TOWARDS ANALYTICAL MIX DESIGN FOR LARGE-STONE ASPHALT MIXES

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Increasing traffic volumes and axle loads in South Africa has recently resulted in traffic loading beyond the current design classes. In addition, there is a strong lobby to increase the legal axle load limit. A need was expressed by the Southern African Bitumen and Tar Industry for an investigation into Heavy Duty Asphalt Pavements. A project focusing on the use of large-aggregate asphalt mixes (37,5 mm and 53 mm) was defined. This paper addresses the development of an analytically based design procedure for large-aggregate asphalt and its application in thirteen trial sections. In addition, the physical and engineering properties of the various materials are discussed and related to the constructability of the mixes. The performance of these trial sections under accelerated trafficking are related to laboratory results.

INTRODUCTION

Increasing traffic growth in terms of both volume and axle loads is a world-wide phenomenon. In South Africa this has resulted in traffic loading on some of the major highways in excess of the current design classes. There is also currently a strong lobby to increase the legal axle load limit from 8,2 tonnes to approximately 10 tonnes. In addition, higher tyre pressures due to new tyre types exacerbate the situation.

Both the South African road authorities and the South African asphalt industry expressed a need for an investigation into Heavy Duty Asphalt Pavements (HDAPs). The main aims of this project were to assess the ability of HDAPs to carry very heavy traffic, to develop design procedures for such materials, to assess their constructability and to evaluate their benefit in terms of economic analysis. The project focused on the use of large-aggregate asphalt mixes as a possible solution to the above problem. The use of 37,5 mm and 53 mm aggregate in various gradings was investigated.

This paper addresses the development of a design procedure for large-aggregate asphalt, the implementation thereof in trial sections, the correlation of laboratory obtained engineering properties with field values, the effect of constructability on engineering properties and the performance of these trials under Heavy Vehicle Simulator (HVS) testing.

As part of this work thirteen trial sections were constructed with various aggregate gradings, binder contents and types of binder. These are located near Cape Town and near Dundee in the province of Natal. The first set of ten sections (the Cape Town sections) were used to investigate the effect of aggregate grading and the modification of the binder in terms of relevant engineering properties and to finalise the development of a new laboratory design procedure for large-aggregate asphalt. This procedure was subsequently used to design three 100 m sections with three different gradings which were evaluated under accelerated testing with the HVS.

LARGE-AGGREGATE ASPHALT

The benefits of large-aggregate mixes fall into two categories (1) :

- improved structural capacity, and
- improved economy.

The concept of using large aggregate in asphalt mixes is not new and their excellent performance in the early 1900's was reported by Davis (2). Acott (3) illustrated that these mixes exhibit sufficient bearing capacity to resist the high stresses induced by log-carrying trucks. These mixes can also resist indentation due to high loads such as are found in a container terminal (Acott et al (4)). Also of importance is that the binder recovered from the early pavements has shown very little hardening. Other instances of good performance by these mixes were reported in Tennessee and Indiana (3).

It is well known that conventional mix design procedures (Marshall and Hveem) do not make provision for large aggregate. Kandhal (5) did some empirical work using a 150 mm Marshall hammer. However, the shortcomings of these conventional methods over the mix design spectrum due to their empirical nature are well documented (6). The modern asphalt mix design practice, which includes large aggregates, modified binders and increased traffic loading, therefore requires a more analytical approach.

Significant factors affecting initial costs are the lower binder content associated with large-aggregate mixes and the lower quarrying cost of larger aggregate fractions. Savings in life cycle cost would derive from improved performance in relation to conventional mixes or alternative materials. However, increased time of production and plant and equipment wear and tear will lead to an increase in production cost although the total cost will still be less than that for a conventional mix.

LABORATORY PROCEDURES

Prior to the design and construction of the field trial sections, laboratory studies had been undertaken to provide input in terms of procedures, engineering properties and design criteria. During this phase a number of laboratory compaction and testing methodologies had been developed or adapted.

