different noises, it is necessary to combine the aforementioned factors into a single number. The equivalent continuous sound pressure (or intensity) level, L_{Aeq}, is used in achieving this.

The equivalent continuous A-weighted sound pressure levels, L_{Aeq}, is defined as the steady sound pressure level which, over a given period, will produce the same total energy as that of the fluctuating sound being measured and expressed as,

$$L_{Aeq} = 10 \log \left[\frac{1}{T} \int_0^T \left(\frac{P_A(t)}{P_{ref}} \right)^2 dt \right] dB$$

where, T = measured time interval
$P_A(t)$ = instantaneous A-weighted sound pressure level, in pascals
P_{ref} = reference pressure which is 20 μPa

L_{Aeq} thus allows different noise events to be compared with regard to their total energies measured over the same time interval. The instrument used is called an integrating sound level meter.

Noise rating levels, L_R

Additional factors which contribute to the overall impact of sound are whether it is of impulsive nature (e.g. riveting, hammering, drum beat...) and whether the sound contains pure tones components (e.g. whine, whistle, music...).

The subjective response of our hearing is such that when presented with a sound containing a broad spectrum and another a pure tone, both of the same magnitude (sound level), we perceive the pure tone to be louder than the broadband noise.

In a similar way we are more sensitive to impulsive sounds than continuous sounds. Consider how annoying the dripping of a tap is even when the sound level is very low.

The rating level, L_R, includes such effects and is defined as the value of the L_{Aeq} measured during a specified time interval, plus special adjustments for tonal character and impulsiveness of the sound. It is derived from the relation:

$$L_R = L_{Aeq} + C_i + C_t$$

where, C_i = impulse correction = 5 dB
C_t = tone correction = 5 dB

Unless or otherwise stipulated, the reference time intervals are: Daytime 06:00 till 18:00hrs, evening 18:00 till 24:00hrs, night-time 00:00 till 06:00hrs. Weekends, Saturday 12:00 till 18:00hrs, Sunday 06:00 till 18:00hrs.

The Rating Level, L_R, of the sound under investigation is then compared with the prevailing residual sound level (with the sound under investigation absent) in the event that the two measurements cannot be conducted separately, the L_R is compared with typical levels in buildings contained in Table 2 of the SABS Code 0103:1994.

Table 2 below taken from the SABS Code 0103:1994 provides typical outdoor and indoor residual sound levels in various districts during the reference time interval defined above.

TABLE 2:Rating level for ambient noise (SABS Code 0103:1994)

1	2	3	4	5	6	7
Type of district	Rating level L_r [1] for ambient noise dBA					
	Outdoors			Indoors, with open windows		
	Day-time	Evenings, weekends	Night-time	Day-time	Evenings, weekends	Night-time
a) Rural districts	45	40	35	35	30	25
b) Suburban districts with little road traffic	50	45	40	40	35	30
c) Urban districts	55	50	45	45	40	35
d) Urban districts with some workshops, with business premises, and with main roads	60	55	50	50	45	40
e) Central business districts	65	60	55	55	50	45
f) Industrial districts	70	65	60	60	55	50

1) The values given in columns 2 to 7 are A-weighted sound pressure levels and include corrections for tonal character and impulsiveness of the noise.

NOTE — If the measurement time interval is considerably shorter than the reference time intervals, significant deviations from the values given in the table may result.

The excess which is over the residual level - or the typical level - is used to predict the probable community response to the noise under investigation by making reference to Table 3 as it appears in the SABS 0103, Table 3 shows a summarised community response to noise exposure.

TABLE 3: Estimated community/group response (SABS Code 0103:1994)

Excess of "new" L_R over existing L_R, dB	Probable community response
0	no observed reaction
$> 0 \leq 5$	sporadic complaints
$> 5 \leq 10$	widespread complaints
$> 10 \leq 15$	threats of community/group action
> 15	vigorous community/group action

It is interesting to see a comparison of the relative noise levels of a number of wearing courses, and to note just how quiet a well-designed porous asphalt can be. A typical example of tyre/road contact noise levels is given in the Table 4 below (Christie, 1994):

TABLE 4: Tyre/road contact noise levels (Christie, 1994)	
Surface type dBA external	**dBA external**
Block paving	82
Concrete	76-85
Surface dressing	74-81
Asphaltic concrete (asphalt pavement)	72-79
Porous asphalt	69-76
80km/h Dry conditions	

The noise levels shown in Table 4 above represent rolling noise of a pavement and therefore a direct comparison can not be made with the rating levels in Table 2. This is mainly because Table 4 represents global index measurements and not individual vehicle noises.

For the assessment of road traffic noise in South Africa the time interval is from 06:00 hours till midnight and is referred to as 18-hour L_{Aeq}. The L_{Aeq} for each hour (or half-hour) is measured from which the 18-hour L_{Aeq} is calculated.

By definition, the *residual noise* is the ambient noise that remains at a given position in a given situation when one or more specific noises are suppressed and the *ambient noise* is the totally encompassing sound in a given situation at a given time, usually composed of sound from many sources, both near and far. In simple terms, ambient noise is when everything is switched on and residual noise is when you switch off other sounds e.g. the pump. When measuring road noise, the background (residual) noise (including any wind noise) shall be at least 10 dBA below that produced by the vehicle or tyre noise.

As mentioned before a Conventional Twinlay porous asphalt is a double layered construction and is made up of a bottom layer of porous asphalt with a coarse single-grained aggregate (11/16) and a thin top layer of fine porous asphalt (4/8).

At 60km/h the Twinlay produces 64dBA as compared to 67 dBA from porous asphalt concrete 0/8, 68 dBA dense asphalt concrete 0/16 and 68.5 dBA from porous asphalt concrete 0/16. Comparing Twinlay with porous asphalt we can see that Twinlay offers a 3 - 5 dBA reduction.

6 MIX DESIGN APPROACH

The foundation of any fundamental approach to asphalt mix design should be the proper manufacture of laboratory samples which simulates the various field processes such as plant mixing, construction compaction and traffic and environmental effects. When preparing asphalt samples in the laboratory it is imperative to settle the question of producing realistic laboratory-fabricated test specimens in whatever form (e.g. cylinders, beams) that will responds to what ever test method or specimen configuration in a manner essential, identical to the response of test specimen taken from field pavements at any given stage of traffic and environmental exposure.

6.1 Process for the selection of optimum binder content

The general process for the selection of optimum binder content for porous asphalt mixes is illustrated in Figure 9 below (Taute et al, 2001):

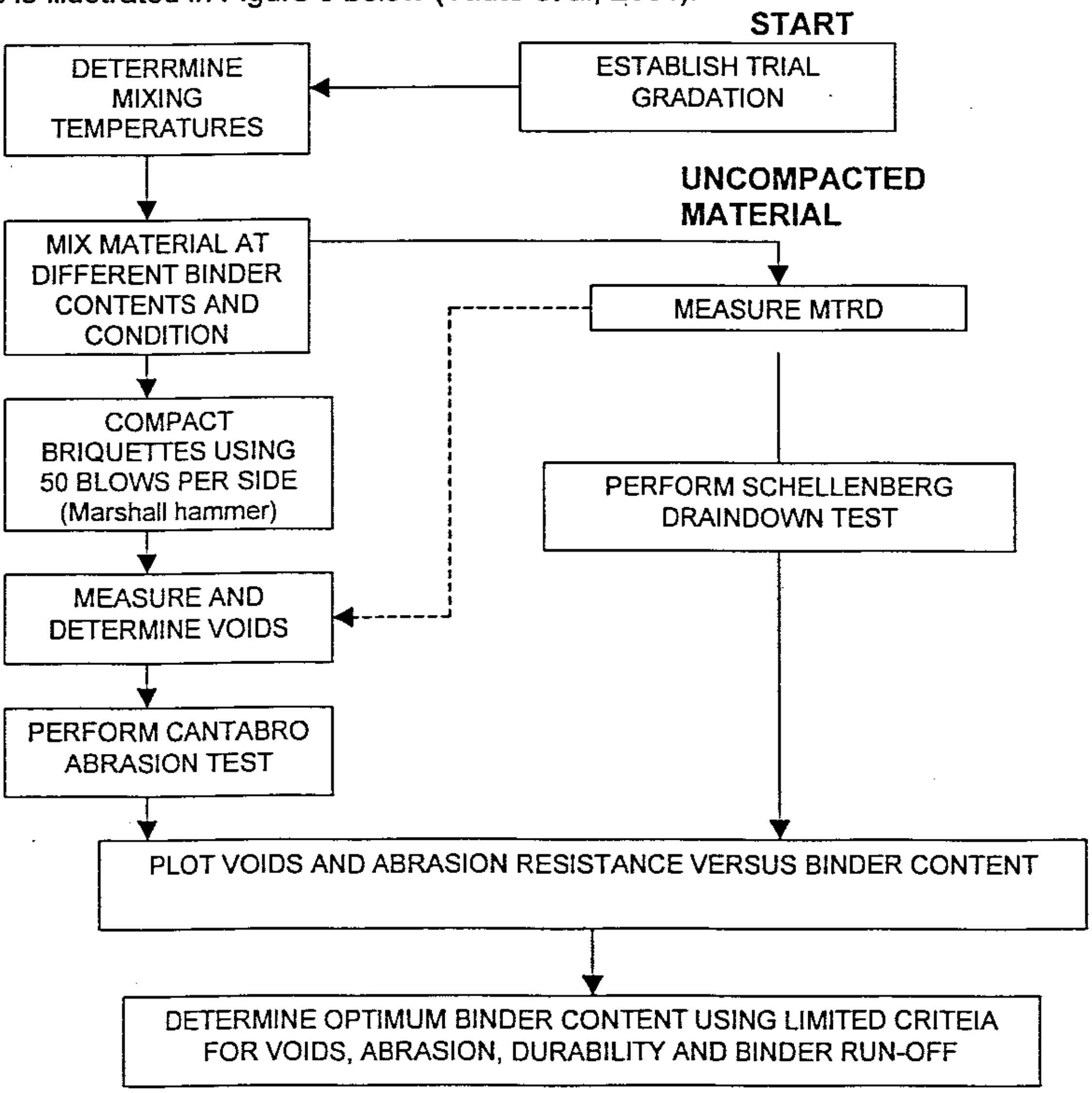

FIGURE 9: Process for the determination of optimum binder content for porous asphalt mixes (after Taute et al, 2001)

6.2 Selection of mix components

As it is the volumetric properties of porous asphalt mixes which reduce the noise levels and improve the drainage capacity, void content should form the essence of the mix design strategy. Binder type and content are equally important, as these influence the selection of an appropriate grading which will have a significant impact on the structural integrity of the mix. Both durability and abrasion resistance depends on the above factors and, in turn, are indirectly dependent on the viscosity properties of the binder/filler matrix (Sabita Manual 17,1995).

Guidelines on the mix design process are as follows (Sabita Manual 17):

- selection and testing of the mix components (aggregate, binder and filler)
- selection of appropriate grading based on target void content and related to the type and properties of the binder to be used
- determination of optimum binder content, with binder run-off, volumetric properties, abrasion resistance and durability being taken into account.
- evaluations of the design mix, in which resistance to deformation, ageing and moisture damage are taken into account or considered.

6.2.1 Selection of mix materials

There are three main variables that are considered important as these give us the desired properties of the asphalt namely:

- Binder type
- Aggregate type
- Filler type

6.2.1.1 Binder type

Binder type and content are important as these influence the selection of an appropriate grading which will have a significant impact on the structural integrity of the mix. The binder should also be in sufficient quantity to provide for durability and resistance to abrasion.

"*It is believed that deformation is mainly dependent on the quantity and type of* binder used but may be affected by grading. High binder contents may result in high film thickness and, if the binder is of low viscosity, the binder system may act as a lubricating agent at elevated temperatures, thus reducing the frictional resistance of the mix" (Verhaeghe, 1992).

In porous mixes, because of the open structure, a thick film of binder coating is recommended to it, in an attempt to retard early ageing. From this point of view binders with high viscosity would be preferred. In selecting the binder, other factors to be considered are weather and traffic volumes. In Spain the grades of binder *specified are 60/70 and 80/100. Rubber bitumen can be used to improve the* engineering properties of the mechanically modified asphalt mixes and to produce a more durable blend. To maintain a high void content, the mix binder is to be modified by thermoplastic elastomers with a very high degree of modification compared to a pure bitumen. Alternatively bitumen stabilizer (such as cellulose fibres) can be added, if required.

The appropriate modification of bituminous binders has increased the option available for either improving existing pavement mixtures or for creating new paving applications. The wide variety of possible additives now available with either verified or perceived benefits, makes it difficult to select a suitable type of additive for a particular application. It is therefore important that the different types of additives currently available to the asphalt industry be classified according to their generic types and principal uses.

The major types of additives can be classified into nine categories, as shown in Table 5 (Verhaeghe, 1992).

TABLE 5: Classification of asphalt additives (Verhaeghe, 1992).	
Genetic Type	**Available products**
Mineral filler	Dust, lime, Portland cement, carbon black, sulphur
Extenders	Sulphur, lignin
Rubbers	Natural latex Synthetic latex (styrene-butadiene rubber or SBR) Block copolymer (styrene-butadiene-styrene or SBS Reclaimed rubber
Plastics	Polyethylene Atactic Polyethylene or APP Ethylene-vinyl acetate or EVA Polyvinyl chloride or PVC
Fibres	Asbestos, rock wool, Polyethylene, polyester, cellulose
Oxidants	Manganese and other mineral salts
Antioxidants	Lead compounds, carbon, calcium salts
Hydrocarbons	Recycling and rejuvenating oils
Anti-stripping agents	Cationic surfactants, hydrated lime, silanes, iron naphthenate

Potential applications of some of the additives listed in Table 5 are shown in Table 6 (Verhaeghe, 1992). For several reasons (compatibility with bitumen, impact on binder and mix properties, practicability of utilization, cost, etc.), the group of additives generally used to modify porous asphalt mixes consists of polymers and fibres.

TABLE 6: Application of certain additives (Verhaeghe, 1992).		
Type of Problem	**Conventional treatment**	**Suitable additives to alleviate problem**
Stripping	Voids control	Anti-stripping additives
Thermal cracking	Softer binder	Rubbers
Rutting	Material selection and mix design	Plastic, fibres, sulphur, rubbers
Hardening of binder	Production and voids control	Anti-stripping agents
Flushing	Mix design	Plastic, fibres, rubbers
Segregation in the aggregate	Plant operations and mix design	High viscosity binder may help to a certain extent
Reflection cracking	None	Recycled rubber and fabrics
Consistency of binder in recycled mixes	Sufficient soft bitumen and sufficient virgin aggregate	Rejuvenating agents

Modifiers commonly used include natural and synthetic rubber, polymers and fibres.

6.2.1.1.1 Important fundamental binder characteristics for PA

In order to ensure a satisfactory service life for a porous asphalt, the binder must fulfil certain important criteria.

Rheology

It is self evident that the binder rheology is of primary importance. What is required is a binder which will not drain off the stones during transportation, will remain workable during application and will perform at the local ambient temperatures. It is clear that these rheological demands become even more severe in countries or regions where the ambient temperature range is wide as the binder will need to resist both densification at high summer temperatures and brittle fractures (with rapid pavement disintegration) at low winter temperatures.

Where the ambient temperature range is wide, most observers consider that modified bitumens exhibiting elastomeric properties and reduced temperature susceptibility give better performance than conventional bitumens or bitumens modified solely to increase softening point and improve workability.

Adhesion

Of very great significance is the question of adhesion. A porous asphalt binder must adhere strongly to the aggregate over a long time period to enable it to perform satisfactorily in the wet and/or high humidity conditions common in much of Europe. To ensure superior adhesion, bitumen additives, such as wetting agents (to ensure good initial binder coverage), adhesion agents and elastomers/polymers which improve adhesion, are often used to promote an intimate bonding to the stone.

The loss of adhesion is a common failure in porous asphalt pavements which normally results in stripping of the binder and subsequent loss of aggregate or raveling by traffic attrition.

Ageing

Rapid hardening of the binder is a specific problem related to porous asphalt.

6.2.1.1.2 Bitumen rubber

Bitumen rubber was first developed in the USA by Charles McDonald, who was experimenting with blends of fine rubber crumbs and bitumen. As early as 1981 South African companies were experimenting with locally formulated bitumen rubbers and hybrids of two overseas technologies. It is estimated to date that in excess of 200 000 tons of bitumen rubber has been produced and applied in South Africa.

Bitumen rubber is comprised of a mixture of penetration grade bitumen, graded rubber crumb and aromatic oils, blended in specific proportions and under very controlled conditions. A typical bitumen rubber blend is shown in Table 7 and a typical grading of the rubber crumb grading is shown in Table 8:

Table 7: Typical bitumen rubber blend (Sadler, 1998)

	% by mass
Bitumen	78
Granulated rubber crumb	20
Extender oil	2

Table 8: Typical rubber crumb grading (Sadler, 1998)

Passing screen (mm)	Mass (%)
0.180	100
0.600	45 - 65
0.075	0 - 5

When bitumen and rubber are mixed under controlled conditions a tough, durable product called bitumen-rubber is formed. This product is most suitable to act as

When bitumen and rubber are mixed under controlled conditions a tough, durable product called bitumen-rubber is formed. This product is most suitable to act as stress relieving membranes, crack filling material, waterproofing membranes, or even as a binder for asphalt for certain specialized applications. The product is however more expensive than bitumen and therefore it is of the utmost importance that the product performs as expected.

Characteristics of bitumen-rubber are as follows (Verhaeghe, 1998):

1. Flexibility down to -26°C
2. Greater viscosity than conventional bitumen at 60°C
3. Tougher and elastic binder
4. Greater resistance to ageing
5. Recycling of used rubber tyres

The properties of bitumen rubber on hot mix asphalt include the following (Verhaeghe, 1998):

- Tolerates higher deflections
- Greater resistance to fatigue
- Greater resistance to reflective cracking
- Good resistance to deformation and
- Good durability

6.2.1.1.3 Polymers

Polymers are categorised under the broad definition of macro-molecular additives. *From the point of view of bitumen modification, polymers can essentially be divided* into two groups:

- Plastomers (or plastics), i.e. those which exhibit predominantly plastic behaviour in the normal operational temperature range and
- Elastomers (or rubbers), which have elastic properties in this temperature range and which are marked by delayed reversible deformation.

Both groups are thermoplastic, i.e. they flow like viscous liquids at elevated temperatures. Obvious choice would be (i) the addition of plastomeric polymers to *standard paving grade bitumens in order to reduce permanent deformation (ii)* the addition of elastomeric polymer materials to bitumens in order to correct low temperature cracking problems. With existing polymeric materials the options are, however, not so limited. It has been proven by field experience (Verhaeghe, 1992) that soft bitumens modified by the addition of plastomers can also resist cracking and that modification by the addition of elastomers reduces rutting, especially when harder bitumen are thus used.

However, in order to obtain beneficial polymer-modified binder properties for improved performance, the achievement of good dispersion stability at high and low *temperatures and good compatibility between polymer and bitumen* are prerequisites. Furthermore, the chemistry of the modified binder should be such as to maintain bitumen-like properties at high temperatures in order to ensure ease of handling with conventional equipment and techniques.

6.2.1.1.4 Cellulose fibres

Cellulose fibres were developed in Europe as a substitute for asbestos fibres (which were banned from the market due to health reasons) in bituminous systems. Fibres usually used are either from mineral origin (natural or synthetic), or from organic origin (mostly cellulose fibres). Cellulose is an organic compound which is frequently found in nature.

Fibres, when added to asphalt mixes, are known to increase the resistance to plastic deformation. The introduction of fibres into bituminous mixes forms a relatively inexpensive means of improving the engineering properties of the mechanically modified asphalt mixes. The fibres reinforce the binder system which causes an increase in the binder's viscosity. Furthermore, depending on the type of fibre used, the chemical composition of the bituminous binder could be enriched to produce a more durable blend.

The resulting mix, therefore, could have higher stability, durability and possible higher resistance to fatigue cracking. The fibres can also prevent binder run-off during the mixing, transportation and lay-down operations, especially of porous asphalt mixes and mixes designed with discontinuous grading. The durability of the porous asphalt mixes may also be improved through the use of higher binder contents with resulting higher film thicknesses but with reduced gravitational drainage of binder through the material.

For inclusion in porous asphalt, the specified fine textured cellulose fibres should be of short length and have a considerable surface area. The organic fibres commonly used are grey, finely fibrillated, long-fibred cellulose with cellulose content of at least 75 percent (dry base) and a pH of 6.0 to 8.5. The maximum length of the fibres is 5 mm with average fibre length of approximately 1.1 mm, and their loose density is around 40 g/l. The fibres generally can resist temperatures of approximately 180°C for one hour without degrading.

Verhaeghe, (1992), concluded that the use of cellulose fibres does not have a significant effect on the volumetric properties of porous asphalt. The addition of cellulose fibres does not improve abrasion loss directly. However, the addition of cellulose fibres allows the use of higher binder contents (without the risk of binder run-off), which in turn improves abrasion resistance. Therefore, properties typical to porous asphalt such, as drainage capacity and noise reduction should not be affected by whether the mix contains cellulose fibres or not. Fibre-modified porous asphalt mixes allow aggregates to be coated with high binder contents, thus allowing aggregates to be coated with high binder film thicknesses, resulting in a mix with good resistance to the damaging effects of the environment (oxidation and moisture damage). However, it was noted that the addition of cellulose fibres or increase in fibre content could result in a decreased resistance to fatigue. Fibre-modified porous asphalt mixes are ideally suited for the approaches to an intersection in that mixes have high stability, good durability, remove excess rain water from the surface and provide the road user with a skid resistant surfacing.

It is highly recommended that fibres be introduced to the bituminous mix in-order to improve the engineering properties of the mechanically modified asphalt mixes. The fibres reinforce the binder system which causes an increase in the binder's viscosity. Depending on the type of fibre used, the chemical composition of the bituminous binder could be enriched to produce a more durable blend.

The resulting mix, therefore, could have higher stability, durability and possibly higher resistance to fatigue cracking. The fibres can also prevent binder run-off during mixing, transportation and lay-down operations, especially of porous asphalt mixes.

6.2.1.1.5 The effect of binder modification

From the literature study conducted by Verhaeghe, (1992), it appears that most international road authorities prefer to use either recycled rubbers or fibres to improve the engineering properties of porous asphalt mixes, and that the use of new polymers seem to be restricted to more dense asphalt mixes. Some comparative studies involving polymers, bitumen-rubber, cellulose fibres and unmodified binders indicated the superiority of fibres and recycled rubbers while the engineering properties of Styrene-Butadiene-Styrene (SBS) modified porous asphalt mixes only showed slight improvements by comparison with those of unmodified mixes.

The reason why polymer modified binders are not used on a large scale is that the modified blend, which initially has good rheological mechanical properties, may deteriorate rapidly with time and, after ageing (oxidation), becomes brittle at low temperatures.

6.2.1.2 Aggregate type

On account of the nature of the grading, the skeleton of porous asphalt should be adequate to resist plastic deformation (given that the aggregate is durable and of high strength and that the porous asphalt layer is well supported (Verhaeghe, 1992).

Aggregate for porous asphalt must be of good quality and conform to high specification. Aggregates considered for use in porous asphalt must undergo vigorous testing in the laboratory to ensure that all criteria specified for in Table 8 (Sabita Manual 17, 1995) are met. Materials that show great resistance to fragmentation, good and stable microtexture, and adequate interlock are recommended. These requirements help distinguish between suitable and unsuitable aggregates for porous asphalt. Fragmentation of aggregates can lead to particle losses, ravelling, and closing up of the surface texture by the separate fines. Aggregate grading and shape are also important factors as these can affect both durability and porosity.

In general terms, a coarse graded mix will show good porosity but may not have sufficient interlocking between the aggregates particles to give adequate durability. Alternatively, a fine graded mix will not drain as well but will be more durable (Woodside et al, 1999).

TABLE 9: Recommended aggregate properties	
Property	Recommendation
10 per cent FACT	>210kN
ACV	<21%
Polished Stone Value	>50
Flakiness Index	<25
Sand Equivalent Value	>45
Water Absorption	<1.0%

6.2.1.3 Filler type

The amount of filler is important as it stiffens the binder. One to two per cent of mineral filler is recommended as it enhances the adhesion properties of the binder and therefore reduces the potential for stripping. Mineral fillers such as commercial limestone powder, hydrated lime and cement are normally used. For binders of relatively low viscosity, higher proportions of filler may be required.

6.2.2 Selection of an appropriate grading

The selection of an appropriate grading depends on the type of binder selected and on the design void content.

It is very important that the void contents of the layer be in excess of 20 percent to regard the mix as porous. This makes it highly suitable for wet weather conditions, reducing traffic noise and increasing skid resistance. This assists in keeping the voids free from blockages such as clogging, will also assist in trying to maintain the mix's initial level of performance. Twinlay is a new generation of porous asphalt with a high void content, boasting high quality noise and permeability performance. The voids are interconnected providing a means of conveying rainwater to the pavement boundaries.

Increasing the void content allow designers to maintain and lengthen the life span of porous asphalt as far as noise and permeability are concerned. Given the fine grain size of the top layer mixture, it is important to keep porosity as high as possible and the flow resistance as low as possible.

The porosity of porous asphalt makes it extremely permeable to rain water. Compared to conventional porous asphalt, Twinlay has a much better drainage ability. This is caused by the higher percentage of voids in the mixtures.

The bottom layer which consists of large single grained aggregate helps discharge water from the pavement surface to the side of the pavement drains. Because of the size of the aggregate voids, water flows easily within them, therefore water does not stand on the surface of the pavement reducing splash and spray.

6.2.3 Laboratory preparations

6.2.3.1 Determination of optimum binder content

The optimum binder content is dependent on a number of limiting parameters which directly or indirectly influence the amount of binder to be used, namely:

- Voids content – the design void for a given grading controls the maximum amount of binder which can be used.

- Abrasion loss – the maximum permissible abrasion loss controls the minimum amount of binder which may be used. Abrasion loss is determined by means of the Cantabro abrasion test.

- Durability – a minimum binder content of 4.5 percent is often specified as a measure to ensure that the binder film thickness is sufficient to ensure good durability.

- Binder run-off – a maximum binder content is specified in order to prevent excessive binder run-off during transport and construction. The binder run-off for a given combination of aggregate, binder and fibre additives (if required) is determined by means of a basket drainage test or schellenberger test.

The optimum binder content is selected from the range determined by these four criteria. The design binder content (see Figure 10) is specified as the average of the higher of the minimum binder contents (durability and abrasion resistance) and the lower of the maximum binder contents (void content and binder run-off). Typical results of the procedures involved in the determination of the optimum binder content are illustrated diagrammatically in Figure 10.

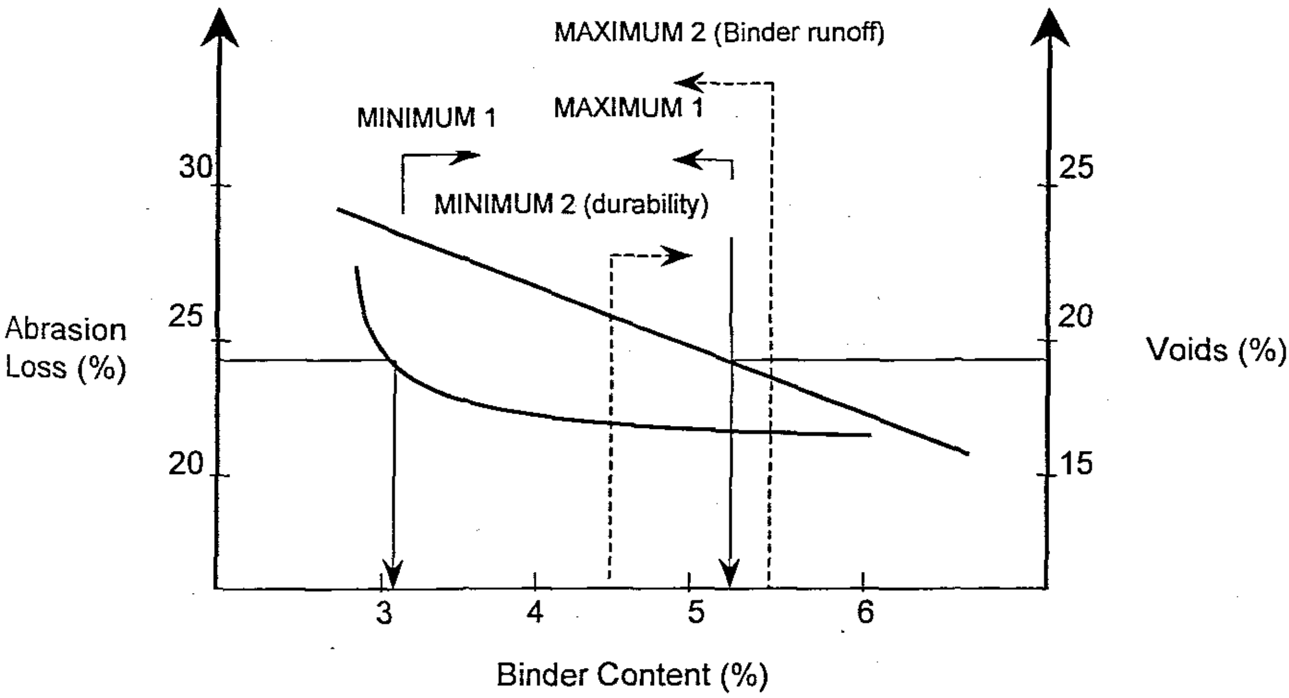

FIGURE 10: Typical graph used for determining optimum binder content (Sabita Manual 17, 1995)

Different stages are involved in the preparation of porous asphalt test specimens. Sample preparation in the laboratory and tests to be performed can be summarised as follows:

i) Mixing procedures should comply with the guidelines given in the appendix to method C2 of TMH 1 (DoT, 1986), *Technical Methods for Highways* ("Procedure for the making of asphalt specimens for the determination of resistance to flow and for voids analysis by the Marshal Method")

ii) Compaction of the briquettes is conducted in similar fashion to the guidelines given in the appendix to method C2 of TMH 1 (DoT, 1986). Crushing may be indicative of inadequate strength and additional tests (such as the Los Angeles rattler test described in ASTM Method C131-81) should be conducted to ensure that the aggregate is fit for its purpose.

iii) Uncompacted mixes are manufactured and cured in the same fashion as above to determine the apparent maximum relative density (Rice's method) and the resistance of the mix to binder run-off.

6.2.3.2 Determination of mix properties

The process for determination of mix properties is in accordance with the Sabita Manual 17 (Sabita Manual 17, 1995). Three criteria are used in the process of selecting the optimum binder content namely:

- total air void content (Volumetric analysis)
- abrasion loss (Cantabro test)

- *abrasion* loss (*Cantabro* test)
- loss of binder by run-off (Basket drainage or Schellenberger tests)

- Basket Drainage test or Schellenberger test, is used to determine the maximum binder content of a particular mix before the effects of binder run-off become excessive. Determining binder run-off for a given combination of aggregate, binder and fibre additives (if required).

- Cantabro abrasion test, determining abrasion loss, analysis of resistance of porous asphalt to abrasion loss. A minimum binder content of 4.5 percent is specified for durability. This is in accordance to European experience.

- Rice's test (used to determine the volumetric properties) it is conducted on the uncompacted mix in order to determine the apparent maximum relative density, alternatively, the apparent maximum density can be approximated by using an equation. The apparent bulk relative density can be determined on compacted samples and the air voids content of the mix (voids in mix) can also be calculated.

7 FACTORS AFFECTING THE DURABILITY OF POROUS ASPHALT MIXTURES

7.1 Introduction

A product which is durable is one which is able to exist for a long period of time without significant deterioration. The factors which affect the durability of bituminous mixtures", under this definition, would include all factors which contribute to deterioration.

Scholz and Brown (1996) defined durability as:

> *"The ability of bituminous paving material structure to resist the effects of water, ageing, and temperature variations, in the context of a given amount of traffic loading, without significant deterioration for an extended period."*

The principal failure mechanism resulting from traffic loading are cracking and permanent deformation, adverse environmental effects can accelerate the deterioration process. Many factors such as the composition of the bitumen, the type of and grading of aggregate, the interaction between bitumen and aggregate, bitumen content, mixture permeability, construction practices and climate affect the durability of bituminous mixtures. Assuming that a pavement layer is constructed according to specifications, it is generally agreed that the two primary factors that affect the durability of the mixture are embrittlement of the bitumen due to age hardening and damage due to moisture (Scholz and Brown, 1996).

If hardening of the bitumen is excessive, the mixture can become brittle and crack, resulting in partial or significant failure of the bound layer. Excessive hardening can also result in decreased adhesion between the bitumen and aggregate, often resulting in loss of material at the layer surface.

Damage due to moisture especially for porous asphalt wearing courses can also significantly influence the durability of bituminous mixtures. It is generally agreed that there are two mechanism by which moisture can degrade the structural integrity of the bitumen-aggregate matrix (Kennedy, 1985; Terrel and Al-Swailmi, 1992):

i) Loss of cohesion (strength) and stiffness of the bitumen;
ii) Failure of the adhesion (or bond) between the bitumen and the aggregate, often referred to as stripping.

Both mechanisms of water damage result in a weaker pavement layer. In addition, stripping can deteriorate the bituminous mixture to a virtually cohesionless state (Lottman, 1982)

Tolman and Van Gorkum (1996) consider that the durability of porous asphalt (PA) can be divided in mechanical and functional durability. Mechanical or structural durability deals with loss of material from the road surface.

Functional durability is concerned with:

- Clogging of pores, resulting in decreased noise reduction and discharge of water from the road surface
- Surface polishing
- Unevenness, caused either by loss of stones or deformation of lower layers
- Icing in winter times, this is not a common problem for South African roads

Mechanical damage can be categorized to its causes:

- Heavy local attack, e.g. by the rim of a tyre
- High shear forces, e.g. in sharp bends
- Gradual loss of stones resulting in a raveled surface and or potholes.

7.2 Water damage to bituminous mixtures

Although many factors contribute to the degradation of bituminous mixtures, moisture appears to play a major role. In general, water can reduce the stiffness or strength of the bitumen and aggregate to fail, both potentially resulting in significant distress to the pavement. The mechanisms of damage due to moisture are not clearly understood. However, many researches have investigated moisture sensitivity of bituminous mixtures and have provided significant advances towards understanding the mechanism involved (Scholz and Brown, 1996).

7.2.1 Mechanisms of moisture damage

It is generally agreed that moisture can degrade the integrity of bituminous mixtures in two ways (Kennedy, 1985; Terrel and Shute, 1989):

i) By causing a reduction in the cohesion strength and stiffness of the mixture, which is charecterised by softening;
ii) By causing failure of the adhesion (or bond) between bitumen and aggregate, referred to as stripping.

Lottman, (1982) provides a more comprehensive list of the moisture damage mechanisms that cause stripping and mixture softening. These are as follows:

i) Pore pressure of water in the mixture voids due to wheel-loading repetitions; thermal expansion-contraction differences produced by ice formation, temperature cycling above freezing, freeze-thaw, and thermal shock; or a combination of these factors. This is generally not a problem in South Africa;
ii) Bitumen removal by water in the mixture at moderate to higher temperatures;
iii) Water-vapour interaction with the bitumen-filler mastic and larger aggregate interfaces;
iv) Water interaction with clay minerals in the aggregate fines.

Of the mechanisms identified above, stripping has been given by far the greatest attention. It has traditionally been thought that stripping is related to rupture of the adhesive bond at the bitumen-aggregate interface, a complex phenomenon involving physical and chemical properties of both the bitumen and the aggregate, with the properties of the aggregate playing an important role in determining the adhesive properties of the bitumen-aggregate bond (Petersen, et al, 1982)

However, recent research has shown that cohesive failures within the bulk aggregate or bitumen (or both) rather than separation at the bitumen-aggregate interface, are a major mechanism where stripping occurs (Jamieson, et al, 1993).

The adhesion and debonding characteristics of a bitumen-aggregate system cannot be determined by the generic aggregate type but must be determined by the physical and chemical nature of the surface with which the bitumen comes in contact (Scholz and Brown, 1996).

7.2.2 Consequences of moisture damage

Scholz and Brown, (1996) explain this phenomenon as follows:

Damage due to moisture occurs in various forms and degrees of severity. As alluded to earlier, the primary consequence of moisture damage is that of stripping, characterised by failure of the bitumen-aggregate bond. Stripping can initially be manifested in localised areas where the bitumen has migrated to the surface of the bituminous layer, referred to as flushing or bleeding. This migration of bitumen results in an unstable matrix in the lower portions of the bituminous layer which can lead to permanent deformation in the form of rutting and/or shoving as well as the development of potholes and cracking under the action of traffic loading. But in general, bleeding is an indication of excess binder in a mix, overfilling the available void space. Excess binder will however promote rutting, but should protect against stripping

Subsequent intrusion of water into these localised water-damaged areas, coupled with traffic loading, further degrades the structural integrity of the pavement layer, possibly, underlying layers, which if not repaired could lead to substantial localised failure of the pavement structure. Stripping can also result in ravelling, which is characterised by loss of material at the surface of the bituminous layer.

The other major consequence of moisture damage is that of a reduction of stiffness in the bituminous layer which decreases the load spreading capabilities of the pavement. Under the action of traffic loading, a pavement with reduced stiffness due to water damage is prone to rutting as a result of increased stresses and strains in the underlying layers. Loss of strength in the bitumen-aggregate matrix may also encourage stripping.

7.2.2.1 Stripping characteristics of porous asphalt

Water ingress can lead to stripping in the lower part of the surface layer, which will adversely affect the cohesion properties of the material, as well as its adhesion to the underlying impervious base course. At the end of the service life, adhesion to the underlying pavement can effectively be reduced to zero if stripping takes place. The effective bearing capacity of the debonded layer can therefore reduce. At the end of service life, adhesion to the underlying pavement can be effectively reduced to zero if stripping takes place (Verhaeghe, 1992).

7.2.3 Ageing of bituminous mixtures

Age hardening of bitumen occurs as a result of compositional changes in the bitumen. For example, ageing due to oxidation, the primary cause of bitumen hardening, is believed to result primarily from the introduction of oxygen-containing chemical functionalities which, due to their polar nature, greatly increase molecular interaction forces, thus increasing viscosity (Petersen, 1990).

The changes that occur as a result of age hardening are, as yet, not well understood, primarily due to bitumen being a rather complex mixture of organic molecules. Bitumen varies widely in its complex mixtures of organic molecules and also in composition.

7.2.3.1 Ageing characteristics of porous asphalt

As a result of the relatively open structure of porous asphalt, the binder is likely to undergo accelerated ageing due to oxidation, which in turn will increase the stiffness of the material considerably. Under site conditions, the penetration of conventional bitumens has been found to drop sharply in the first month. Binder containing recycled elastomers such as bitumen-rubber, age at a slower rate. The ageing of binders with elastomers is midway between that of conventional bitumens and bitumen-rubber (Verhaeghe, 1992).

The increased thickness of the binder layer in the case of fibre-structured asphalt and rubber powder-based bitumen containing antioxidants, or the use of polymer bitumen represents a great advantage in the field.

7.2.4 Effects of temperature

Verhaeghe, (1992) explains the effects of temperature as follows:

The thermal characteristics of porous asphalt mixes have a positive impact on the overall structure of the pavement. It has been postulated that the suction and pumping action of tyres passing over porous asphalt surfaces, coupled with wind motion, will promote continuous circulation of air within the pores. In consequence, the temperature in porous asphalt wearing courses is more likely to remain closer to the prevailing air temperature than that in dense-graded surfacing materials. This is especially important in summer months, where the temperature of dense asphalt roads can rise to as high as 60°C. Under such conditions, the stiffness of asphalt structures with porous asphalt courses is less affected by the warm weather. In comparison with structures of dense asphalt wearing courses, the relative stiffness of the structure effectively increases, which reduces the strain in the lower part of the structure and therefore extends the fatigue life. This implies that thinner constructions could be used in order to achieve a given fatigue life.

Since the temperature differences between structures with porous asphalt and dense asphalt wearing courses are expected to increase as a function of the ambient temperature, structures with porous asphalt are likely to retain a far better resistance to rutting. On pavements in the Netherlands it was observed that, whereas an average rut depth growth of 1.5 mm/year was measured on conventional wearing courses, there was hardly any evidence of rutting on porous asphalt test sections during a service life of 10 years, the reason being that the porous asphalt mixes contained less fines and had a better mechanical interlock of coarse aggregates than the conventional wearing courses.

7.2.4.1 Densification or rutting of porous asphalt wearing courses

In this type of mix with very high void content (in excess of 20 percent), not surprisingly, the mix design is critically important in ensuring good performance. The MMLS Mk3 is commonly used to provide essential information on the pavement distresses such as plastic deformation (densification or rutting, fatigue e.t.c). However, even with careful mix design, densification under the action of heavy traffic is a well recorded phenomenon and can be attributed to the viscous flow of the binder under the effects of continued wheel loading. As with conventional asphalt, porous asphalt deforms under the effect of wheel load. Remove the load and much of the deformation recovers. The small amount of permanent residual strain that remains in the asphalt is due to the viscous flow of the binder.

For a viscous binder (such as normal bitumen) under most circumstances, the higher the level of heavy traffic, the faster the rate of densification. In addition, as bitumen viscosity reduces with increasing temperature, for any particular grade of bitumen, densification tends to increase with increase in temperature.

Most observers consider that binders which exhibit elastomeric properties increase the resistance to compaction of porous asphalt mix.

As mentioned earlier, deformation depends on the quantity and type of binder used but may be affected by the grading. By incorporating an elastomer in the binder, the visco-elastic balance of the binder is changed making the asphalt less susceptible to deformation and compaction under traffic thus extending pavement life. Other types of polymer modified bitumen can also reduce the rate of porous asphalt by stiffening the binder (effectively raising its viscosity at the ambient temperature) and hence reduce the viscous flow.

7.2.5 Clogging

Experience has shown that the high air voids content (in excess of 20 percent) may become partially filled with dust, reducing the effectiveness of the mix in the long-term. This is known as void clogging and is a very commonly reported problem of porous asphalt. Porous asphalt can be blocked very quickly with detritus such as tyre rubber, leaves, dust, soil, crushed aggregate and other road debris.

Some authorities claim that the most effective answer is to design a mix with a very high void content, thereby creating larger interconnecting voids which are likely to trap the debris. However, as a general rule, the larger the void content of the mix, the more demanding the role of the binder in ensuring that the aggregate mix is properly bound and capable of resisting compaction, and that the binder ageing and stripping will be minimised.

In practice it has been found that clogging of the pores by ingress of silt reduces the absorption properties of porous road surfaces after a few years. These surfaces are difficult to keep clean on roads with low speed traffic although on high speed roads air pumping action of tyre provides a self cleaning action (Jongens, 1995). Many observers consider that, on highly trafficked roads, the pumping action of tyres assist in keeping the voids free from debris and the asphalt free draining.

"The most important aspect in the practical wide spread application of porous asphalt surfaces however, is the expected performance after several years. It is known that due to clogging and ageing of the surface, both the absorption and the texture degrades which will lead to a significant loss of reduction capacity" (Van Blokland, 1997)

Preventative and curative measures have to be found to eliminate, or at least to retard the clogging effect, subsequently optimizing the resistance against clogging of a porous asphalt pavement.

With the introduction of a Twinlay porous layer, it is expected that the clogging effect will be reduced. This is due to the top thin layer with finer aggregates acting as a sieve preventing the pores of the bottom layer from being clogged. The dirt concentrated in the top layer can easily be removed with a special cleaning technique.

Clogging up of the voids of the porous asphalt with detritus occurs over time (Hiersche and Freund, 1992). It was proven that thicker porous asphalt layers [and multi-layers] have a better resistance to clogging as compared to thin layers [20 mm] of porous asphalt which clogged up over a period of 1 to 3 years (Thompson, 1993). A number of research initiatives conducted in Europe revealed as general anticipation that a properly designed drainage asphalt, laid on major road or motorway will be free draining for at least seven or eight years before densification and blockage by debris renders the asphalt non-porous.

It should also be noted that the asphalt doesn't necessarily need to be free draining to exhibit noise reduction properties. Some pavements in France with asphalt having void content of only 10 to 12 percent (not free draining) have shown that there is still a very significant reduction in tyre/road noise.

7.2.6 Aggregate loss due to abrasion

One of the major mechanisms of failure of porous asphalt is loss of aggregate by traffic attrition i.e. by abrasion (Sabita Manual 17, 1995). The working conditions of porous asphalt show that the most common reason for the loosening of the friction coarses, is that of the abrasive action of the traffic (Colonna, 1996). The selection of a higher binder content and the use of a high viscosity binder e.g. bitumen rubber will improve the durability and the resistance to loss of aggregate by abrasion.

The strong tangent tensions which come from abrasive action of the traffic, especially in the presence of open mixtures, can cause great problems to the asphalt wearing coarse and lead to the rupture by means of stripping or detachment.

The Cantabro Abrasion Test can be used to simulate the abrasion that takes place on the road in the laboratory in order to protect the layer against premature aggregate loss.

8 EVALUATION OF DESIGN MIX

It is important that the porous asphalt mix be subjected to accelerated testing procedures in order to assess the pavement performance prior to construction. A number of test that can be performed include:

- Resistance to permanent deformation
- Resistance to ageing
- Resistance to moisture damage
- Accelerated Pavement Test (APT)
- Road and traffic noise measurement tests

Resistance to permanent deformation

- Wheel tracking test, a wheel tracking test simulates asphalt materials under a rolling tyre and is more accurate for characterising asphalt materials. A further aspect of interest is water sensitivity of bituminous pavements, in many cases a crucial factor for the service life of bituminous layers. The immersed wheel tracking test is regarded as more realistic for studying the resistance to stripping.

- Confined dynamic creep test (triaxial test), the use of a conventional triaxial cell appears to be the best method of carrying out confined tests.

Resistance to ageing

- Accelerated ageing test, used to ensure that polymerization of the binder in service does not result not result in an excessive reduction in cohesive and adhesive strength which, in turn, may lead to raveling of the design mix.

Resistance to moisture damage

- Lottman method, used to conduct moisture conditioning. This method has been designed to simulate the long-term effect of moisture damage as a result of environmental conditions and traffic forces.

Accelerated Pavement Test (APT)

- Model Mobile Load Simulator (MMLS Mk3), this is an Accelerated Pavement Test (APT) performed on a pavement. This test allows a rapid assessment of factors such as rutting and fatigue potential of different asphalt mixes under laboratory controlled conditions.

Road and traffic noise measurement tests

For the purpose and scope of this research, only the Impedance or the standing wave tube apparatus was used to assess the acoustic properties of a Superfine Twinlay porous asphalt layer. Below is a list of all possible tests for evaluating road/traffic noise in the lab or in the field and these are as follows:

1. Standing wave tube, Measures sound power absorption coefficient of a porous material. This test is highly recommended for assessing the sound absorption properties of a freshly compacted Marshall briquette in the laboratory before the road is constructed in the field.

2. $\propto$-in-situ measurement of plane wave absorption (Texture and in-situ absorption measurements), this device measures the acoustic absorption characteristic on the location. This is a non-destructive test for porous pavements. This device is still being developed at UCT acoustics lab.

3. Trailor test or close proximity test, it is performed on a finished road surface and measures the noise produced by the tyre. New standards are being developed for this test.

4. Drive – by test, measures all noise from the car.

9 CONCLUSIONS

Since the inception of porous asphalt surfaces in the 1950s. Many countries world-wide have been engaged in an ongoing attempt to reduce road traffic noise. Road traffic noise is the most important single source of community noise, which may be because traffic noise is the most difficult noise to eradicate. The continuous increase in noise pollution poses a serious threat to the environment. The focus has been on reducing noise from the source i.e. rolling noise, as this is a predominating effect at vehicle speeds above 50 km/h. Porous asphalt reduces road traffic noise by about 4 decibels in dry conditions and by about 8 decibels in wet conditions as compared to densely graded asphalt mixes. Porous asphalt mixes can also be used for reducing aquaplaning subsequently splash and spray and improved visibility, improving permeability leading to improved skid resistance, improved driver comfort and many other advantages. The voids in the mix play an important role in the performance of porous asphalt surfaces.

But the clogging of the voids soon dissipates its excellent properties. Twinlay was developed with an intention of offering solutions to the drawbacks of conventional porous asphalt surfaces and most importantly to reduce road traffic noise produced by tyre/road contact. Moisture damage of porous asphalt surfaces has an adverse effect on durability. The performance of this surface design can be further improved by introducing a finer top layer with a more single grained aggregate grading. A high viscosity binder e.g. bitumen rubber will improve its durability and resistance to abrasion.

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CHAPTER 3

VOLUMETRIC ANALYSIS OF SUPERFINE TWINLAY

1 INTRODUCTION

Porous asphalt is expected to be the future trend for flexible pavements or rigid pavements in South Africa, especially in wet areas. Porous asphalt has gained prominence due to its excellent functional properties. Porous asphalt wearing courses are bituminous mixes with discontinuous grading whose void content are in excess of 20 percent and in which the nature of the voids is such that rainwater can be conveyed through a system of interconnecting voids to the boundaries of the pavement.

Porous asphalt surfaces have proven to be an effective and reliable way to reduce rolling noise from road vehicles. The primary properties of porous asphalt is its high porosity; its capacity for reducing traffic noise pollution; its good resistance to aquaplaning and reduction in splash and spray from vehicles in wet weather thereby improving the skid resistance.

However, as a result of the relatively open structure of porous asphalt, the binder is likely to undergo accelerated ageing due to oxidation, which in turn will increase the stiffness of the material and decrease the ductility of the binder system. This in turn may lead to early fatigue failure and to ravelling. Also porous asphalt has relatively low structural strength (low stiffness, indirect tensile strength, and shear strength) by comparison with that of dense-graded asphalt mixes and the relatively thin films holding the aggregate structure together may be insufficient to counter the loss of aggregate particles as a result of moisture attack and of the abrasive forces of traffic (Sabita Manual 17, 1995).

There is thus a great need to manufacture and produce realistic asphalt samples in the laboratory that simulate closely the field processes (e.g. plant mixing, construction etc.). It is also important that a stringent approach be followed during the mix design stage as it is the volumetric properties of porous asphalt which reduce the noise levels and improve the drainage capacity, void content should form the essence of the mix design strategy and the design strategy should be able develop a balance design to optimise both the functional and structural properties of porous asphalt.

The mix design adopted for this research project was a Superfine Twinlay with the bottom layer consisting of thick layer of 9.5 - 13.2 mm (materials passing 13.2 mm sieve and retained in a 9.5 mm sieve) coarse single grained aggregates with an upper layer consisting of a thick overlaying of superfine porous asphalt aggregates 2.36 - 4.75 mm mix and a rubber-bitumen binder (with 20 percent rubber crumbs) for both layers. At this stage the overall thickness of the layer was not taken into account. Chapter 4 covers a number of mix designs with different thicknesses.

2 APPROACH TO THE STUDY (OBJECTIVES)

The main aim at this stage is to determine the optimum binder content to be used for this particular mix design. For the purpose of volumetric analysis it is important to note that each layer both top and bottom were evaluated separately. This study involved the making of realistic samples of Superfine Twinlay and subjecting them to different tests.

A flowchart showing different stages involved in the preparation, compaction and testing of the briquettes is shown in Figure 1.

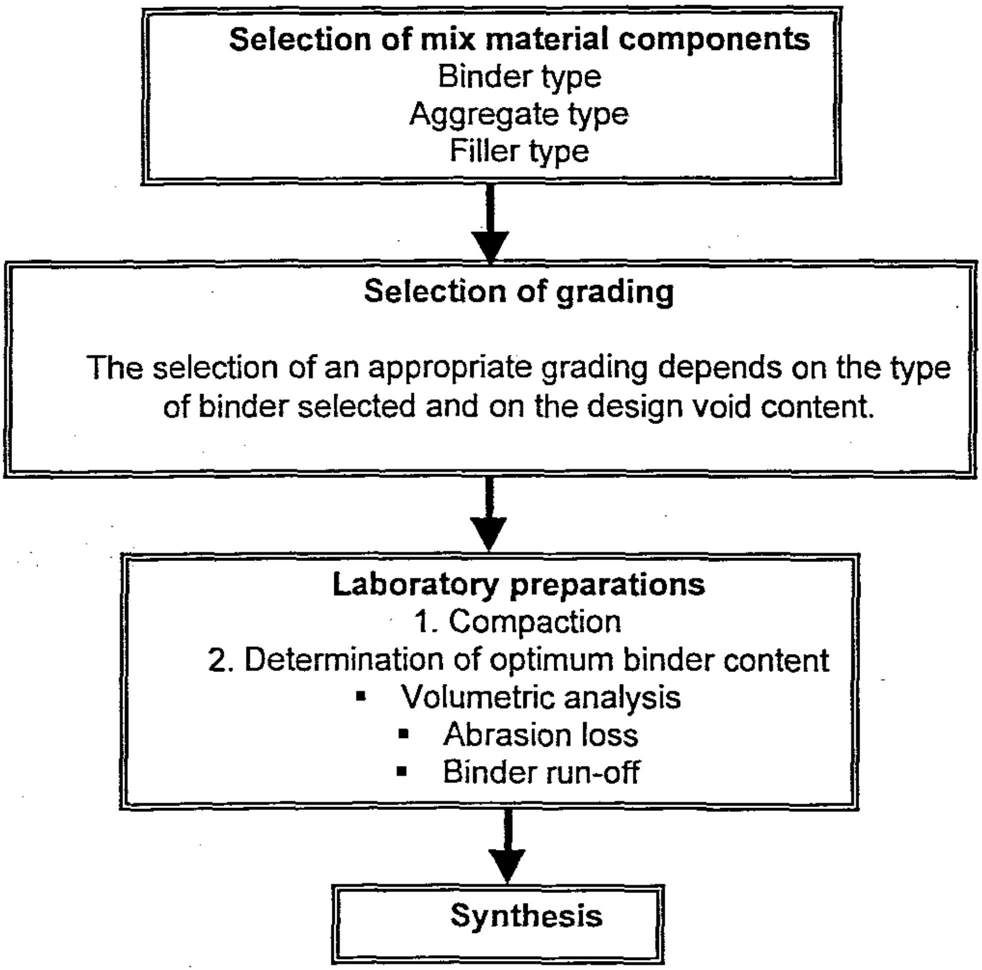


FIGURE 1: A flowchart showing a schematic overview of the different stages involved in the preparation, compaction and testing

3 EXPERIMENTAL DESIGN

3.1 Independent variables

The following factors were investigated and are reported upon:

- Effects of binder content;
- Effect of grading type, and
- Effects of filler type.

Binder content

It is suggested that at least four binder contents be investigated in the manufacture of porous asphalt mixes with the binder content starting from 3.5 percent by mass of total mix, in increments of 0.5 percent (SABITA Manual 17, 1995). Overseas practice specifies a minimum binder content for durability purposes (Verhaeghe, 1992). The minimum binder content depends on the abrasion loss of the mix.

Binder type

Only one binder type was used which is a 60/70 penetration grade bitumen with 20 percent rubber crumbs. The rubber crumb grading and properties are indicated in Table 2. Binder type and content are important as these influence the selection of an appropriate grading which will have a significant impact on the structural integrity of the mix. High viscosity binders such as bitumen rubber are recommended for mixes with very high void contents (in excess of 22 percent).

The physical properties of the binder, before mixing and compaction are given in Table 1. The results indicate that the binder is within the specification (except for the resilient modulus and the 0.600 mm fraction of the rubber falls outside the specification) and but nevertheless it is still fit for its use.

TABLE 1: BINDER PROPERTIES					
Time Elapsed in Min.	**60**	**120**	**180**	**240**	**300**
Ring & Ball (°C)	68.3	62.6	59.9	58.3	57.3
Viscosity @190°C	5500	5000	4400	3800	3400
Flow (mm)	14.3	23.4	29.7	33.2	31.6
Ball Penetration	3	5	7	9	8
Compression Recovery (%)					
5 Minutes	94.5	89.1	96.2	97.4	97.9
60 Minutes	98.4	93.3	98.1	98.4	98.8
4 Days	37.7	54.6	54.3	42	36.9

Please note that the compression recovery was done after the elapsed time as indicated in Table 1.

TABLE 2: RUBBER CRUMB GRADING & PROPERTIES			
Sieve	**Crumb**	**Specification**	
1.18 mm	100	100	100
0.600 mm	63	40	60
0.300 mm	27		
0.150 mm	9		
0.075 mm	2.1	0	5
Resilience (%)		91	
Loss of Resilience (%)		10.9	
Natural Rubber Hydro C %		20	

The manufacture of bitumen rubber for the Twinlay mix

Tyres for recycling were shredded and graded to the correct size. At a normal asphalt facility, the resulting rubber crumb was mixed together with bitumen at a temperature between 180-210°C. the bitumen-rubber blend was then allowed to react for 1-4 hours.

Aggregate type

Aggregates from the Peak/Eerste River quarry were used for this research project. The type of aggregate was a Malmelsbury Hornfels. The recommended aggregate properties are given in Table 3. The results indicate that these aggregates fall within the specified recommendations.

TABLE 3: Recommended aggregate properties

Property	Recommendation	Peak/Eerste River Quarry
10 per cent FACT	>210kN	446kN
ACV	<21%	9%
Polished Stone Value	>50	55
Flakiness Index	<25	23
Sand Equivalent Value	>45	55
Water Absorption	<1.0%	0.5

Grading type

The design voids content can be achieved by the selection of an appropriate grading. The grading that was used is shown in Table 4 and the grading curve for the top and bottom layers are shown in Figure 2. Selection of this grading depends on the design voids content (exceeding 20percent) and the type of binder (e.g. bitumen rubber) selected. The mix components for the top layer are shown in Appendix D Table D-1 and the bottom layer in Table D-2.

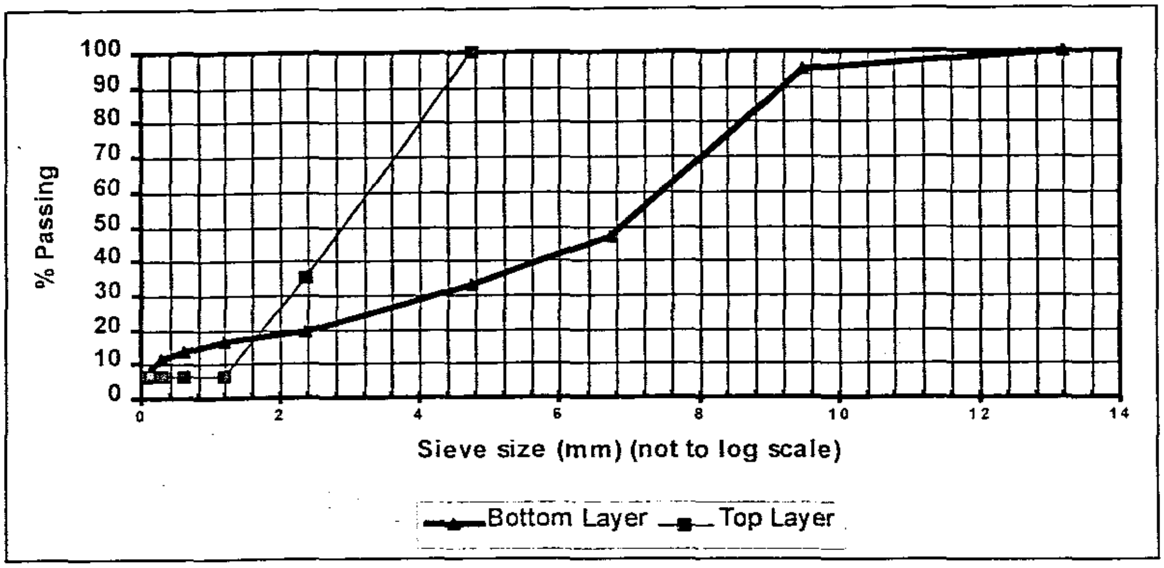


FIGURE 2: Design grading curve for the Top and Bottom layer

TABLE 4: Gradation for Superfine Twinlay (Percentage Passing)

Sieve size (mm)	Bottom layer (%)	Top layer (%)
26.500		
19.000	100	
13.200	95	
9.500	47	
6.700		
4.750	19	100
2.360	9	20
1.18		6
0.600		
0.300		
0.150		
0.075	3	3

Filler type

The amount of filler is important as it stiffens the binder. Normally one to two per cent of mineral filler is recommended to enhance the adhesion properties of the binder and therefore reduces the potential for stripping. Nevertheless, 3 percent cement was used because of the type of grading for Superfine Twinlay with a very high void content (see Table 4).

Experimental design

The experimental matrix adopted and followed for this research project is given in Table 5 below:

TABLE 5: Experimental design

	Binder content						
GRADING TYPE:	4.0 %	4.5 %	5.0 %	5.5 %	6.0 %	6.5 %	7.0%
2.36 - 4.75mm Top Layer	X	X	X	X	X	X	X
9.5 - 13.2mm Bottom Layer	X	X	X	X	X	X	X

3.2 Response variables

The variables monitored and the number of test repetition for each condition were as follows:

- Volumetric properties — 3 repetitions per condition
- Abrasion resistance — 3 repetitions per condition
- Binder run-off — 1 repetition per condition

Aggregates and all moulds were heated in the oven prior to mixing and compaction. Mixing procedures were in accordance with the appendix to method C2 of TMH1 (DoT, 1986). During mixing, the bitumen-rubber binder was mixed with the aggregates at 145°C, the void, or airspaces, became an important component of the material. The mixture was then placed into the pre heated moulds and compacted at 130°C using a pre heated Marshall hammer.

The recommended mixing and compaction temperatures for bitumen-rubber asphalt are indicated in Table 6. The materials were mixed according to Appendix D, Table D-1 and Table D-2. The mixing and compaction temperatures were monitored using a Laser Thermometer.

TABLE 6: Recommended mixing and compaction temperatures (Sabita Manual 17, 1986)		
Binder type	**Temperature**	
	Mixing	**Compaction**
Bitumen-rubber asphalt	140 °C +/- 5 °C	130 °C +/- 5 °C

Bitumen rubber asphalt need not be subjected to conditioning procedures prior to compaction to simulate the process of mix production, transportation and paving since it is a heterogeneous binder with temperature- and time-dependent properties. Compaction of the briquettes was also done in accordance with the appendix to method C2 of TMH1 (DoT, 1986). All porous asphalt briquettes were compacted 50 blows to each face of the specimens using a standard Marshall hammer.

After extrusion of the briquette from the metal mould, the heights of the cooled specimens were determined to the nearest 0.1 mm using a pair of Callipers. The density of compacted porous asphalt briquettes was determined from the dry mass of the specimen (in grams) and its volume (in cubic centimetres). The volume was calculated by taking the diameter of the sample as the internal diameter of the mould (usually 101.6 mm). The density (mass over volume) was then converted to apparent bulk relative density by dividing the density by 0.99707 g/cm^3, the density of water at 25°C. Voids content was then calculated using the apparent maximum relative density and apparent bulk relative density.

Three Cantabro abrasion tests were conducted for each grading, filler type and binder content. The maximum permitted abrasion loss value for freshly compacted specimens is 25 percent; this is based on overseas experience.

Only one basket drainage test was conducted for each binder content and grading type.

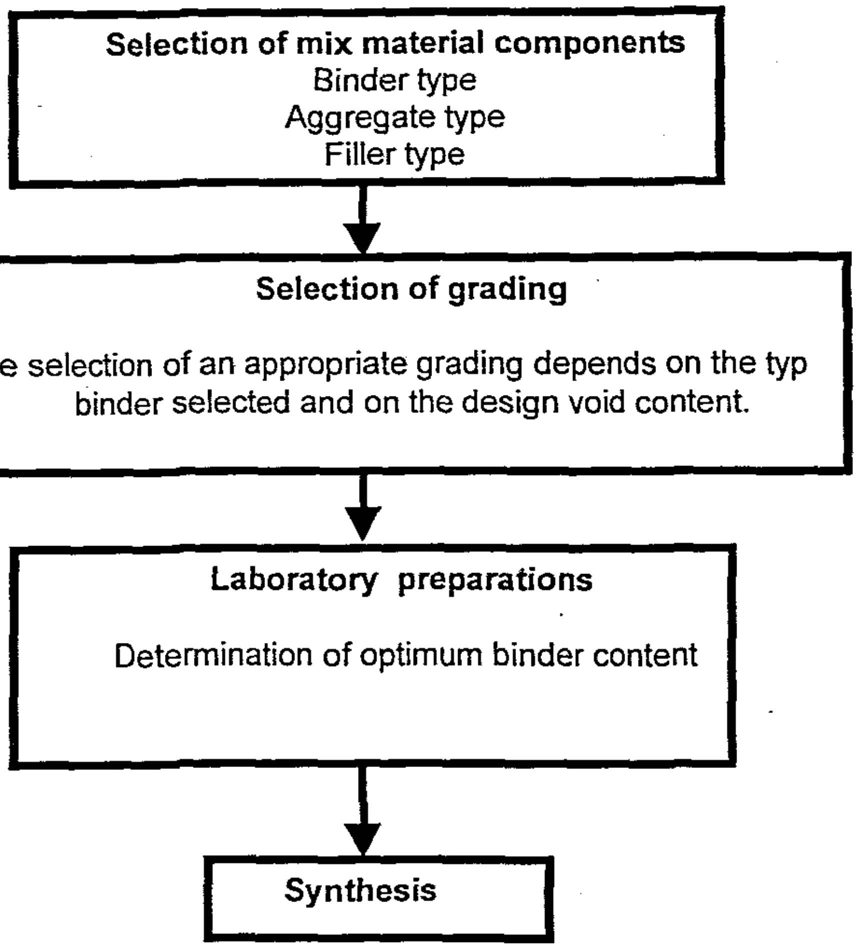
4 DESCRIPTION OF TEST METHODS USED

A number of laboratory tests were performed at the University of Stellenbosch in order to analyse the volumetric properties of a Superfine Twinlay. These are summarized as indicated in Table 7.

TABLE 7: Tests on the mix designs.

Test method	Used to determine
1. Rice's test	Determine apparent maximum relative density includes apparent maximum density and voids content (volumetric properties).
2. Cantabro abrasion test	Determine abrasion loss due to traffic attrition.
3. Basket drainage test	To simulate and quantify the amount of binder run-off for a particular mix type which take place during construction operations (transportation and laying)

A summarised flow chart showing all the different stages that were followed in the selection, manufacture and testing of the mix design under investigation for the volumetric analysis are shown in the chart below:



5 RESULTS FROM LABORATORY TESTS PERFORMED ON SUPERFINE TWINLAY DESIGN MIX

5.1 Results from the Volumetric Analysis

The apparent maximum theoretical relative density was obtained by conducting Rice's Test Method. This test was conducted on an uncompacted mix as in accordance to Method C4 (DoT, 1986) and the apparent bulk density was conducted as described in Sabita Manual 17 (Sabita Manual 17, 1995). For the detailed results (refer to Appendix C, Table C-1), these results indicated that:

- Both Superfine Twinlay grading have a very high void content with the bottom layer yielding a higher void content as compared to the top layer.

- There was a slight reduction in void content, as the bitumen content was increased from 4 to 7 percent at half percent intervals.

5.2 Results from the Basket Drainage Test

The Basket Drainage test is used to determine the maximum binder content of a particular mix before the effects of binder run-off become excessive. This test was performed at Colas South (Pty). Ltd. – Eester River laboratories under the supervision of Mr. H. J. Appolis (Technical manager). This test was performed on uncompacted porous asphalt mixes. A summarized test procedure of a Basket Drainage test is shown in Appendix E. The uncompacted porous asphalt mixes were prepared at various binder contents ranging from 4 to 7 percent at half percent increments. These samples were tested and yielded the following results (as indicated in Appendix B, Table B-1:

- There was no drainage of bitumen for both gradings (top and bottom) and for all bitumen content increments contents ranging from 4 to 7 percent at half percent increments.

5.3 Results from the Cantabro Abrasion Test

The Cantabro abrasion test allows porous asphalt briquette's resistance to abrasion loss to be analyzed. The operational procedure for this method is described in Appendix F. A comparison with respect to abrasion resistance was made between using cement and lime as filler in the mix. This test was performed at SOILLAB (Pty) Ltd. under the supervision of Mr. W. A. Venter (Director).

The results of this test (see Appendix C, Table C-2 and Table C-3) using cement and lime filler indicated that:

- Resistance against aggregate loss due to abrasion increases with an increase in binder content.

- Both grading for the top and bottom layer with lime or cement filler showed (see Appendix A, Figure A-1 and Figure A-2) a poor abrasion resistance especially at low binder contents (4.0 and 4.5 percent).

- The top layer with cement showed a better resistance against abrasion (less than 25 percent suggested maximum permitted abrasion loss value for freshly compacted Marshall briquettes) at high binder content (6 percent and above)

- A mixture with cement as a filler performed significantly better than the mixture with lime.

- Using lime for the bottom layer yielded very poor resistance against aggregate loss when subjected to the Los Angeles Rattler.

The above observations indicate that for this type of grading with a very high void content, the use of cement filler offers a better resistance of the mix to abrasion loss. The selection of a higher binder content in the mix reduces the potential of abrasion loss.

5.4 Volumetric properties

The following volumetric properties were determined and are reported upon:

- apparent maximum relative density
- apparent bulk relative density
- Voids content

The apparent maximum relative density, apparent bulk relative density and voids content for the top and bottom layer compacted mix designs are given in Table 8. The results indicate that as the bitumen content increases, there is a reduction in the voids content. At high bitumen binder content (6.5 percent), the voids in the mix are still large enough to classify the mix as a porous asphalt mix, but at higher bitumen binder content (7 percent), the mix could no longer be classified as a porous mix (voids less than 20 percent). The grading of the bottom layer indicate a higher void content in the mix than that of the top layer, but there was no significant variation between the void contents of both gradings.

TABLE 8: Apparent maximum relative density (D_m), Apparent bulk relative density (G_b) and Voids in mix V_m (percent)

	Binder content						
GRADING TYPE:	4.0 %	4.5 %	5.0 %	5.5 %	6.0 %	6.5 %	7.0%
2.36 - 4.75mm Top Layer							
G_b	1.830	1.841	1.872	1.894	1.919	1.969	2.017
D_m	2.556	2.539	2.526	2.504	2.497	2.463	2.475
V_m	28.4	27.5	25.9	24.3	23.2	20.1	18.5
9.5 - 13.2mm Bottom Layer							
G_b	1.854	1.868	1.896	1.902	1.923	1.959	1.980
D_m	2.614	2.583	2.576	2.546	2.481	2.474	2.462
V_m	29.1	27.7	26.4	25.3	22.5	20.8	19.6

6 ENGINEERING PROPERTIES

6.1 Results from the Cantabro abrasion test

A comparison between using cement and lime as filler was made. The same amount of cement and lime filler was added for both top and bottom layer grading. The summarized Cantabro abrasion test results are indicated in Table 9 and the graphical presentation in Appendix A, Figure A-1 and Figure A-2. The full table of results is given in Appendix C, Table C-2 for 3 percent cement and Table C-3 for 3 percent lime. NB, the results shown in Table 9 are average values for the three repetitions per binder content as investigated.

TABLE 9: Cantabro abrasion test using 3% cement							
	Binder content						
GRADING TYPE:	4.0 %	4.5 %	5.0 %	5.5 %	6.0 %	6.5 %	7.0%
2.36 - 4.75mm Top Layer	67.3%	49.7%	31.9%	21.3%	17.9%	10.4%	5.1%
9.5 - 13.2mm Bottom Layer	79.0%	61.6%	48.8%	30.9%	24.5%	19.3%	12.0%
Cantabro abrasion test using 3% Lime							
	Binder content						
GRADING TYPE:	4.0 %	4.5 %	5.0 %	5.5 %	6.0 %	6.5 %	7.0%
2.36 - 4.75mm Top Layer	100.0	88.6	59.1	42.9	24.5	19.1	11.4
9.5 - 13.2mm Bottom Layer	100.0	93.7	72.8	52.6	38.2	26.8	19.4

7 OPTIMUM BINDER CONTENT

The optimum binder content is dependent on a number of limiting parameters which directly or in directly influence the amount of binder to be used and these parameters are: void content, abrasion, durability and binder run-off (Sabita Manual 17, 1995). A minimum binder content of 4.5 percent is specified to ensure good durability.

The design binder content was specified as the average of the higher of the minimum binder contents (durability and abrasion resistance) and the lower of the maximum binder contents (void content and binder run-off). Results of the test conducted on Superfine Twinlay are illustrated in Figure 3 and 4.

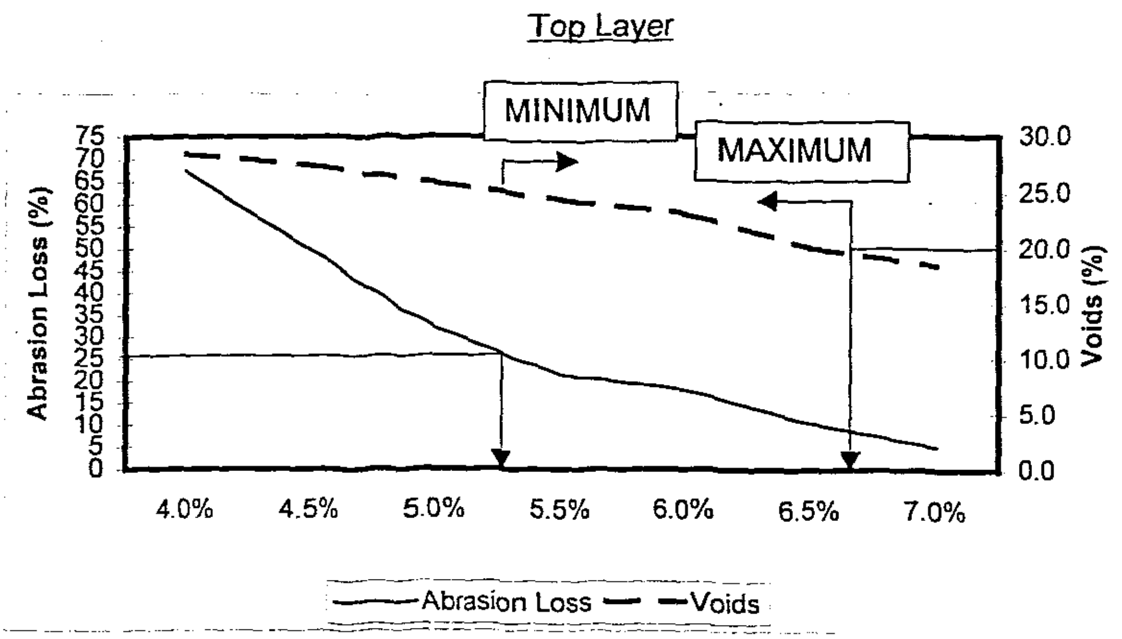


FIGURE 3: Determination of suitable binder content for the top layer

Bottom layer

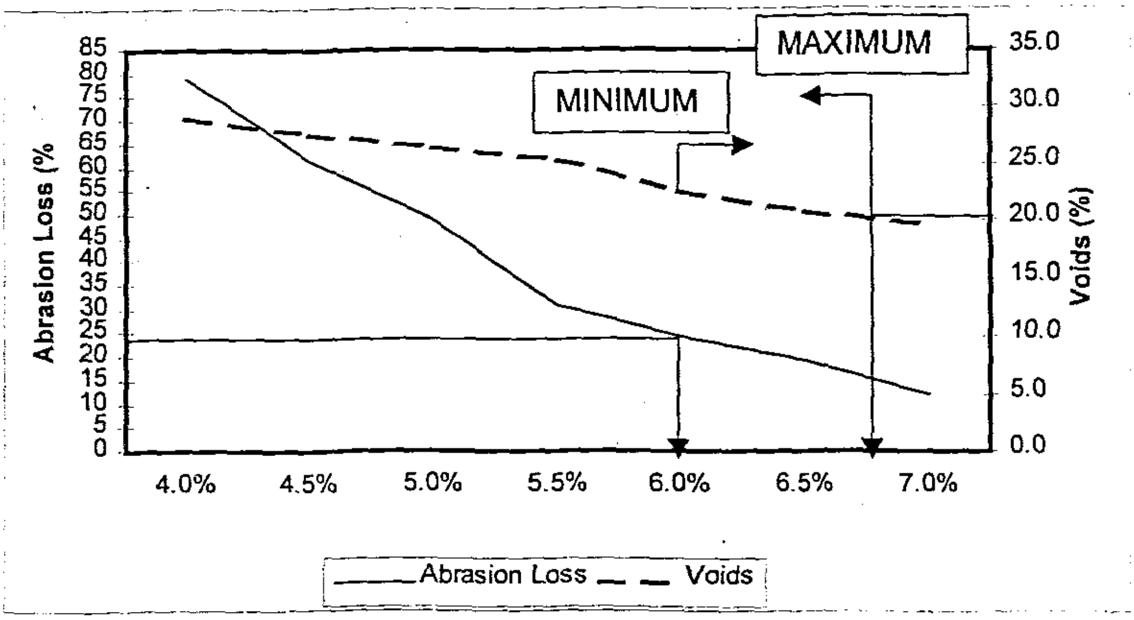


FIGURE 4: Determination of suitable binder content for the bottom layer

The minimum binder content limit is specified in order to ensure resistance of the mix against aggregate loss due to traffic attrition and to improve durability. The maximum binder content limit is specified to prevent binder run-off especially during transportation of the mix to site and during paving and compaction.

The following observations were made from Figure 3: the results indicate that the minimum binder content for the top layer is 5.3 percent and the maximum 6.5 percent. Figure 4 results indicate that the minimum binder content for the bottom layer is 6 percent and the maximum 6.8 percent. In Section 4.12, it was clearly shown that using bitumen rubber as a binder can retard binder run-off in the mix.

8 CONCLUSIONS

The main aim behind this research was to determine the optimum binder content that can be used for both Top and Bottom layer gradings. Conclusions relevant to the variables and test methods used to obtain engineering properties for the different materials tested, yielded the following:

- The void content decreases as the binder content increases, but at high binder content the voids are still large enough for the mix to be classified as a porous asphalt mix (void content in excess of 20 percent).
- In general the mixtures performed poorly with regard to abrasion resistance however a better abrasion resistance was noted when cement filler was used. Nevertheless, the addition or use of cement as filler might render the mix brittle. The top layer also performed significantly better than the bottom layer for each binder content (4 to 7 percent by weight of total mix).
- The use of bitumen rubber (with 20 percent rubber crumbs) allows very high bitumen content to be used without the risk of the binder draining from the mix during transportation.

The grading of the top and bottom layer yielded a very high void content. The researcher therefore concludes that the use of cement filler will strengthen the mix resistance to abrasion significantly. At high bitumen content the void content is still large enough to allow good drainage of rainwater to the side drains, and is also expected to offer a good sound absorption.

At 6 percent and 5.5 percent for bottom and top layer respectively, bitumen rubber binders are concluded to be the optimum binder content to be adopted for this research project

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CHAPTER 4

ACOUSTIC ANALYSIS OF POROUS ASPHALT SURFACES

1 INTRODUCTION

Road traffic noise is one of the major contributors to noise pollution therefore there is a great need to try and eradicate or at least retard rolling noise due to tyre/road interaction. It is also equally important to measure a mixture's ability to absorb noise in the laboratory. Characterising a mixture's ability to attenuate noise in the laboratory during mix design is very important in terms of avoiding the expense and time of constructing field sites for measurements. The Standing Wave Tube Apparatus or Impedance Tube was used to measure sound power absorption coefficient of porous materials.

In this chapter a comparison with respect to sound absorption was made between the different selected mix type different mix components as adopted for investigation (see Table 1).

TABLE 1: Mix type investigated

Mix type	Overall layer thickness	Top	Bottom
1. Conventional Porous Asphalt	4cm	-	-
2. Superfine Twinlay (proposed)	7cm	2.5cm	4.5cm
3. Superfine Twinlay	8cm	3.0cm	5.0cm
4. Superfine Twinlay	9cm	3.5cm	5.5cm
5. Cityfalt	7cm	2.5cm	4.5cm
6. Conventional Twinlay	7cm	2.5cm	4.5cm
7. Fluisterfalt	7cm	2.5cm	4.5cm

NB: Superfine Twinlay is the proposed mix design type which is a further development from the conventional Twinlay. A clear distinction should be made between the two mix types to avoid confusion.

The Department of Infrastructure and Maintenance in Europe, Netherlands recently conducted research with the aim of determining a low noise pavement or optimizing the pavements acoustic performance by using a double layer system instead of the normal single porous asphalt layer. Six different test sections were laid and compacted. The different pavement sections laid were: Cityfalt by Breda Wegenbouw, 2-laags ZOAB by HWZ, Twinlay by Heijmans, Microdrain by Heijmans, Duolay by KWS and Fluisterfalt by NBM (Department Of Infrastructure And Maintenance, 1998).

A series of tests were performed on these test sections e.g. Airdrain measurements, ∝-in-situ measurements and Static Pass By (SPB) measurements. Microdrain, performed significantly better than other mix types or the purpose of this research project the researcher decided to use Cityfalt, Twinlay and Fluisterfalt. Cityfalt and Fluisterfalt were chosen on account of the good performance exhibited during testing and Twinlay was chosen because this research is based on the further development of this type of wearing course.

It is important to note that South African sieves and mixing materials were used in the manufacturing of Cityfalt, Twinlay and Fluisterfalt Marshall samples. The manufacture of these mixes was primarily for acoustic evaluation, this means that tests performed on these mixes were limited to sound absorption measurements. Nevertheless, the volumetric properties were evaluated, and these yielded results that correlated closely to the results obtained in the Netherlands. The mix materials shown in Table 4, 6 and 8 are those used in Europe to manufacture the different mixes, but the ones in brackets are the South African mix materials used to manufacture Cityfalt, Twinlay and Fluisterfalt. This means that the researcher used the South African materials and sieve sizes to manufacture Cityfalt, Twinlay and Fluisterfalt. This was done to simulate the European mix types and ensuring at the same time that there is a close coloration with those manufactured in Europe using local materials.

As mentioned in previous chapters, the control of traffic noise at the source has in recent years been focused on tyre-road noise, since this noise component appears to be the major contributor to wayside noise at traffic speeds above 50 km/h (Von Meier, 1988) and (Jongens, 1995).

2 OBJECTIVES

A Superfine Twinlay porous mix (with small chipping) subscribes to the requirement with regard to optimal flow resistance as well as to a shorter wave-length texture (Von Meier et al, 1990). The primary objective of this investigation is to study and improve the fundamental acoustical behaviour of freshly compacted Superfine Twinlay briquette and compare it with Cityfalt, conventional Twinlay and Fluisterfalt.

In summary, the objectives are:

- To assess the acoustic quality of each mix type material as outlined in Table 1;
- To monitor and quantify the absorption properties of each of the porous mix types as shown in Table 1, and to compare each mix type against the other for all the mixtures under investigation.
- To determine the influence that thickness has on the absorption coefficient of a porous layer.

NB: The manufacture of these mixes was primarily for acoustic evaluation, this means that tests performed on these mixes were limited to sound absorption measurements.

3 DESCRIPTION OF METHODS USED

3.1 Sample preparation

3.1.1 Mix components and sieve analysis for the different variations

Porous Asphalt mixes have a high void content (in excess of 20 percent) therefore the type of aggregate and grading used is very important. For the purpose of this research, aggregates from the Eerste River quarry were used and they also meet the requirements as recommended in the Sabita Manual 17 (Sabita Manual 17, 1995).

There are three main variables that should be considered important in trying to obtain the desired properties of porous asphalt mixtures and these are:

- Binder type – binder type and content are important as these have an impact on the structural integrity of the mix,
- Aggregate type – due to the open structure of the mix, aggregates must meet recommendations as stated in Chapter 3, Table 3.
- Filler type – in order to stiffen the binder a limited amount of filler must be added.

This has been covered in detail in Chapter 3.

The tables below (Table 2 to Table 11) show the mix components and sieve analysis for the different mix types as adopted for this study as indicated in Table 1.

Table 2 shows the mix components for 4cm Conventional Porous Asphalt.

TABLE 2: Mix components for 4cm Conventional Porous Asphalt	
Mix composition	**Layer (%)**
13.2 mm, Malmesbury Hornfels, ex RMM Eerste River	42.7
9.5 mm, Malmesbury Hornfels, ex RMM Eerste River	38.7
CRUSHER DUST, Malmesbury Hornfels, ex RMM Eerste River	13.0
Filler (Hydrated Lime ex-Cape Lime)	0.2
Rubber bitumen	5.4

Table 3 shows the gradation for Conventional Porous Asphalt (sieve analysis and percentage passing) and the grading curve is shown in Appendix I, Figure I-1.

TABLE 3: Grading for Porous Asphalt	
Sieve size (mm)	**(% Passing)**
26.500	
19.000	100
13.200	98
9.500	58
6.700	
4.750	15
2.360	10
1.180	7
0.600	6
0.300	6
0.150	4
0.075	2.9

Table 4 shows the mix components for Cityfalt by Breda Wegenbouw

TABLE 4: Mix components for Cityfalt		
Mix components	**Top layer (%)**	**Bottom layer (%)**
Grauwkwartsiet 5/8(Malmesbury Hornfels, ex RMM Eerste River)	95.3	-
Nederlandse steenslag 8/11(Malmesbury Hornfels, ex RMM Eerste River)	-	8.9
Nederlandse steenslag 11/16 (Malmesbury Hornfels, ex RMM Eerste River)	-	79.7
Brekerzand 0/2 (natural sand)	-	6.5
Wigro 60K (natural filler)	4.2	4.4
Eigen stof (natural filler)	0.5	0.5
Arbocell ZZ8/1 (cellulose fibre)	0.15	0.15
Sealoflex 5-50 (binder, SBS)	5.1	4.2

Table 5 shows the gradation for Cityfalt (sieve analysis and percentage passing) and the grading curve is shown in Appendix I, Figure I-2.

TABLE 5: Gradation for Cityfalt (Percentage Passing)		
Sieve number	**Bottom layer (%)**	**Top layer (%)**
C22.4 (26.5)	100	
C16 (19)	96	
C11.2 (13.2)	37.5	
C8 (9.5)	16.5	98
C5.6 (6.7)	14.5	35.5
C4 (4.75)		
2mm (2.36)	12	8
500μm (0.600)		
180μm (0.150)		
63μm (0.075)	5.3	6.3

Table 6 shows the mix components for Twinlay by Heijmans.

TABLE 6: Mix components for Twinlay		
Mix components	**Top layer (%)**	**Bottom layer (%)**
Grauwkwartsiet 4/8 (Malmesbury Hornfels, ex RMM Eerste River)	93.7	-
Grauwkwartsiet 11/16 (Malmesbury Hornfels, ex RMM Eerste River)	-	88.9
Brekerzand (crushed sand)	-	8.5
Rhecal 40 (natural filler)	5.3	1.6
Eigen stof (natural filler)	1.0	1.0
Rubberbitumen (rubber bitumen binder)	6.5	4.2

Table 7 shows the gradation for Twinlay (sieve analysis percentage passing) and the grading curve is shown in Appendix I, Figure I-3.

TABLE 7: Gradation for Twinlay (Percentage Passing)		
Sieve number	**Bottom layer (%)**	**Top layer (%)**
C22.4 (26.5)	100	
C16 (19)	96.5	
C11.2 (13.2)	45.1	100
C5.6 (6.7)	-	95.6
2mm (2.36)	14.4	10.1
63μm (0.075)	3.5	6.3

Table 8 shows the mix components for Fluisterfalt by NBM.

TABLE 8: Mix components for Fluisterfalt		
Mix components	**Top layer (%)**	**Bottom layer (%)**
Grauwkwartsiet 4/8 (Malmesbury Hornfels, ex RMM Eerste River)	91.5	-
Grauwkwartsiet 11/16 (Malmesbury Hornfels, ex RMM Eerste River)	-	91.7
Nederlands Brekerzand (crushed sand)	4.9	4.8
Rhecom 60 (natural filler)	3.6	3.5
Styrelf 26 (80/100 pen grade bitumen binder)	5.3	4.8

Table 9 shows the gradation for Fluisterfalt (sieve analysis and percentage passing) and the grading curve is shown in Appendix I, Figure I-4.

TABLE 9: Gradation for Fluisterfalt (Percentage Passing)		
Sieve number	**Bottom layer (%)**	**Top layer (%)**
C22.4 (26.5)	100	
C16 (19)	96	
C11.2 (13.2)	25	100
C8 (9.5)	14.4	96.5
C5.6 (6.7)	13	38.8
C4 (4.75)		
2mm (2.36)	11	12.5
500μm (0.600)		
180μm (0.150)		
63μm (0.075)	5.5	5.5

Table 10 shows the mix components for proposed Superfine Twinlay.

TABLE 10: Mix components for Superfine Twinlay		
Mix composition	**Top layer (%)**	**Bottom layer (%)**
9.5 - 13.2 mm (passing 13.2 mm sieve and retained on 9.5 mm sieve), Malmesbury Hornfels, ex RMM Eerste River	-	84.0
2.36 – 4.75 mm, Malmesbury Hornfels, ex RMM Eerste River	91.5	-
CRUSHER DUST, Malmesbury Hornfels, ex RMM Eerste River	-	7.0
Filler (Cement)	3.0	3.0
Rubber bitumen	5.5	6.0

Table 11 shows the gradation table for Superfine Twinlay (sieve analysis and percentage passing) and the grading curve is shown in Appendix I, Figure I-5.

TABLE 11: Gradation for Superfine Twinlay (Percentage Passing)		
Sieve size (mm)	**Bottom layer (%)**	**Top layer (%)**
26.500		
19.000	100	
13.200	95	
9.500	47	
6.700		
4.750	19	100
2.360	9	20
1.18		6
0.600		
0.300		
0.150		
0.075	3	3

3.1.2 Mixing and compaction of the samples

The mix design procedure was performed in accordance to Method C2 of TMH1 [Procedure for the making of asphalt specimens for the determination of resistance to flow and for voids analysis by the Marshall method"] (DoT, 1986).

Three briquettes per mix type were compacted in the laboratory using a standard Marshall hammer. 140°C and 130°C temperatures were used during mixing and compaction respectively as recommended for bitumen-rubber asphalt in the Sabita manual (Sabita Manual 17, 1995). The mixing and compaction temperatures were monitored using a laser thermometer. After extrusion from the metal moulds, the heights of the cooled Marshall specimens were measured to the nearest 0.01 m by using a pair of Callipers. Photographs of freshly compacted Marshall briquettes are shown in Appendix K, Figure K-1, for Fluisterfalt, Cityfalt, Twinlay, Superfine Twinlay and Conventional Porous Asphalt.

4 TYRE/ROAD INTERACTIONS

Chapter two covers this topic in detail. The noise emission from road vehicles is composed of several different noise producing mechanisms and these can be divided into the following three main categories (Jongens, 1995):

1. Power-train – being engine, air intake, fan, exhaust, gearbox and transmission.
2. Tyre/road interaction.
3. Aerodynamic noise – due to air turbulence around the vehicle.

It is possible to reduce road traffic noise by controlling noise from the source. This can be done by applying low-noise road surfaces e.g. porous asphalt surfaces. The control of traffic noise at the source has in recent years been focussed on tyre/road noise, since this noise component appears to be the major contributor to traffic noise at traffic speeds above 50km/h as mentioned earlier.

In the attempt of reducing road traffic noise with regard to rolling noise it is important to understand the tyre/road noise generation mechanism.

The beneficial effects of porous asphalt surfaces on tyre/road noise are twofold (Van Blokland, 1997):

- The open structure of the surface reduces the compression and expansion of air in the tyre tread profile;
- The acoustic absorption suppresses mechanical and aerodynamic (due to air turbulence around the vehicle) noise generated by the rolling tyre on the road.

And the reduction in noise level results from (Sabita Manual 17, 1995):

- Sound absorption by the voids of the layer;
- The elimination of air pumping at the tyre/pavement interface and;
- The excellent surface evenness of this type of wearing course when properly laid.

4.1 Generation of rolling noise

In the attempt at reducing road traffic noise with regard to rolling noise it is important to understand the tyre/road noise generation mechanism. Pavement-tyre contact noise depends on the type of tyre used (tread patterns etc) and also on the type of pavement overlays. The mechanism of tyre/road noise generation is complex but can be summarized into the three following phenomena (Jongens, 1995) and (Van Blokland, 1997):

- IMPACT NOISE: produced by the impact of the tyre treads on the surface of the overlay, its intensity depending on the geometry of both tread patterns and aggregates as well as on the overlay macrotexture.

- AIR PUMPING: due to vibration of the air caught in the treads under the effect of stress caused by the tyre deformations.

- SLIP AND STICK: this phenomenon is comparable to the SUCTION EFFECT, due to the grip of the tyre rubber on aggregates at the pavement surface.

The generation of pavement-tyre contact noise thus depends to a large extent on the aggregate grading size of the wearing course. Reducing the effects of one of the three above mentioned causes can increase the effects of the other two, which makes the reduction of tyre/road noise a difficult task.

5 ABSORPTION MEASUREMENTS ON CORES

When a porous material is subjected to the action of acoustic pressure, the porous material not only undergoes elastic compression but there is also movement of the fluid (air) back and forth in voids within the material. The process of "absorption" is the conversion of acoustic energy into heat, which takes place as a result of:

- Friction between air particles and flow constrictions in the material,
- Internal friction of the material depending on the degree of elastic deformation.

The effectiveness of porous absorbers in absorbing sound depends on the following physical characteristics:

1. Porosity – which is the ratio of the interconnecting voids within the material to the total volume of the material.
2. Structural factor – which relates to the shape of the air voids and how they are interconnected.
3. Specific flow resistance – which is the resistance to airflow through the material and

4. Thickness of the porous material – which is simply what it means, how thick the material is.

The measurement of sound absorption of a porous material is very important since we need to evaluate the mixture's ability to reduce noise in the laboratory before laying it out in the field. The standing wave tube test was used to measure the sound absorption of the porous materials. A summarized description is shown in Appendix G "Using the Standing–Wave Tube Apparatus to measure plane wave sound absorbing properties of a material."

5.1 Basic assumptions

- 1000Hz is the dominating frequency for vehicle speeds above 70km/h (Heijmans, 1995). For acoustical optimization to be obtained it is therefore important that the maximum absorption be placed at 1000Hz.