Laboratory compaction methods

Laboratory studies indicated that samples compacted with the Marshall hammer yielded static creep values significantly higher than those compacted by the Hugo hammer even though densities were similar (7). The USA Strategic Highway Research Program (SHRP) also illustrated that the compaction method has a significant effect on the engineering properties of asphalt (8). Initially a number of laboratory compaction methods were therefore evaluated. These included a Gyratory compactor, vibrating table compaction, the Marshall method (using 150 mm diameter moulds) and the Hugo method (9) which is a modification of the Marshall method. Due to economic restraints a method using expensive equipment as standard, was not favoured and the project focused on the last two methods. The Marshall compaction method needs no introduction, however, indications are that this method is outdated. The Hugo method is based on the Marshall method with a number of differences. These include a modification of the face of the hammer with indents (see Figure 1) combined with turning of the hammer after every blow, providing a kneading effect in the compaction of the material.

Both the Marshall and Hugo methods were adapted to be used with 150 mm diameter moulds. Based on the concept of applying the same amount of energy per volume of asphalt, the compaction effort was increased by using a larger weight and more blows per sample. For the large Hugo hammer, the depth of the indents was increased. These changes are shown in Table 1 below.

Mould size	100 mm diameter	150 mm diameter
Number of blows	75	110
Mass of weight	4,436 kg	10,438 kg
Height of fall	475 mm	475 mm
Depth of indents (Hugo hammer)	3,2 mm	6 mm

Table 1 : Comparison of Compaction in 100 mm and 150 mm Mould.

Laboratory testing systems

Materials testing conducted addressed the following engineering properties :

- indirect tensile stiffness (resilient modulus);
- tensile strength;
- strain at maximum stress, and
- creep modulus (static and dynamic).

These properties were measured with an INSTRON testing facility which had been upgraded prior to this study by the addition of micro computer hardware and software. An Asphalt Testing System (ATS) drives the INSTRON, providing a wide range of loading and movement wave functions, acquires and stores all data and calculates the specific engineering properties.

The indirect tensile test (10) was used to measure the first three properties. The test had, however, been modified by the placing of the lateral measurement device directly on to the sample (11). This new way of measuring the horizontal displacement enabled the measurement of the strain at maximum stress. Furthermore, the improved accuracy of measurement yielded a significant increase in the validity of the Poisson's ratio's calculated.

The stiffness and indirect tensile strength of the samples were measured according to the standard ASTM method (12) using the improved measuring device.

For the determination of the stiffness a frequency of 10 Hz was used (0,1 s loading and 0,9 s rest period). A formula suggested by Kennedy et al (10) was used to calculate the strain at maximum stress.

A dynamic creep test, which has gained wide acceptance in the UK (13) was used to assess the permanent deformation characteristics of the samples. However, most of the tests were conducted on 150 mm diameter samples and the results are reported as a dynamic creep modulus as opposed to the UK method of reporting the strain. A creep modulus of 10 MPa (at 100 kPa, 10 °C) corresponds to a strain of 1 per cent.

THE CAPE TOWN TRIAL SECTIONS

The basic work conducted in the first phase of the HDAPs project provided input into the planning, design and construction of ten experimental sections (each 20 m long) near Cape Town. The sections contained trial mixes with various aggregate gradings, binder contents and binder type in a 150 mm asphalt base. The major objective of this experiment was to assist in the development of a large-aggregate mix design method based on the procedures described above. A 2^2 factorial experiment with the main independent variables being preparation method (5 methods) and type of mix (10 mixes), was used.

Mixes

The composition of the ten large-aggregate mixes constructed, is given in Table 2. It should be emphasized that a simplified design approach, incorporating experience and some innovation was used in selecting the gradings to be evaluated. The aggregates used consisted of crushed Hornfels, dune sand and a 60/70 penetration grade bitumen.

No	Grading	Stone size	% Binder	Binder type
1	Continuous	37,5 mm	4,0 %	conventional
2	Continuous	37,5 mm	4,5 %	conventional
3	Continuous	37,5 mm	5,0 %	conventional
4	Continuous	37,5 mm	5,0 %	EVA modified
5	Continuous	53,0 mm	4,0 %	conventional
6	Semi-gap	37,5 mm	4,5 %	conventional
7	Experimental A	37,5 mm	4,5 %	conventional
8	Experimental A	53,0 mm	4,0 %	conventional
9	Experimental A	53,0 mm	4,5 %	EVA modified
10	Experimental B	53,0 mm	4,0 %	conventional

Table 2 : Mixes used at the Cape Town Trials.