- A double-layer of porous mixture behaves acoustically in a similar way as a single homogeneous layer of porous asphalt (Van Blokland, 1997).

- If tyre vibration is to be minimized (which will result in subsequent reduction in noise production) and if the flow resistance is to be increased and if a short-wavelength texture is to be achieved a finer mixture in the top layer must be used. For instance instead of using 4/8 aggregates, superfine aggregates contained between 2.36 – 4.75 mm sieves can be used.

- The overall thickness of the porous layer has an influence on the absorption coefficient. The result of this investigation will show us the influence thickness has on the absorption.

5.2 Theoretical predictions

The sound absorption coefficient (α) as a function of frequency of the porous layers was predicted using the following formulae (Von Meier et al, 1990)

$$\alpha = 1 - \left|\frac{w - \rho c}{w + \rho c}\right|^2$$

Where

$$w = -j\frac{\rho c}{\sigma}\sqrt{\left(1 - j\frac{\Xi\sigma}{\omega\rho\chi}\right)\chi}.\cot\left[d.\frac{\omega}{c}\sqrt{\left(1 - j\frac{\Xi\sigma}{\omega\rho\chi}\right)\chi}\right]$$

And

$$\omega = 2\pi f$$

$$\Xi = \frac{10^{-2}}{1.7.k^2.\sigma^2.d} Ns.m^{-4}$$

σ : Porosity

ρ : Density of air (1.21 kg/m^3)

Ξ : Specific flow resistance of the porous material
d : Thickness of the layer
χ : Configuration or structural factor of the porous material
c : Speed of sound in air ≈ 344 m/s
k : Chipping diameter (mm)
j : mean that it is a complex equation

The above mentioned formulae were used to calculate the predicted sound power absorption coefficient (α) of all the mix design as shown in Table1 at each frequency up to 2000 Hz. The graphical representations of the results are shown in Section 5.3.

For the predicted calculations the following parameters were used (values used for Twinlay, Cityfalt and Fluisterfalt were provided by the Department of Infrastructure and Maintenance, 1998 (Netherlands):

4 cm porous asphalt
σ : 20 percent
ρ : Density of air (1.21 kg/m^3)
d : 4 cm
χ : 5 (this is an assumed value, for common stone chippings ranges from χ = 3 to 7).

7 cm Cityfalt
σ : 25 percent
ρ : Density of air (1.21 kg/m^3)
d : 7 cm
χ : 5 (this is an assumed value, for common stone chippings ranges from χ = 3 to 7).

7 cm Fluisterfalt
σ : 24 percent
ρ : Density of air (1.21 kg/m^3)
d : 7 cm
χ : 4.6 (this is an assumed value, for common stone chippings ranges from χ = 3 to 7).

7 cm Conventional Twinlay
σ : 23 percent
ρ : Density of air (1.21 kg/m^3)
d : 7 cm
χ : 4.6 [assumed value, for common stone chippings ranges from χ = 3 to 7] (Von Meier, 1988)

7 cm Superfine Twinlay
σ : 24 percent
ρ : Density of air (1.21 kg/m^3)
d : 7 cm
χ : 5 (this is an assumed value, for common stone chippings ranges from χ = 3 to 7).

8 cm Superfine Twinlay
σ : 24 percent
ρ : Density of air (1.21 kg/m^3)
d : 8 cm
χ : 5 (this is an assumed value, for common stone chippings ranges from χ = 3 to 7).

9 cm Superfine Twinlay
σ : 24 percent
ρ : Density of air (1.21 kg/m^3)
d : 9 cm
χ : 5 (this is an assumed value, for common stone chippings ranges from χ = 3 to 7).

5.3 Results from laboratory tests performed on the Standing-Wave Apparatus

5.3.1 Porous Asphalt 4cm

Predicted results

Predicted calculations yielded the following results demonstrated by the graph in Figure 1.

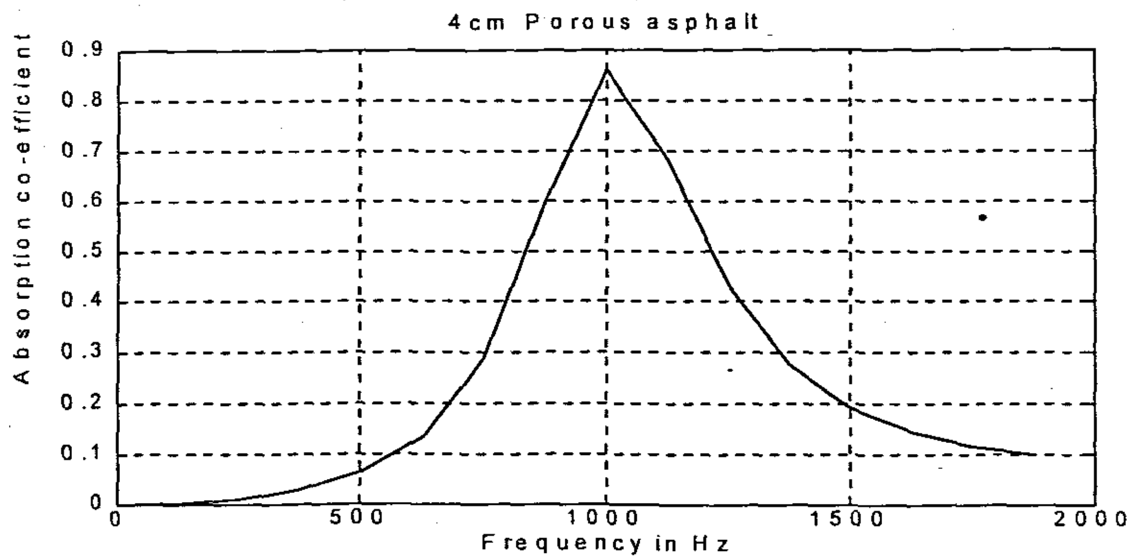

FIGURE 1. Absorption Coefficient Vs frequency of 4cm Porous Asphalt

Measured results

The detailed results of the measurements on freshly compacted Marshall briquettes in the Impedance Tube are shown in Appendix H, Table H-1, H-2 and H-3. Figure 2 shows the graphical representation of the results.

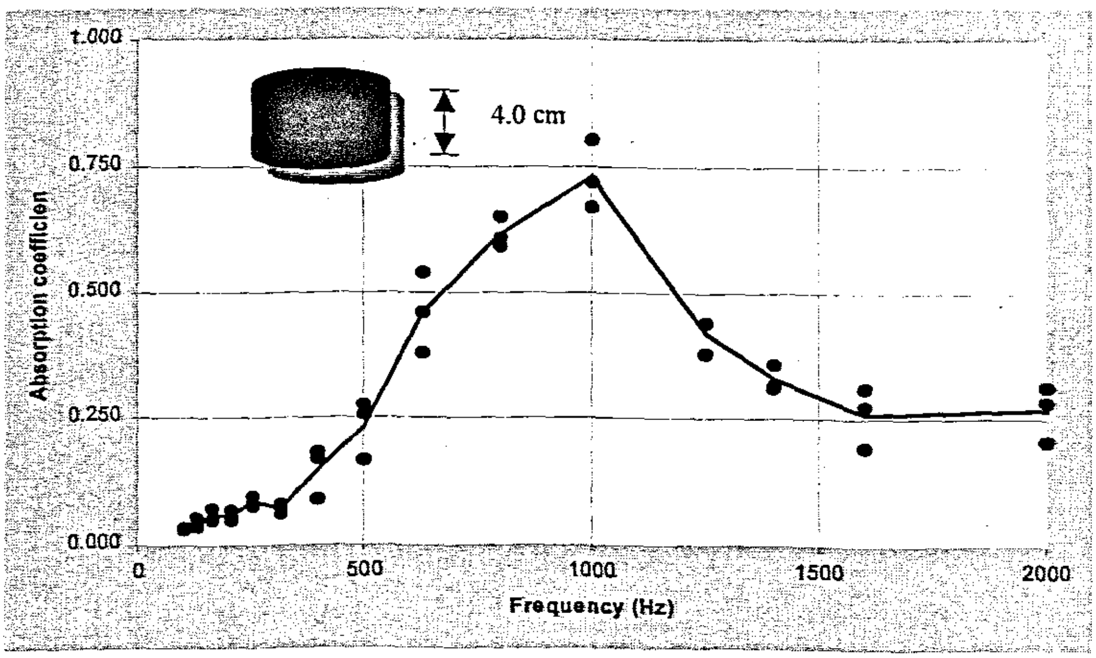

FIGURE 2. Absorption Coefficient Vs frequency of 4cm Porous Asphalt cores

5.3.2 Cityfalt 7cm

Predicted results

Predicted calculations yielded the following results demonstrated by the graph in Figure 3.

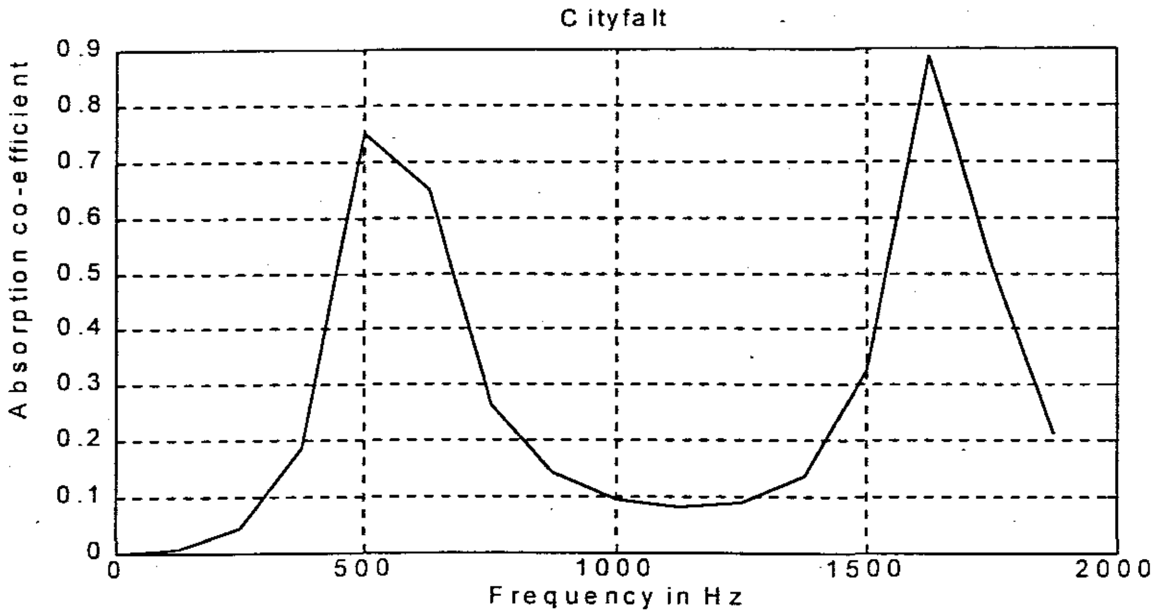

FIGURE 3. Absorption Coefficient Vs frequency of 7cm Cityfalt

Measured results

The detailed results of the measurements on freshly compacted Marshall briquettes in the Impedance Tube are shown in Appendix H, Table H-4, H-5 and H-6. Figure 4 shows the graphical representation of the results.

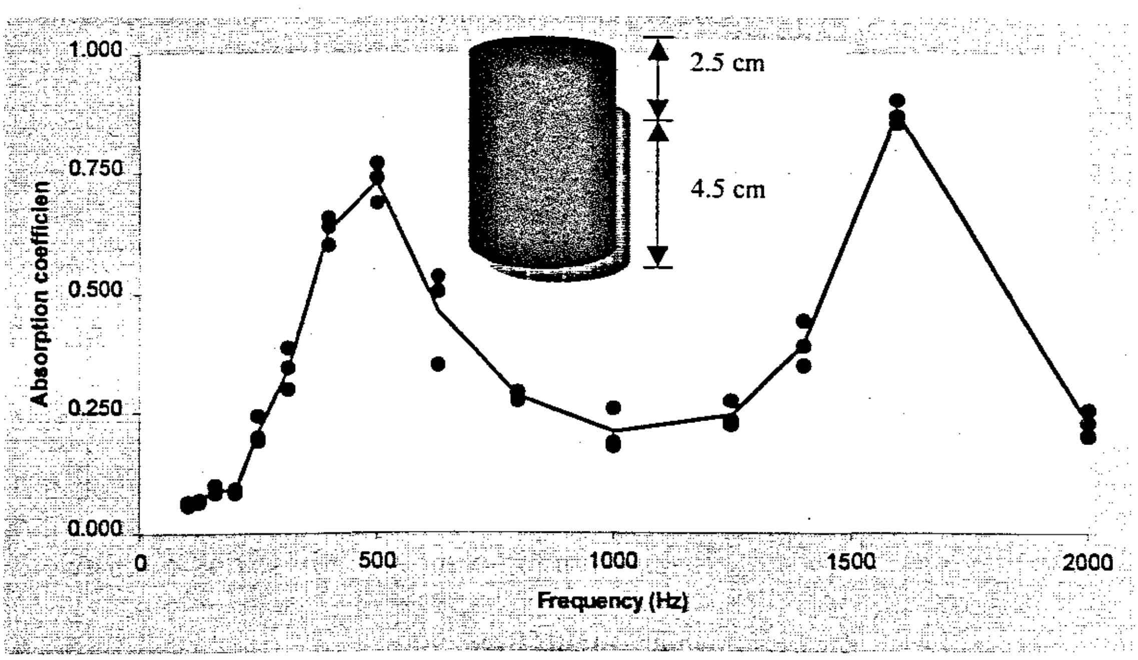

FIGURE 4. Absorption Coefficient Vs frequency of 7cm Cityfalt cores

5.3.3 Fluisterfalt 7cm

Predicted results

Predicted calculations yielded the following results demonstrated by the graph in Figure 5.

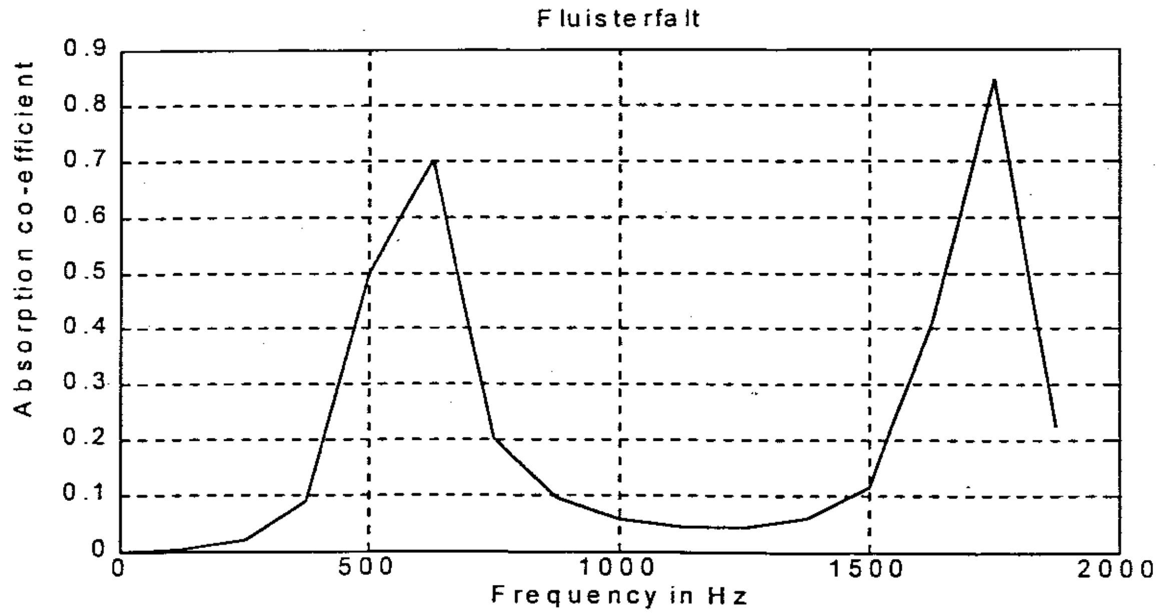

FIGURE 5. Absorption Coefficient Vs frequency of 7cm Fluisterfalt

Measured results

The detailed results of the measurements on freshly compacted Marshall briquettes in the Impedance Tube are shown in Appendix H, Table H-5, H-6 and H-7. Figure 6 shows the graphical representation of the results.

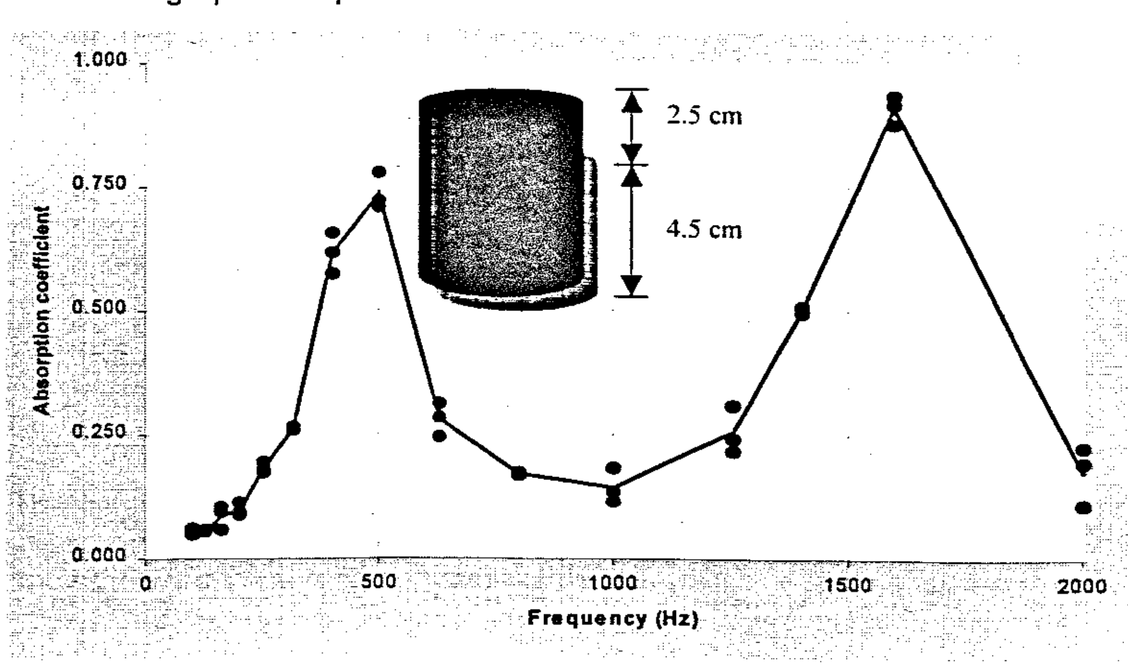

FIGURE 6. Absorption Coefficient Vs frequency of 7cm Fluisterfalt cores

5.3.4 Conventional Twinlay 7cm

Predicted results

Predicted calculations yielded the following results demonstrated by the graph in Figure 7.

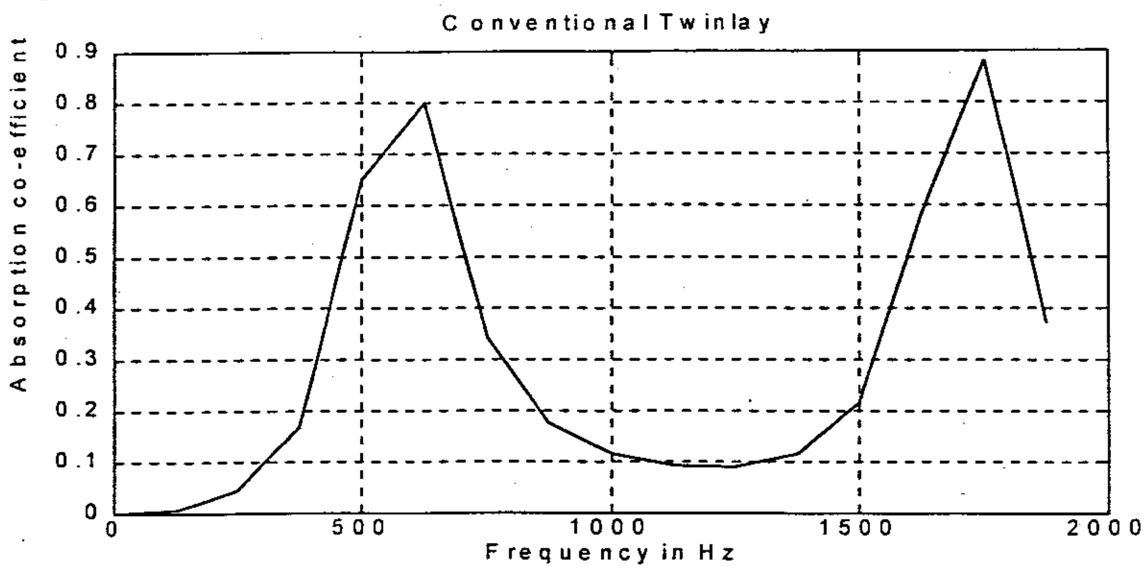

FIGURE 7. Absorption Coefficient Vs frequency of 7cm Twinlay

Measured results

The detailed results of the measurements on freshly compacted Marshall briquettes in the Impedance Tube are shown in Appendix H, Table H-8, H-9 and H-10. Figure 8 shows the graphical representation of the results.

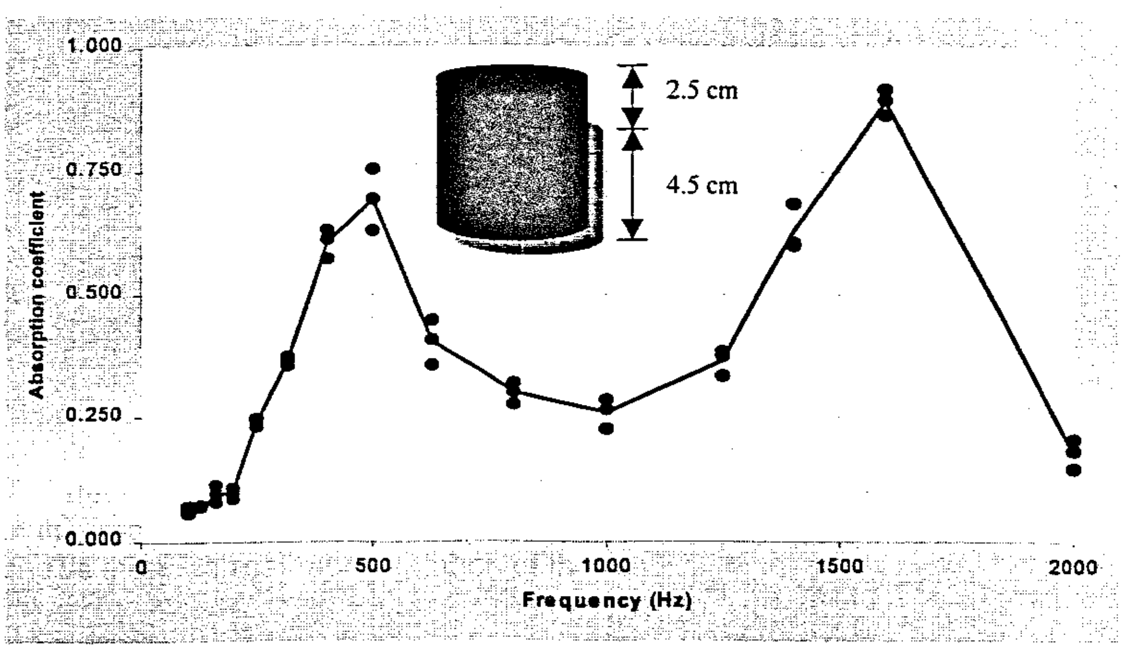

FIGURE 8. Absorption Coefficient Vs frequency of 7cm Twinlay cores

5.3.5 Superfine Twinlay 7cm

Predicted results

Predicted calculations yielded the following results demonstrated by the graph in Figure 9.

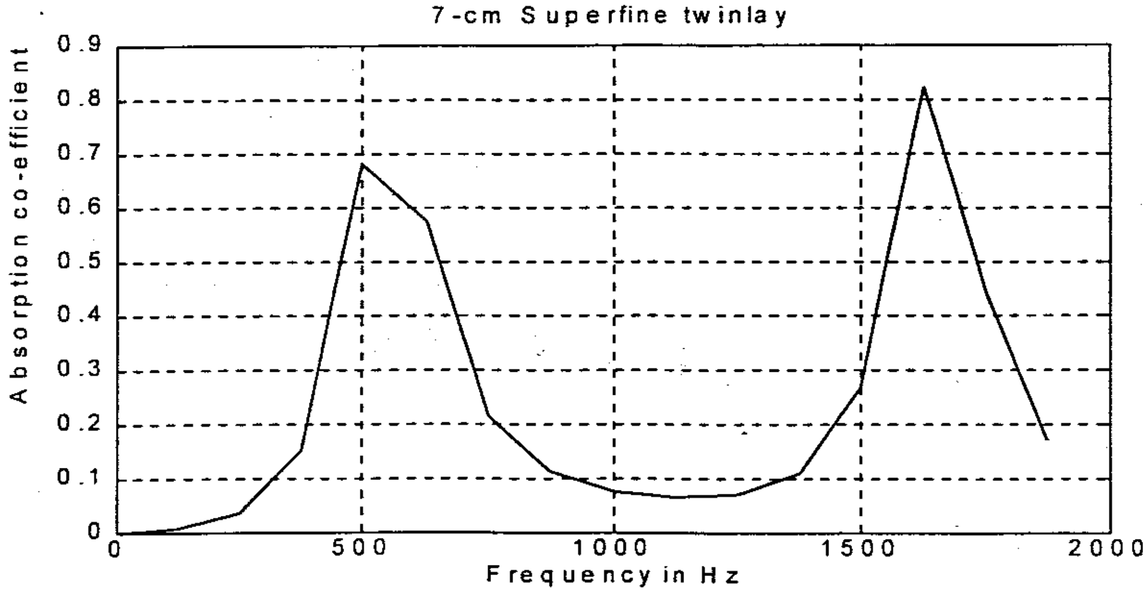

FIGURE 9. Absorption Coefficient Vs frequency of 7cm Superfine Twinlay

Measured results

The detailed results of the measurements on freshly compacted Marshall briquettes in the Impedance Tube are shown in Appendix H, Table H-11, H-12 and H-13. Figure 10 shows the graphical representation of the results.

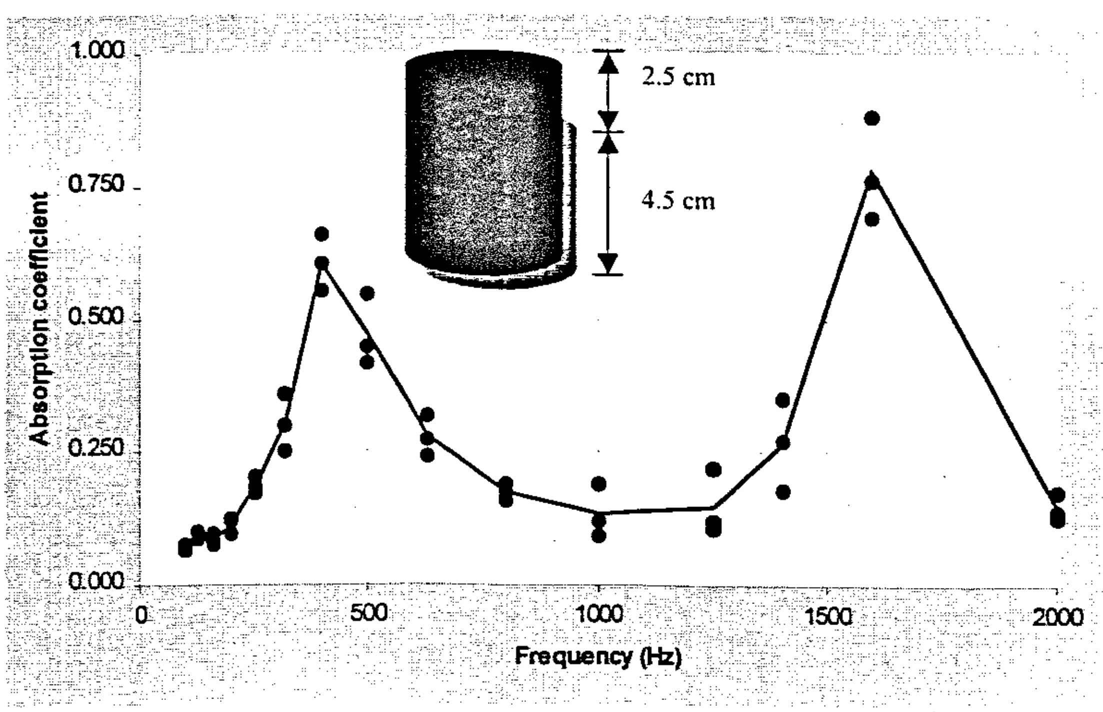

FIGURE 10. Absorption Coefficient Vs frequency of 7cm Superfine Twinlay

5.3.6 Superfine Twinlay 8cm

Predicted results

Predicted calculations yielded the following results demonstrated by the graph in Figure 11.

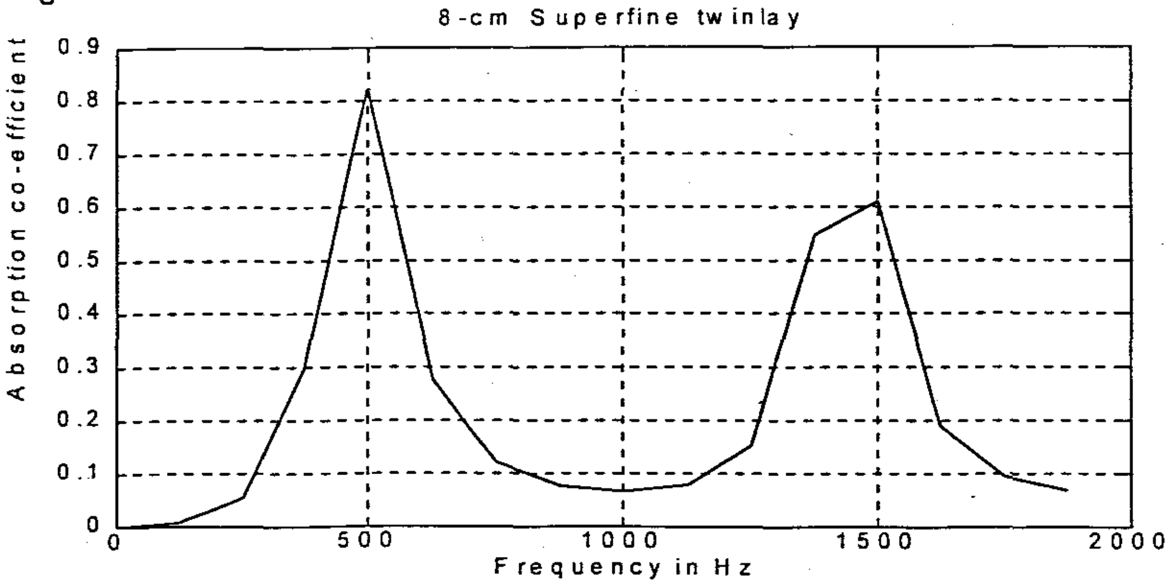

FIGURE 11. Absorption Coefficient Vs frequency of 8cm Superfine Twinlay

Measured results

The detailed results of the measurements on freshly compacted Marshall briquettes in the Impedance Tube are shown in Appendix H, Table H-14, H-15 and H-16. Figure 12 shows the graphical representation of the results.

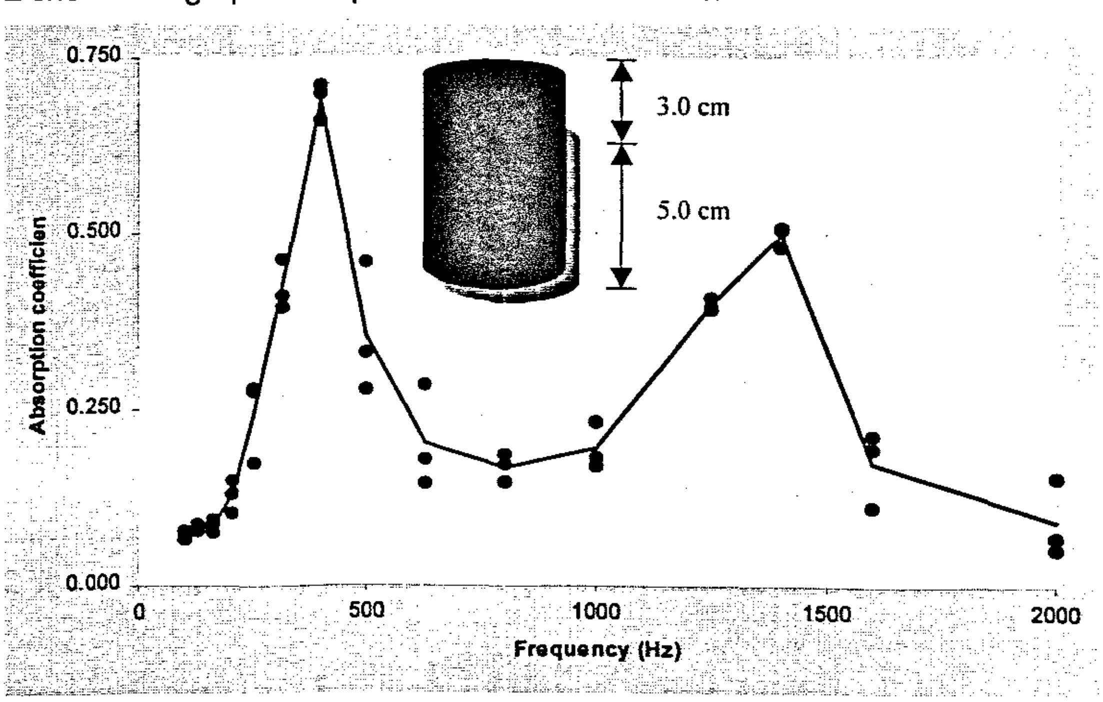

FIGURE 12. Absorption Coefficient Vs frequency of 8cm Superfine Twinlay

5.3.7 Superfine Twinlay 9cm

Predicted results

Predicted calculations yielded the following results demonstrated by the graph in Figure 13.

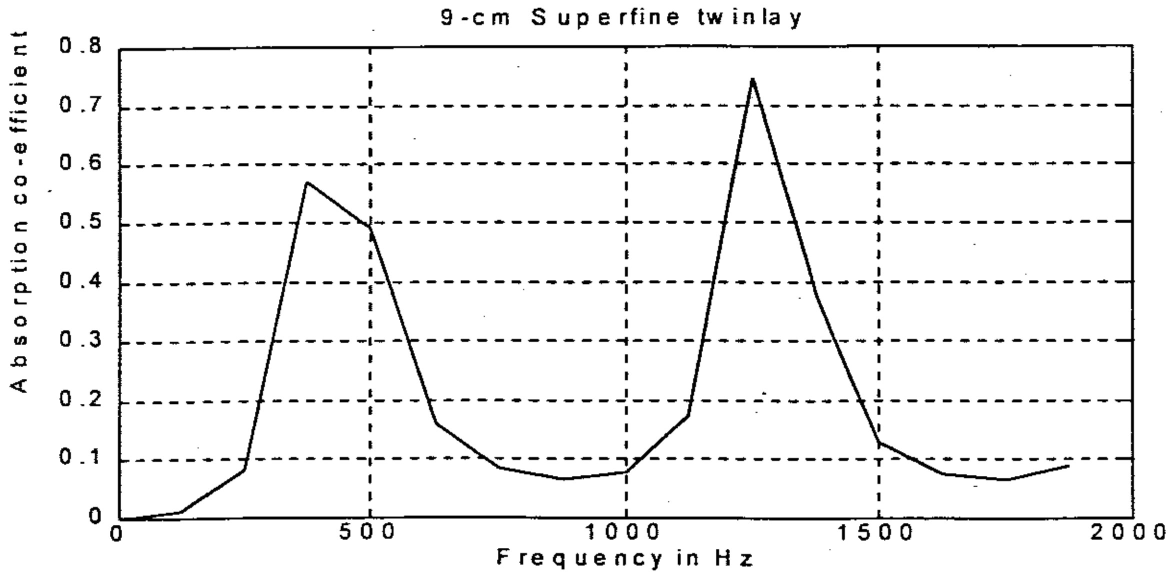

FIGURE 13. Absorption Coefficient Vs frequency of 9cm Superfine Twinlay

Measured results

The detailed results of the measurements on freshly compacted Marshall briquettes in the Impedance Tube are shown in Appendix H, Table H-17, H-18 and H-19. Figure 14 shows the graphical representation of the results.

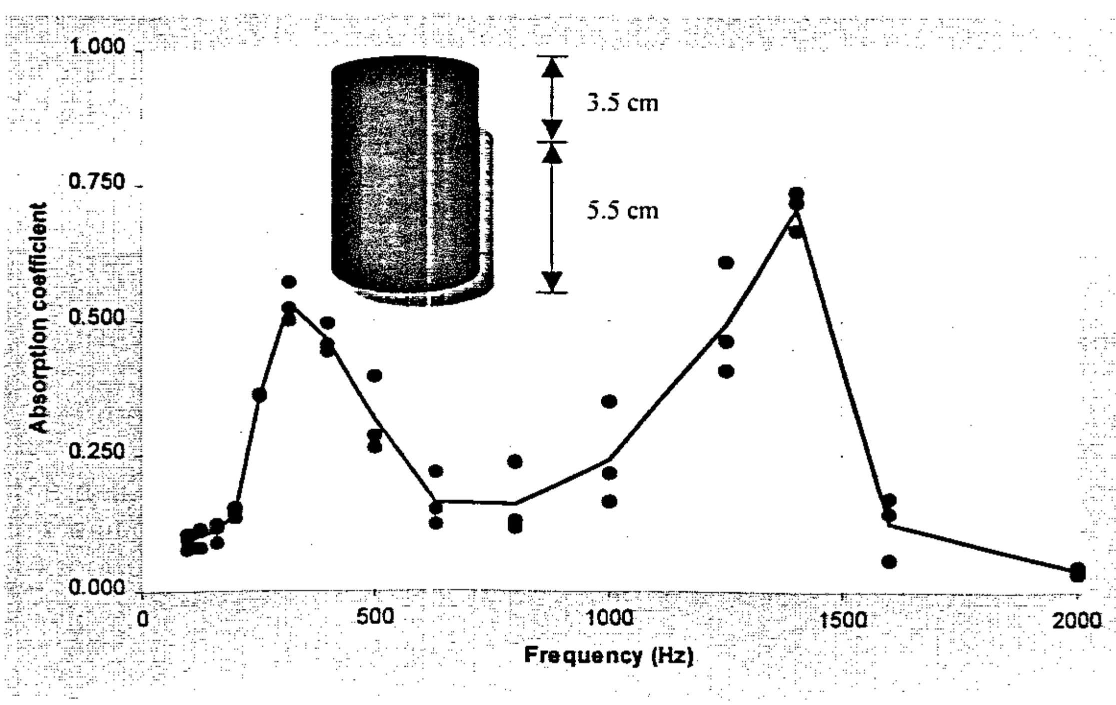

FIGURE 14. Absorption Coefficient vs. freq. of 9cm Superfine Twinlay cores

5.4 Results analysis

5.4.1 A comparative analysis of the results

The detailed results to Figure 15 below are shown in Appendix J, Table J-1. Figure 15 represents the average sound absorption coefficient (α) for the measurements taken on three different Marshall briquettes as a function of frequency.

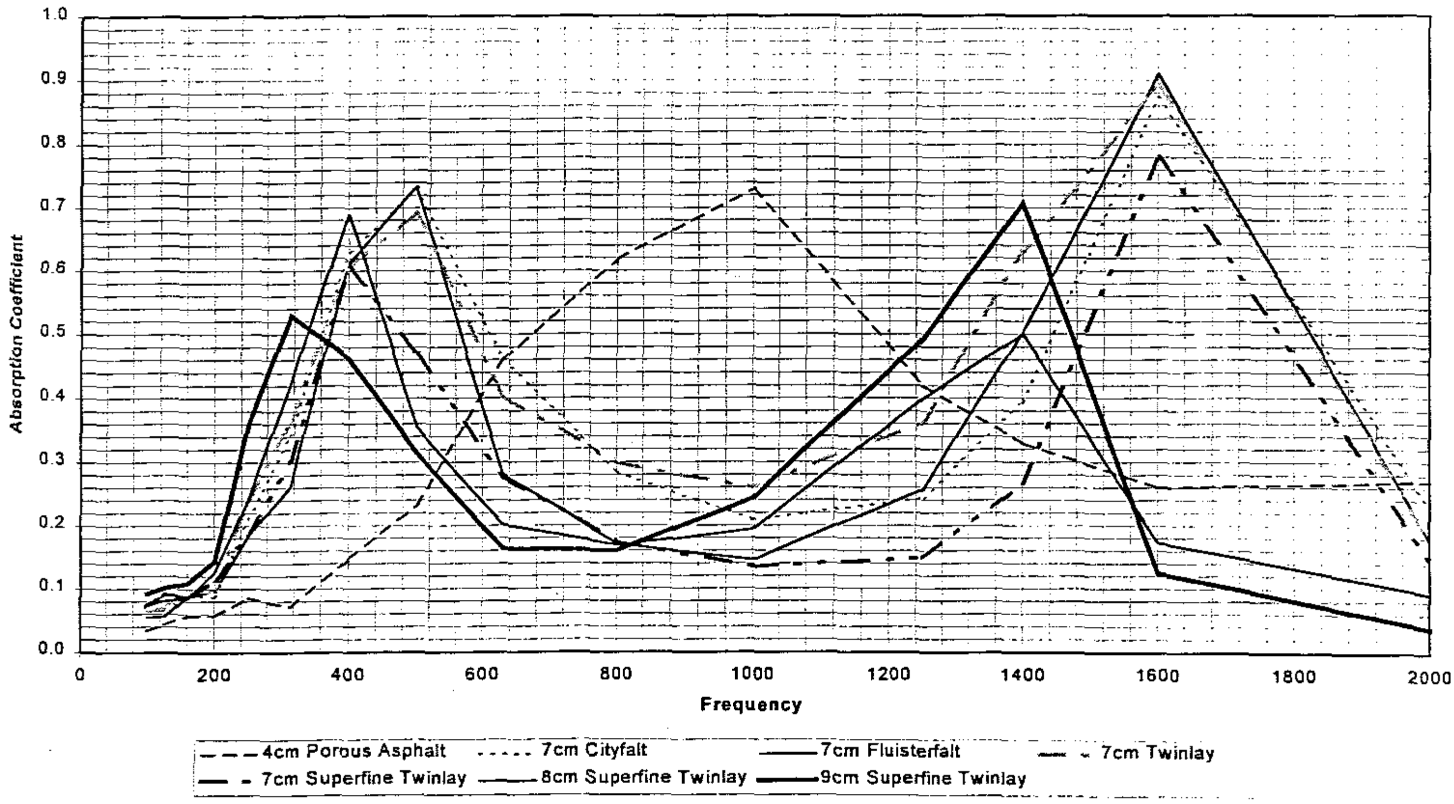

FIGURE 15. Absorption Coefficient of a 4cm thick conventional Porous Asphalt, 7cm thick Superfine Twinlay, 8cm thick Superfine Twinlay, 9cm thick Superfine Twinlay, 7cm thick Cityfalt, 7cm thick Twinlay and 7cm thick Fluisterfalt.

In interpreting the results, the 4 cm thick single porous asphalt layer displays a higher *absorption coefficient* (α) *over a narrow frequency band at 1000 Hz frequency* as opposed to double layer 7 cm thick Superfine Twinlay, 8cm thick Superfine Twinlay, 9cm thick Superfine Twinlay, Cityfalt, Twinlay and Fluisterfalt with more than two peaks over a broad frequency band. The 4 cm thick homogeneous porous asphalt produced a longer wave-length texture as compared to the other double layer mixtures, meaning that there will be an increase in tyre vibration leading to noise production.

Cityfalt, Twinlay and Fluisterfalt showed a better sound absorption coefficient with a short wave-length over a broader frequency band than all the other mixtures under investigation.

5.4.2 The influence of thickness on the absorption coefficient

The summarized results of the average absorption coefficient at the first maximum point $f\alpha_{,max}$ (Hz) for all mix design under investigation are shown in Table 12 and Table 13 and the graphical representation is shown in Figure 16.

TABLE 12: *Absorption Coefficient at the first maximum point* $f\alpha_{,max}$

Briquette no.	4cm Porous Asphalt		7cm Cityfalt		7cm Conventional Twinlay		7cm Fluisterfalt	
	α	$f\alpha_{,max}$	α	$f\alpha_{,max}$	α	$f\alpha_{,max}$	α	$f\alpha_{,max}$
1	0.67	1000	0.77	500	0.63	500	0.78	500
2	0.80	1000	0.74	500	0.76	500	0.72	500
3	0.72	1000	0.68	500	0.70	500	0.71	500
Mean	0.73	1000	0.73	500	0.69	500	0.73	500
St. Deviation	0.06	0	0.03	0	0.05	0	0.03	0
Minimum	0.67	1000	0.65	500	0.63	500	0.71	500
Maximum	0.80	1000	0.77	500	0.76	500	0.78	500

TABLE 13: Absorption Coefficient at the first maximum point $f\alpha_{,max}$

Briquette no.	7cm *Superfine Twinlay*		8cm *Superfine Twinlay*		9cm *Superfine Twinlay*	
	α	$f\alpha_{,max}$	α	$f\alpha_{,max}$	α	$f\alpha_{,max}$
1	0.55	400	0.66	400	0.52	315
2	0.66	400	0.70	400	0.57	315
3	0.60	400	0.71	400	0.50	315
Mean	0.61	400	0.69	400	0.53	315
St. Deviation	0.04	0	0.02	0	0.03	0
Minimum	0.55	400	0.66	400	0.50	315
Maximum	0.66	400	0.71	400	0.57	315

A 4cm single layer of porous asphalt displayed a high absorption at 1000Hz meaning that it has been acoustically optimized with a narrow frequency band. Increasing the thickness from 7cm to 8cm produced a higher sound absorption. But if we further increase the thickness to 9cm the frequency of the first maximum point of absorption shifts further down to a lower frequency with a lower absorption at that point as indicated in Table 13.

From Table 12 and 13 it is evident that Fluisterfalt followed by Cityfalt then Twinlay offer a better sound absorption at the first maximum point. But there a lot other considerations that contribute to the ultimate reduction in tyre/road noise. The most important one being the size of the aggregate used. It is anticipated that the Superfine Twinlay will reduce the noise production significantly. The 8 cm Superfine Twinlay yielded the best results.

Sound absorption and noise reduction should always be treated with equal importance if the overall road traffic noise is to be reduced.