The gradings used are shown in Figure 2. The target grading for the continuously graded mixes was derived from a grading suggested by Brown & Cooper (13) which is a function of the filler content and an n-value (which describes the shape of the grading curve). For the above work a filler content of 7,5 per cent and an n-value of 0,45 were used. The effect of binder content was evaluated by constructing three sections with the continuous grading and 37 mm aggregate - at the laboratory-predicted optimum binder content as well as above and below it. The two experimental gradings both contained a high percentage of large aggregate (40 and 60 respectively) as well as relatively high filler contents.

Due to the lack of a proven design procedure the mixes were designed from a volumetric point of view using the large Hugo hammer for sample preparation. The binder content was then selected on the basis of maximum density, a target void content and minimum voids in the mineral aggregate (VMA). The binder content was selected on the dry side as dictated by VMA considerations to maximize stone-to-stone contact.

Preparation methods

The six preparation methods used were derived from a combination of production and compaction methods (see Table 3).

No	Method of mixing	Method of compaction
1	Batch plant	In situ field compaction (Vibratory)
2	Batch plant	Marshall lab compaction (reheated mixes)
3	Batch plant	Hugo lab compaction (reheated mixes)
6	Batch plant	Hugo lab compaction at batch plant
4	Hand mixing	Marshall lab compaction
5	Hand mixing	Hugo lab compaction

Table 3 : Sample Preparation Methods used at the Cape Town Experiment.

The field samples were obtained directly from the 200 ton/hour batch plant used for the construction of the trial sections. As shown in Table 3, samples were compacted in the site laboratory (No. 6) as well as at a later stage after reheating of the material (Nos. 2 and 3). In addition, cores were taken from all the sections after construction. Both the Marshall and the Hugo methods (150 mm diameter hammer, 10,438 kg at 110 blows for both methods) were used to compact samples using laboratory mixes.

Correlation of lab with field properties

The **density** attainable is influenced by both the compaction method and the mix production method. The effect of the latter is, however, more significant. The use of reheated field mixes in preparing samples yields densities much closer to that of the field cores than when laboratory prepared mixes are used. Although less significant, the densities obtained using the Hugo hammer were closer to the field values tha those obtained using the Marshall hammer (see Figure 3).

The **stiffness** obtained is not significantly influenced by the laboratory compaction method. However, the mix preparation method has a major influence. In particular, reheated field produced mixes yield stiffness values far higher than laboratory prepared mixes or field cores (see Figure 4). The same trend was observed with the indirect tensile strength results indicating that reheating of field produced mixes can produce misleading results.

The **permanent deformation characteristics** of the asphalt were significantly influenced by the compaction method although the mix preparation method played a minor role. Figure 5 indicates that the dynamic creep modulus measured after compaction with the Marshall hammer can be up to 200 per cent higher than that obtained from field cores. However, the Hugo compaction method simulated the vibratory roller field compaction well in terms of dynamic creep modulus measured. The finer graded mixes (No's 1,2,3,4 and 6) yielded moduli slightly lower than that of the field cores. The medium graded mixes (No's 5,7 and 10) showed behaviour similar to that of the field cores and finally the coarser mixes (No's 8 and 9) yielded values higher than those obtained form the field cores. This phenomenon can probably be attributed to the relative constructability of the mixes and will be discussed in more detail below.

PROPOSED INTERIM LARGE AGGREGATE MIX DESIGN METHOD

The procedures discussed here are based on work conducted on large-aggregate mixes and specific gradings (continuously and semi-gap graded). The method can be divided into four phases :

- selection of the materials;
- laboratory sample manufacturing;
- testing of laboratory samples, and
- analysis of test results.

The design methodology is essentially an elimination process, starting with the gradings achievable with the quarry blends, then the percentage voids criterion, the stiffness criterion, the dynamic creep criterion and finally one of the acceptable bitumen/filler/grading combinations is selected. The final selection is based on :

- performance and behaviour required from the material (eg fatigue life vs resistance to deformation);
- specific constructability aspects, and
- economic analysis.