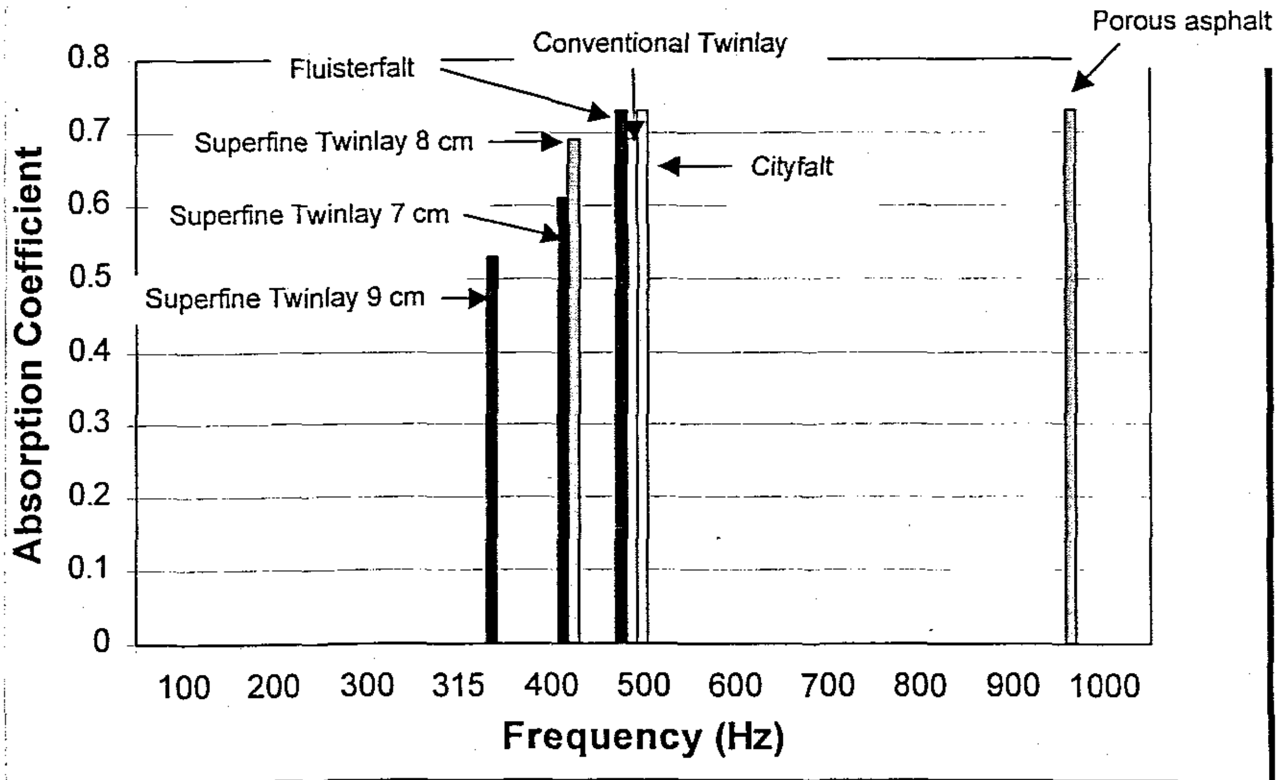

FIGURE 16. Absorption Coefficient as a function of frequency for each mix designs

6 CONCLUSIONS AND RECOMMENDATIONS

In general, rolling noise is very dependent on the type of wearing course. Wearing courses with rough macrotexture tend to generate greater rolling noise. A double layer (know as Twinlay) porous asphalt construction offers a higher sound absorption coefficient (α) on a broad frequency range as opposed to a single homogeneous porous asphalt layer construction. The excellent acoustic performance of double layer construction is due to the thin top layer with small aggregate sizes. The small aggregate size increases the flow resistance and subsequently providing the desired short-wave length.

It can therefore be concluded that the stone grading and the resulting surface texture is an extremely important parameter. The effectiveness of using finer aggregates in the top structure can be easily monitored by conducting a Static Pass By (SPB) method of measuring road traffic noise. The double layer construction also provides low and high-speed reductions. The 4 cm thick homogeneous porous asphalt has a high absorption coefficient at a frequency of 1000 Hz meaning that it is acoustically optimized but with a narrow frequency band, meaning that low speed noise will not be catered for in the absorption process of this layer. The long-wave length texture of this material is in opposition with the requirement of optimal flow resistance and short-wave length texture.

In order for the double layer construction to be acoustically optimized we need to ensure that the maximum absorption coefficient is shifted to the desired frequency around the 1000 Hz frequency. This can be achieved by reducing the layer thickness or the configuration factor. There is also a need to try and strike a balance between excellent sound absorption and good water drainage. The 9 cm thick Superfine Twinlay offers solutions on improving low frequency performance of sound absorbing porous road surfaces.

The 8 cm Superfine Twinlay has an excellent absorption properties compared to all the other mixes under investigation, but a 7 cm superfine Twinlay will adopted for use. This is simply because of financial reasons, an 8 cm is too thick and expensive to construct. The 7 cm is the second best with regard to sound absorption.

In summary, the double layer construction gives the desired short-wave length texture and optimal flow resistance as opposed to a single layer of porous asphalt. Nevertheless the single layer of porous asphalt normally displays optimum absorption at frequencies around 1000 Hz, noise is considered to be predominant around this frequency. By using a double layer system, low frequency performance of an absorbing road surface is possible. In a double layer system, since the absorption coefficient is not yet at the desired frequency (in order to shift the maximum to the desired 1000 Hz, either the total layer thickness and/or the configuration or structural factor should be reduced).

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CHAPTER 5

1 INTRODUCTION

This chapter covers the use of the MMLS Mk3 test for Accelerated Pavement Testing (APT). Porous asphalt wearing coarses are excellent sound absorption pavements structures with a relatively good drainage of water from the pavement surface. But the clogging of the pores subsequently affecting permeability soon reduces the excellent acoustic properties of this material. This is due to the open structure of the layer, which also causes oxidation of the binder (bitumen) due to ultra violet radiation. The high void content of the mix also causes densification of the pavement especially if constructed in an area dominated by heavy traffic. This renders porous asphalt less durable. Therefore a need exist to monitor and quantify the mixtures initial level of performance of a newly laid pavement and the long-term pavement performance with respect to sound absorption and permeability.

Permeability of water is one of the characteristic properties of porous asphalt. This is what makes porous asphalt superior from conventional, dense-graded wearing courses, and is also one of the great advantages of porous asphalt. Its high void contents allow rainwater to be transported within the surfacing layer towards the pavement edges through a system of interconnecting voids. This drainage ability allows vehicle tyres to remain in permanent contact with the surface of the pavement under all conditions. It thus reduces the risk of aquaplaning, which might occur on conventional pavements when wet and being traveled over at high speeds.

The use of porous asphalt also reduces splash and spray behind vehicles (especially trucks), and reduces reflections by the surface of the otherwise wet pavement both by day and by night, thus making road marking more visible and the second advantage is the ability of these mixes to reduce noise pollution. These properties also rely on the high void contents of such mixes, which increases noise absorption and reduces air pumping at the tyre/pavement interface.

Verhaeghe, (1992), said that:

> *"In order for porous asphalt surfaces to be economically viable they should have a design life of at least 10 years. On account of the high void contents of such mixes, environmental forces such as moisture, heat and ultra-violet radiation may seriously affect their durability. If wearing courses are not adequately designed to resist these forces, stripping and aggregate loss may take place prematurely, resulting in shorter maintenance cycles and lower benefit-cost ratios.*

There are a number of possibilities that can be introduced in an effort to try and reduce the above-mentioned premature failure of porous asphalt wearing courses. These may be summarized as follows:

- Introduction of more binder (preferably of high viscosity such as rubber bitumen) in the mix;
- By the addition of bitumen stabilizer (such as cellulose fibres), if required or
- By adding polymer-modified binders

It is generally considered that due to the open structure of porous asphalt and the effect of traffic axles, the durability of porous asphalt can be drastically reduced. The premature clogging of the voids with sand also contributes to the reduction in service life, leading to ineffective drainage of surface water.

2 SCOPE OF THE REPORT

In this report the performance of Superfine Twinlay porous asphalt wearing course is covered. A Superfine Twinlay porous asphalt wearing course mixture was investigated. In rutting test (A), a slab was investigated under accelerated trafficked conditions at 50°C. Rutting test (B) included the rutting and stripping tests which were done on asphalt briquettes submerged in water heated to 50°C. For both tests a Model Mobile Load Simulator Mk3 (MMLS Mk3) was used. The two rutting tests were performed under different conditions. Rutting test (A) investigated the performance of Superfine Twinlay under accelerated dry conditions. Sound absorption measurement and permeability measurements were performed on the slab before and after trafficking. Rutting test (B) investigated the performance of Superfine Twinlay under accelerated wet conditions.

3 RUTTING TEST (A) – KANGO HAMMER COMPACTED SLABS

3.1 Scope of the investigation

This study reports on the rutting test, permeability test and sound absorption measurement test. Conclusions were then drawn with regards to the performance of the Superfine Twinlay wearing course. For rutting test MMLS Mk3 was used and the test was performed at an average temperature of 50°C. The asphalt slab was manufactured on a wooden mould 900 × 450 × 70 mm in dimension and used for the rutting test. Only superfine Twinlay wearing course mixture was investigated.

The slabs were compacted using a Kango hammer and the trafficking of the slab using MMLS Mk3 was done at the University of Stellenbosch. Permeability measurements were also performed at the University of Stellenbosch by Soil Lab (Pty) Ltd. Sound absorption measurements using the Impedance Tube were done at the University of Cape Town's Acoustics Lab.

This report gives details of the slab manufacturing processes, details of the test configurations as well as MMLS Mk3 specifications applied during rutting test. Also included is an overview of the materials used in the manufacturing of the slabs for MMLS Mk3 rutting test. A brief overview of the MMLS Mk3 testing has also been included. Photographs referred to in the text are shown in Appendix B. These photographs were taken during the study.

3.2 Objectives of the test

The main objectives behind the proposed test configuration was to assess and quantify the rutting behaviour of superfine Twinlay and subsequently the evaluation of the acoustic performance and monitor the permeability of water of a Superfine Twinlay pavement before and after trafficking.

For permeability measurements, it is important to note that the analysis of the flow through individual pores was not necessary. However, in the engineering problems involving seepage through pavements it is not the micro-flow through individual pores that is of interest, but rather the combined macro-flow through all pores of the surfacing layer.

In summary the objectives are:

- To access the permeability of water through the pavement by measuring permeability of water through the pavement before and after the pavement was subjected to the accelerated trafficking.
- To monitor the pavement's long-term performance with regard to rutting.
- To access the pavement's ability to absorb sound by measuring the sound absorption coefficient before and after the pavement has been subjected to the MMLS Mk3 trafficking.

3.3 Experimental wearing coarse surface

A Superfine Twinlay was constructed for the experiment with an overall thickness of 7 cm. As mentioned before, the upper layer consists of a 2.5 cm thick overlay with a superfine porous asphalt 2.36 – 4.75 mm mix and the bottom layer consists of a 4.5 cm thick layer of 9.5 - 13.2 mm (materials passing 13.2 mm and retained on 9.5 mm sieve) coarse single grained aggregate. Both layers consist of a certain percentage of rubber-bitumen binder (with 20 percent rubber crumbs). The mix was compacted using a Kango hammer, ensuring that crushing of the aggregate does not occur.

Table 1 and 2 show the mix components and gradation of superfine Twinlay as adopted for this study.

TABLE 1: Mix components for Superfine Twinlay		
Mix composition	**Top layer (%)**	**Bottom layer (%)**
9.5 - 13.2 mm, Malmesbury Hornfels, ex RMM Eerste River	-	84.0
2.36 - 4.75mm, Malmesbury Hornfels, ex RMM Eerste River	91.5	-
CRUSHER DUST, Malmesbury Hornfels, ex RMM Eerste River	-	7.0
Filler (Cement)	3.0	3.0
Rubber bitumen	5.5	6.0

TABLE 2: Gradation table for Superfine Twinlay (Sieve analysis and percentage passing)		
Sieve size (mm)	**Bottom layer (%)**	**Top layer (%)**
26.500		
19.000	100	
13.200	95	
9.500	47	
6.700		
4.750	19	100
2.360	9	20
1.18		6
0.600		
0.300		
0.150		
0.075	3	3

3.4 Tests to be performed on the slab

The Superfine Twinlay slab will be subjected to a series of test; these tests are summarized in Table 3.

TABLE 3: Tests performed on the slab

Test Method	Used to determine
Model Mobile Load Simulator (MMLS Mk3).	Accelerated pavement testing to evaluate the long-term performance of the pavement.
Rutting test using the profilometer.	To evaluate and measure the amount of rutting in a pavement wearing course.
Standing wave tube test or impedance tube.	Measures the acoustic absorption characteristic of porous asphalt materials.
Water permeability test using LCS Drainometer.	Measures the rate at which water can flow through the asphalt pavement structure.

3.5 Test programme adopted

The MMLS Mk3 rutting test was performed on the Superfine Twinlay wearing course pavement. Two wooden mould configuration slabs were manufactured at the University of Stellenbosch. The first slab manufactured was 900 × 450 × 70 mm in dimension as shown in Figure 1 and this particular slab was used for rutting test. A second wooden slab with the dimensions of 450 × 450 × 70 mm was also manufactured in the lab. This slab was used for assessing Superfine Twinlay performance before (untrafficked performance) it was subjected to the MMLS Mk3 test. Figure 2 shows the configuration of this slab.

The mix design stage involved mixing materials types as shown in Section 3.3 Table 1. The grading of the materials were mixed in accordance with Section 3.3 Table 2. Both layers, top and bottom were mixed separately. 140°C and 130°C temperatures were used during mixing and compaction respectively as recommended in the Sabita manual 17 (Sabita Manual 17, 1995) for bitumen-rubber asphalt. The mass of the material placed in the mould was measured to ensure that the densities of all slabs manufactured are the same.

Slabs were compacted to the required height (according to their respective densities) in the wooden moulds using a Kango hammer. The bottom layer was compacted first then immediately followed by the top layer. Because the stone particles of the top layer settled into the course texture of the bottom layer, a relatively thin layer could be applied and stone-to-stone contact was achieved. Each layer was compacted separately because a certain thickness must be achieved and each layer has its own density. This was also done achieve the desired void content.

The head of the Kango hammer was modified by welding a square base plate (150 mm x 150 mm) onto the existing circular head (Van de Ven et al, 2000). For the rutting test, a wooden mould (see Figure B-1) was manufactured to hold and confine the 900 mm x 450 mm x 70 mm slab. The slab was placed on a 25 mm thick hard wooden plank overlying a concrete base. This was done to ensure that the slab was always under compression during MMLS Mk3 trafficking head (Van de Ven et al, 2000).

For the rutting test profilometer measurements were taken after specific intervals to obtain the rut depths and rate of rutting during MMLS Mk3 trafficking. These ranged from 0 to 200 000 axles i.e. after 0, 10, 100, 500, 1000, 5000, 10 000, 50 000, 100 000 and 200 000. These measurements represent the vertical deformation of the asphalt under trafficking.

These measurements were taken at strategic points along the slab. The positions of which are indicated by dotted lines in Figure 1. The positions range between 1 through to 8 in the direction of loading.

Permeability and absorption measurement were carried out on the same positions A, B and C (ref. Figure 1). In Figure 2, sound absorption was carried out on position D and permeability measurement on point E.

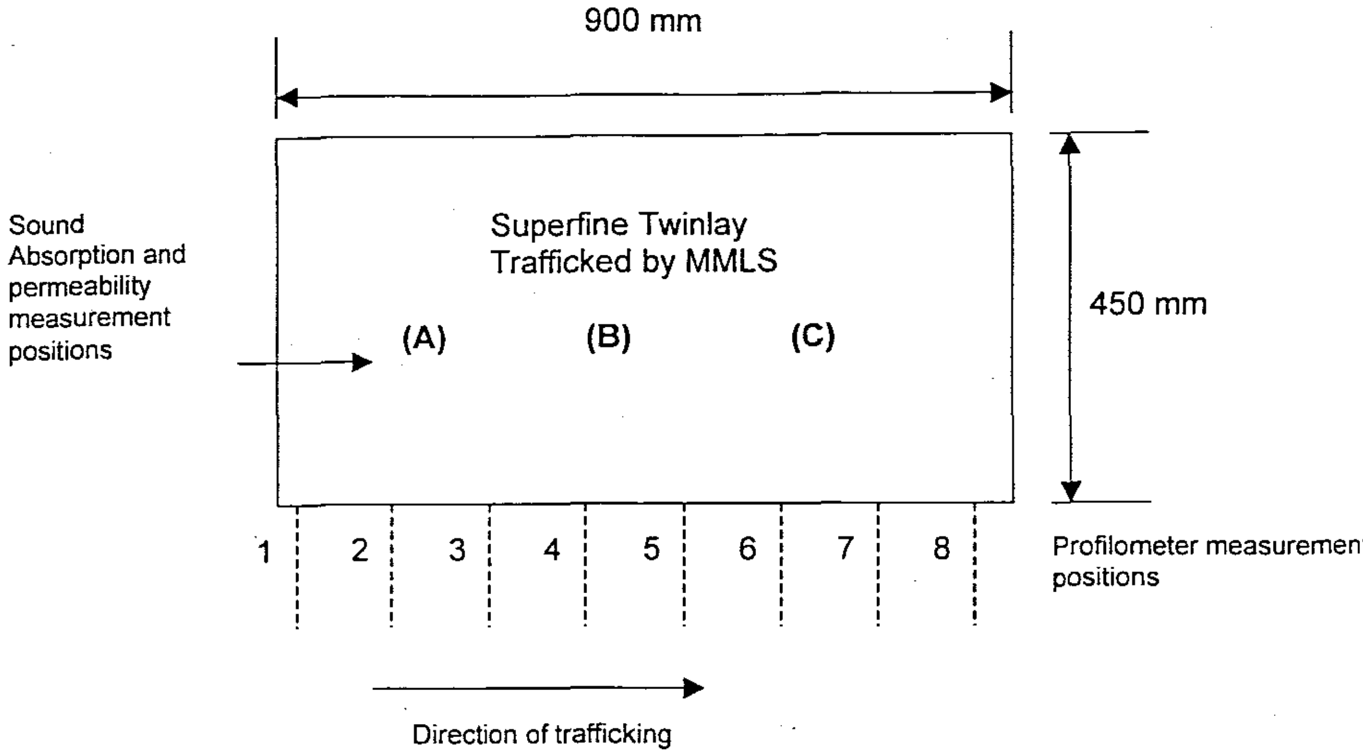

FIGURE 1: Slab configuration for the MMLS Mk3 trafficking

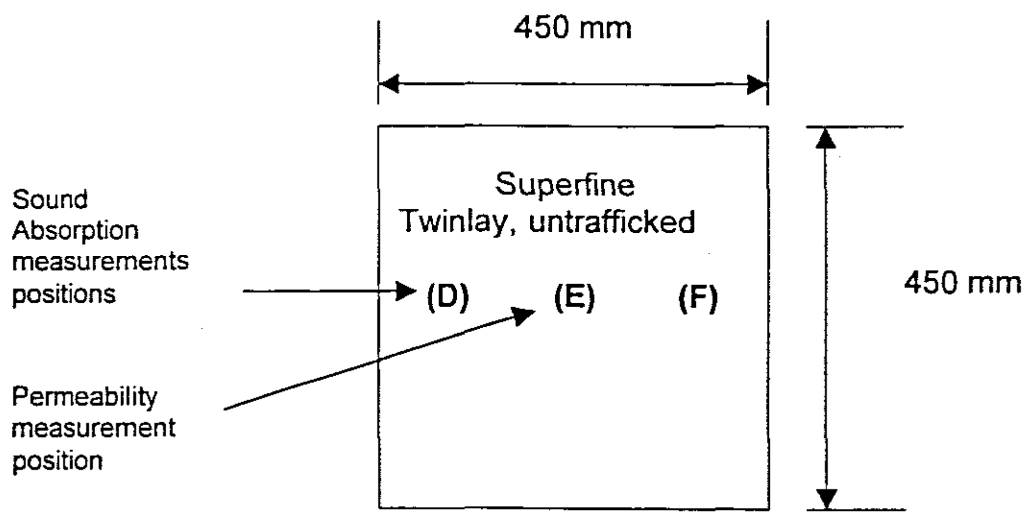

FIGURE 2: Slab configuration for the sound absorption and permeability measurements without MMLS Mk3.

The slab was also monitored for any possibility fatigue failure. The slab was placed on a flexible rubber mat to induce tensile strains beneath the slab during MMLS Mk3 trafficking. The flexible rubber mat was 25 mm thick and had a shore hardness of about 70. The rubber mat undergoes elastic deformation under loading, which in turn leads to the development of tensile strains beneath the asphalt slab. Fatigue monitoring was done through a visual assessment of the slab on the surface of the asphalt slab at regular intervals during MMLS Mk3 trafficking to determine the number of axles at which cracks had developed.

During the rutting test, an environmental chamber (see Figure M-7 and Figure M-8) was used to allow tight control over the test temperature. Thermocouples were placed within the asphalt slab before testing to monitor the asphalt temperature during testing. The temperature during the rutting test was maintained at 50°C. After profilometer measurements it was necessary to reheat the asphalt slabs to 50°C for some time before recommencing with MMLS Mk3 trafficking.

The test condition for the MMLS Mk3 were as follows:

- Number of total load repetitions 200 000
- Tyre pressure 690kPa
- Wheel load 2.1 kN
- Test temperature of the asphalt briquette 50°C
- Loading rate 7200 repetitions per hour

3.6 Accelerated pavement testing (APT)

3.6.1 Short summary of the MMLS Mk3 testing

Metcalf (1998) defined Accelerated pavement testing (APT) as:

> *"...the controlled application of a prototype wheel loading, at or above the appropriate legal load limit to a prototype or actual, layered, structural pavement system to determine pavement response and performance under a controlled, accelerated, accumulation of damage in a compressed time period." For small scale APT, the definition must include wheel loading below the legal limit.*

The Model Mobile Load Simulator (MMLS Mk3) as shown in Figure 3, is a vehicle-load simulator for accelerated trafficking of model or full-scale, dry and wet pavements. The MMLS Mk3 device is 2.4 m long by 0.6 m wide by 1.2 m high.

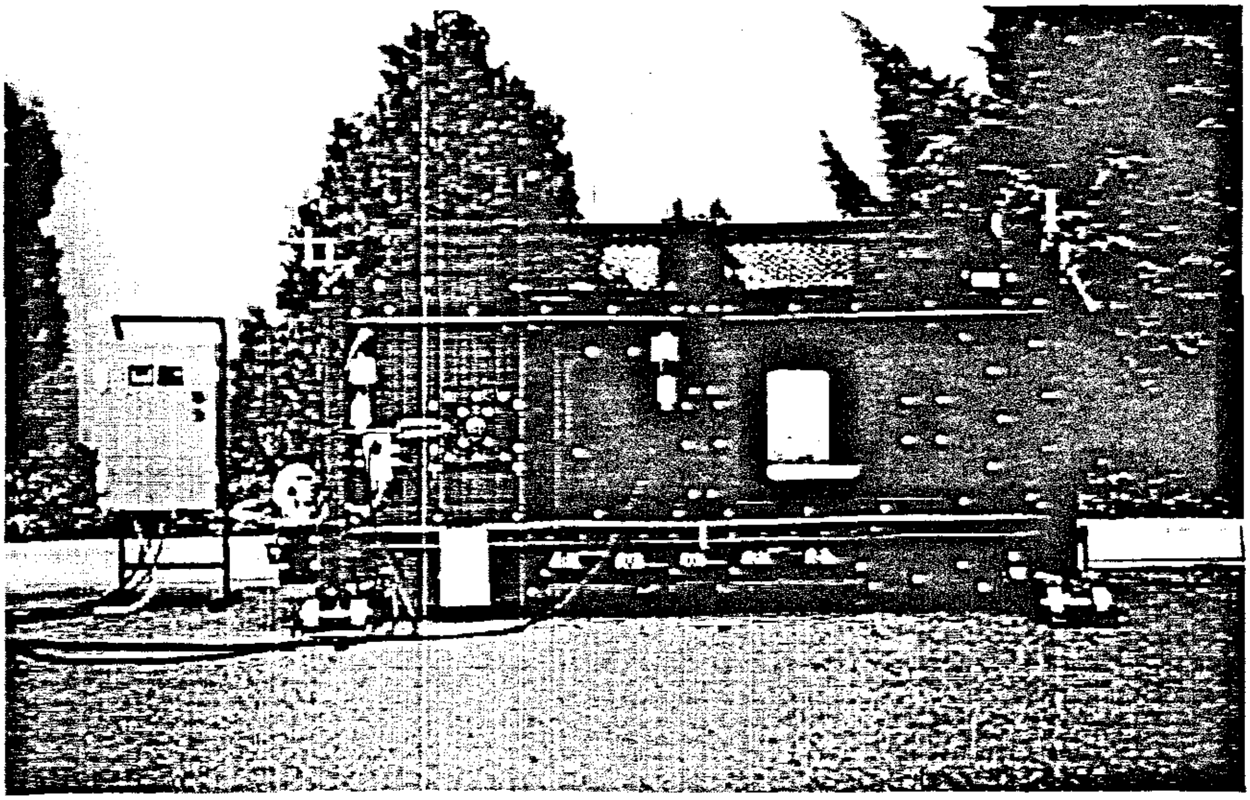

FIGURE 3: Photographic representation of the MMLS Mk.3

The immediate benefits of scaled APT are that testing can be done at a fraction of the cost of full-scale APT. Furthermore, testing can be done either in the laboratory or in the field under controlled environmental and testing conditions (Van de Ven et al, 2000). The temperature during trafficking can be controlled by placing the MMLS Mk3 in an environmental chamber. The main advantages of this type of scaled APT device can be summarised as follows (Van de Ven et al, 2000):

- The load is always moving in one direction.
- Many repetitions are possible in a short period.
- A relatively high trafficking speed is possible.

This APT device is low-cost and applies a scaled load on four 300 mm diameter, pneumatic tyres that are 3/10 or approximately one-third the diameter of standard truck tires. A wheel load of up to 2.7 kN (approximately one-ninth of the load on one wheel of a dual tyre standard single axle) is utilized for trafficking the pavement. The wheel load can be set to 2.1 kN or 2.7 kN, for the tests described in this report, the MMLS Mk3 wheel load was set to 2.1 kN and the tyre pressure 690 kPa. No lateral wander was applied during testing and the rate of testing was maintained at 7200 axles per hour for all rutting tests. The pneumatic tyres are normally inflated to 690 kPa, but maximum pressures up to 800 kPa can be used. A maximum of 7200 single-wheel load repetitions can be applied per hour at a speed of up to 2.6 m/sec that corresponds approximately to a 4 Hz frequency of loading for a measured tread length of 0.11 m.

For a standard truck tyre with a measured tread length of approximately 0.25 m, the simulated speed of the MMLS Mk3 is calculated as 21 km/hr. The schematic representation of the MMLS Mk3 wheel configuration is shown in Figure 4.

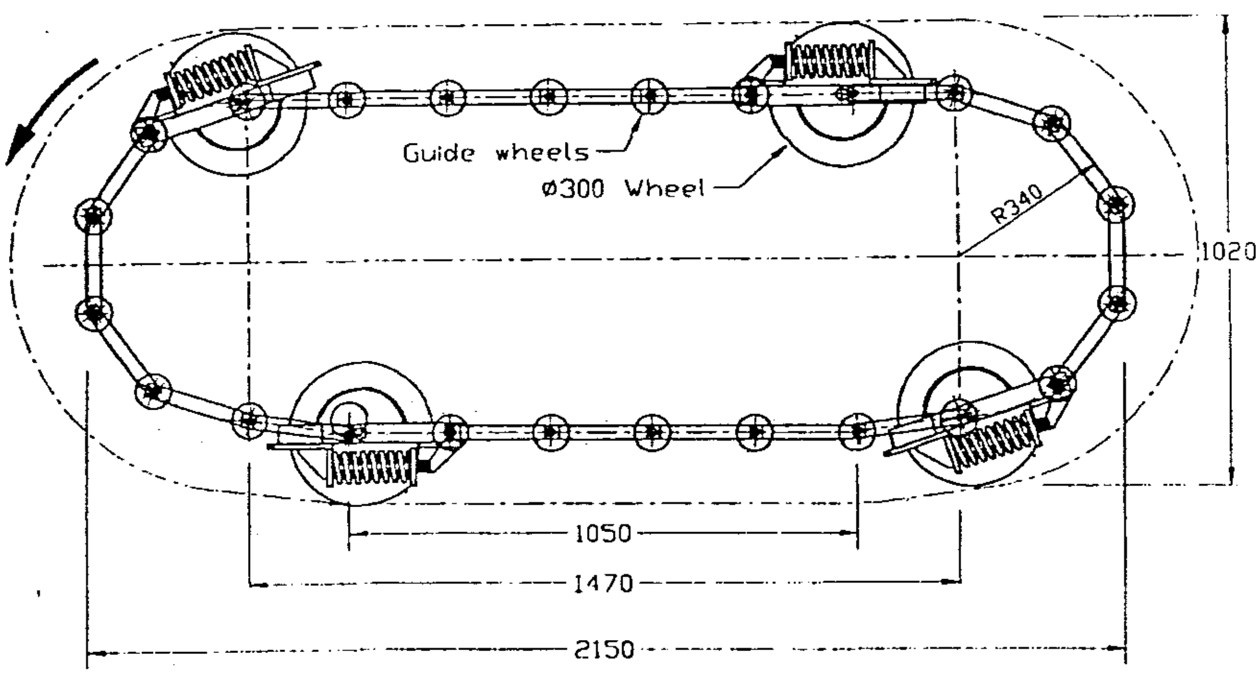

FIGURE 4: schematic overview of the wheel configuration of the MMLS Mk3 with a single wheel configuration.

3.6.2 MMLS Mk3 rutting test results

The MMLS Mk3 was set-up on top of the slab as shown in Figure M-2 and Figure M-3. Profilometer measurements were taken along transverse position 1 to 8 as indicated on Figure 1. Measurements were taken every 10 mm across the slab before MMLS Mk3 trafficking (0 axles reading) and at 10, 100, 500, 1000, 5000, 10000, 100000 and 200000 load repetitions. As anticipated for porous asphalt mixture, no significant rutting was observed during testing (see Figure M-1).

The transverse profile measurements taken during testing are given in Appendix L for each of the profilometer positions. From these graphs it is notable that the slab was uneven even prior to testing.

On pavements in the Netherlands it was observed that, whereas an average rut depth growth of 1.5mm/year was measured on conventional wearing courses, there was hardly any evidence of rutting on porous asphalt test sections during a service life of 10 years, the reason being that the porous asphalt mixes contain less fines and had a better mechanical interlock of course aggregate than did the conventional wearing courses (Verhaeghe, 1992).

The rutting profiles measurements were taken after 10, 100, 500, 1000, 5000, 10 000, 50 000, 100 000 and 200 000 axle loads relative to the profile measurement (0) before

MMLS Mk3 trafficking. These results have been summarized and are represented in Figure 5, which shows the cumulative average maximum rutting as a function of increased axle loading.

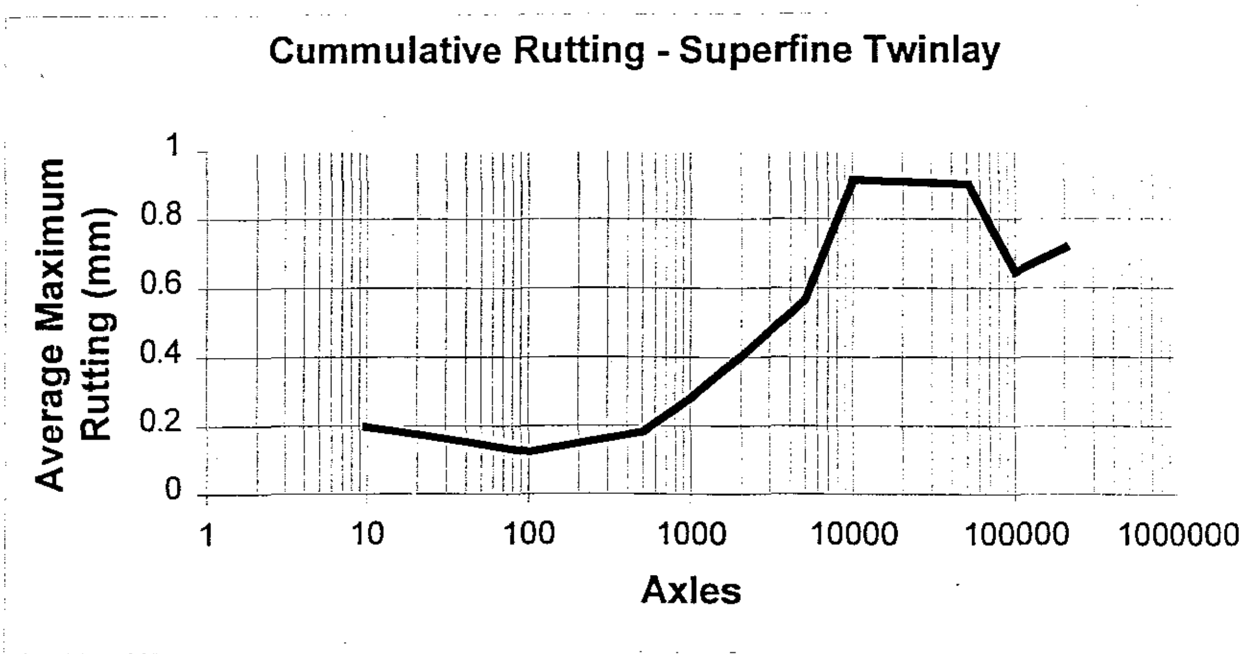

FIGURE 5: Cumulative rutting as a function of axle loading for MMLS Mk3

Figure 5 indicates that this material behaves in a rather interesting way when exposed to high temperatures and loading, with the average maximum rutting occurring at 10 000 axles. This material showed a fluctuation of rutting during testing. This is proof of the theory which states that porous asphalt deforms under the effect of wheel load as with conventional asphalt. Remove the load and much of the deformation recovers. The small amount of permanent residual strain that remains in the asphalt is due to the viscous flow of the binder. For a viscous binder (such as normal bitumen) under most circumstances, the higher the level of heavy traffic, the faster the rate of densification. In addition, as bitumen viscosity reduces with increasing temperature, for any particular grade of bitumen, densification tends to increase with increasing temperature. Most observers consider that binders which exhibit elastomeric properties increase the resistance to compaction of porous asphalt mixes.

3.6.3 Discussions

It is quite conspicuous from the results that this type of mix has a very good resistance to rutting with the average maximum rutting of less than 1 mm which is almost neglectable, considering that 3.5 mm of rutting at 100 000 axle repetitions at 50°C, is considered a border value.

As with conventional asphalt, porous asphalt deforms under the effect of wheel load. When the load is removed much of the deformation recovers, this explains the fluctuating effects in Figure 5. When porous asphalt is loaded very little deformation can be recorded, as the loading increases; deformation reaches a point where no more deformation is possible. This mainly due to the stone structure of porous asphalt and the rubberized bituminous binder used and the temperature during loading plays an important role.

Polishing of surface was also visible on the pavement surface at the end of testing (see Figure M-1).

3.6.4 Conclusions

It can therefore be concluded that Superfine Twinlay has an excellent resistance against rutting. This is due to the grading of the mix and the use of bitumen rubber as a binder. Consequently, it is assumed that due to thermal insulation by the porous wearing coarse, the stiffness of asphalt structures with porous asphalt wearing coarses is less affected by warm weather conditions. Superfine Twinlay porous asphalt showed signs of deforming under the effect of wheel load as it is with conventional asphalt. When the load was removed much of the deformation was recovered, this was not done in detail, and visual inspection was used to monitor the deformation recovery.

3.7 Sound absorption measurements

3.7.1 Sound absorption test results

In order to be able to assess the noise reducing properties of a road surface at an early stage (before the road is constructed) the absorption coefficient of a freshly compacted Marshall briquette can be measured.

A generally known method is the Impedance-tube or Standing wave measurement. The operational procedure for performing this test is given in Chapter 4, Appendix G. 100 mm briquettes were cored at strategic points from the slabs as indicated in Figure 1 and 2. Three briquettes were cored out from each slab and taken to UCT Acoustics Laboratory for sound absorption measurements. For the trafficked slab, measurements were taken after 200 000 axles only.

Figure 6 and 7 shows the graphical representation of the results of the absorption measurements taken on superfine Twinlay briquettes. These results show good absorption of sound by the superfine Twinlay porous asphalt samples. The detailed results of the absorption measurements taken on superfine Twinlay samples are shown in Appendix N.

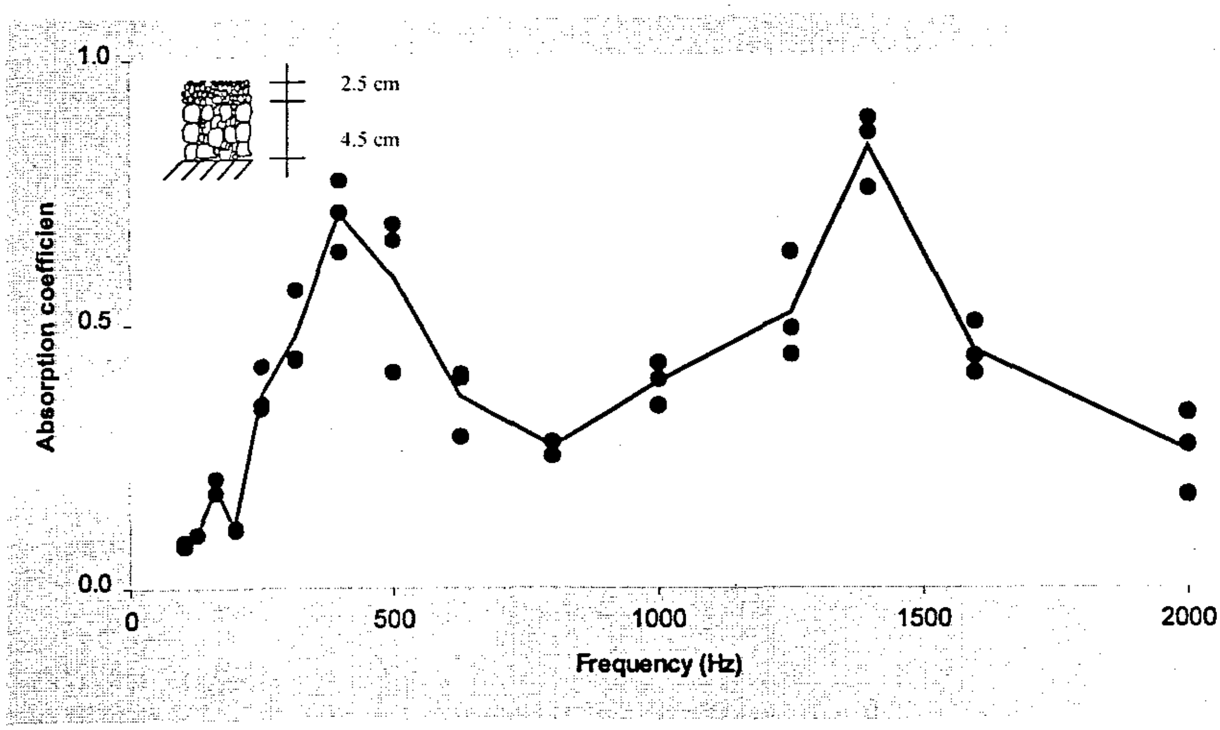

FIGURE 6: Absorption coefficient as a function of frequency of untrafficked Superfine Twinlay

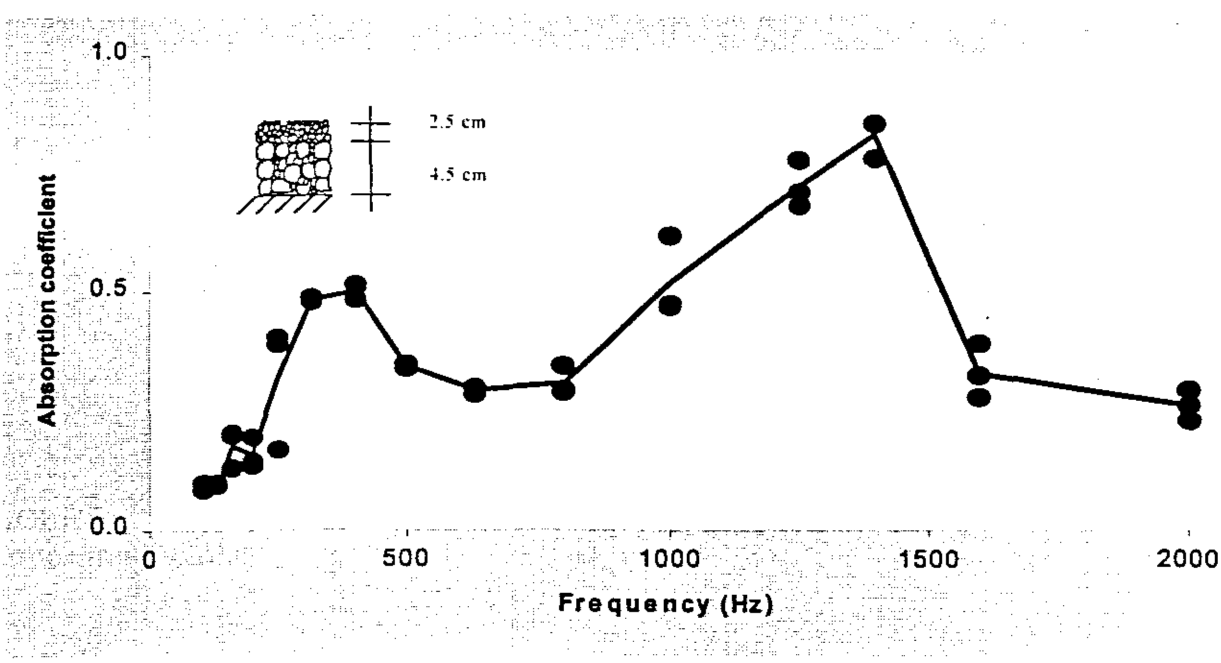

FIGURE 7: Absorption coefficient as a function of frequency of trafficked Superfine Twinlay using MMLS Mk3

3.7.2 Discussions

Figure 6 and Figure 7 show the normal (vertical) incidence sound absorption coefficient as a function of frequency for the two slabs investigated (trafficked and untrafficked by MMLS Mk3). The absorption coefficient was measured by means of a standardised method using the Impedance Tube into which Marshall briquettes cored from the test slabs. This method can be used to assess the acoustic quality of the material before the road is laid on site.

The requirements with regard to optimal flow resistance as well as to a short wave-length texture leads to porous mixtures of small chipping size. This is in conflict with demands for good water drainage properties of the road. Double layer construction provides solutions to this problem. Measurements on Marshall tablets indicate that such a structure behaves acoustically in a similar way as a homogeneous layer (Von Meier et al, 1990).

In interpreting the results, the 7 cm thick slab (untrafficked) of Superfine Twinlay porous asphalt displays a higher absorption coefficient (α) over a broad frequency as opposed to the 7 cm thick slab (trafficked by MMLS Mk3) of Superfine Twinlay porous asphalt displaying a lower absorption coefficient (α) over a broad frequency band. This is due to the slight reduction in voids content of the trafficked slab. The slight difference in sound absorption reduction is prominent at low frequencies.

3.7.3 Conclusions

A slight reduction in sound absorption coefficient was observed at lower frequencies. There is a slight reduction in sound absorption after a total of 200 000 axles. This is also due to the fact that porous asphalt wearing courses have a good resistance against rutting. This also proves the fact that clogging rather than densification causes the ultimate reduction capacity.

3.8 Permeability test measurements

3.8.1 Permeability test results

The water permeability test (LCS Drainometer) enables the drainage capacity, the in-situ voids content and the homogeneity of the finished surface to be assessed. It is therefore considered as an important test for assessment of the quality of a porous asphalt wearing coarse. The permeability of an asphalt mix is normally assessed in seconds. It is the voids in mix that make porous asphalt such a good mix with regard to draining of rain water to the side drains.

On account of the high void content of porous asphalt mixes, the Marvil drainometer is not suitable for assessing drainage capacity. It is suggested that a device (see Figure 8) be used. This device is called the LCS Drainometer, which is currently used in several European countries (Sabita Manual 17, 1995). A summarized test procedure is given in Appendix O.

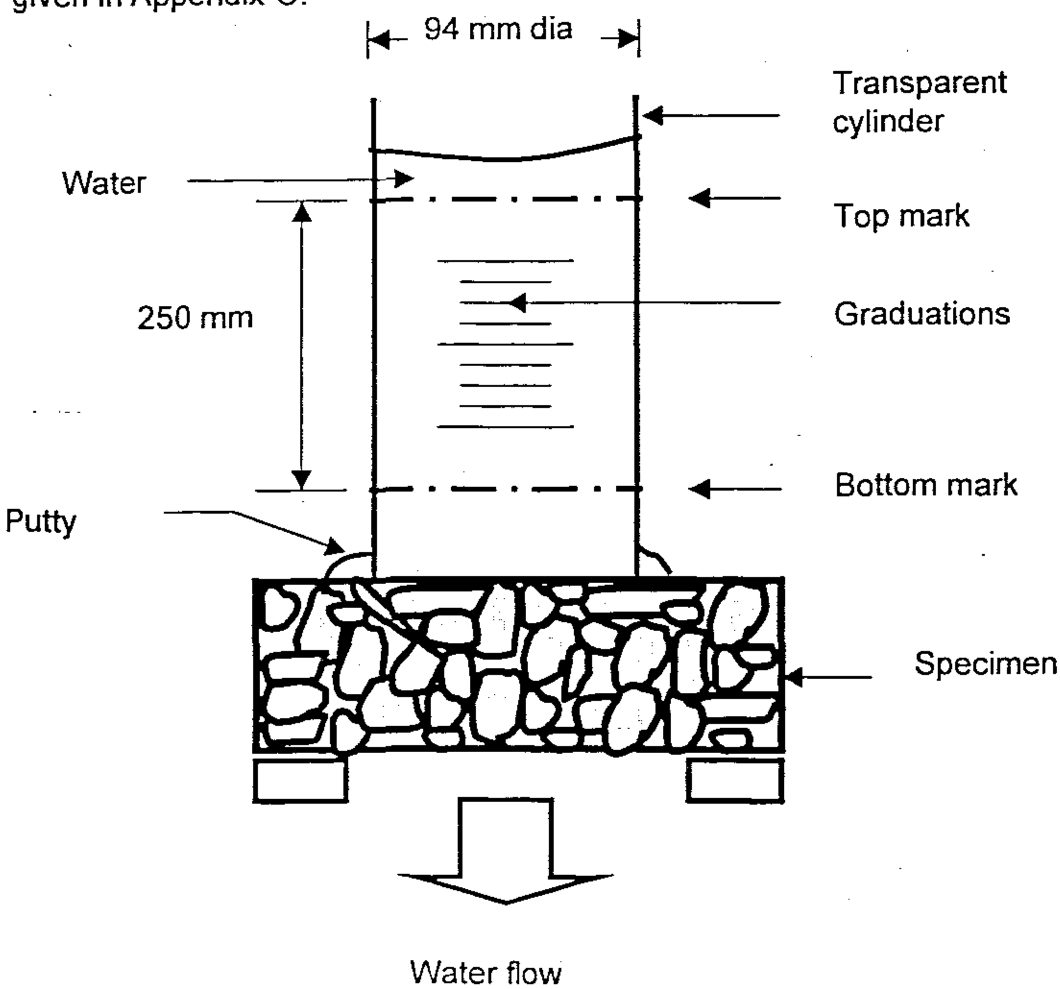

FIGURE 8: LCS Drainometer permeability set-up

Permeability measurements were performed at the University of Stellenbosch by Soil Lab (Pty) Ltd staff. For the permeability measurements, the LCS Drainometer device was placed on top of the asphalt slabs (trafficked and untrafficked).