For continuous gradings, the target grading is derived from the following formula (13) :

$$P = \frac{(100 - F)(d^n - 0{,}075^n)}{(D^n - 0{,}075^n)} + F$$

where

P is the percentage passing sieve size d (mm);
D is the maximum stone size;

F is the filler content, and
n determines the shape of the gradation curve.

The use of at least three n values (0,5; 0,6 and 0,7) and two filler contents (eg 5 per cent and 8 per cent) is recommended. The same formula can be used to determine the shape of semi-gap grading curves by addition of a small quantity (10 to 15 per cent) of the 0,30 mm size aggregate.

It is suggested that at least three binder contents be investigated for each grading. Binder contents of 3,5 per cent, 4,0 per cent and 4,5 per cent are recommended for the continuous gradings. For the semi-gap gradings a 0,5 per cent increase in binder content can be expected due to the additional fines.

Cognisance should be taken of the following in the design of heavy duty asphalt:

- the use of natural sand should be minimized and the use of crushed fines is recommended to enhance the resistance to deformation;
- it is recommended that at least 75 per cent (by mass) of the crushed aggregate have two or more fractured faces, and
- a high viscosity binder, preferable a 40/50 penetration grade, is recommended unless the pavement structure is very flexible.

The Hugo compaction method and 150 mm diameter mould should be used for the manufacturing of the samples. The compaction and mixing temperatures used for specific binder types should be the same as for conventional methods. In addition to the volumetric properties the following engineering properties should be determined :

- the stiffness (resilient modulus);
- the indirect tensile strength;
- the strain at maximum stress, and
- the dynamic creep modulus.

Table 4 gives the criteria for selecting the bitumen/filler/grading combination which should be used in conjunction with specific constructability parameters and economic analysis.

PROPERTY	CRITERION
Voids	min - 2 % max - 6 %
Density	maximum density
VMA	dry side of minimum VMA vs binder curve
Stiffness @ 25°C/10 Hz	For stiff layer: min - 2000 MPa
Stiffness @ 25°C/10 Hz	For flexible layer: min - 1500 MPa max - 2500 MPa
ITS @ 25°C	min - 800 kPa
Strain at maximum stress	to be developed by accumulating data
Dynamic creep modulus	min - 10 MPa

Table 4 : Design Criteria for the proposed Mix Design Method

ACCELERATED TESTING OF DUNDEE TRIAL SECTIONS

The main objective of this phase was to verify the interim mix design procedure proposed above and specifically the design criteria by correlating laboratory test results of both cores and laboratory prepared samples with field performance under the Heavy Vehicle Simulator (HVS). The design procedure was used in the design and construction of three large-aggregate asphalt sections of 100 meter each at Dundee in the province of Natal. A maximum aggregate size of 37 mm was used in the sections with the aggregate gradings being continuous, semi-gap graded and semi-open. The grading curves are shown in Figure 6. The aggregate consisted of a high quality crushed dolerite, crusher dust and, in order to achieve the semi-gap grading in the field, a rounded pit sand had to be used. Due to the cost of constructing these trials, only one grading/filler combination (filler 5 per cent and n = 0,5) was used for the continuous and semi-gap graded mixes whilst the semi-open grading was considered to be of an experimental nature.

Using the above method, the optimum binder contents (using a 60/70 penetration grade bitumen) for the continuous and semi-gap gradings were determined as 3,5 per cent. The optimum binder content for the semi-open mix was selected as 4,0 per cent.

Although the evaluation process included laboratory studies, the focus of the work was on accelerated testing of the pavement sections. The accelerating testing was conducted in two stages. Firstly a series of rapid tests using high wheel loads (100 kN) was conducted on all three trial sections, followed by an extensive test using more realistic loads on the most promising section. Measurements conducted included surface rutting and deflections as well as deflection and permanent deformation within all the pavement layers.