Measurements were taken at strategic points as shown in Figure 1. As mentioned before, this test was performed in accordance to Appendix O (Test procedure for the LCS drainometer). The test yielded the following results taken at strategic points (see Table 4). For the trafficked slab, measurements were taken after 200 000 axles only.

TABLE 4: Permeability measurement and voids content				
Trafficked MMLS3 slab (200 000 repetitions)				Untrafficked slab
Position	**A**	**B**	**C**	**E**
Actual measurement (sec)	45.8	27	28	22.5
Permeability coef. (k)	2.31	2.26	2.26	2.24
Voids (%)	18.3	21.4	21.2	22.7

3.8.2 Discussions

Traffic compaction is the additional compaction resulting from the kneading action of the traffic. This is due to the densification process in which particles are brought nearer together with an overall greater unit weight. This is generally a common reported problem with densely graded asphalt mixes.

The permeability results from the untrafficked superfine Twinlay porous asphalt slab (ref. Figure 2) were not so much better than those from the trafficked superfine Twinlay porous asphalt slab (ref. Figure 1). This was expected due to porous asphalt mixtures good resistance to rutting. The permeability results correlate with the voids content, the higher the permeability the higher the voids content.

3.8.3 Conclusions

Once again the Superfine Twinlay showed an excellent resistance against rutting. This can be clearly seen from the permeability measurements. There was a slight change in the permeability coefficient (k) after the slab was subjected to a total of 200 000 axle loading. Generally the voids content of the trafficked slab are still high enough to regard the mix as a porous mix (voids content in excess of 20 percent). It is anticipated that clogging of the voids will cause a drastic reduction in the permeability levels instead.

4 RUTTING TEST (B) – SUPERPAVE GYRATORY COMPACTED BRIQUETTES

4.1 Scope of the investigation

This section of the study reports on the rutting test carried under wet conditions (extreme conditions). Conclusions are then drawn with regards to the performance of the Superfine Twinlay wearing course. For this rutting test MMLS Mk3 was used and the test was performed at an average temperature of 50°C. The asphalt briquettes were manufactured using a Gyratory Compactor with a diameter of 150 mm. These briquettes were then used for the rutting test. As in Section 3, only superfine Twinlay wearing course mixture was investigated. The mixes were compacted with the SUPERPAVE gyratory compactor at temperatures of approximately 130°C as recommended in the Sabita Manual 17 (Sabita Manual 17, 1995). The same compaction procedure as in Section 3.5 was followed. The bottom layer was compacted first (to the required thickness using its densities) then immediately followed by the top layer. Because the stone particles of the top layer settled into the course texture of the bottom layer, a relatively thin layer could be applied and stone-to-stone contact was achieved.

The briquettes were compacted and trafficked using MMLS Mk3 at the University of Stellenbosch. This report gives details of the briquette manufacturing processes, details of the test configurations as well as MMLS Mk3 specifications applied during rutting test. Photographs referred to in the text are shown in Appendix P. These photographs were taken during the study.

4.2 Problem statement

Terrel and Al-Swailmi (1992) concluded that repeated loading (i.e., simulation of traffic loading) is a very important variable to be included in water conditioning protocols. Similarly, in an earlier study, Lottman (1971) found that heavy traffic volumes appeared to increase the rate of damage due to moisture more effectively than climatic extremes of precipitation and temperature.

4.3 Objective of the test

The experimental wearing course surface adopted is the same as the one mentioned in Section 3.3.

The main objectives behind the proposed test configuration are to assess, evaluate and quantify the rutting performance of a Superfine Twinlay pavement underwater and to monitor the stripping of the asphalt-wearing course under accelerated pavement testing with the MMLS Mk3 on the asphalt briquettes compacted using a SUPERPAVE gyratory compactor.

4.4 Test programme adopted

The MMLS Mk3 rutting test was used on the Superfine Twinlay wearing coarse gyratory compacted briquettes. Eight briquettes were compacted or manufactured on the gyratory compactor at the University of Stellenbosch.

As in Section 3, the mix design stage involved mixing material types as shown in Section 3.3 Table 1. Both layers, top and bottom were mixed separately. 140°C and 130°C temperatures were used during mixing and compaction respectively as recommended in the Sabita manual 17 (Sabita Manual 17, 1995) for bitumen-rubber asphalt. The mass of the material placed in the mould was measured to ensure that the densities of all slabs manufactured are the same.

After mixing, the samples were compacted into the Superpave Gyratory Compactor. *Samples were compacted to 50 gyrations for the bottom layer and 150 gyrations for* the top layer. The bottom and top layers, were compacted one immediately on top of the other to form a homogeneous sample. As mentioned earlier eight 150 mm briquettes were compacted for MMLS Mk3 testing. These briquettes were cut to a specific shape and size (see Figure Q-6) in order to fit in the test set up. The samples were cut to a height of 60 +/- 1 mm. All eight samples were placed in a water bath on a steel platform as indicated in Figure 9 and Figure Q-1. The water was heated with elements with the briquettes inside the mould (see Figure Q-3) and a pump was connected to the system to circulate the water. The water temperature was regulated with a thermostat and the asphalt temperature with thermocouples which were placed in the specimens.

For the rutting test, profilometer measurements were taken after specific intervals to obtain the rut depths and rate of rutting during MMLS Mk3 trafficking (see Figure Q-4). These ranged from 0 to 200 000 axles i.e. after 0, 10, 100, 500, 1000, 5000, 10 000, 50 000, 100 000 and 200 000. These measurements represent the vertical deformation of the asphalt under trafficking. The data was captured using a computer (see Figure Q-5).

The position at which these measurements were taken was at each briquette. The positions range between 1 through to 8 in the direction of loading. Two measurements were taken on each briquette and these were 10 mm apart on the centreline perpendicular to the trafficking direction.

Stripping of the briquette was visually monitored on the surface of the briquette after each set of loading.

The MMLS Mk3 was placed on top of the briquettes which were submerged in water and set to run for a total of 200 000 axle (see Figure Q-2). In summary the test condition for the MMLS Mk3 were as follows (this applied to both tests, A and B):

▪ Number of total load repetitions	200 000
▪ Tyre pressure	690kPa
▪ Wheel load	2.1 kN
▪ Test temperature of the asphalt briquette	50°C
▪ Loading rate	7200 repetitions per hour

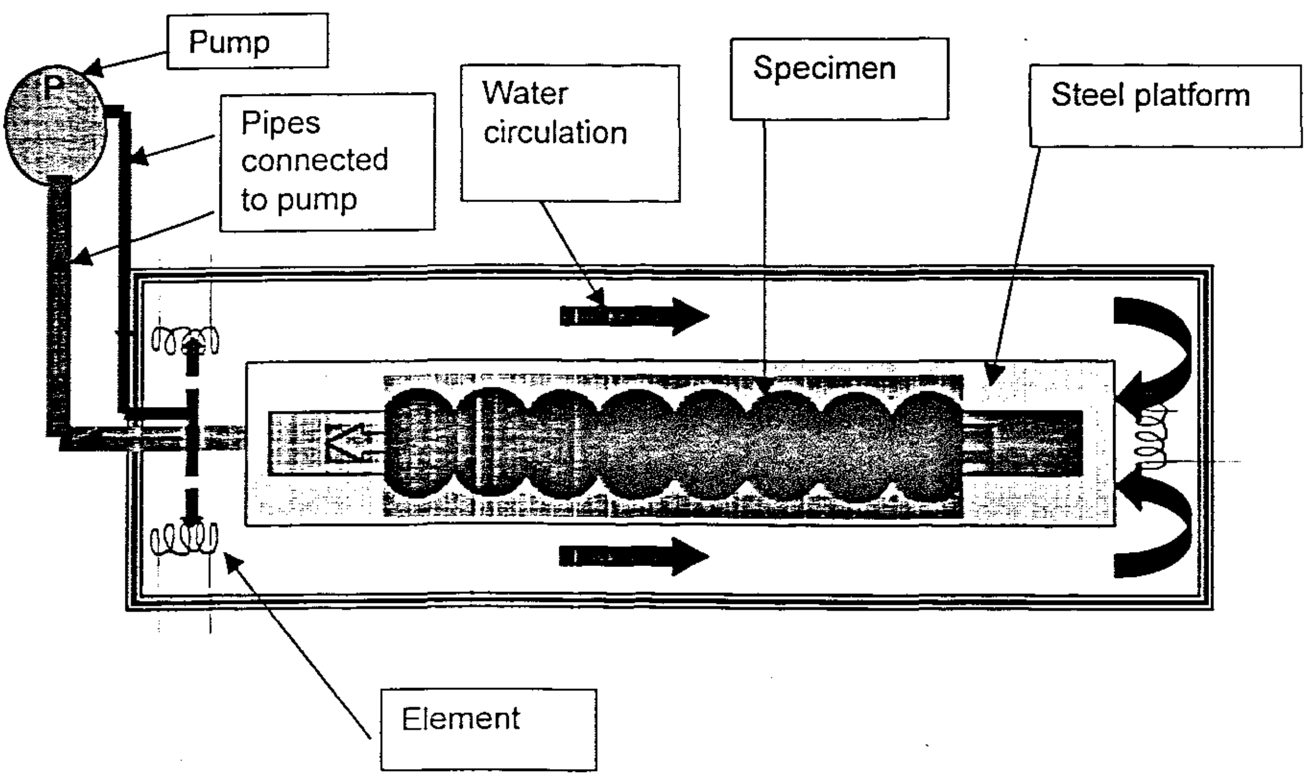

FIGURE 9: Rutting test set-up for MMLS Mk3

4.5 MMLS Mk3 rutting test results

As mentioned earlier, rutting profilometer measurements were taken along the transverse positions from 1 to 8. Measurements were taken every 2 mm across the surface of the briquettes before MMLS Mk3 trafficking (0 axles reading) and at 100, 500, 1000, 5000, 10 000, 100 000 and 200 000 load repetitions. A series of eight briquettes were tested as a single unit during MMLS Mk3 testing.

The transverse profile measurements taken during testing are given in Appendix P for each of the profilometer positions. From these graphs it is obvious that the samples were uneven before testing.

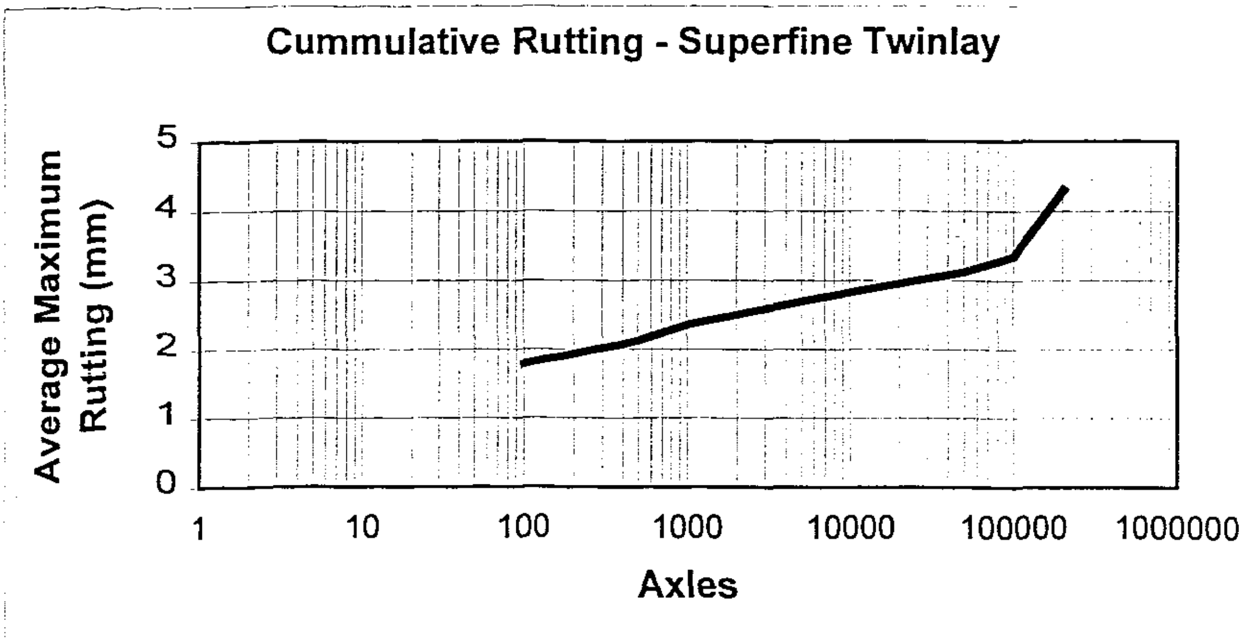

FIGURE 10: Average cumulative rutting as a function of axle loading for MMLS Mk3

Signs of stripping manifested at an early stage of axle loading. Ravelling was evident on the briquettes and was probably due to moisture damage. Stripping lead to ravelling, which is characterised by the loss of aggregate at the surface of the briquettes, resulted in deformation of the mix on the surface of the briquette. The aoverage cumulative rutting as a function of axle loading is shown in Figure 10. The maximum average rut was 4.3 mm. This is probably due to the consequences of moisture damage. It is important to note that the rutting measurements displayed in Figure 10 are probably due to the ravelling of the samples during MMLS Mk3 trafficking.

Figure 10 shows a good relationship of load repetitions and failure of the surface, the more the loading the greater the extent of damage.

4.6 Discussions

Damage due to moisture occurs in various forms and degree of severity. The primary consequence of moisture damage is that of stripping, characterized by failure of the bitumen-aggregate bond. The rutting measurements taken during the study were an indication of ravelling which was observed through visual inspections during and after MMLS Mk3 rutting test.

The strong tangent tensions which come from abrasive action of the traffic, especially in the presence of open mixtures, can cause great problems to the asphalt wearing course and lead to the rupture by means of stripping or detachment.

4.7 Conclusions

After a series of axle repetitions on the briquettes submerged in heated water at 50°C there was clear evidence that moisture has an adverse effect on the durability characteristics of a Superfine Twinlay porous asphalt surfaces. Moisture damage can manifest in a form of loss of adhesion between the bitumen and aggregate and or loss of cohesion in the bitumen –filler mastic.

Stripping of the bitumen rubber was nevertheless unmistakably recognisable since it preceded the appearance of catastrophic ravelling failure, which is categorised as moisture damage.

The presence of water had an adverse effect on the Superfine Twinlay briquettes under trafficking. This caused the samples to undergo an escalated process of stripping of the bitumen rubber which resulted in ravelling which is characterised by the loss of material at the surface of the Superfine Twinlay.

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CHAPTER 6

1 CONCLUSIONS

The objectives of this research, which is the design of a porous asphalt pavement surface that will provide larger reductions with regard to noise production and a pavement which has a high absorption coefficient at low and high frequencies without compromising permeability of rain water from the surface of the pavement to the side drains were met.

Permeability is also very important, as this is what makes it highly suitable for wet-weather conditions to improve the road safety. This research was based on assessment of the properties of a typical Twin-layer design, which was initially developed in the Netherlands. A superfine top layer was used with a coarse single grain bottom layer with both layers acting as a homogeneous layer. A series of test and investigations were conducted and the following conclusions were drawn from this research:

- High void contents were achieved and very high binder contents were also achieved with the Superfine Twinlay. The top layer yielded 24.3 percent and 22.5 percent for the bottom layer. This makes Superfine Twinlay an excellent sound absorbing surfacing layer.

- An increase in binder content causes a reduction in void content, nevertheless the void content of the mixes were still large enough to regard the mix as a porous asphalt mix, with the void content above 20 percent. Therefore the increase in binder content does not have a significant effect on the void content.

- The addition of rubber crumbs to the bitumen does not have an effect on the volumetric properties of porous asphalt mixes. Therefore, the drainage capacity and noise reduction should not be affected by whether the mix has rubber or not.

- This type of mix showed a general poor resistance to abrasion loss when subjected to the Cantabro Abrasion test carried out on the Los Angeles Rattle. This poor performance was immediately improved when cement was used as a filler instead of the lime.

- Bitumen rubber consisting of 20 percent recycled rubber crumbs was used to modify the bitumen. Very high binder contents were used without the risk of binder drainage from the mix, this is mainly due to the use of bitumen rubber as a binder. Bitumen rubber has an appropriate rheological property to prevent binder run-off. In general, the type and amount of binder in a mix plays a significant role in ensuring that the mix will be sufficiently resistant to damaging effects of both traffic and environment. This makes the selection of an appropriate binder a crucial consideration in the mix design stage. As a result of a number of tests that were performed on Superfine Twinlay an optimum binder content of 5.5 percent for the top layer and a binder content of 6 percent for the bottom layer were selected.

- In order to improve and enhance the durability of porous asphalt mixtures, additives such as: polymers, fibres and rubber crumbs must be added.

- Superfine Twinlay offers a higher sound absorption coefficient on a broader frequency range as opposed to a single homogeneous porous asphalt layer. The production of noise is also drastically reduced due to the introduction of a superfine top layer. Benefits of using a double layer as opposed to a single layer of porous asphalt surfacing includes most importantly, good sound absorption at low and high vehicle speeds, this is probably due to the small aggregate size in the top layer which increases the flow resistance subsequently providing the desired short-wave length texture. The generation of road traffic noise is a result of several interacting factors with the pavement/tyre or rolling noise being the contributing factor at vehicle speeds above 50 km/h. There is a general agreement that a considerable reduction in noise generation from tyre/road generation contact can be achieved by the use of a special pavement mix design such as porous asphalt. Wearing courses with rough macrotexture tend to generate greater rolling noise. In general porous asphalt surfacing layers provide a cost-effective way of reducing road traffic noise. In general, the higher the voids, the better the absorption and the finer the aggregates, the more the reduction in tyre/road noise.

- Superfine Twinlay porous asphalt surfaces have an excellent resistance against rutting. This wearing course deforms slightly under the effect of a wheel load. It is assumed (based on international experience and visual inspection during testing that when the load is removed much of the deformation recovers. On the other hand Superfine Twinlay showed signs of having poor resistance against moisture damage during MMLS Mk3 rutting test under water. Moisture can adversely affect the durability characteristic of a Superfine Twinlay porous asphalt mixture. Stripping of the binder was observed which resulted in ravelling of the samples during testing. Moisture damage can manifest itself in loss of adhesion between the bitumen rubber and the aggregate and possibly loss of cohesion in the bitumen –filler mastic.

- The South African road users are to benefit more if Superfine Twinlay is constructed on some of our road pavements. The benefits will come about in the form of reduction of aquaplaning subsequently splash and spray and improved visibility, reduction of rolling noise, improved permeability leading to improved skid resistance, improved driver comfort and many other advantages as mentioned in the report.

A number of researches into road traffic noise revealed that, whilst a relative volume of noise depends on the speed of the vehicle, rolling noise is produced for a number of sources, namely, general engine noise and transmission noise, noise generated by the pavement/tyre contact and aerodynamic noise. Measurements showed that pavement/tyre contact or rolling noise continues to increase as the speed increases. And most importantly it has been shown that rolling noise very much depends on the type of overlay.

2 RECOMMENDATIONS

Bitumen rubber is a high viscosity binder. The minimum binder requirements for Superfine Twinlay mixes are high; this helps to provide sufficient resistance to abrasion. Cement filler is also highly recommended, as this will improve the structural integrity of the mix, but might cause fatigue cracking.

As it has been mentioned in this report, road traffic noise pollution is becoming an increasing problem especially with the significant increase in traffic densities. Immediate and corrective measures need to be taken to protect the environment and most importantly the people. Road traffic is the most important single source of community noise, which may be because traffic noise is the most difficult noise to eradicate.

As a result of this research findings and conclusions the following recommendations are seen as imperative:

- The impact of traffic noise from new or existing transportation on neighbouring communities needs to be coupled or connected with growing public awareness of environmental issues in South Africa. Therefore, the environmental noise levels of the new and existing transport systems need to be predicted or measured for assessing their magnitude of impact on neighbouring communities.

- More research into road traffic noise will show how to reduce nuisance caused by road/traffic noise, it can produce methods of examining different options and it can develop methods of presentation of the results to members of the public and to policy makers, i.e. government. It will then remain the responsibility of those policy makers to weigh one consideration against another (porous asphalt is only one of the alternatives) and come to what they consider the best solution, which will always be a compromise.

- The road traffic noise emission should be coupled with the political aim which is that road traffic noise has to be accepted in a more pronounced way by the population by means of a significant reduction of the future exterior noise limit values. New regulations aimed at putting people first needs to be implemented if road traffic noise is to be controlled.

- Recognising that human development depends on a healthy environment and healthy social structures. Municipalities can enhance awareness by including environmental issues in their planning processes.

- Under no circumstances should Superfine Twinlay be constructed on top of a layer that is not 100 percent impervious and which has no crossfall. The impervious layer will prevent the ingress of water on the underlying layers thereby preventing premature failure of the road structure during service life.

- One of the major mechanical failure mechanisms of porous asphalt is stripping and ravelling due to the damaging effects of environmental forces. An innovative and related design criteria is required to enable the effects of moisture damage during the mix design stage phase. Accelerated conditioning tests for moisture and temperature are recommended to assess ability to withstand environment and traffic.

- For the purpose of good drainage of rainwater into the side drains it is recommended that a minimum layer thickness of 40 mm be adhered to for all porous asphalt surfacings.

APPENDICES

APPENDIX A

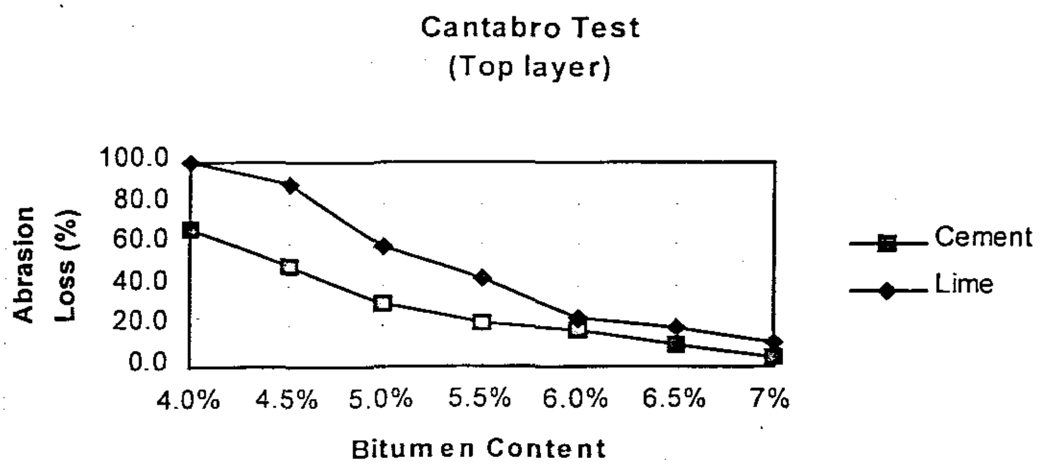

FIGURE A- 1: Abrasion loss as a function of bitumen content for the top layer.

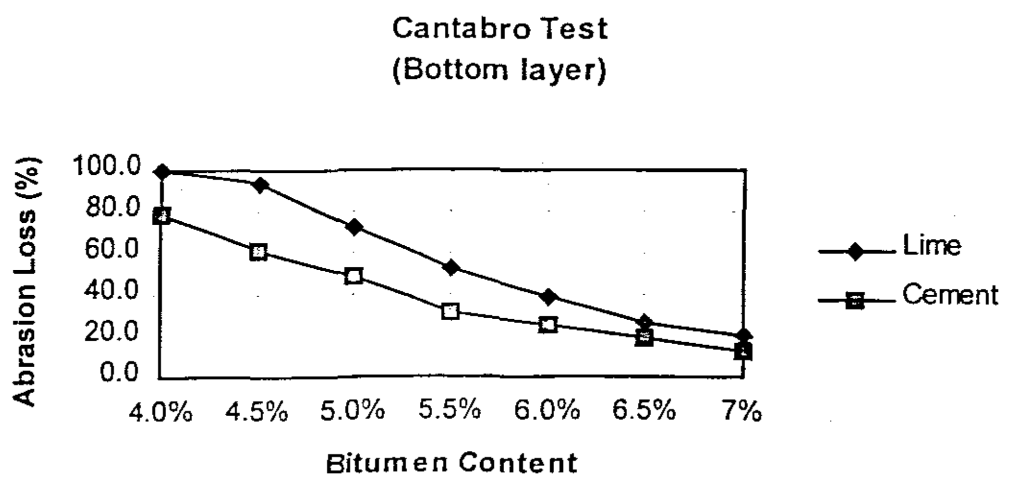

FIGURE A- 2: Abrasion loss as a function of bitumen content for the bottom layer.

APPENDIX B

TABLE B- 1: Basket drainage test results for the top and bottom layer

TABLE B-1: Basket drainage test							
	Binder content						
GRADING TYPE:	**4.0 %**	**4.5 %**	**5.0 %**	**5.5 %**	**6.0 %**	**6.5 %**	**7.0%**
1.18/2.36mm Top Layer	0	0	0	0	0	0	0
9.5/13.2mm Bottom Layer	0	0	0	0	0	0	0

APPENDIX C

TABLE C- 1: Void content as a percentage at each binder content

TABLE C-1: Void content (%) for three briquettes at different binder contents								
		Binder content						
GRADING TYPE:		4.0 %	4.5 %	5.0 %	5.5 %	6.0 %	6.5 %	7.0%
1.18/2.36mm Top Layer	1	29.8	28.2	26.0	22.7	21.9	20.0	18.4
	2	29.1	27.8	22.7	22.7	22.3	21.0	19.3
	3	23.8	25.1	27.6	25.2	25.2	19.3	17.8
9.5/13.2mm Bottom Layer	1	29.5	28.6	26.7	24.9	22.7	19.2	17.7
	2	29.1	28.3	26.8	26.3	23.1	21.7	20.9
	3	28.6	26.2	25.7	24.7	21.7	21.5	20.1

TABLE C- 2: Abrasion loss as a function of binder content for cement filler

TABLE C-2: Cantabro Abrasion Loss (%) with 3% cement filler								
		Binder content						
GRADING TYPE:		4.0 %	4.5 %	5.0 %	5.5 %	6.0 %	6.5 %	7.0%
1.18/2.36mm Top Layer	1	64.1	50.5	33.9	19.6	17.8	8.6	5.3
	2	70.0	48.8	32.7	23.1	16.6	10.2	5.7
	3	67.6	49.7	29.1	21.2	19.3	12.5	4.2
9.5/13.2mm Bottom Layer	1	80.2	61.8	49.7	33.0	25.7	18.5	11.5
	2	77.6	60.1	49.5	29.3	24.3	20.9	11.9
	3	79.4	63.0	47.2	30.4	23.6	18.4	12.5

TABLE C- 3: Abrasion loss as a function of binder content for lime filler

TABLE C-3: Cantabro Abrasion Loss (%) with 3% lime filler								
		Binder content						
GRADING TYPE:		4.0 %	4.5 %	5.0 %	5.5 %	6.0 %	6.5 %	7.0%
1.18/2.36mm Top Layer	1	100	89.6	62.8	42.7	25.2	22.0	11.5
	2	100	87.9	59.6	41.6	23.7	11.3	12.2
	3	100	88.2	54.9	44.5	24.6	23.9	10.7
9.5/13.2mm Bottom Layer		100	94.2	73.7	52.3	38.5	26.5	19.5
		100	93.2	72.7	51.0	37.6	27.8	18.3
		100	93.8	71.8	54.6	38.5	26.2	20.4

APPENDIX D

TABLE D- 1: Mix components for the Top layer of Superfine Twinlay

TABLE D-1: Mix components							
Mix composition	**Top layer (%)**						
9.5/13.2 mm, Malmesbury Hornfels, ex RMM Eerste River	-	-	-	-	-	-	-
1.18/2.36 mm, Malmesbury Hornfels, ex RMM Eerste River	93.0	92.5	92.0	91.5	91.0	90.5	90.0
CRUSHER DUST, Malmesbury Hornfels, ex RMM Eerste River	-	-	-	-	-	-	-
Filler (Cement)	3.0	3.0	3.0	3.0	3.0	3.0	3.0
Rubber bitumen	4.0	4.5	5.0	5.5	6.0	6.5	7.0

TABLE D- 2: Mix components for the bottom layer of Superfine Twinlay

TABLE D-2: Mix components							
Mix composition	**Bottom layer(%)**						
9.5/13.2 mm, Malmesbury Hornfels, ex RMM Eerste River	86.0	85.5	85.0	84.5	84.0	83.5	83.0
1.18/2.36 mm, Malmesbury Hornfels, ex RMM Eerste River	-	-	-	-	-	-	-
CRUSHER DUST, Malmesbury Hornfels, ex RMM Eerste River	7.0	7.0	7.0	7.0	7.0	7.0	7.0
Filler (Cement)	3.0	3.0	3.0	3.0	3.0	3.0	3.0
Rubber bitumen	4.0	4.5	5.0	5.5	6.0	6.5	7.0

APPENDIX E

THE TEST PROCEDURE FOR THE BASKET AND SCHELLENBERGER DRAINAGE TESTS 1

Purpose of the test

The tests are designed to simulate and quantify the amount of binder run-off for a particular mix type which can take place during construction operations (transportation and laying).

Test procedure for the Basket Drainage Test

The operational procedure of the Basket Drainage Test is as follows:

1. Mixes are manufactured and compacted in Duriez moulds under a pressure of 30 bars;

2. These moulds are then laid on a grid and the set is placed in an oven at 180 °C for 7 hours 30 minutes (these severe conditions are chosen to simulate the occasional cases where bitumen drains through the aggregate);

3. The bitumen which drained through the mix to the grid is recovered and the loss of bitumen is calculated with respect to the initial content.

The binder used for these tests is normally 80/100 penetration grade bitumen doped with 0.3 per cent of adhesion agent, but this test lends itself ideally for determining the decreased amount of binder run-off due to binder modification or due to the addition of cellulose fibres.

Test procedure for the Schellenberger Drainage Test

The testing methodology consists of placing 1000g to 1100g samples of asphalt in 800ml glass receivers and which are then placed in an oven at different temperatures. Similar to the Basket Drainage Test, the amount of binder is determined with respect to the initial amount of bitumen during mixing.

References

BMJA Verhaeghe, 1992. Properties of cellulose fibre – modified porous asphalt mixes, Roads and Transport Technology, Contract report DRTT – C/222

APPENDIX F

THE CANTABRO ABRASION TEST PROCEDURE 1

Purpose of the test

The purpose of the Cantabro test (see Figure F-1) is to determine the loss of aggregate due to abrasion which can be used in a mix design method for the determination of an optimum binder content.

Summary of method

The resistance of porous asphalt briquettes to abrasion loss is analyzed through the Cantabro test. This is an abrasion and impact test carried out in the Los Angeles rattler. In the test, a Marshall sample compacted with 50 blows on each side is used. The mass of the specimen is determined to the nearest 0.1 gram, and is recorded as P1. The test specimen is then placed in the Los Angeles Rattler without the abrasive charge of steel spheres. The machine is switched on and allowed to operate for 3000 revolutions at a speed of 3.1 to 3.5 rad/sec (30 to 33 rpm). After the required number of revolutions is attained, the test specimen is removed and again weighed to the nearest 0.1 gram (P2). The percentage abrasion loss is then calculated according to the following formula:

$$P = \frac{P1 - P2}{P1} \times 100$$

The maximum permitted abrasion loss value for freshly compacted specimens is 25 per cent (based on overseas experience). With this test, a minimum amount of binder is determined. In any case, the binder content has to be at least four per cent to ensure adequate coating thickness.

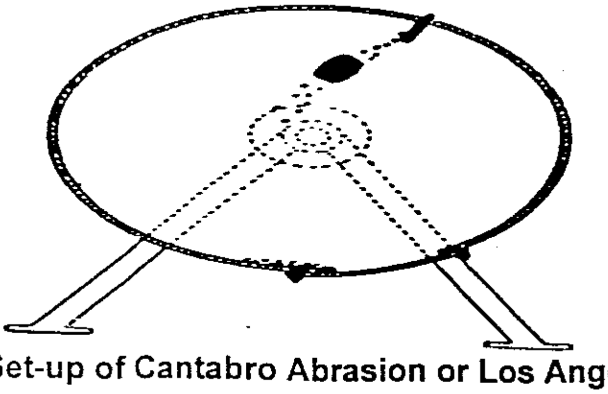

FIGURE F-1: Test Set-up of Cantabro Abrasion or Los Angeles Rattler

References

BMJA Verhaeghe, 1992. Properties of cellulose fibre – modified porous asphalt mixes, Roads and Transport Technology, Contract report DRTT – C/222

APPENDIX G

ABSORPTION TEST 1: Using the standing–wave tube apparatus to measure plane wave sound absorbing properties of a material

The Standing Wave Tube or Impedance Tube (see Figure G-1) method provides a convenient laboratory method of measuring acoustic absorption coefficient and acoustic or plane wave impedance of a material sample. An Impedance Tube consists of a small circular tube with a sound source at one end and a sample of the solid material to be tested at the other end. A travelling microphone is located in the tube and is used to measure the standing wave ratio.

The sample to be measured is mounted at one end of a stiff walled tube. Mounted on the other end is a loud speaker with its axis coincident with that of the tube. A pure tone signal from the loud speaker is therefore partially reflected from the sample and the reflected wave interferes with the incident wave producing a standing wave.

The 100mm diameter tube is suitable for range 100-1000Hz (normally 90 to 1800Hz) and the 25mm diameter tube is suitable for range 1000-4000Hz (normally 800 to 6500Hz).

A microphone probe is placed at the first maximum and minimum points of the standing wave away from the sample. The amplitude of (A + B) and (A - B) from a graph of the standing wave pattern in the impedance tube are then measured. The distance x must be recorded, where x is the distance from the surface of the test specimen in the impedance tube to the first minimum (A - B) of the standing wave pattern in the tube.

Calculations: To obtain the Real and Imaginary parts of the normalised impedance and absorption values.

Standing wave ratio (SWR) =

$$\frac{A + B}{A - B}$$

$$\frac{B}{A} = \frac{SWR - 1}{SWR + 1}$$

Sound power reflection coefficient

$$\propto_r = \frac{(SWR-1)^2}{(SWR+1)^2}$$

Sound power absorption coefficient

$$\propto_n = 1 - \propto_r$$

Specific acoustic impedance, is the complex ratio of the sound pressure at the surface of the medium to the effective particle velocity at that point.

Phase angle θ (rad)= $-2k_1 x - \pi$

$$k_1 = \frac{2\pi f}{c_1}$$

and x is the distance from the surface of the test specimen to the first minimum (A - B) of the standing wave pattern in the impedance tube. C_1= 343 m/s for air yields.

Specific acoustic impedance

$$\overline{z_n} = r_n + jx_n$$

Therefore the Real (R_n) and Imaginary (X_n) part of the normalised impedance are as follows:

$$\frac{R_n}{\rho_1 c_1} = \frac{1 - \propto_r}{1 - 2\frac{B_1}{A_1}\cos\theta + \propto_r}$$

$$\frac{X_n}{\rho_1 c_1} = \frac{2\frac{B_1}{A_1}\sin\theta}{1 - 2\frac{B_1}{A_1}\cos\theta + \propto_r}$$

$$\bar{z} = \sqrt{(R_n)^2 + (X_n)^2}$$

Compiling results

Measurements are then tabulated and a graph of absorption coefficient versus log frequency ratio is prepared and Real and Imaginary parts of the normalised impedance versus log frequency ratio on the same graph is also plotted. Conclusions on the laboratory measurements are then drawn.

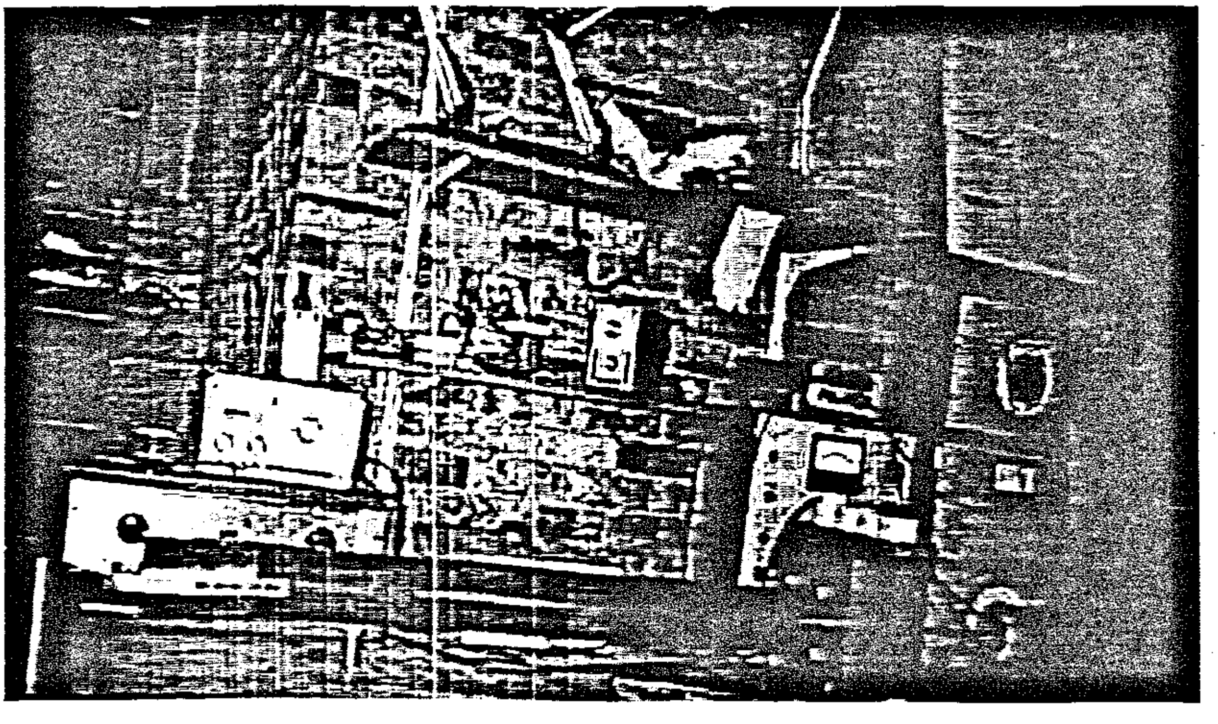

FIGURE G-1: Photograph of the Standing Wave Apparatus used to measure the sound absorption coefficient of porous materials.

APPENDIX H

Absorption measurements taken during the study Table H- 1 to H-21

TABLE H-1: Absorption coefficient of 4cm Porous asphalt briquette no. 1

c	Hz	Log(Hz)	Ratio	A+B	A-B	x (in m)	SWR	Alpha (r)	Theta	Alpha(n)
344	100	2.000	1.050	81.7	0.659	0.848	123.976	0.968	-0.044	0.032
344	125	2.097	1.048	54.9	0.517	0.659	106.190	0.963	-0.132	0.037
344	160	2.204	1.102	35.2	0.451	0.493	78.049	0.950	-0.260	0.050
344	200	2.301	1.151	26.9	0.342	0.373	78.655	0.950	-0.416	0.050
344	250	2.398	1.199	17.8	0.35	0.289	50.857	0.924	-0.502	0.076
344	315	2.498	1.249	14.59	0.227	0.231	64.273	0.940	-0.483	0.060
344	400	2.602	1.301	10.29	0.244	0.244	42.172	0.909	0.424	0.091
344	500	2.699	1.349	19.18	0.87	0.194	22.046	0.834	0.402	0.166
344	630	2.799	1.400	17.61	2.09	0.143	8.426	0.621	0.149	0.379
344	800	2.903	1.452	9.4	2.17	0.107	4.332	0.390	-0.015	0.610
344	1000	3.000	1.500	4.64	1.25	0.089	3.712	0.331	0.110	0.669
344	1250	3.097	1.548	9.18	1.087	0.069	8.445	0.621	0.009	0.379
344	1400	3.146	1.573	1.558	0.149	0.054	10.456	0.681	-0.380	0.319
344	1600	3.204	1.602	0.386	0.031	0.051	12.452	0.725	-0.161	0.275
344	2000	3.301	1.651	1.013	0.096	0.038	10.552	0.684	-0.365	0.316

TABLE H-2: Absorption coefficient of 4cm Porous asphalt briquette no. 2

c	Hz	Log(Hz)	Ratio	A+B	A-B	x (in m)	SWR	Alpha (r)	Theta	Alpha(n)
344	100	2.000	1.050	81.6	0.694	0.83	117.579	0.967	-0.110	0.033
344	125	2.097	1.048	52.9	0.547	0.641	96.709	0.959	-0.215	0.041
344	160	2.204	1.102	35.72	0.492	0.477	72.602	0.946	-0.354	0.054
344	200	2.301	1.151	27.5	0.382	0.352	71.990	0.946	-0.570	0.054
344	250	2.398	1.199	50.8	1.298	0.251	39.137	0.903	-0.849	0.097
344	315	2.498	1.249	14.14	0.295	0.259	47.932	0.920	-0.161	0.080
344	400	2.602	1.301	10.17	0.511	0.229	19.902	0.818	0.205	0.182
344	500	2.699	1.349	17.32	1.385	0.193	12.505	0.726	0.384	0.274
344	630	2.799	1.400	16.38	2.51	0.145	6.526	0.539	0.195	0.461
344	800	2.903	1.452	8.52	1.88	0.106	4.532	0.408	-0.044	0.592
344	1000	3.000	1.500	2.83	1.09	0.086	2.596	0.197	0.000	0.803
344	1250	3.097	1.548	7.94	55	0.066	0.144	0.559	-0.128	0.441
344	1400	3.146	1.573	1.492	0.164	0.055	9.098	0.643	-0.329	0.357
344	1600	3.204	1.602	0.301	0.028	0.046	10.750	0.689	-0.453	0.311
344	2000	3.301	1.651	0.91	0.076	0.024	11.974	0.715	-1.388	0.285

TABLE H-3: Absorption coefficient of 4cm Porous asphalt briquette no. 3										
c	Hz	Log(Hz)	Ratio	A+B	A-B	x (in m)	SWR	Alpha (r)	Theta	Alpha(n)
344	100	2.000	1.050	84.9	0.762	0.844	111.417	0.965	-0.058	0.035
344	125	2.097	1.048	50.2	0.684	0.646	73.392	0.947	-0.192	0.053
344	160	2.204	1.102	31.36	0.565	0.484	55.504	0.930	-0.313	0.070
344	200	2.301	1.151	26.8	0.476	0.357	56.303	0.931	-0.533	0.069
344	250	2.398	1.199	55.19	1.207	0.28	45.725	0.916	-0.584	0.084
344	315	2.498	1.249	17.28	0.325	0.259	53.169	0.928	-0.161	0.072
344	400	2.602	1.301	9.88	0.458	0.242	21.572	0.831	0.395	0.169
344	500	2.699	1.349	16.91	1.257	0.189	13.453	0.742	0.311	0.258
344	630	2.799	1.400	19.48	3.73	0.144	5.223	0.460	0.172	0.540
344	800	2.903	1.452	7.29	1.88	0.111	3.878	0.348	0.102	0.652
344	1000	3.000	1.500	3.49	1.07	0.091	3.262	0.282	0.183	0.718
344	1250	3.097	1.548	7.85	54.5	0.066	0.144	0.560	-0.128	0.440
344	1400	3.146	1.573	1.484	0.139	0.059	10.676	0.687	-0.124	0.313
344	1600	3.204	1.602	0.391	0.021	0.05	18.619	0.807	-0.219	0.193
344	2000	3.301	1.651	0.91	0.053	0.037	17.170	0.792	-0.438	0.208

TABLE H-4: Absorption coefficient of Cityfalt briquette no. 1										
c	Hz	Log(Hz)	Ratio	A+B	A-B	x (in m)	SWR	Alpha (r)	Theta	Alpha(n)
344	100	2.000	1.050	29.3	0.46	0.833	63.696	0.939	-0.099	0.061
344	125	2.097	1.048	23.9	0.399	0.654	59.900	0.935	-0.155	0.065
344	160	2.204	1.102	12.81	0.329	0.497	38.936	0.902	-0.237	0.098
344	200	2.301	1.151	10.24	0.242	0.406	42.314	0.910	-0.175	0.090
344	250	2.398	1.199	19.77	1.372	0.308	14.410	0.757	-0.329	0.243
344	315	2.498	1.249	5.72	0.691	0.234	8.278	0.615	-0.449	0.385
344	400	2.602	1.301	9.03	2.35	0.185	3.843	0.345	-0.438	0.655
344	500	2.699	1.349	4.64	1.615	0.181	2.873	0.234	0.164	0.766
344	630	2.799	1.400	5.39	0.573	0.142	9.407	0.653	0.126	0.347
344	800	2.903	1.452	13.51	1.069	0.111	12.638	0.728	0.102	0.272
344	1000	3.000	1.500	2.47	0.183	0.083	13.497	0.743	-0.110	0.257
344	1250	3.097	1.548	8.1	0.641	0.061	12.637	0.728	-0.356	0.272
344	1400	3.146	1.573	2.75	0.399	0.054	6.892	0.557	-0.380	0.443
344	1600	3.204	1.602	0.306	0.161	0.052	1.901	0.096	-0.102	0.904
344	2000	3.301	1.651	0.373	0.024	0.039	15.542	0.773	-0.292	0.227

TABLE H-5: Absorption coefficient of Cityfalt briquette no. 2										
c	Hz	Log(Hz)	Ratio	A+B	A-B	x (in m)	SWR	Alpha (r)	Theta	Alpha(n)
344	100	2.000	1.050	28.5	0.426	0.83	66.901	0.942	-0.110	0.058
344	125	2.097	1.048	24.1	0.41	0.655	58.780	0.934	-0.151	0.066
344	160	2.204	1.102	15.81	0.345	0.504	45.826	0.916	-0.196	0.084
344	200	2.301	1.151	10.1	0.213	0.41	47.418	0.919	-0.146	0.081
344	250	2.398	1.199	21.6	1.141	0.313	18.931	0.809	-0.283	0.191
344	315	2.498	1.249	5.45	0.571	0.244	9.545	0.657	-0.334	0.343
344	400	2.602	1.301	4.77	1.179	0.187	4.046	0.364	-0.409	0.636
344	500	2.699	1.349	8.16	2.64	0.172	3.091	0.261	0.000	0.739
344	630	2.799	1.400	4.88	0.841	0.142	5.803	0.498	0.126	0.502
344	800	2.903	1.452	11.55	0.985	0.11	11.726	0.710	0.073	0.290
344	1000	3.000	1.500	4.57	0.238	0.087	19.202	0.812	0.037	0.188
344	1250	3.097	1.548	6.94	0.445	0.066	15.596	0.773	-0.128	0.227
344	1400	3.146	1.573	2.41	0.257	0.057	9.377	0.652	-0.226	0.348
344	1600	3.204	1.602	0.311	0.145	0.051	2.145	0.133	-0.161	0.867
344	2000	3.301	1.651	0.49	0.036	0.048	13.611	0.745	0.365	0.255

TABLE H-6: Absorption coefficient of Cityfalt briquette no.3										
c	Hz	Log(Hz)	Ratio	A+B	A-B	x (in m)	SWR	Alpha (r)	Theta	Alpha(n)
344	100	2.000	1.050	29.8	0.501	0.814	59.481	0.935	-0.168	0.065
344	125	2.097	1.048	25.6	0.454	0.62	56.388	0.932	-0.311	0.068
344	160	2.204	1.102	19.98	0.453	0.501	44.106	0.913	-0.213	0.087
344	200	2.301	1.151	12.47	0.297	0.398	41.987	0.909	-0.234	0.091
344	250	2.398	1.199	21.82	1.208	0.268	18.063	0.801	-0.694	0.199
344	315	2.498	1.249	5.87	0.519	0.248	11.310	0.701	-0.288	0.299
344	400	2.602	1.301	4.94	1.107	0.182	4.463	0.402	-0.482	0.598
344	500	2.699	1.349	8.1	2.27	0.164	3.568	0.316	-0.146	0.684
344	630	2.799	1.400	4.72	0.886	0.152	5.327	0.468	0.357	0.532
344	800	2.903	1.452	11.34	0.972	0.106	11.667	0.709	-0.044	0.291
344	1000	3.000	1.500	4.867	0.241	0.089	20.195	0.820	0.110	0.180
344	1250	3.097	1.548	6.65	0.438	0.068	15.183	0.768	-0.037	0.232
344	1400	3.146	1.573	2.39	0.294	0.052	8.129	0.610	-0.482	0.390
344	1600	3.204	1.602	0.324	0.144	0.047	2.250	0.148	-0.395	0.852
344	2000	3.301	1.651	0.371	0.021	0.048	17.667	0.797	0.365	0.203

TABLE H-7: Absorption coefficient of Conventional Twinlay briquette no. 1

c	Hz	Log(Hz)	Ratio	A+B	A-B	x (in m)	SWR	Alpha (r)	Theta	Alpha(n)
344	100	2.000	1.050	29.57	0.434	0.819	68.134	0.943	-0.150	0.057
344	125	2.097	1.048	25.9	0.481	0.656	53.846	0.928	-0.146	0.072
344	160	2.204	1.102	12.67	0.319	0.507	39.718	0.904	-0.178	0.096
344	200	2.301	1.151	9.35	0.213	0.409	43.897	0.913	-0.153	0.087
344	250	2.398	1.199	23.6	1.55	0.312	15.226	0.769	-0.292	0.231
344	315	2.498	1.249	5.312	0.618	0.295	8.595	0.627	0.253	0.373
344	400	2.602	1.301	4.901	1.025	0.249	4.781	0.428	0.497	0.572
344	500	2.699	1.349	8.947	2.18	0.168	4.104	0.370	-0.073	0.630
344	630	2.799	1.400	6.015	0.78	0.136	7.712	0.594	-0.012	0.406
344	800	2.903	1.452	10.745	0.959	0.104	11.204	0.699	-0.102	0.301
344	1000	3.000	1.500	3.43	0.287	0.08	11.951	0.715	-0.219	0.285
344	1250	3.097	1.548	8.713	1.015	0.063	8.584	0.626	-0.265	0.374
344	1400	3.146	1.573	1.85	0.415	0.059	4.458	0.401	-0.124	0.599
344	1600	3.204	1.602	0.318	0.177	0.056	1.797	0.081	0.132	0.919
344	2000	3.301	1.651	0.318	0.0161	0.041	19.752	0.817	-0.146	0.183

TABLE H-8: Absorption coefficient of Conventional Twinlay briquette no. 2

c	Hz	Log(Hz)	Ratio	A+B	A-B	x (in m)	SWR	Alpha (r)	Theta	Alpha(n)
344	100	2.000	1.050	28.89	0.44	0.829	65.659	0.941	-0.113	0.059
344	125	2.097	1.048	23.01	0.431	0.655	53.387	0.928	-0.151	0.072
344	160	2.204	1.102	16.734	0.343	0.598	48.787	0.921	0.354	0.079
344	200	2.301	1.151	10.215	0.286	0.412	35.717	0.894	-0.132	0.106
344	250	2.398	1.199	23.5	1.665	0.315	14.114	0.753	-0.265	0.247
344	315	2.498	1.249	5.197	0.569	0.253	9.134	0.644	-0.230	0.356
344	400	2.602	1.301	4.481	1.092	0.2	4.103	0.370	-0.219	0.630
344	500	2.699	1.349	8.731	2.95	0.17	2.960	0.245	-0.037	0.755
344	630	2.799	1.400	5.681	0.836	0.132	6.795	0.553	-0.104	0.447
344	800	2.903	1.452	10.277	0.984	0.103	10.444	0.681	-0.132	0.319
344	1000	3.000	1.500	4.345	0.335	0.078	12.970	0.734	-0.292	0.266
344	1250	3.097	1.548	8.414	1.005	0.071	8.372	0.619	0.100	0.381
344	1400	3.146	1.573	1.943	0.548	0.057	3.546	0.314	-0.226	0.686
344	1600	3.204	1.602	0.321	0.149	0.048	2.154	0.134	-0.336	0.866
344	2000	3.301	1.651	0.367	0.021	0.042	17.476	0.795	-0.073	0.205

TABLE H-9: Absorption coefficient of Conventional Twinlay briquette no. 3										
c	Hz	Log(Hz)	Ratio	A+B	A-B	x (in m)	SWR	Alpha (r)	Theta	Alpha(n)
344	100	2.000	1.050	28.22	0.517	0.799	54.584	0.929	-0.223	0.071
344	125	2.097	1.048	26.5	0.481	0.645	55.094	0.930	-0.196	0.070
344	160	2.204	1.102	10.85	0.327	0.501	33.180	0.886	-0.213	0.114
344	200	2.301	1.151	8.35	0.213	0.398	39.202	0.903	-0.234	0.097
344	250	2.398	1.199	24.2	1.67	0.305	14.491	0.758	-0.356	0.242
344	315	2.498	1.249	5.512	0.618	0.282	8.919	0.637	0.103	0.363
344	400	2.602	1.301	4.677	1.085	0.246	4.311	0.389	0.453	0.611
344	500	2.699	1.349	8.95	2.58	0.157	3.469	0.305	-0.274	0.695
344	630	2.799	1.400	6.02	0.658	0.144	9.149	0.645	0.172	0.355
344	800	2.903	1.452	11.974	0.962	0.109	12.447	0.725	0.044	0.275
344	1000	3.000	1.500	4.43	0.283	0.082	15.654	0.774	-0.146	0.226
344	1250	3.097	1.548	9.431	0.95	0.07	9.927	0.667	0.055	0.333
344	1400	3.146	1.573	1.84	0.422	0.054	4.360	0.393	-0.380	0.607
344	1600	3.204	1.602	0.32	0.164	0.051	1.951	0.104	-0.161	0.896
344	2000	3.301	1.651	0.329	0.013	0.042	25.308	0.854	-0.073	0.146

TABLE H-10: Absorption coefficient of Fluisterfalt briquette no.1										
c	Hz	Log(Hz)	Ratio	A+B	A-B	x (in m)	SWR	Alpha (r)	Theta	Alpha(n)
344	100	2.000	1.050	28.4	0.392	0.833	72.449	0.946	-0.099	0.054
344	125	2.097	1.048	23.9	0.341	0.663	70.088	0.945	-0.114	0.055
344	160	2.204	1.102	11.78	0.297	0.506	39.663	0.904	-0.184	0.096
344	200	2.301	1.151	10.02	0.23	0.408	43.565	0.912	-0.161	0.088
344	250	2.398	1.199	22.1	1.048	0.317	21.088	0.827	-0.247	0.173
344	315	2.498	1.249	5.44	0.418	0.242	13.014	0.735	-0.357	0.265
344	400	2.602	1.301	4.76	1.231	0.181	3.867	0.347	-0.497	0.653
344	500	2.699	1.349	9.3	3.32	0.17	2.801	0.225	-0.037	0.775
344	630	2.799	1.400	5.48	0.51	0.143	10.745	0.688	0.149	0.312
344	800	2.903	1.452	14.27	0.668	0.106	21.362	0.829	-0.044	0.171
344	1000	3.000	1.500	3.48	0.176	0.081	19.773	0.817	-0.183	0.183
344	1250	3.097	1.548	7.56	0.699	0.06	10.815	0.690	-0.402	0.310
344	1400	3.146	1.573	2.34	0.406	0.056	5.764	0.496	-0.278	0.504
344	1600	3.204	1.602	0.273	0.151	0.042	1.808	0.083	-0.687	0.917
344	2000	3.301	1.651	0.283	0.018	0.039	15.722	0.775	-0.292	0.225

TABLE H-11: Absorption coefficient of Fluisterfalt briquette no. 2										
c	Hz	Log(Hz)	Ratio	A+B	A-B	x (in m)	SWR	Alpha (r)	Theta	Alpha(n)
344	100	2.000	1.050	28	0.44	0.83	63.636	0.939	-0.110	0.061
344	125	2.097	1.048	22.8	0.343	0.655	66.472	0.942	-0.151	0.058
344	160	2.204	1.102	11.51	0.319	0.5	36.082	0.895	-0.219	0.105
344	200	2.301	1.151	11.13	0.273	0.399	40.769	0.907	-0.226	0.093
344	250	2.398	1.199	26.8	1.461	0.3	18.344	0.804	-0.402	0.196
344	315	2.498	1.249	5.44	0.418	0.259	13.014	0.735	-0.161	0.265
344	400	2.602	1.301	5.23	1.094	0.226	4.781	0.428	0.161	0.572
344	500	2.699	1.349	4.85	1.493	0.168	3.248	0.280	-0.073	0.720
344	630	2.799	1.400	14.96	1.255	0.136	11.920	0.714	-0.012	0.286
344	800	2.903	1.452	6.21	0.298	0.105	20.839	0.825	-0.073	0.175
344	1000	3.000	1.500	15.62	0.479	0.082	32.610	0.885	-0.146	0.115
344	1250	3.097	1.548	2.5	0.154	0.062	16.234	0.781	-0.311	0.219
344	1400	3.146	1.573	2.1	0.357	0.059	5.882	0.503	-0.124	0.497
344	1600	3.204	1.602	0.302	0.146	0.053	2.068	0.121	-0.044	0.879
344	2000	3.301	1.651	0.199	0.011	0.042	18.091	0.801	-0.073	0.199

TABLE H-12: Absorption coefficient of Fluisterfalt briquette no. 3										
c	Hz	Log(Hz)	Ratio	A+B	A-B	x (in m)	SWR	Alpha (r)	Theta	Alpha(n)
344	100	2.000	1.050	27.8	0.354	0.821	78.531	0.950	-0.142	0.050
344	125	2.097	1.048	22.6	0.319	0.648	70.846	0.945	-0.183	0.055
344	160	2.204	1.102	16.3	0.245	0.489	66.531	0.942	-0.283	0.058
344	200	2.301	1.151	9.87	0.294	0.385	33.571	0.888	-0.329	0.112
344	250	2.398	1.199	21.48	1.07	0.289	20.075	0.819	-0.502	0.181
344	315	2.498	1.249	5.29	0.398	0.241	13.291	0.740	-0.368	0.260
344	400	2.602	1.301	5.287	1.24	0.219	4.264	0.384	0.058	0.616
344	500	2.699	1.349	10.86	3.24	0.166	3.352	0.292	-0.110	0.708
344	630	2.799	1.400	6.48	0.452	0.14	14.336	0.756	0.080	0.244
344	800	2.903	1.452	15.88	0.724	0.109	21.934	0.833	0.044	0.167
344	1000	3.000	1.500	4.68	0.171	0.081	27.368	0.864	-0.183	0.136
344	1250	3.097	1.548	8.95	0.622	0.065	14.389	0.757	-0.174	0.243
344	1400	3.146	1.573	2.491	0.437	0.058	5.700	0.492	-0.175	0.508
344	1600	3.204	1.602	0.277	0.166	0.052	1.669	0.063	-0.102	0.937
344	2000	3.301	1.651	0.31	0.009	0.041	34.444	0.890	-0.146	0.110

TABLE H-13: Absorption coefficient of 7 cm Superfine Twinlay briquette no.1

c	Hz	Log(Hz)	Ratio	A+B	A-B	x (in m)	SWR	Alpha (r)	Theta	Alpha(n)
344	100	2.000	1.050	23.4	0.395	0.824	59.241	0.935	-0.132	0.065
344	125	2.097	1.048	17.01	0.374	0.655	45.481	0.916	-0.151	0.084
344	160	2.204	1.102	12.95	0.254	0.522	50.984	0.925	-0.091	0.075
344	200	2.301	1.151	7.07	0.181	0.409	39.061	0.903	-0.153	0.097
344	250	2.398	1.199	26.57	1.364	0.317	19.479	0.814	-0.247	0.186
344	315	2.498	1.249	5.12	0.451	0.254	11.353	0.702	-0.219	0.298
344	400	2.602	1.301	2.51	0.498	0.203	5.040	0.447	-0.175	0.553
344	500	2.699	1.349	8.07	1.081	0.164	7.465	0.583	-0.146	0.417
344	630	2.799	1.400	4.77	0.329	0.132	14.498	0.759	-0.104	0.241
344	800	2.903	1.452	5.75	0.301	0.099	19.103	0.811	-0.248	0.189
344	1000	3.000	1.500	4.072	0.13	0.076	31.323	0.880	-0.365	0.120
344	1250	3.097	1.548	7.15	0.229	0.058	31.223	0.880	-0.493	0.120
344	1400	3.146	1.573	2.85	0.139	0.053	20.504	0.823	-0.431	0.177
344	1600	3.204	1.602	0.319	0.092	0.048	3.467	0.305	-0.336	0.695
344	2000	3.301	1.651	0.331	0.016	0.043	20.688	0.824	0.000	0.176

TABLE H-14: Absorption coefficient of 7 cm Superfine Twinlay briquette no.2

c	Hz	Log(Hz)	Ratio	A+B	A-B	x (in m)	SWR	Alpha (r)	Theta	Alpha(n)
344	100	2.000	1.050	25.1	0.499	0.826	50.301	0.924	-0.124	0.076
344	125	2.097	1.048	17.5	0.452	0.657	38.717	0.902	-0.142	0.098
344	160	2.204	1.102	10.77	0.276	0.497	39.022	0.903	-0.237	0.097
344	200	2.301	1.151	3.95	0.13	0.383	30.385	0.877	-0.343	0.123
344	250	2.398	1.199	25.7	1.454	0.317	17.675	0.797	-0.247	0.203
344	315	2.498	1.249	6.08	0.671	0.259	9.061	0.642	-0.161	0.358
344	400	2.602	1.301	3.41	0.894	0.212	3.814	0.342	-0.044	0.658
344	500	2.699	1.349	8.7	1.69	0.169	5.148	0.455	-0.055	0.545
344	630	2.799	1.400	8.46	0.672	0.132	12.589	0.727	-0.104	0.273
344	800	2.903	1.452	10.37	0.494	0.101	20.992	0.826	-0.190	0.174
344	1000	3.000	1.500	4.88	0.255	0.08	19.137	0.811	-0.219	0.189
344	1250	3.097	1.548	11.98	0.745	0.059	16.081	0.780	-0.447	0.220
344	1400	3.146	1.573	2.25	0.241	0.056	9.336	0.650	-0.278	0.350
344	1600	3.204	1.602	0.288	0.142	0.05	2.028	0.115	-0.219	0.885
344	2000	3.301	1.651	0.3	0.011	0.039	27.273	0.864	-0.292	0.136

TABLE H-15: Absorption coefficient of 7 cm Superfine Twinlay briquette no.3

c	Hz	Log(Hz)	Ratio	A+B	A-B	x (in m)	SWR	Alpha (r)	Theta	Alpha(n)
344	100	2.000	1.050	25.8	0.495	0.825	52.121	0.926	-0.128	0.074
344	125	2.097	1.048	16.21	0.405	0.656	40.025	0.905	-0.146	0.095
344	160	2.204	1.102	13.87	0.308	0.484	45.032	0.915	-0.313	0.085
344	200	2.301	1.151	7.01	0.224	0.404	31.295	0.880	-0.190	0.120
344	250	2.398	1.199	26.83	1.266	0.318	21.193	0.828	-0.237	0.172
344	315	2.498	1.249	6.42	0.46	0.258	13.957	0.750	-0.173	0.250
344	400	2.602	1.301	2.45	0.558	0.203	4.391	0.396	-0.175	0.604
344	500	2.699	1.349	7.88	1.161	0.164	6.787	0.552	-0.146	0.448
344	630	2.799	1.400	4.06	0.385	0.13	10.545	0.684	-0.150	0.316
344	800	2.903	1.452	6.97	0.301	0.1	23.156	0.841	-0.219	0.159
344	1000	3.000	1.500	4.06	0.1	0.079	40.600	0.906	-0.256	0.094
344	1250	3.097	1.548	7.85	0.22	0.06	35.682	0.894	-0.402	0.106
344	1400	3.146	1.573	2.01	0.16	0.327	12.563	0.727	13.582	0.273
344	1600	3.204	1.602	0.341	0.118	0.039	2.890	0.236	-0.862	0.764
344	2000	3.301	1.651	0.233	0.008	0.031	29.125	0.872	-0.877	0.128

TABLE H-16: Absorption coefficient of 8 cm Superfine Twinlay briquette no.1

c	Hz	Log(Hz)	Ratio	A+B	A-B	x (in m)	SWR	Alpha (r)	Theta	Alpha(n)
344	100	2.000	1.050	28.2	0.491	0.825	57.434	0.933	-0.128	0.067
344	125	2.097	1.048	24.1	0.487	0.656	49.487	0.922	-0.146	0.078
344	160	2.204	1.102	13.72	0.271	0.497	50.627	0.924	-0.237	0.076
344	200	2.301	1.151	8.08	0.282	0.408	28.652	0.870	-0.161	0.130
344	250	2.398	1.199	19.1	1.531	0.312	12.476	0.725	-0.292	0.275
344	315	2.498	1.249	5.22	0.69	0.251	7.565	0.588	-0.253	0.412
344	400	2.602	1.301	3.98	1.052	0.196	3.783	0.339	-0.278	0.661
344	500	2.699	1.349	13.37	2.04	0.17	6.554	0.541	-0.037	0.459
344	630	2.799	1.400	7.97	0.66	0.136	12.076	0.717	-0.012	0.283
344	800	2.903	1.452	12.01	0.568	0.103	21.144	0.828	-0.132	0.172
344	1000	3.000	1.500	2.4	0.119	0.077	20.168	0.820	-0.329	0.180
344	1250	3.097	1.548	7.18	0.891	0.058	8.058	0.607	-0.493	0.393
344	1400	3.146	1.573	2.941	0.516	0.051	5.700	0.492	-0.533	0.508
344	1600	3.204	1.602	0.352	0.021	0.041	16.762	0.787	-0.745	0.213
344	2000	3.301	1.651	0.454	0.019	0.032	23.895	0.846	-0.804	0.154

TABLE H-17: Absorption coefficient of 8 cm Superfine Twinlay briquette no.2										
c	Hz	Log(Hz)	Ratio	A+B	A-B	x (in m)	SWR	Alpha (r)	Theta	Alpha(n)
344	100	2.000	1.050	27.1	0.531	0.83	51.036	0.925	-0.110	0.075
344	125	2.097	1.048	24.6	0.556	0.659	44.245	0.914	-0.132	0.086
344	160	2.204	1.102	13.71	0.308	0.508	44.513	0.914	-0.172	0.086
344	200	2.301	1.151	9.62	0.26	0.408	37.000	0.898	-0.161	0.102
344	250	2.398	1.199	23.5	1.12	0.326	20.982	0.826	-0.164	0.174
344	315	2.498	1.249	4.92	0.616	0.266	7.987	0.604	-0.081	0.396
344	400	2.602	1.301	3.04	0.889	0.201	3.420	0.300	-0.205	0.700
344	500	2.699	1.349	15.7	1.269	0.17	12.372	0.723	-0.037	0.277
344	630	2.799	1.400	6.4	0.312	0.134	20.513	0.823	-0.058	0.177
344	800	2.903	1.452	13.75	0.706	0.102	19.476	0.814	-0.161	0.186
344	1000	3.000	1.500	3.43	0.225	0.078	15.244	0.769	-0.292	0.231
344	1250	3.097	1.548	6.33	0.795	0.066	7.962	0.603	-0.128	0.397
344	1400	3.146	1.573	2.57	0.419	0.059	6.134	0.518	-0.124	0.482
344	1600	3.204	1.602	0.4	0.012	0.049	33.333	0.887	-0.278	0.113
344	2000	3.301	1.651	0.389	0.007	0.039	55.571	0.931	-0.292	0.069

TABLE H-18: Absorption coefficient of 8 cm Superfine Twinlay briquette no.3										
c	Hz	Log(Hz)	Ratio	A+B	A-B	x (in m)	SWR	Alpha (r)	Theta	Alpha(n)
344	100	2.000	1.050	24.8	0.497	0.84	49.899	0.923	-0.073	0.077
344	125	2.097	1.048	21.4	0.449	0.662	47.661	0.919	-0.119	0.081
344	160	2.204	1.102	12.52	0.306	0.512	40.915	0.907	-0.149	0.093
344	200	2.301	1.151	9.48	0.38	0.42	24.947	0.852	-0.073	0.148
344	250	2.398	1.199	22.15	1.8	0.348	12.306	0.722	0.037	0.278
344	315	2.498	1.249	4.57	0.705	0.281	6.482	0.537	0.092	0.463
344	400	2.602	1.301	2.76	0.832	0.212	3.317	0.288	-0.044	0.712
344	500	2.699	1.349	13.9	1.383	0.18	10.051	0.671	0.146	0.329
344	630	2.799	1.400	6.54	0.253	0.147	25.850	0.857	0.241	0.143
344	800	2.903	1.452	15.28	0.6	0.99	25.467	0.855	25.790	0.145
344	1000	3.000	1.500	4.54	0.211	0.54	21.517	0.830	16.585	0.170
344	1250	3.097	1.548	6.89	0.899	0.49	7.664	0.592	19.233	0.408
344	1400	3.146	1.573	2.87	0.507	0.45	5.661	0.490	19.872	0.510
344	1600	3.204	1.602	0.39	0.021	0.34	18.571	0.806	16.731	0.194
344	2000	3.301	1.651	0.375	0.005	0.23	75.000	0.948	13.662	0.052

TABLE H-19: Absorption coefficient of 9cm Superfine Twinlay briquette no.1										
c	Hz	Log(Hz)	Ratio	A+B	A-B	x (in m)	SWR	Alpha (r)	Theta	Alpha(n)
344	100	2.000	1.050	26.5	0.654	0.836	40.520	0.906	-0.088	0.094
344	125	2.097	1.048	23.2	0.701	0.659	33.096	0.886	-0.132	0.114
344	160	2.204	1.102	10.86	0.354	0.605	30.678	0.878	0.395	0.122
344	200	2.301	1.151	9.76	0.354	0.404	27.571	0.865	-0.190	0.135
344	250	2.398	1.199	23.3	2.56	0.326	9.102	0.643	-0.164	0.357
344	315	2.498	1.249	4.42	0.804	0.264	5.498	0.479	-0.104	0.521
344	400	2.602	1.301	5.43	0.812	0.218	6.687	0.547	0.044	0.453
344	500	2.699	1.349	15.85	1.214	0.17	13.056	0.736	-0.037	0.264
344	630	2.799	1.400	6.46	0.209	0.131	30.909	0.879	-0.127	0.121
344	800	2.903	1.452	12.15	0.42	0.1	28.929	0.871	-0.219	0.129
344	1000	3.000	1.500	2.42	0.148	0.075	16.351	0.783	-0.402	0.217
344	1250	3.097	1.548	5.89	0.909	0.067	6.480	0.537	-0.082	0.463
344	1400	3.146	1.573	1.844	0.494	0.058	3.733	0.333	-0.175	0.667
344	1600	3.204	1.602	0.383	0.015	0.046	25.533	0.855	-0.453	0.145
344	2000	3.301	1.651	0.47	0.004	0.043	117.500	0.967	0.000	0.033

TABLE H-20: Absorption coefficient of 9cm Superfine Twinlay briquette no. 2										
c	Hz	Log(Hz)	Ratio	A+B	A-B	x (in m)	SWR	Alpha (r)	Theta	Alpha(n)
344	100	2.000	1.050	27.5	0.554	0.872	49.639	0.923	0.044	0.077
344	125	2.097	1.048	23.1	0.483	0.659	47.826	0.920	-0.132	0.080
344	160	2.204	1.102	10.71	0.251	0.495	42.669	0.911	-0.248	0.089
344	200	2.301	1.151	3.99	0.158	0.401	25.253	0.853	-0.212	0.147
344	250	2.398	1.199	19.6	2.18	0.311	8.991	0.640	-0.301	0.360
344	315	2.498	1.249	4.05	0.836	0.249	4.844	0.433	-0.276	0.567
344	400	2.602	1.301	6.27	1.052	0.206	5.960	0.508	-0.132	0.492
344	500	2.699	1.349	13.39	1.668	0.17	8.028	0.606	-0.037	0.394
344	630	2.799	1.400	6.25	0.385	0.128	16.234	0.781	-0.196	0.219
344	800	2.903	1.452	10.91	0.731	0.098	14.925	0.765	-0.278	0.235
344	1000	3.000	1.500	2.31	0.246	0.072	9.390	0.652	-0.511	0.348
344	1250	3.097	1.548	5.91	1.363	0.063	4.336	0.391	-0.265	0.609
344	1400	3.146	1.573	1.537	0.494	0.062	3.111	0.264	0.029	0.736
344	1600	3.204	1.602	0.3	0.014	0.041	21.429	0.830	-0.745	0.170
344	2000	3.301	1.651	0.255	0.003	0.04	85.000	0.954	-0.219	0.046

TABLE H-21: Absorption coefficient of 9 cm Superfine Twinlay briquette no.3

c	Hz	Log(Hz)	Ratio	A+B	A-B	x (in m)	SWR	Alpha (r)	Theta	Alpha(n)
344	100	2.000	1.050	24.8	0.688	0.851	36.047	0.895	-0.033	0.105
344	125	2.097	1.048	23.1	0.672	0.656	34.375	0.890	-0.146	0.110
344	160	2.204	1.102	11.57	0.356	0.399	32.500	0.884	-0.810	0.116
344	200	2.301	1.151	8.48	0.349	0.317	24.298	0.848	-0.826	0.152
344	250	2.398	1.199	23.45	2.61	0.275	8.985	0.640	-0.630	0.360
344	315	2.498	1.249	4.67	0.8	0.233	5.838	0.501	-0.460	0.499
344	400	2.602	1.301	5.59	0.808	0.187	6.918	0.559	-0.409	0.441
344	500	2.699	1.349	14.37	1.205	0.178	11.925	0.714	0.110	0.286
344	630	2.799	1.400	7.62	0.309	0.13	24.660	0.850	-0.150	0.150
344	800	2.903	1.452	8.2	0.25	0.105	32.800	0.885	-0.073	0.115
344	1000	3.000	1.500	2.46	0.11	0.077	22.364	0.836	-0.329	0.164
344	1250	3.097	1.548	6.98	0.907	0.066	7.696	0.593	-0.128	0.407
344	1400	3.146	1.573	1.955	0.6	0.059	3.258	0.281	-0.124	0.719
344	1600	3.204	1.602	0.396	0.006	0.045	66.000	0.941	-0.511	0.059
344	2000	3.301	1.651	0.554	0.005	0.042	110.800	0.965	-0.073	0.035

APPENDIX I

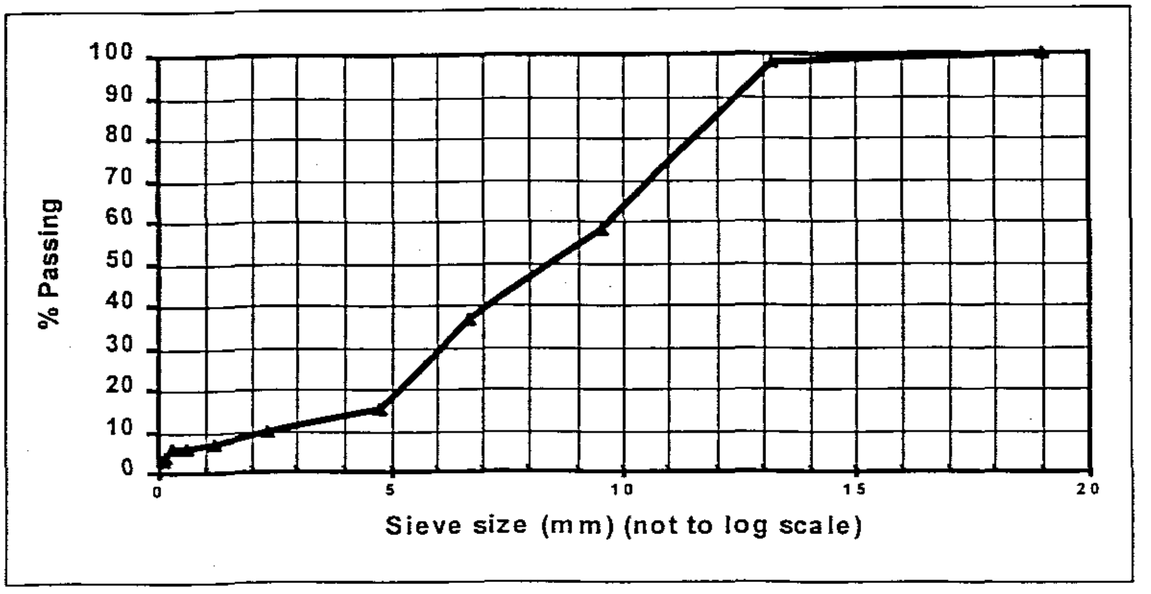

FIGURE I-1: Conventional Porous Asphalt grading curve

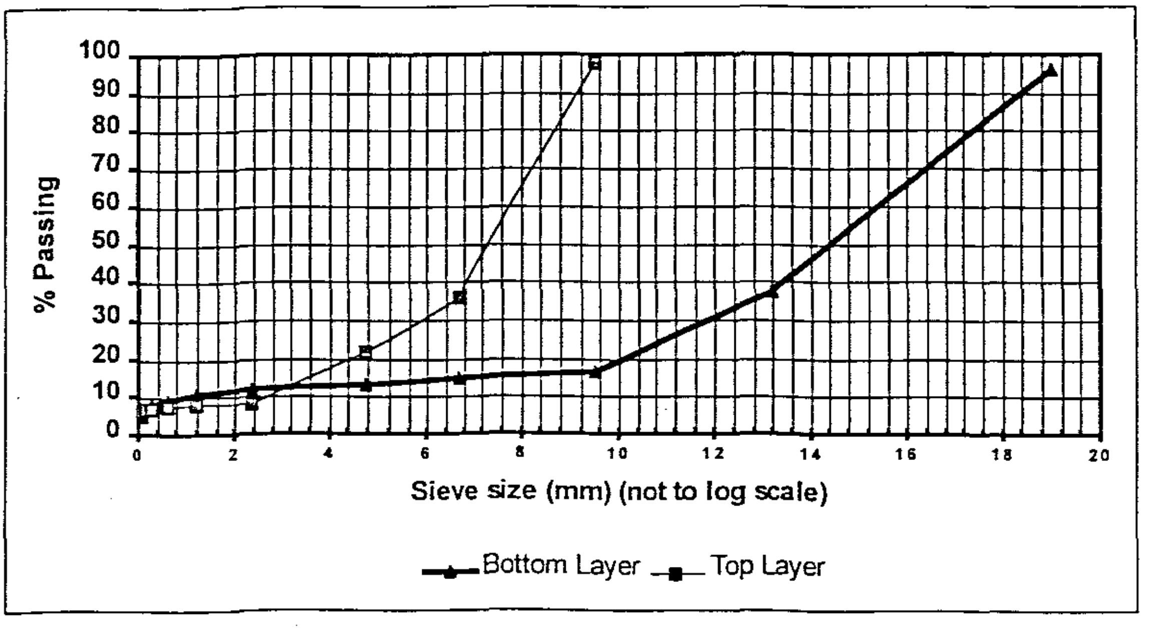

FIGURE I-2: Cityfalt grading curve

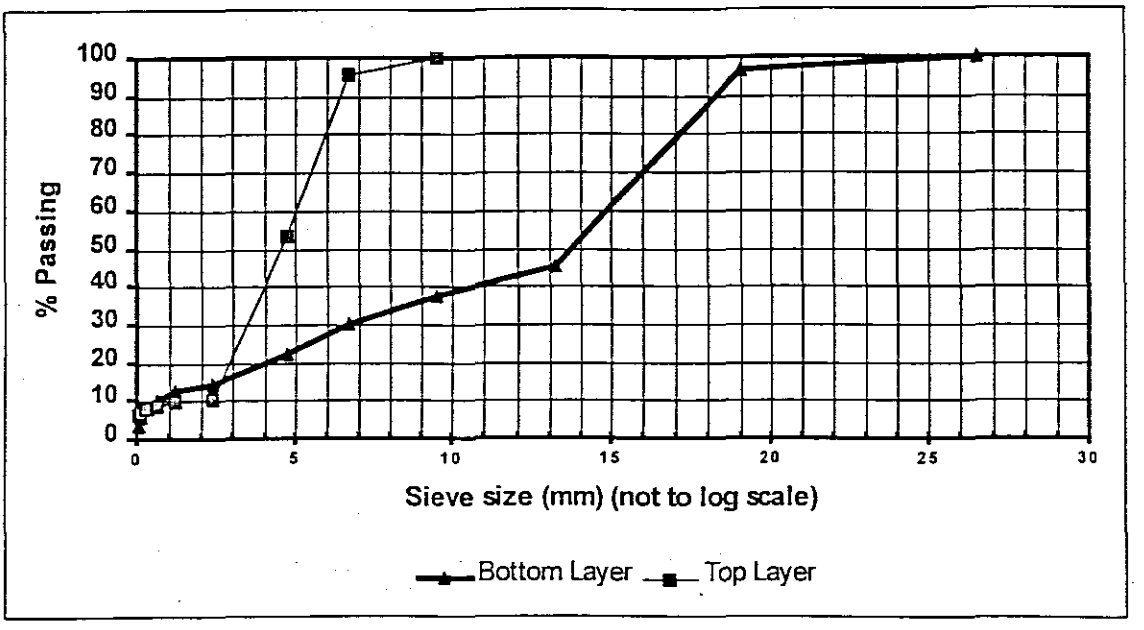

FIGURE I-3: Twinlay grading curve

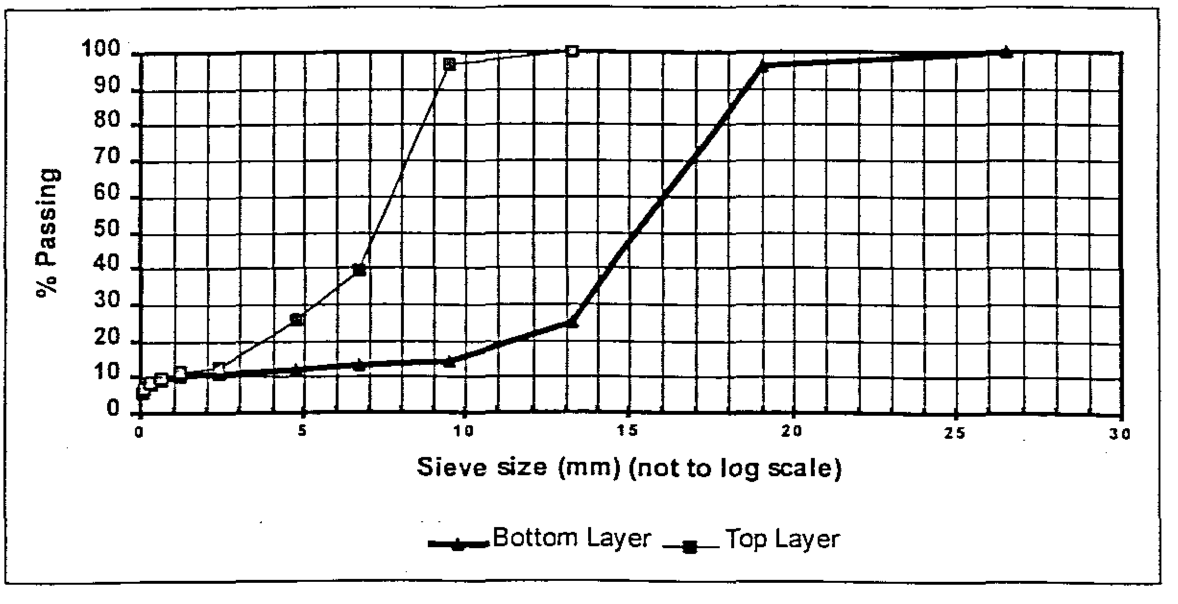

FIGURE I-4: Fluisterfalt grading curve

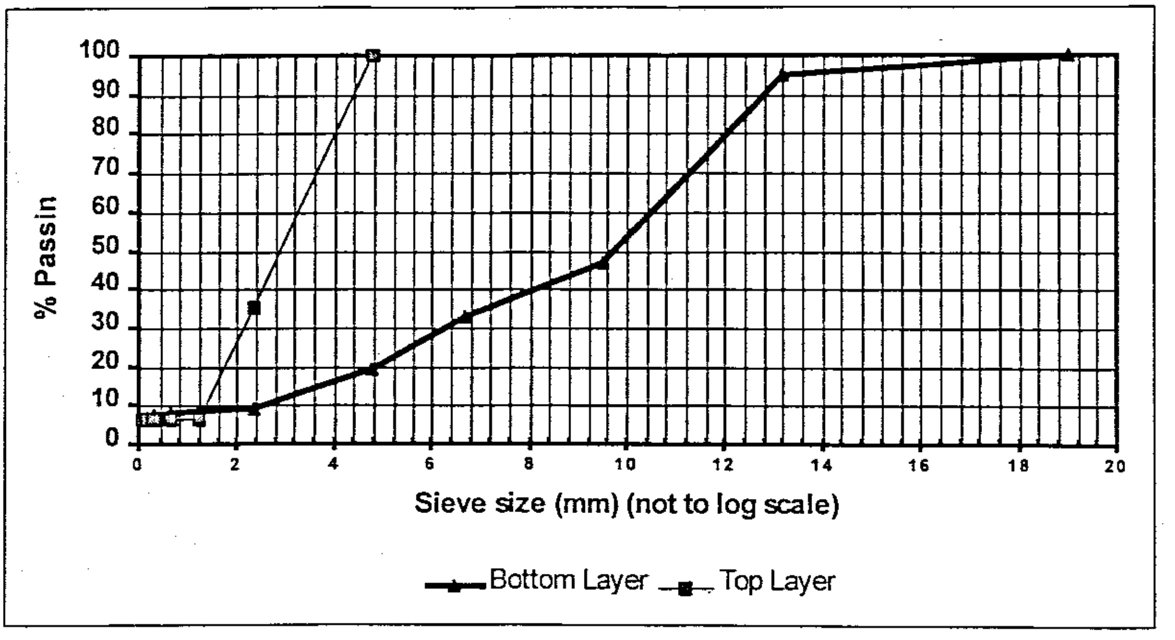

FIGURE I-5: Superfine Twinlay grading curve

APPENDIX J

TABLE J-1: Average sound absorption coefficient for each mix design

TABLE J-1: AVERAGE ABSORPTION COEFFICIENTS							
Freq. (Hz)	PA	Cityfalt	Fluisterfalt	Twinlay	7cm SF Twinlay	8cm SF Twinlay	9cm SF Twinlay
100	0.033	0.061	0.055	0.062	0.072	0.073	0.092
125	0.044	0.066	0.056	0.071	0.093	0.082	0.101
160	0.058	0.089	0.086	0.096	0.086	0.085	0.109
200	0.057	0.087	0.098	0.097	0.114	0.127	0.145
250	0.086	0.211	0.183	0.240	0.187	0.242	0.359
315	0.071	0.342	0.263	0.364	0.302	0.424	0.529
400	0.147	0.630	0.614	0.605	0.605	0.691	0.462
500	0.233	0.730	0.734	0.693	0.470	0.355	0.315
630	0.460	0.460	0.280	0.403	0.277	0.201	0.163
800	0.618	0.284	0.171	0.298	0.174	0.168	0.160
1000	0.730	0.208	0.145	0.259	0.134	0.194	0.243
1250	0.420	0.243	0.257	0.363	0.149	0.399	0.493
1400	0.330	0.394	0.503	0.631	0.267	0.500	0.707
1600	0.260	0.874	0.911	0.894	0.781	0.173	0.125
2000	0.270	0.228	0.177	0.178	0.147	0.092	0.038

APPENDIX K

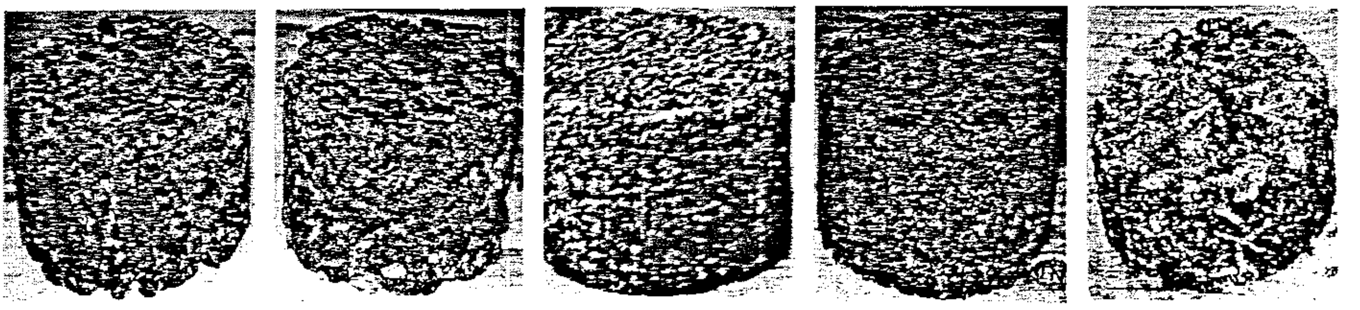

FIGURE K-1: Photographs of Marshall briquettes, from left to right, Fluisterfalt, Cityfalt, Twinlay, Superfine Twinlay and Conventional Porous Asphalt.

APPENDIX L

Transverse rutting profiles for rutting test L

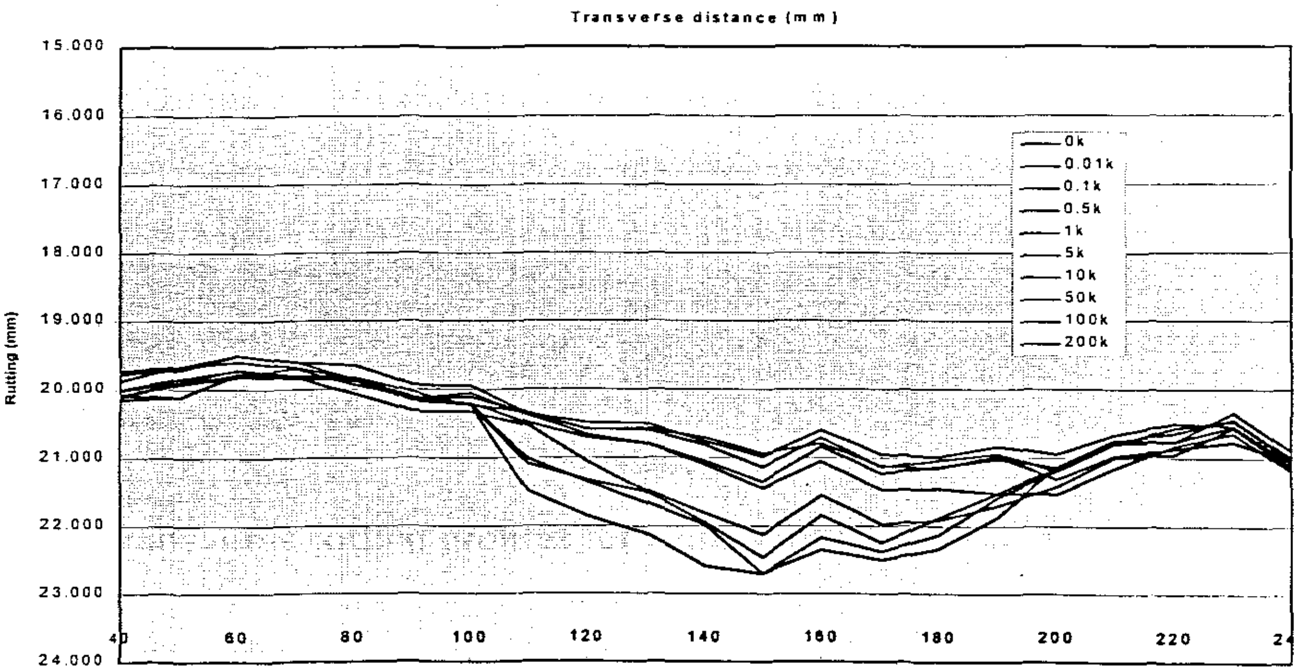

FIGURE L- 1: Transverse rutting profile at position 1

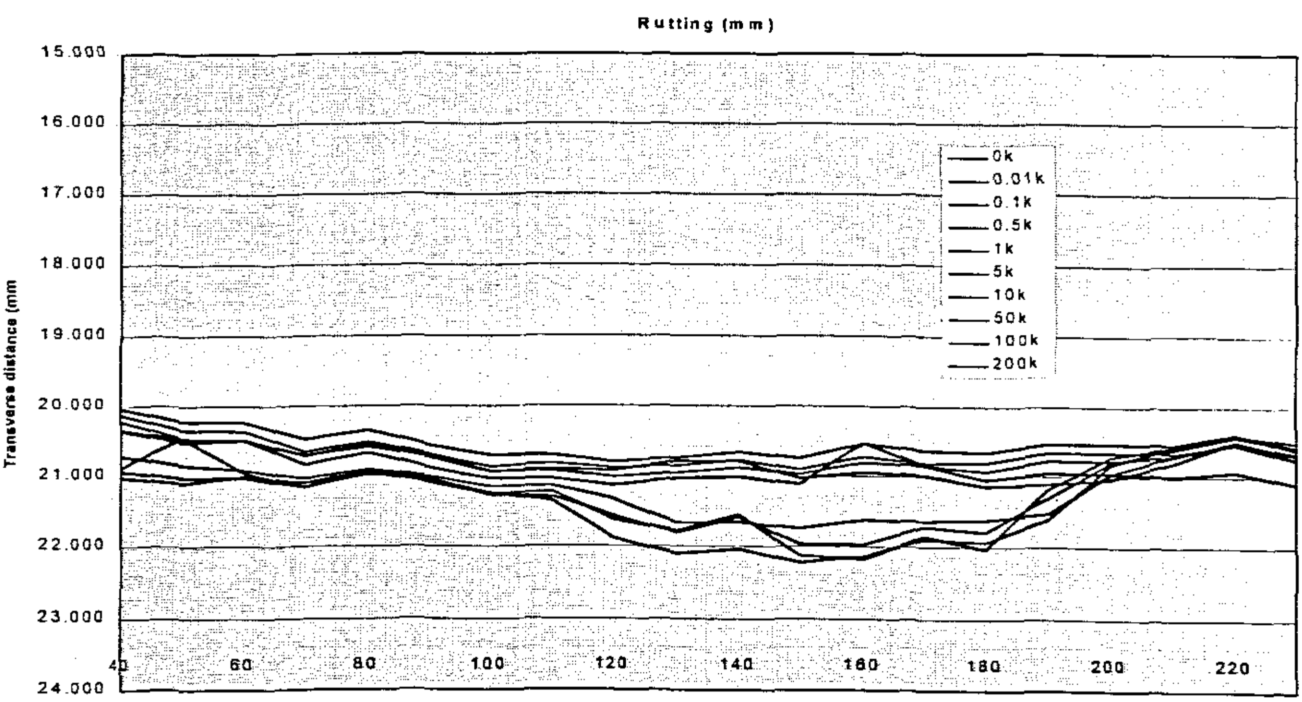

FIGURE L- 2: Transverse rutting profile at position 2

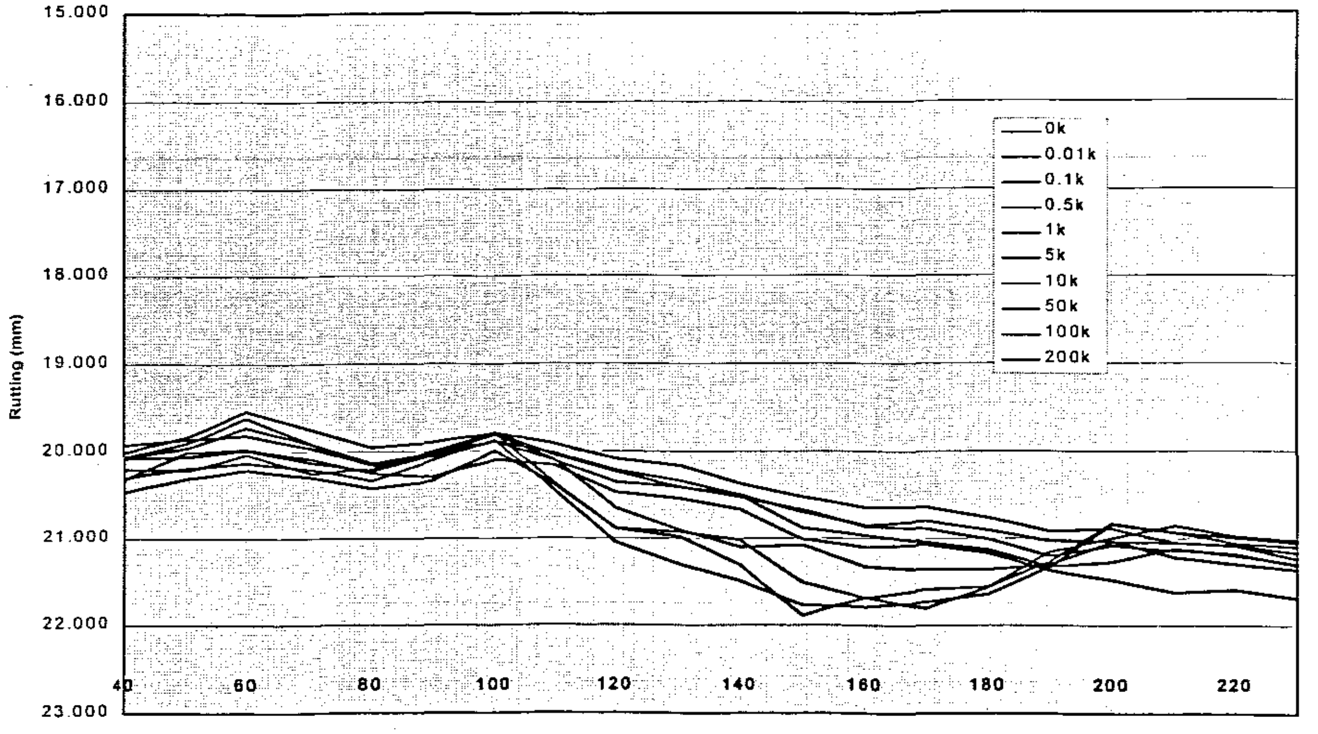

FIGURE L- 3: Transverse rutting profile at position 3

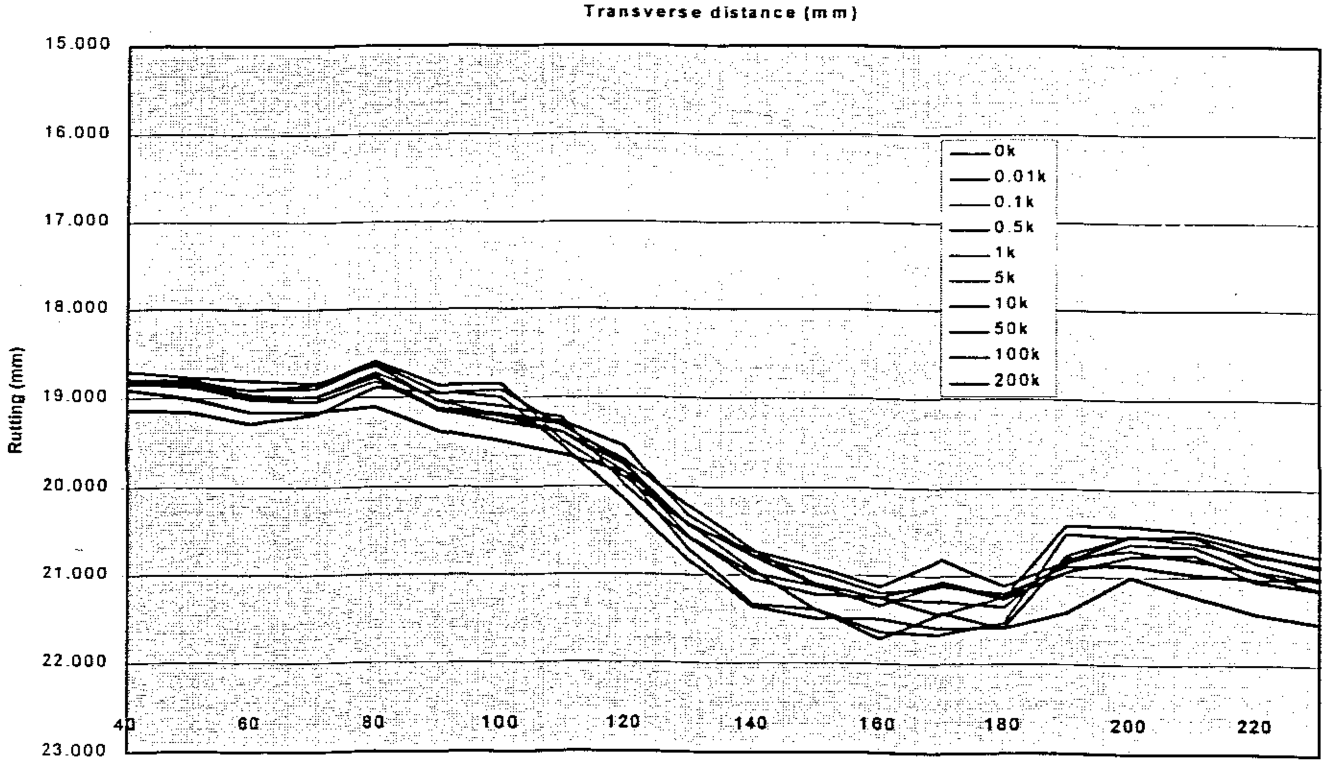

FIGURE L- 4: Transverse rutting profile at position 4

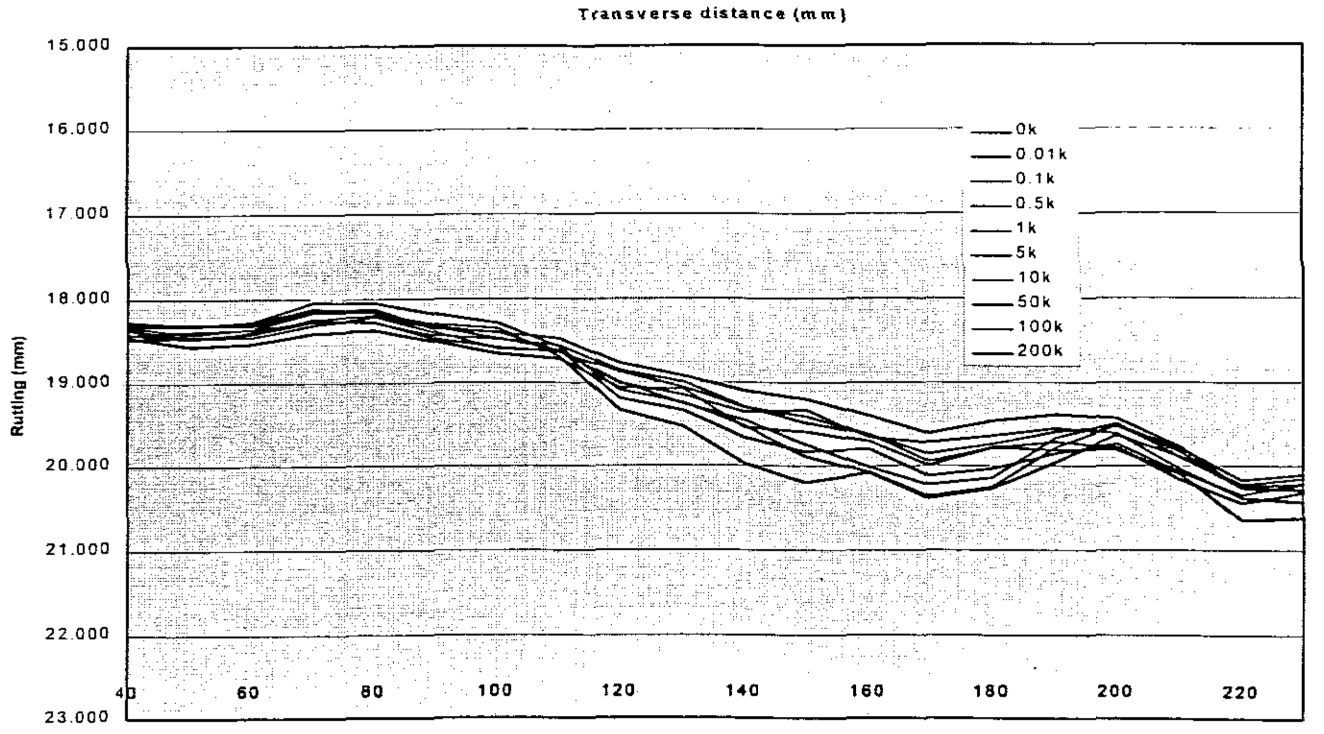

FIGURE L- 5: Transverse rutting profile at position 5

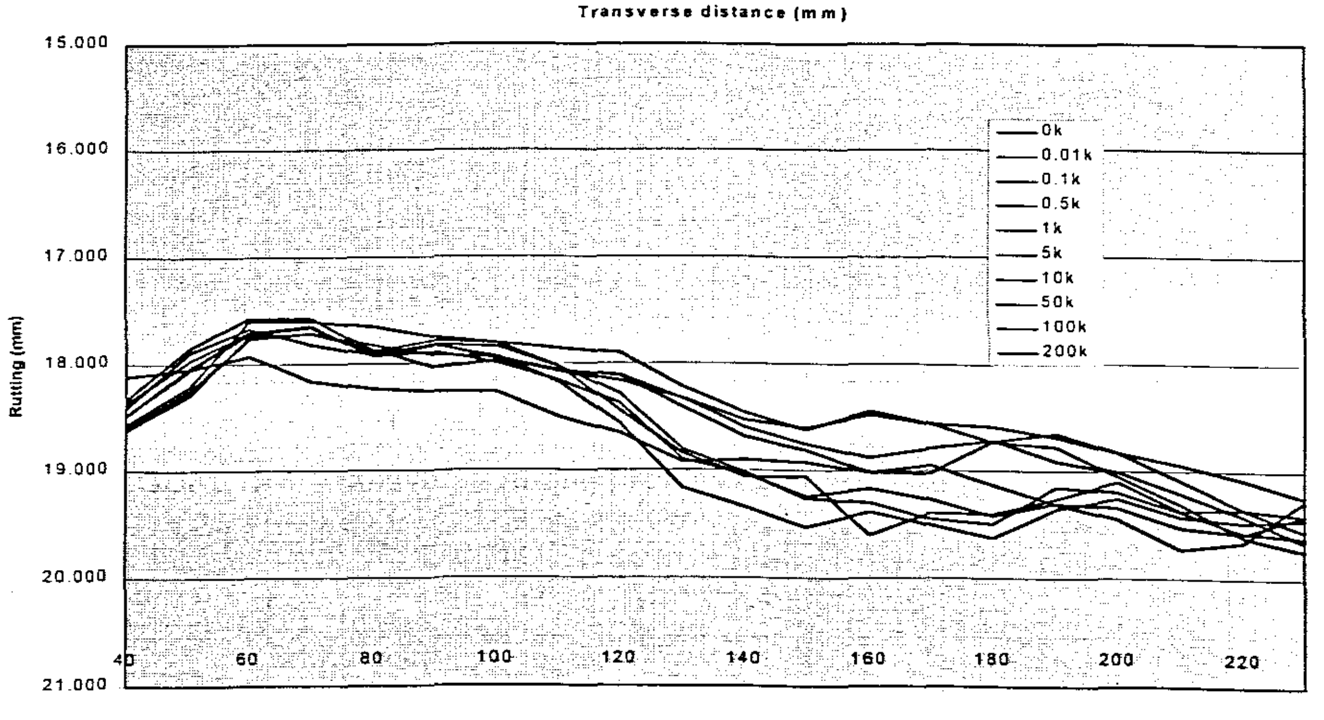

FIGURE L- 6: Transverse rutting profile at position 6

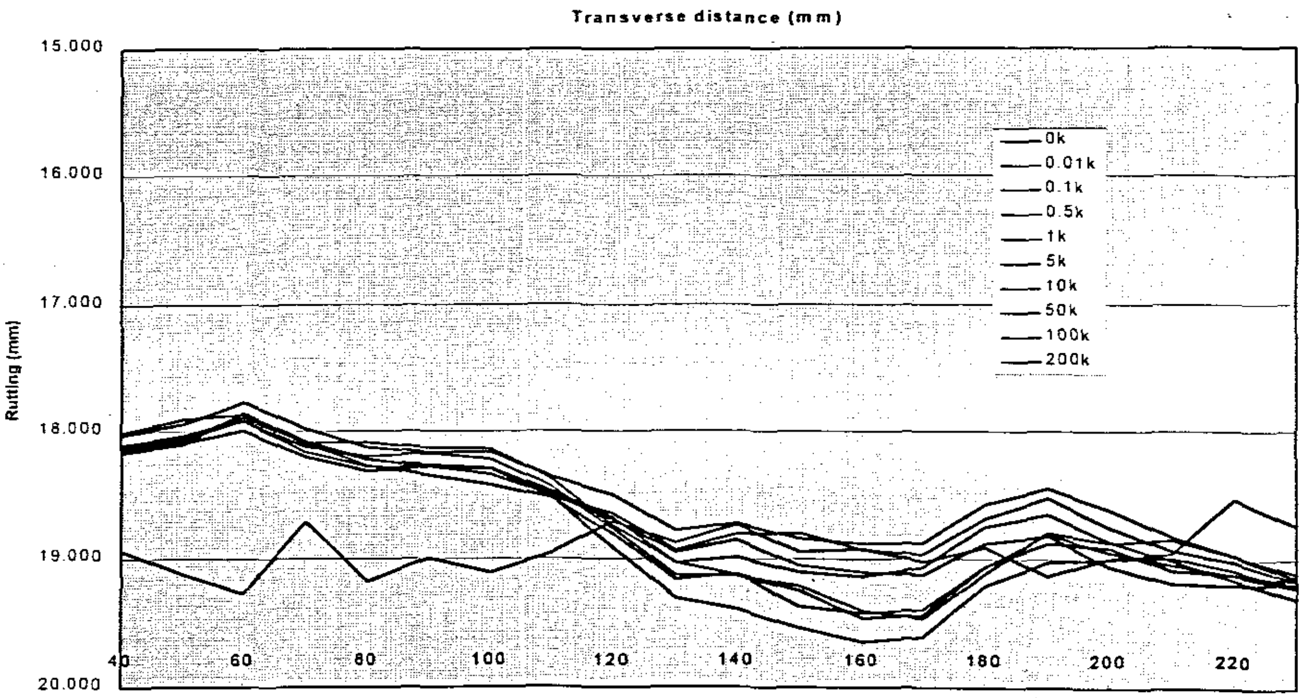

FIGURE L- 7: Transverse rutting profile at position 7

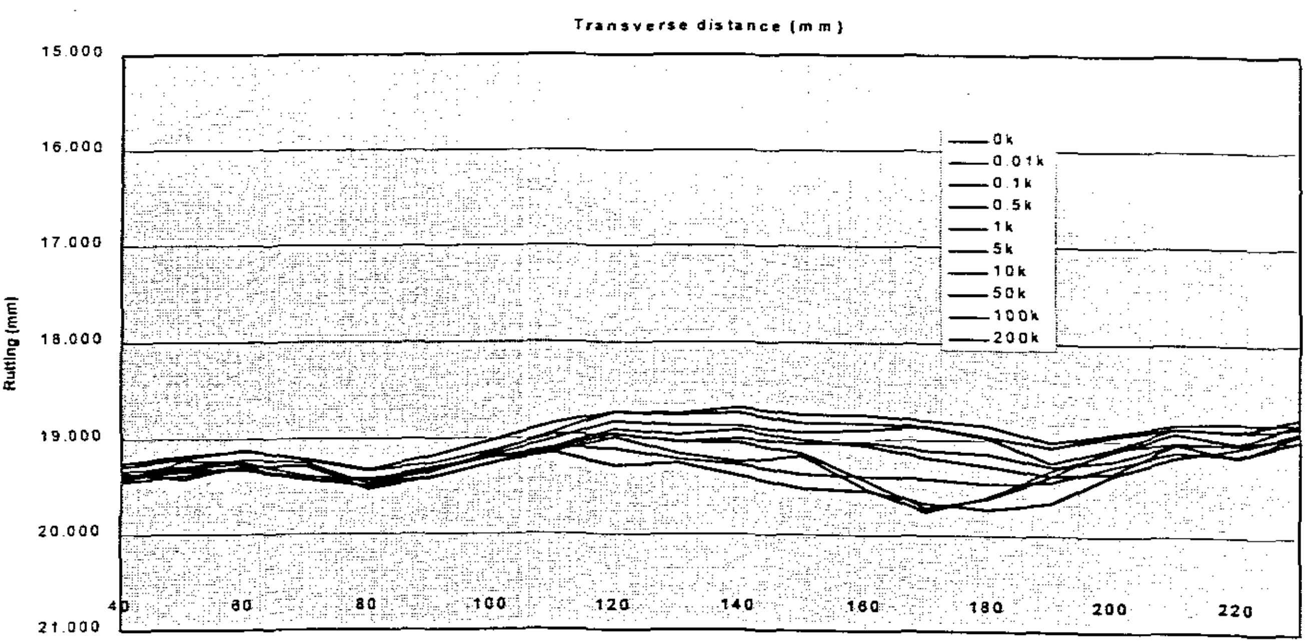

FIGURE L- 8: Transverse rutting profile at position 8

APPENDIX M

Photos taken during the study

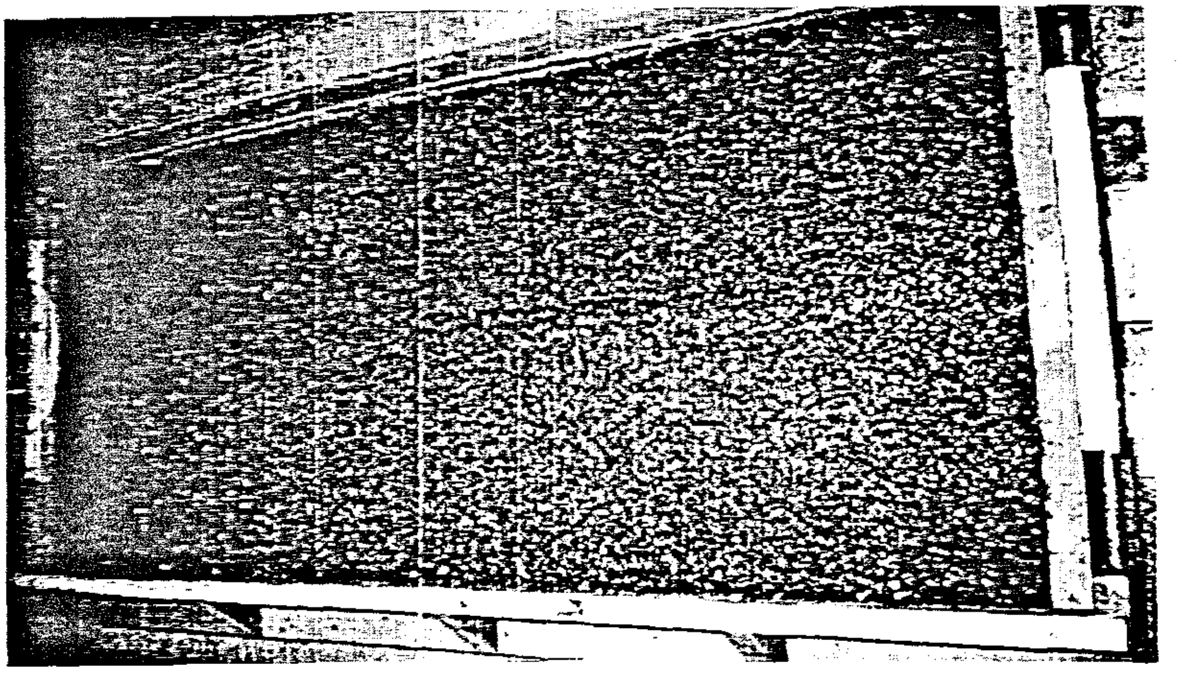

FIGURE M-1: Slab after rutting test and the wooden mould used for rutting test

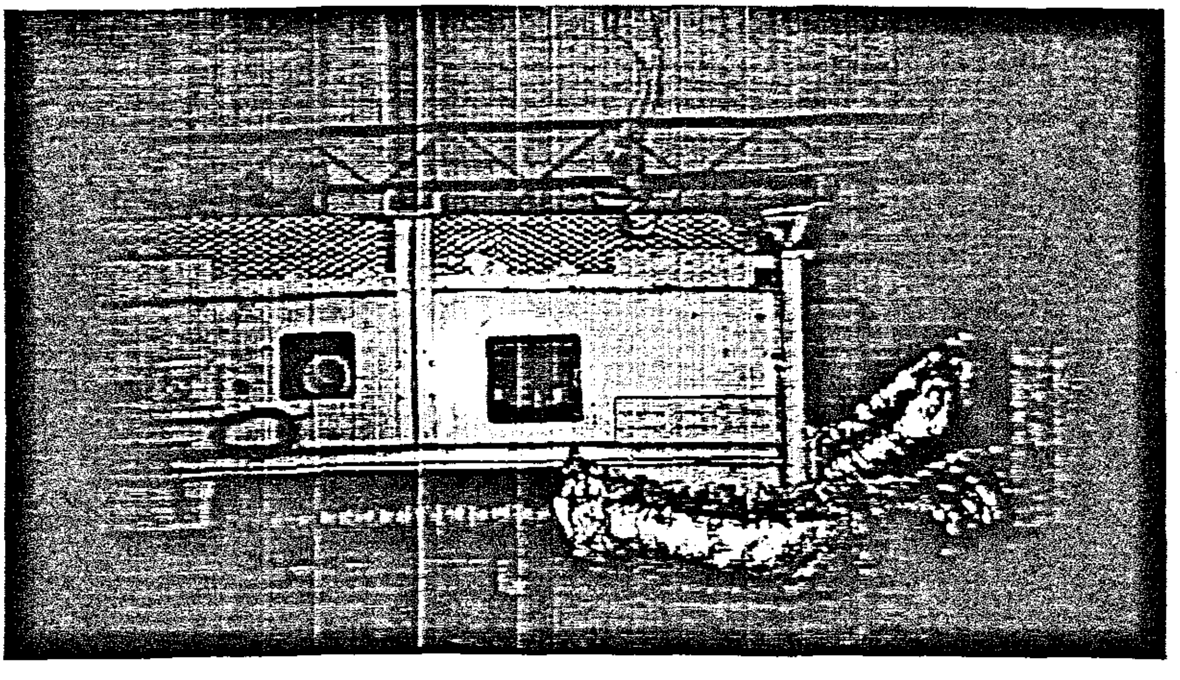

FIGURE M-2: MMLS Mk3 set-up on the test slab

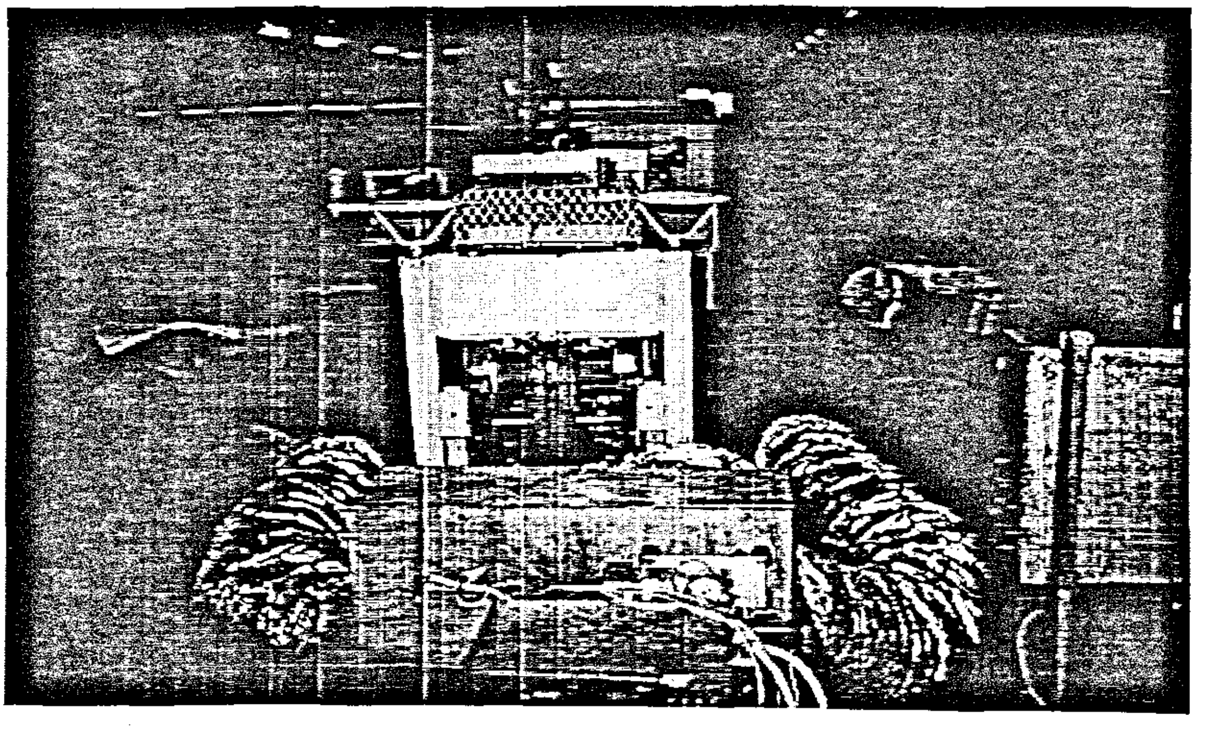

FIGURE M-3: Side view of the MMLS Mk3

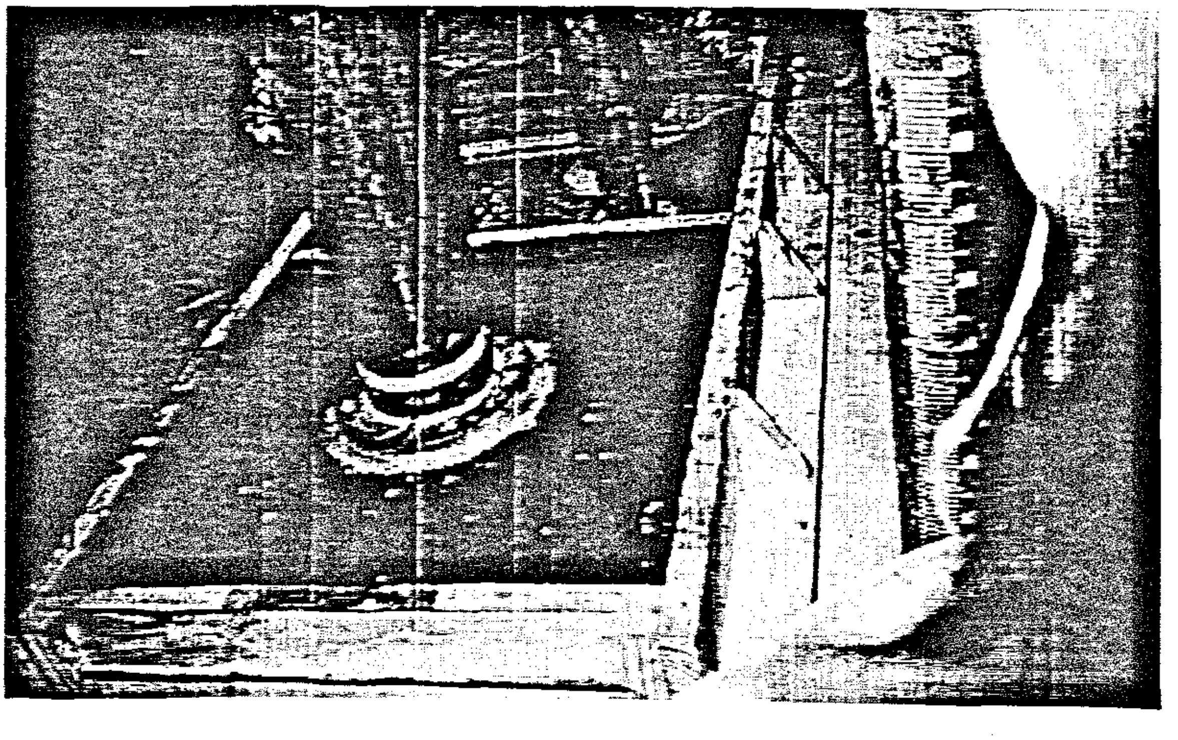

FIGURE M-4: Permeability measurements on the untrafficked slab

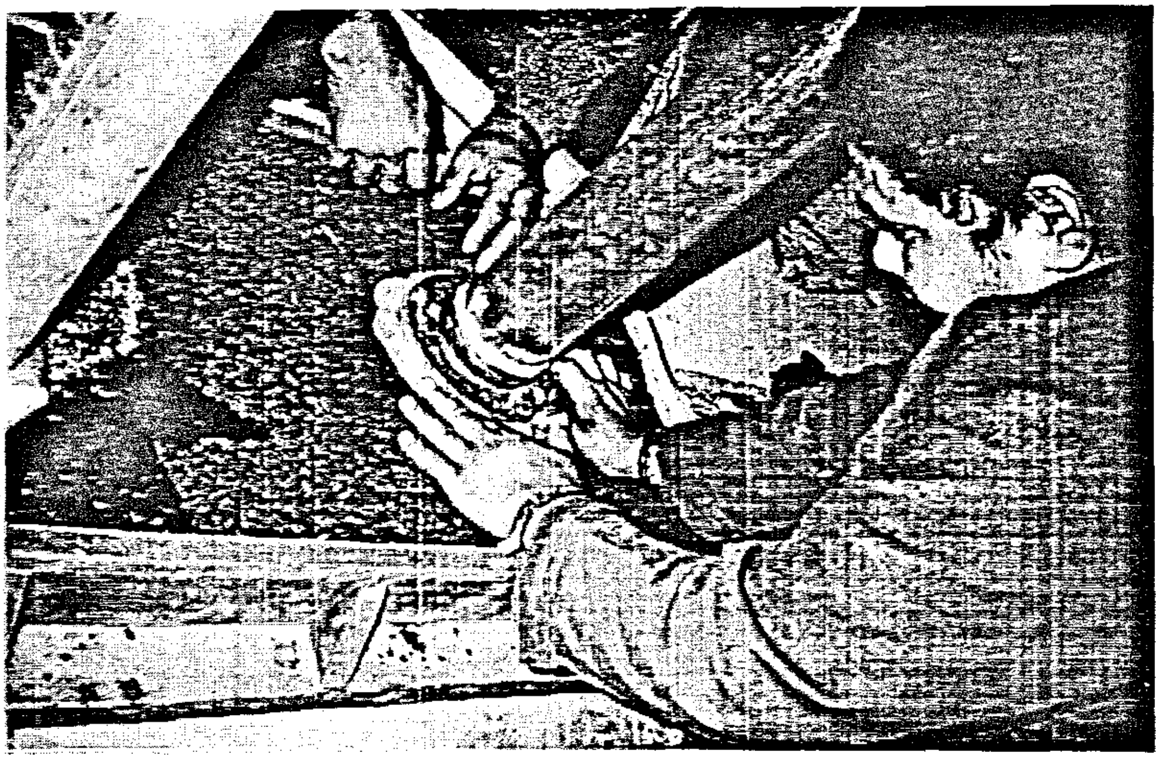

FIGURE M-5: LCD permeability set-up on the wheel track area

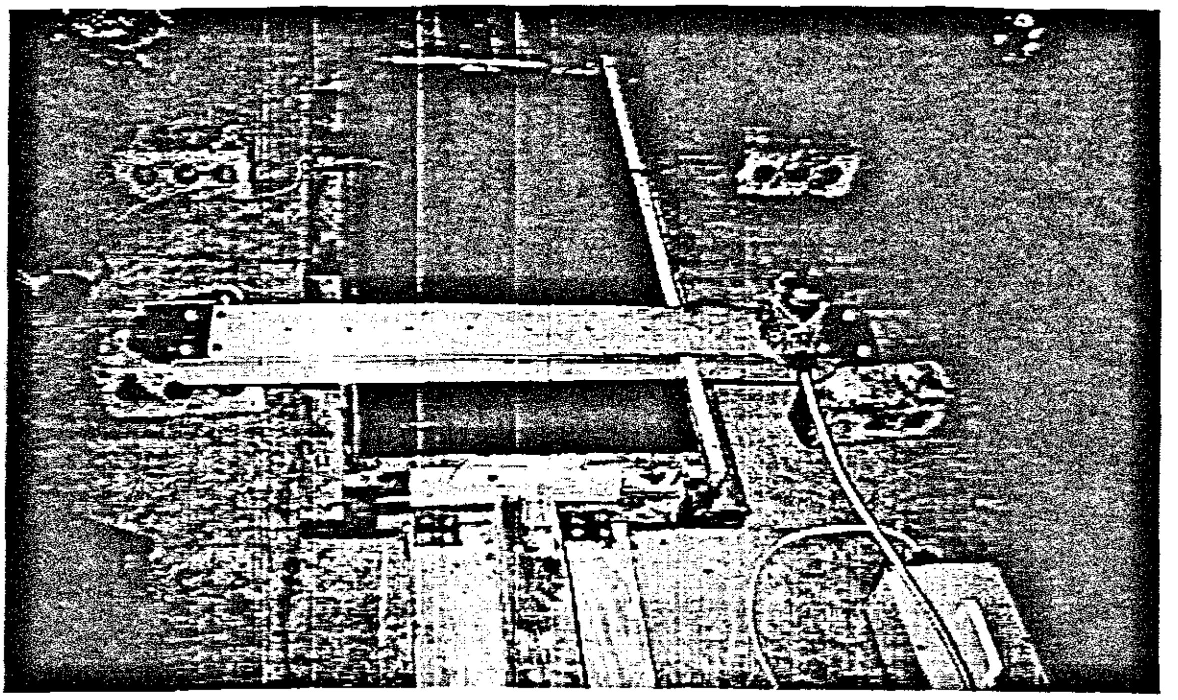

FIGURE M-6: Profilometer measurements on the slab

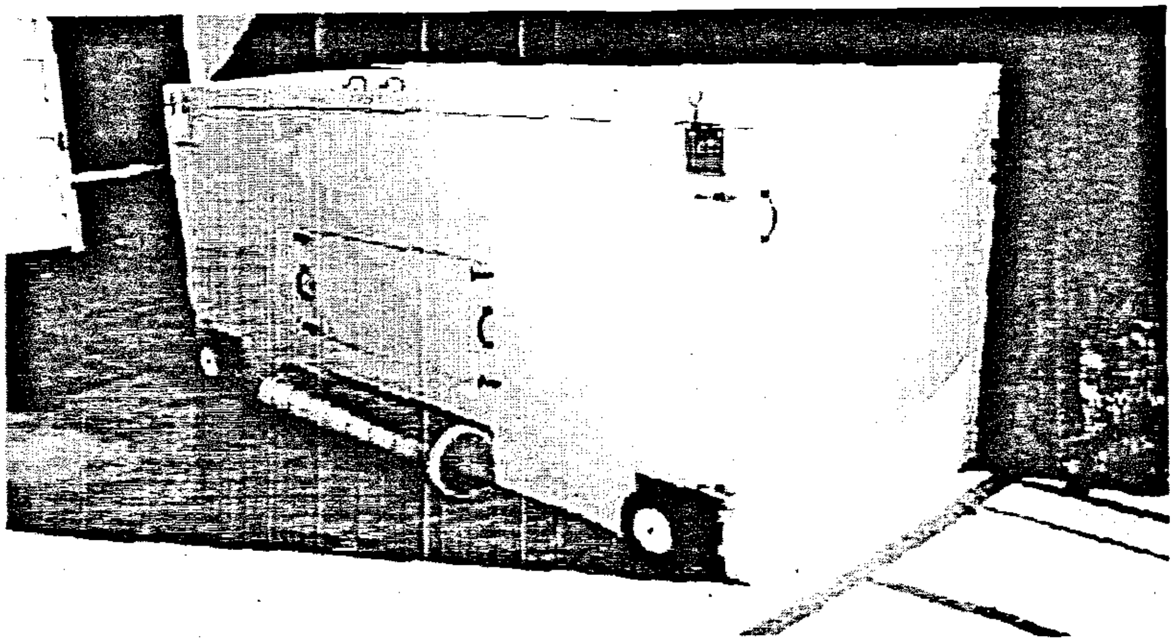

FIGURE M-7: Outside view of the environmental chamber

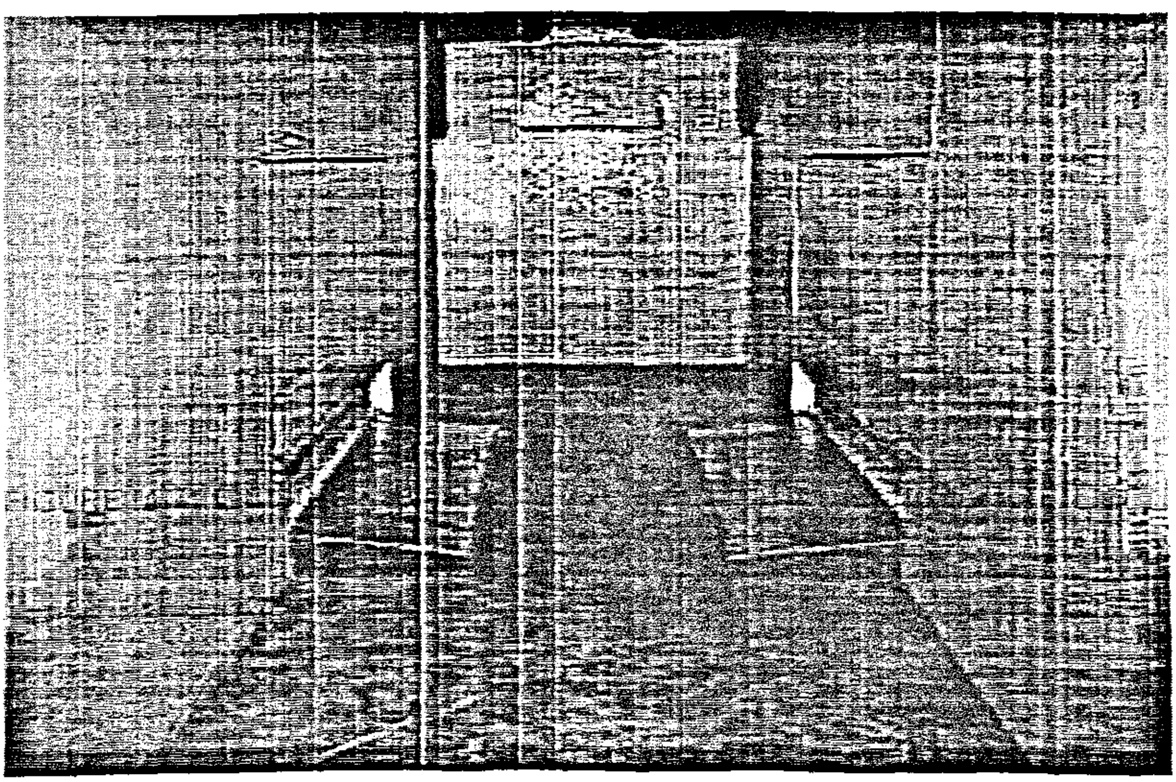

FIGURE M- 8: Photograph showing side view of the environmental chamber.

APPENDIX N

Sound absorption measurement results for sound, traffic and untrafficked slabs 1

Superfine Twinlay 7cm - untrafficked sample no. 1 (D)

c	Hz	Log(Hz)	Ratio	A+B	A-B	x (in m)	SWR	Alpha (r)	Theta	Alpha(n)	Rn	Xn
344	100	2.000	1.050	26.8	0.596	0.812	44.966	0.915	-0.175	0.085	2.726	-10.687
344	125	2.097	1.048	22.1	0.599	0.637	36.895	0.897	-0.233	0.103	1.906	-8.108
344	160	2.204	1.102	6.31	0.366	0.476	17.240	0.793	-0.359	0.207	1.647	-4.978
344	200	2.301	1.151	9.31	0.274	0.396	33.978	0.889	-0.248	0.111	1.817	-7.582
344	250	2.398	1.199	17.74	2.39	0.292	7.423	0.581	-0.475	0.419	1.859	-3.097
344	315	2.498	1.249	4.71	0.957	0.233	4.922	0.439	-0.460	0.561	2.228	-2.335
344	400	2.602	1.301	4.41	1.084	0.191	4.068	0.366	-0.351	0.634	2.761	-1.813
344	500	2.699	1.349	12.42	1.611	0.16	7.709	0.593	-0.219	0.407	4.538	-3.739
344	630	2.799	1.400	6.73	0.567	0.118	11.869	0.713	-0.426	0.287	1.637	-3.986
344	800	2.903	1.452	9.01	0.643	0.089	14.012	0.751	-0.541	0.249	0.939	-3.367
344	1000	3.000	1.500	2.2	0.301	0.062	7.309	0.577	-0.877	0.423	0.700	-1.929
344	1250	3.097	1.548	4.37	1.066	0.041	4.099	0.369	-1.269	0.631	0.625	-1.151
344	1400	3.146	1.573	1.002	0.491	0.036	2.041	0.117	-1.300	0.883	0.945	-0.706
344	1600	3.204	1.602	0.322	0.055	0.031	5.855	0.502	-1.330	0.498	0.428	-1.182
344	2000	3.301	1.651	0.271	0.021	0.016	12.905	0.733	-1.973	0.267	0.111	-0.656

Superfine Twinlay 7cm - untrafficked sample no. 2 (E)

c	Hz	Log(Hz)	Ratio	A+B	A-B	x (in m)	SWR	Alpha (r)	Theta	Alpha(n)	Rn	Xn
344	100	2.000	1.050	27.8	0.562	0.828	49.466	0.922	-0.117	0.078	5.293	-15.261
344	125	2.097	1.048	22	0.598	0.631	36.789	0.897	-0.260	0.103	1.547	-7.319
344	160	2.204	1.102	6.36	0.318	0.48	20.000	0.819	-0.336	0.181	1.645	-5.410
344	200	2.301	1.151	9.82	0.291	0.39	33.746	0.888	-0.292	0.112	1.343	-6.524
344	250	2.398	1.199	18.01	1.85	0.293	9.735	0.662	-0.466	0.338	1.624	-3.513
344	315	2.498	1.249	5.4	0.76	0.226	7.105	0.567	-0.541	0.433	1.567	-2.811
344	400	2.602	1.301	4.4	1.32	0.174	3.333	0.290	-0.599	0.710	1.773	-1.516
344	500	2.699	1.349	9.44	2.46	0.168	3.837	0.344	-0.073	0.656	3.768	-0.492
344	630	2.799	1.400	6.53	0.836	0.119	7.811	0.598	-0.403	0.402	2.295	-3.457
344	800	2.903	1.452	8.58	0.688	0.088	12.471	0.725	-0.570	0.275	0.944	-3.156
344	1000	3.000	1.500	2.31	0.287	0.063	8.049	0.607	-0.840	0.393	0.693	-2.046
344	1250	3.097	1.548	5.41	0.77	0.042	7.026	0.564	-1.224	0.436	0.414	-1.341
344	1400	3.146	1.573	1.385	0.462	0.033	2.998	0.250	-1.454	0.750	0.662	-0.876
344	1600	3.204	1.602	0.32	0.041	0.018	7.805	0.597	-2.090	0.403	0.170	-0.568
344	2000	3.301	1.651	0.293	0.029	0.017	10.103	0.672	-1.900	0.328	0.149	-0.705

Superfine Twinlay 7cm - untrafficked sample no. 3 (F)

c	Hz	Log(Hz)	Ratio	A+B	A-B	x (in m)	SWR	Alpha (r)	Theta	Alpha(n)	Rn	Xn
344	100	2.000	1.050	26.5	0.587	0.838	45.145	0.915	-0.080	0.085	10.530	-19.071
344	125	2.097	1.048	22.8	0.608	0.661	37.500	0.899	-0.123	0.101	5.921	-13.643
344	160	2.204	1.102	6.85	0.345	0.51	19.855	0.817	-0.161	0.183	5.618	-8.903
344	200	2.301	1.151	10.14	0.301	0.402	33.688	0.888	-0.205	0.112	2.627	-8.983
344	250	2.398	1.199	18.55	1.97	0.304	9.416	0.653	-0.365	0.347	2.419	-4.023
344	315	2.498	1.249	5.9	0.82	0.23	7.195	0.571	-0.495	0.429	1.778	-2.980
344	400	2.602	1.301	4.8	1.68	0.186	2.857	0.232	-0.424	0.768	2.170	-1.118
344	500	2.699	1.349	9.86	2.79	0.178	3.534	0.312	0.110	0.688	3.416	0.607
344	630	2.799	1.400	6.93	0.872	0.128	7.947	0.603	-0.196	0.397	4.986	-3.794
344	800	2.903	1.452	8.68	0.701	0.098	12.382	0.723	-0.278	0.277	3.162	-5.330
344	1000	3.000	1.500	2.84	0.299	0.074	9.498	0.655	-0.438	0.345	1.820	-3.629
344	1250	3.097	1.548	5.69	0.94	0.052	6.053	0.513	-0.767	0.487	1.010	-2.064
344	1400	3.146	1.573	1.305	0.588	0.042	2.219	0.143	-0.994	0.857	1.173	-0.869
344	1600	3.204	1.602	0.29	0.041	0.02	7.073	0.566	-1.973	0.434	0.201	-0.643
344	2000	3.301	1.651	0.233	0.011	0.009	21.182	0.828	-2.484	0.172	0.053	-0.340

Superfine Twinlay 7cm - trafficked sample no. 1 (A)

c	Hz	Log(Hz)	Ratio	A+B	A-B	x (in m)	SWR	Alpha (r)	Theta	Alpha(n)	Rn	Xn
344	100	2.000	1.050	26.8	0.592	0.811	45.270	0.915	-0.179	0.085	2.607	-10.502
344	125	2.097	1.048	22.5	0.562	0.64	40.036	0.905	-0.219	0.095	1.986	-8.638
344	160	2.204	1.102	6.4	0.354	0.492	18.079	0.801	-0.266	0.199	2.687	-6.365
344	200	2.301	1.151	9.74	0.354	0.388	27.514	0.865	-0.307	0.135	1.475	-6.120
344	250	2.398	1.199	18.44	2.26	0.286	8.159	0.611	-0.530	0.389	1.485	-3.016
344	315	2.498	1.249	4.84	0.781	0.244	6.197	0.521	-0.334	0.479	3.049	-3.015
344	400	2.602	1.301	4.83	0.85	0.202	5.682	0.491	-0.190	0.509	4.434	-2.305
344	500	2.699	1.349	14.13	1.499	0.153	9.426	0.653	-0.347	0.347	2.605	-4.129
344	630	2.799	1.400	7.7	0.641	0.114	12.012	0.716	-0.518	0.284	1.155	-3.411
344	800	2.903	1.452	7.96	0.682	0.086	11.672	0.709	-0.628	0.291	0.839	-2.856
344	1000	3.000	1.500	2.36	0.371	0.06	6.361	0.530	-0.950	0.470	0.688	-1.735
344	1250	3.097	1.548	4.12	1.224	0.047	3.366	0.294	-0.995	0.706	1.003	-1.292
344	1400	3.146	1.573	1.108	0.491	0.041	2.257	0.149	-1.045	0.851	1.118	-0.877
344	1600	3.204	1.602	0.252	0.031	0.036	8.129	0.610	-1.037	0.390	0.478	-1.649
344	2000	3.301	1.651	0.242	0.021	0.029	11.524	0.706	-1.023	0.294	0.354	-1.727

Superfine Twinlay 7cm - trafficked sample no. 2 (B)

c	Hz	Log(Hz)	Ratio	A+B	A-B	x (in m)	SWR	Alpha (r)	Theta	Alpha(n)	Rn	Xn
344	100	2.000	1.050	28.6	0.758	0.81	37.731	0.899	-0.183	0.101	2.940	-10.068
344	125	2.097	1.048	26.3	0.684	0.626	38.450	0.901	-0.283	0.099	1.265	-6.786
344	160	2.204	1.102	22.1	0.775	0.488	28.516	0.869	-0.289	0.131	1.595	-6.481
344	200	2.301	1.151	6.43	0.347	0.383	18.530	0.806	-0.343	0.194	1.686	-5.242
344	250	2.398	1.199	9.54	0.429	0.232	22.238	0.835	-1.023	0.165	0.187	-1.767
344	315	2.498	1.249	4.9	0.791	0.185	6.195	0.521	-1.013	0.479	0.633	-1.619
344	400	2.602	1.301	4.69	0.763	0.148	6.147	0.519	-0.979	0.481	0.673	-1.671
344	500	2.699	1.349	13.73	1.467	0.11	9.359	0.651	-1.132	0.349	0.361	-1.513
344	630	2.799	1.400	8.63	0.764	0.077	11.296	0.701	-1.370	0.299	0.219	-1.201
344	800	2.903	1.452	6.17	0.641	0.058	9.626	0.659	-1.447	0.341	0.234	-1.105
344	1000	3.000	1.500	2.22	0.52	0.056	4.269	0.385	-1.096	0.615	0.752	-1.350
344	1250	3.097	1.548	3.74	1.335	0.05	2.801	0.225	-0.858	0.775	1.281	-1.185
344	1400	3.146	1.573	1.301	0.47	0.038	2.768	0.220	-1.198	0.780	0.888	-0.995
344	1600	3.204	1.602	0.259	0.021	0.036	12.333	0.723	-1.037	0.278	0.323	-1.706
344	2000	3.301	1.651	0.294	0.019	0.029	15.474	0.772	-1.023	0.228	0.266	-1.751

Superfine Twinlay 7cm - trafficked sample no. 3 (C)

c	Hz	Log(Hz)	Ratio	A+B	A-B	x (in m)	SWR	Alpha (r)	Theta	Alpha(n)	Rn	Xn
344	100	2.000	1.050	27.2	0.6	0.861	45.333	0.916	0.004	0.084	45.025	3.726
344	125	2.097	1.048	23.8	0.588	0.642	40.476	0.906	-0.210	0.094	2.131	-8.987
344	160	2.204	1.102	6.48	0.367	0.494	17.657	0.797	-0.254	0.203	2.945	-6.519
344	200	2.301	1.151	9.91	0.383	0.39	25.875	0.857	-0.292	0.143	1.705	-6.347
344	250	2.398	1.199	18.76	2.374	0.288	7.902	0.601	-0.511	0.399	1.603	-3.049
344	315	2.498	1.249	4.89	0.808	0.249	6.052	0.513	-0.276	0.487	3.611	2.900
344	400	2.602	1.301	4.93	0.884	0.204	5.577	0.484	-0.161	0.516	4.671	-2.017
344	500	2.699	1.349	14.75	1.512	0.195	9.755	0.663	0.420	0.337	1.915	3.770
344	630	2.799	1.400	7.85	0.674	0.116	11.647	0.709	-0.472	0.291	1.393	-3.661
344	800	2.903	1.452	8.1	0.687	0.088	11.790	0.712	-0.570	0.288	0.990	-3.127
344	1000	3.000	1.500	2.29	0.365	0.062	6.274	0.526	-0.877	0.474	0.793	-1.864
344	1250	3.097	1.548	4.44	1.236	0.052	3.592	0.319	-0.767	0.681	1.347	-1.549
344	1400	3.146	1.573	1.152	0.51	0.043	2.259	0.149	-0.942	0.851	1.224	-0.899
344	1600	3.204	1.602	0.266	0.026	0.038	10.231	0.676	-0.921	0.324	0.477	-1.923
344	2000	3.301	1.651	0.254	0.019	0.032	13.368	0.741	-0.804	0.259	0.474	-2.270

APPENDIX O

TEST PROCEDURE1: TEST PROCEDURE FOR THE LCS (Laboratoria de Caminos Santander) DRAINOMETER

Purpose of the test

The purpose of the LCS Drainometer is to assess the drainage capacity, the in-situ voids content and the homogeneity of the finished road surface.

Summary of method

The water permeability of an asphalt wearing course can be analysed through the LCS Drainometer device, which was developed in 1981 at the University of Cantabria in Santander (Spain). The test procedure consists of placing the drainometer on the road surface and filling the transparent cylinder with water to a level approximately 150 mm above the top marking of the cylinder. Then 150 mm of water is allowed to drain out of the drainometer to wet the porous asphalt layer. When the water level reaches the top marking, recording of the time should commence until the water level reaches the bottom marking. The recorded time (T, measured in seconds) can then be used to:

- Determine the permeability coefficient (k), using the following equation.

$$\ln(k) = 7.624 - 1.348\ln(T)$$

- Determine the approximated void content of the porous asphalt layer, using the following equation.

$$\text{Voids}(\%) = \frac{58.6}{T^{0.305}}$$

References

SABITA, 1995. The design and use of porous asphalt mixes, SABITA Manual 17.

NLT-327/88, 1988. Permeabilidad in situ de pavimentos drenantes mediante el pemeametro LCS (Determination of the in-situ permeability of porous pavements using the LCS permeability apparatus, CEDEX-MOPU, Madrid.

A Ruiz, R Alberola, F Perez, B Sanchez, 1990. Porous asphalt mixtures in Spain, Transportation Research Record 1265, Transportation Research Board, Washington D.C.

APPENDIX P

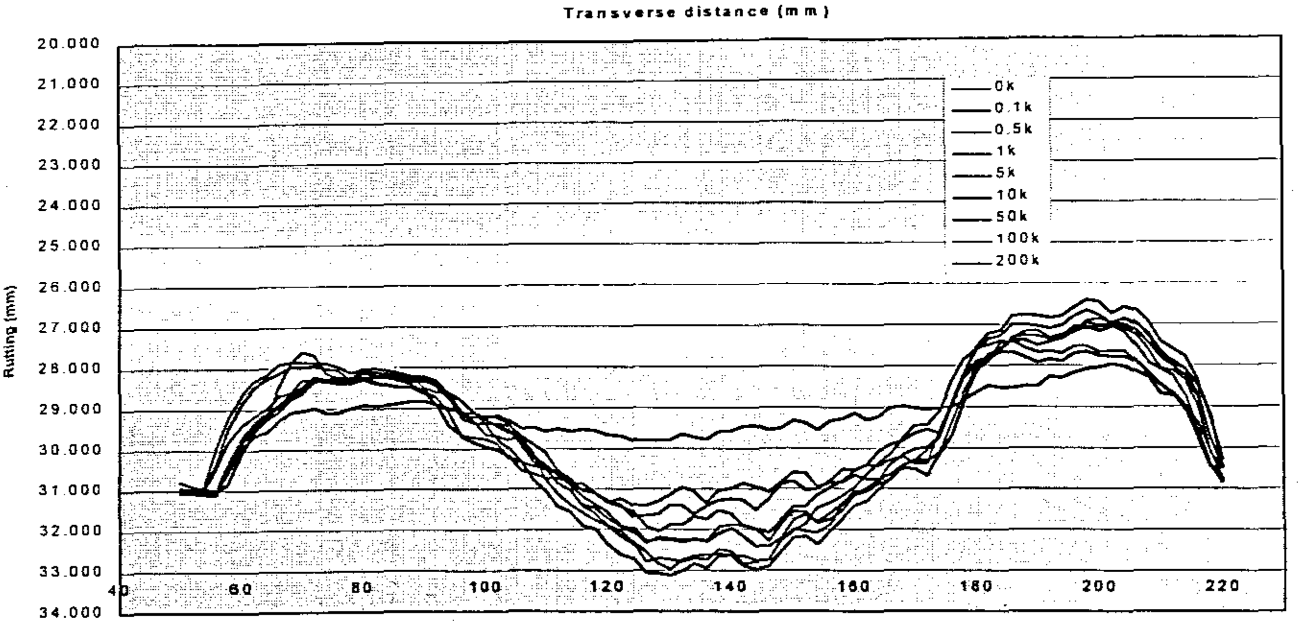

FIGURE P-1: Transverse rutting profile at position 1

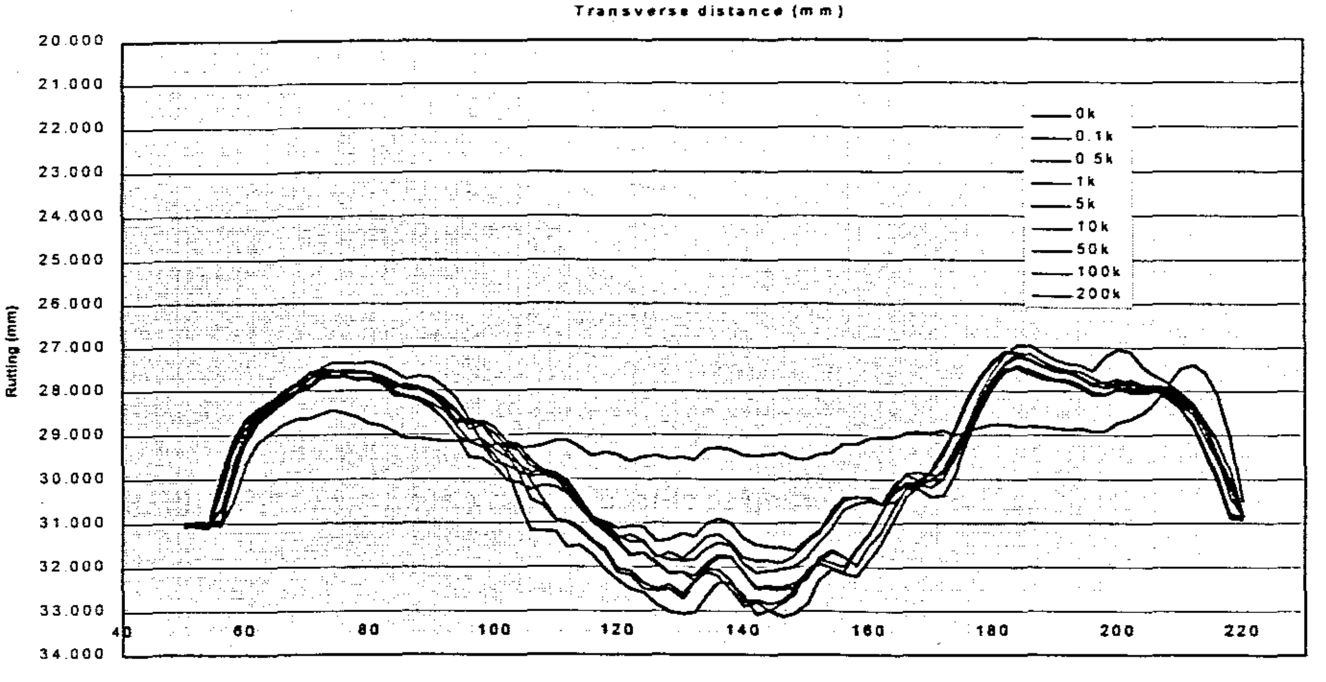

FIGURE P-2: Transverse rutting profile at position 2

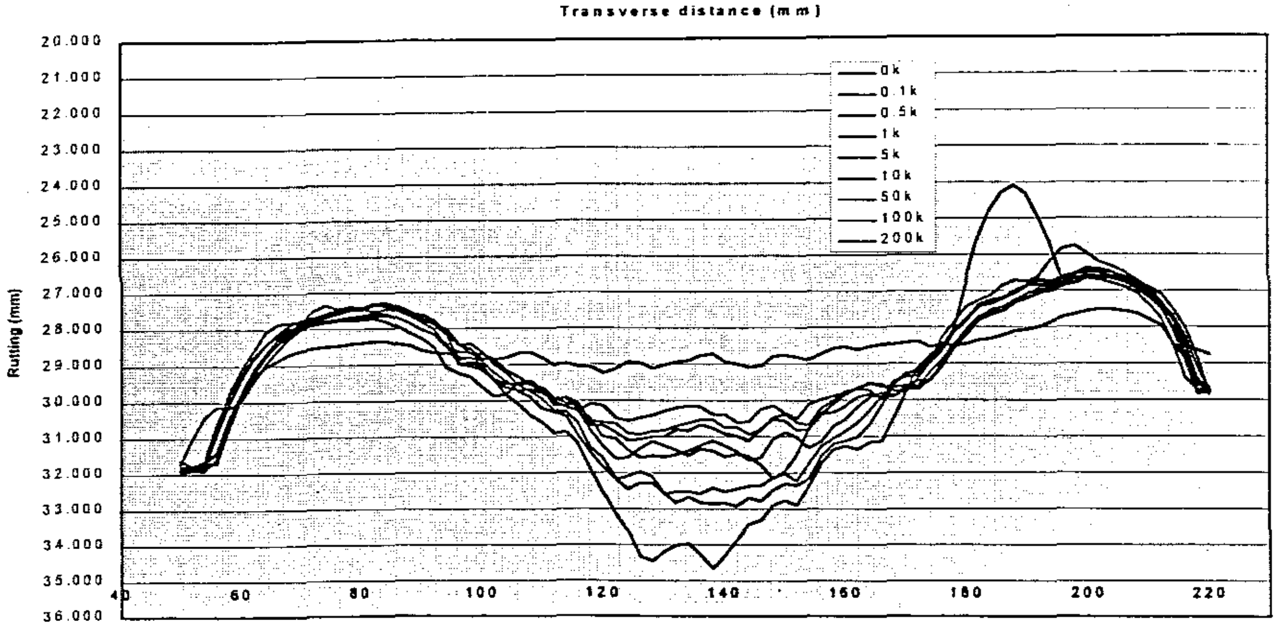

FIGURE P-3: Transverse rutting profile at position 3

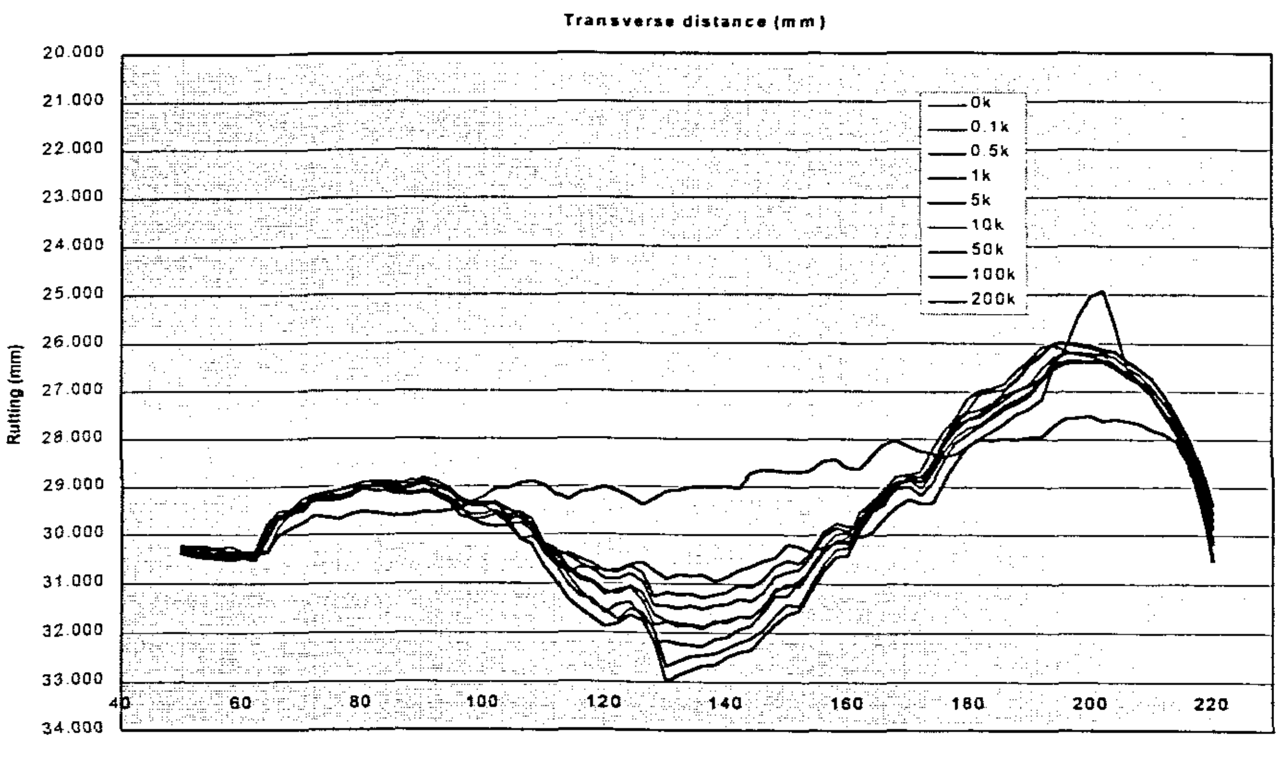

FIGURE P-4: Transverse rutting profile at position 4

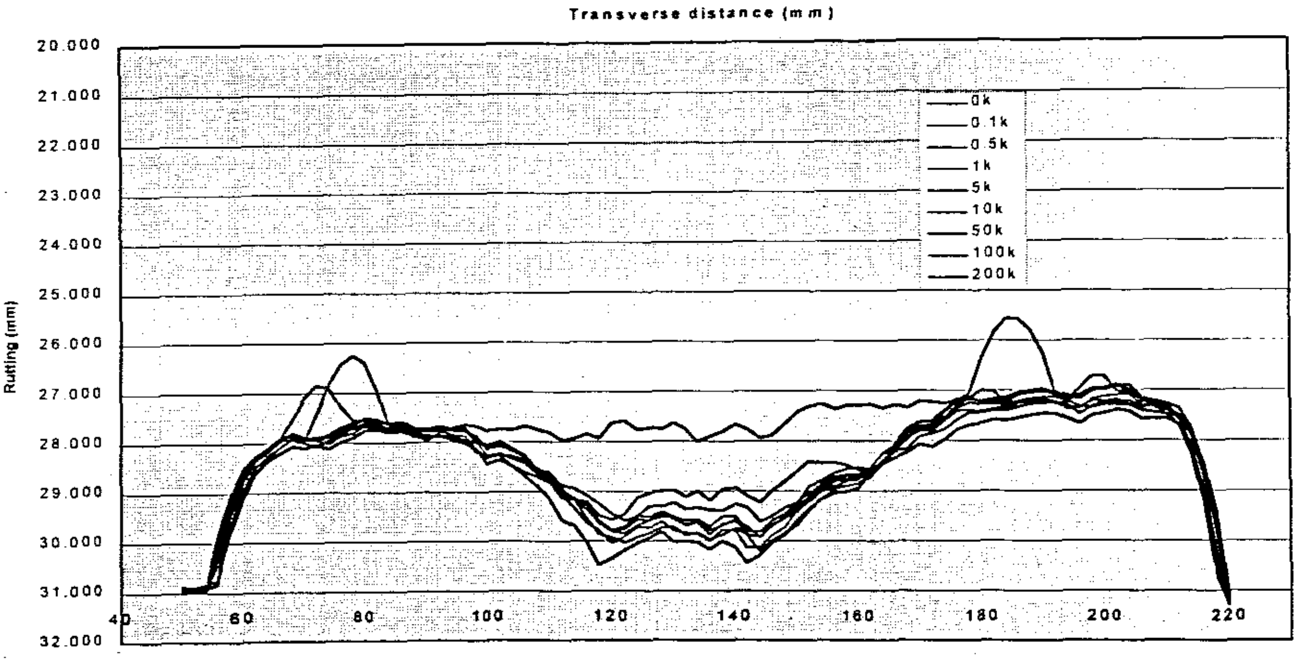

FIGURE P-5: Transverse rutting profile at position 5

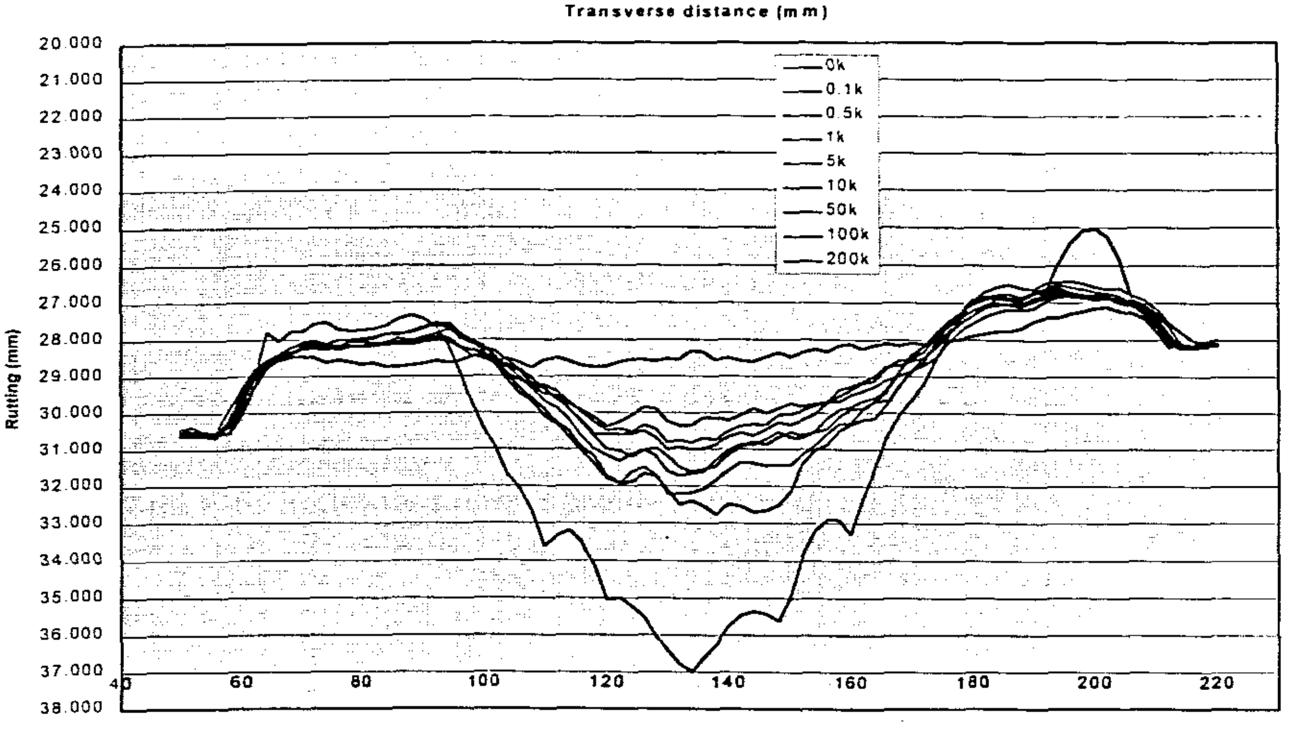

FIGURE P-6: Transverse rutting profile at position 6

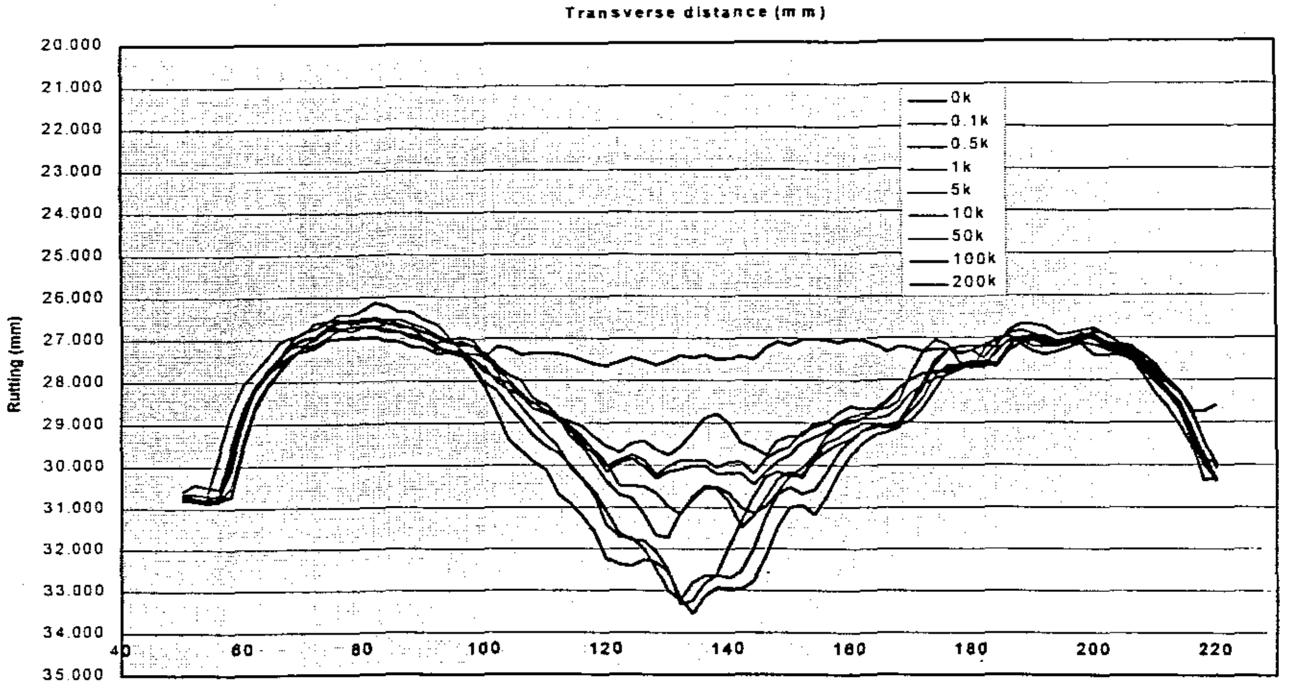

FIGURE P-7: Transverse rutting profile at position 7

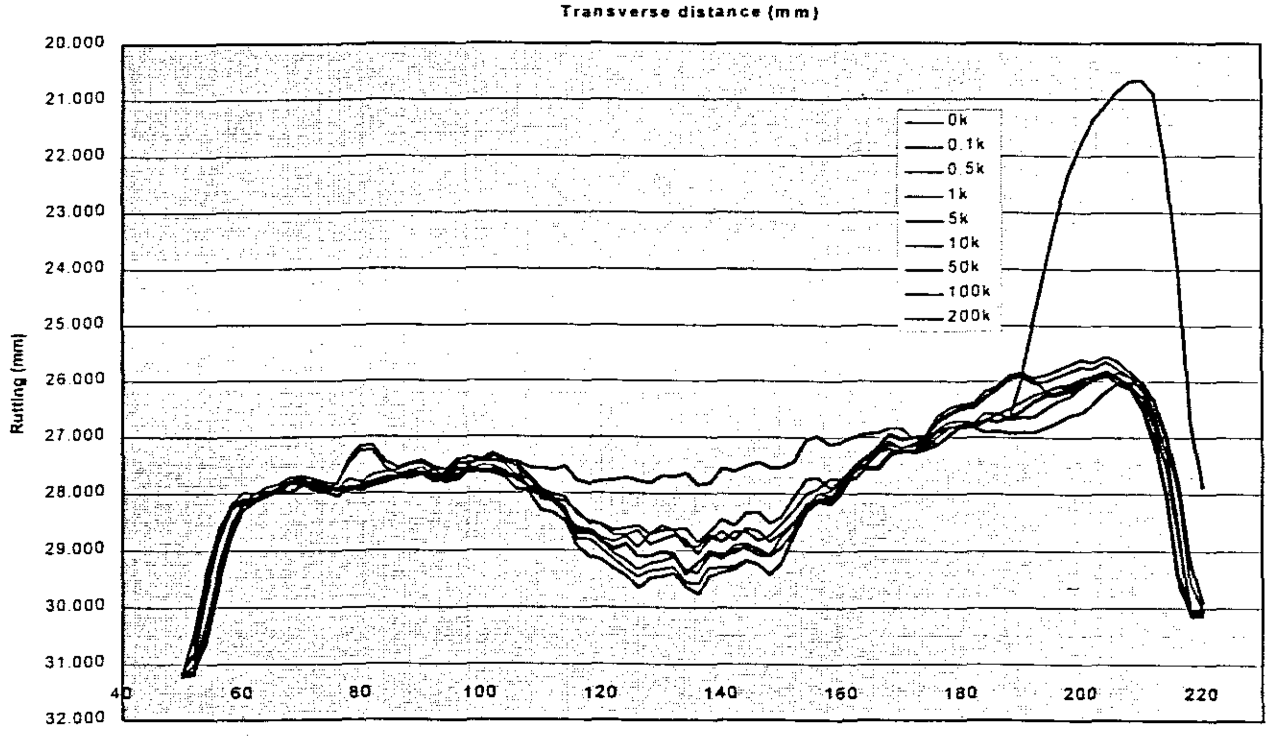

FIGURE P-8: Transverse rutting profile at position 8

APPENDIX Q

Photos taken during the study

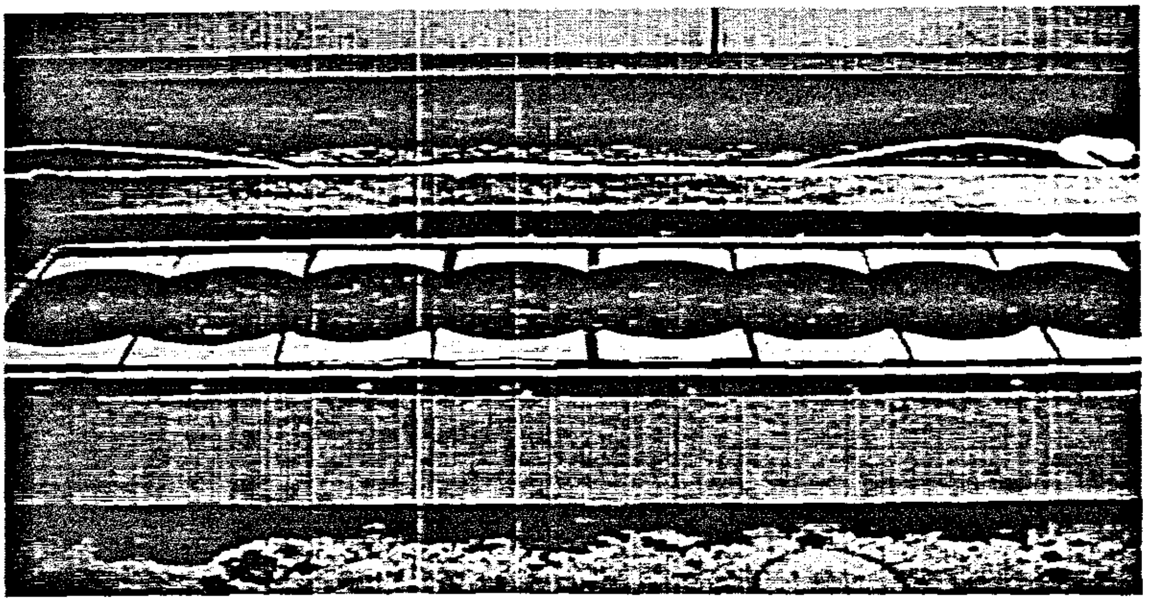

FIGURE Q-1: Briquette set-up on the mould before rutting test

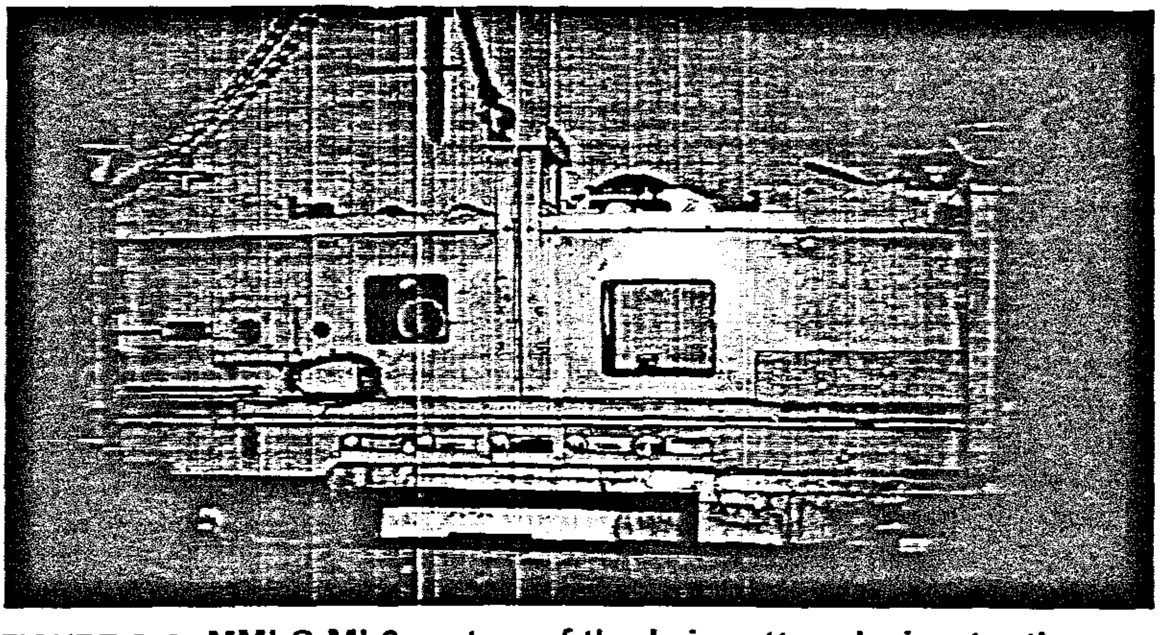

FIGURE Q-2: MMLS Mk3 on top of the briquettes during testing

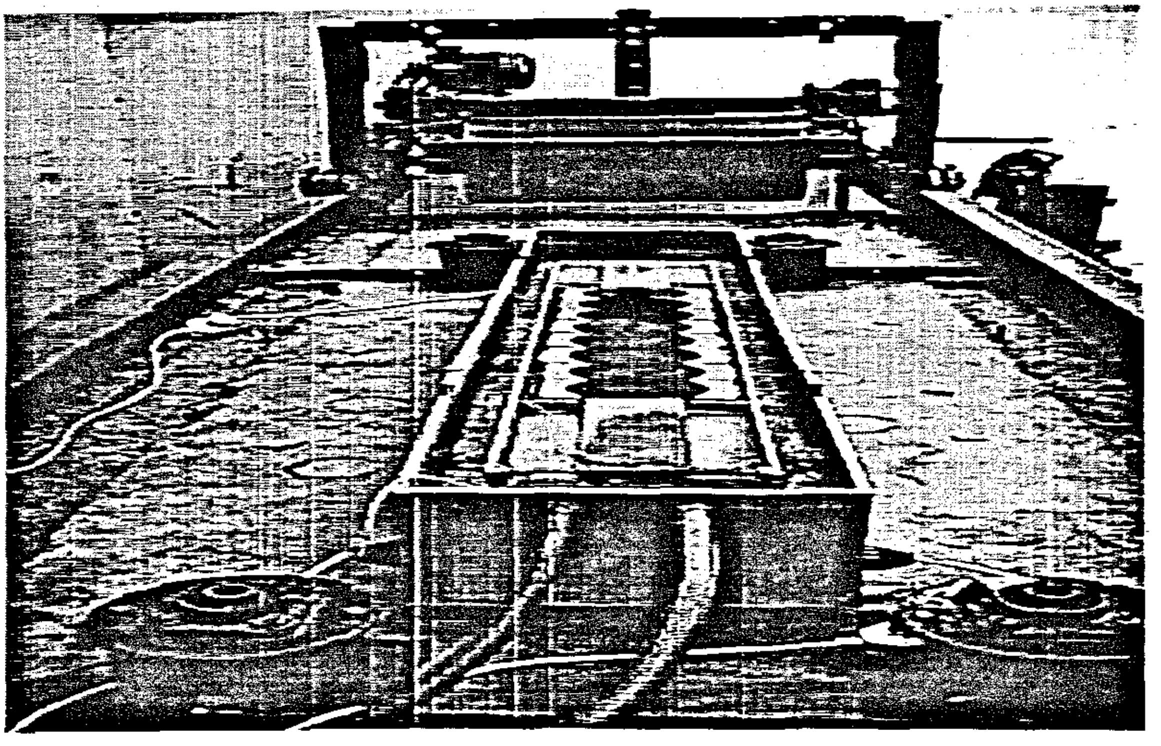

FIGURE Q-3: Briquettes submerged in heated water bath

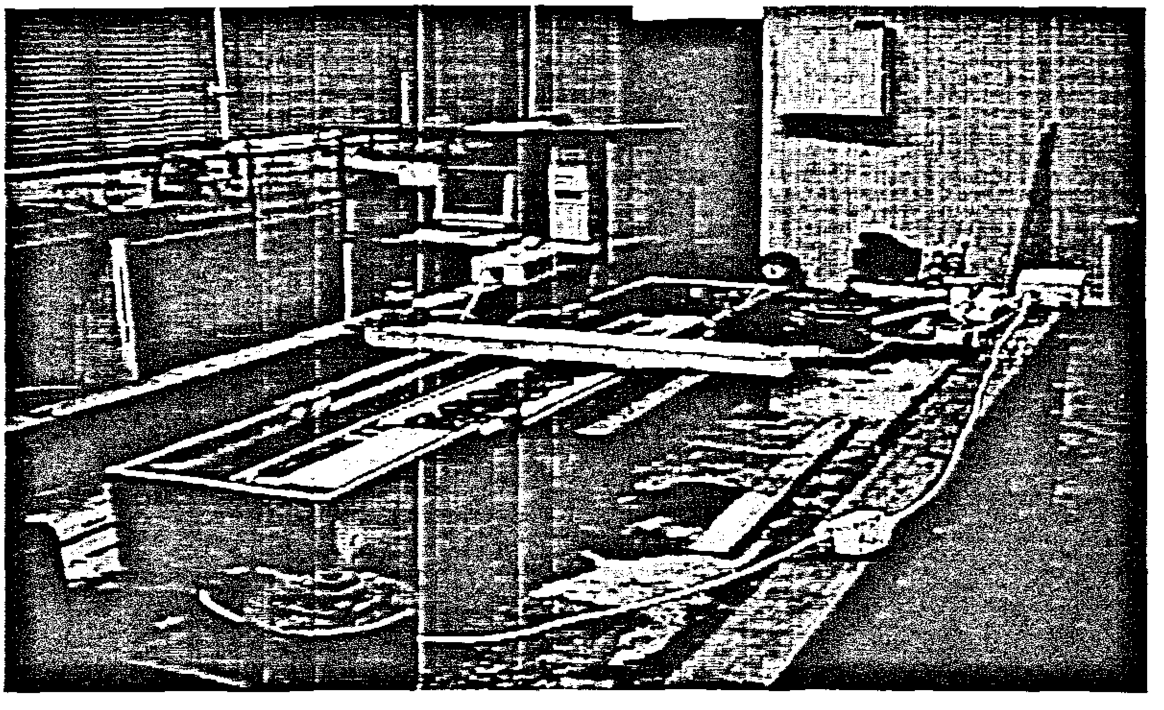

FIGURE Q-4: Profilometer measurements on the briquettes

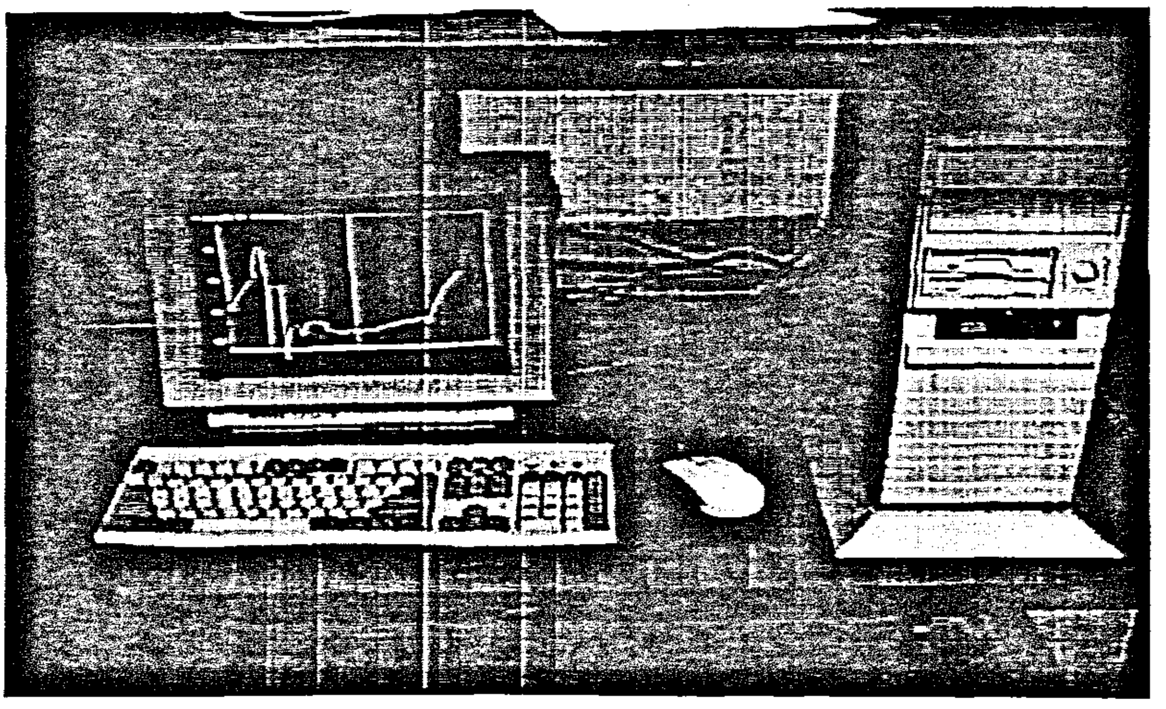

FIGURE Q-5: Data capturing using a computer

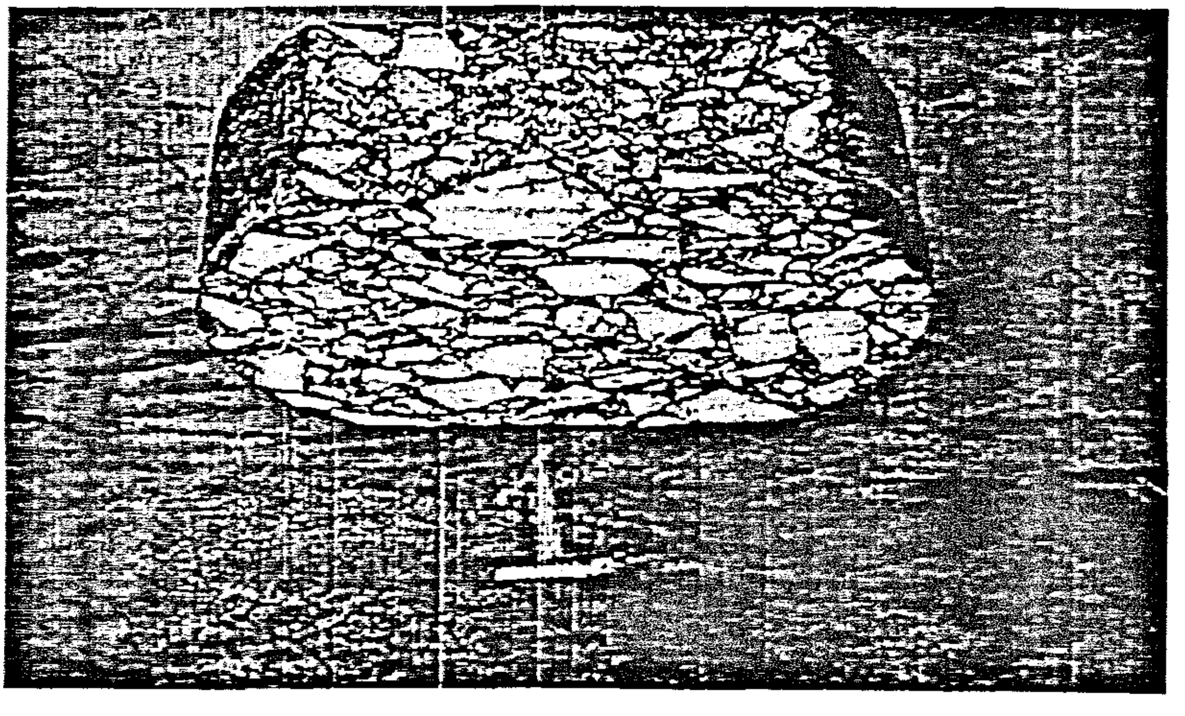

FIGURE Q-6: Briquettes cut to size and shape before testing