In addition to the conventional HVS testing, in-depth deflections were also measured at speeds higher than that achievable by the HVS by using a two-axle truck loaded to 8,2 tonnes on the back axle. The results were used to back calculate stiffness moduli for the various pavement layers using linear elastic theory. The effect of vehicle speed and pavement temperature on the stiffness of the pavement layers can be seen in Figure 7.

Method	Back calculated stiffness (High speed MDD)	Indirect Tensile stiffness of cores	Indirect Tensile stiffness Hugo/Field mix	Indirect Tensile stiffness Hugo/Lab mix
Semi-gap	1136	1298	1369	1505
Semi-open	1360	1380	1470	1477
Continuous	1138	1318	1381	1543

Table 5 : Field versus Laboratory Measurements of Stiffness (MPa).

Grading (Dundee trials)	Dynamic creep modulus measured on cores at 40 °C (MPa)	Deformation within asphalt layer (MDD) at ambient temperature
Semi-gap grading	14.5	2 mm
Semi-open grading	34.3	< 1 mm
Continuous grading	32.6	< 1 mm

Table 6 : Dynamic creep Modulus versus Field permanent Deformation in HVS Testing

Table 5 shows that the stiffness measured in the improved ITT test correlates very well with the back calculated field moduli. Furthermore, the moduli measured for the laboratory manufactured samples were very realistic.

The rapid HVS tests consisted of 20 000 repetitions at 40 kN; 20 000 repetitions at 60 kN and 110 000 repetitions at 100 kN. At temperature levels in the region of 20°C very little deformation of the asphalt layers occurred (see Table 6). The semi-gap graded mix (with rounded sand) deformed the most (see Figure 8). In the conventional HVS test to date (August 1991), the continuously graded mix has been trafficked to one million repetitions using a 40 kN dual wheel load. No signs of any rutting or cracking had been observed.

Table 6 shows that the dynamic creep moduli of the field cores correlate well with the actual field rutting. Contrary to the previous trials, the dynamic creep moduli of the Hugo compacted samples underestimated the dynamic creep moduli obtained from the cores (see Figure 9). This could be related to the method of field compaction used in each case (static vs vibratory) as well as post construction compaction (discussed below). This is being further investigated. However, the trend in the field cores is still very similar to the laboratory obtained values (both laboratory prepared and field prepared samples) and it seems as if a shift factor of approximately 3 will result in an excellent prediction. In the case of the semi-open mix, there was a discrepancy between the creep moduli obtained from the laboratory mixed material and the field mixed material. This was probably due to the segregation which occurred in this mix in the field.

As part of the Dundee rehabilitation project a continuously graded mix with 26 mm maximum size aggregate was called for. It had been indicated that, for the continuously graded mixes, the addition of 37 mm aggregate to the grading resulted in a 96 per cent increase in the dynamic creep modulus. Furthermore, the lower optimum binder content (due to the larger aggregate) resulted in a 43 per cent saving in binder content.

If the rate of permanent deformation within the asphalt bases tested above is extrapolated, then indications are that these mixes should carry traffic well in excess of 70 million standard axles without failure in terms of deformation within the base (using 20 mm rutting as failure citerion).

THE EFFECT OF CONSTRUCTABILITY

The constructability of large-aggregate mixes, in particular field densities attainable, segregation, plant wear and tear and pavability is important. In addition, the effect of these factors on the uniformity of engineering properties needs to be determined.

In the two sets of trial sections described above, different manufacturing and compaction processes as well as different materials were used. For the Cape Town trial sections, a batch plant and Hornfels aggregate was used whilst a vibrating steel wheel roller provided the breakdown compaction effort. For the Dundee trials a drum mix plant and Dolerite as aggregate was used and breakdown compaction achieved with a static steel wheel roller. In addition the hauling distance was more than 40 km in the case of the second set of trials.

Visual assessment of the constructability of the mixes used in the Cape Town trials, indicated that the continuously graded and semi-gap graded mixes were constructed with relative ease. The continuously graded mix with 53 mm maximum aggregate size also exhibited no significant production and construction problems. In the case of the experimental open gradings significant segregation was observed particularly where 53 mm aggregate was used.

Of the three mixes used in the Dundee trial, the constructability of the continuously graded mix was rated as excellent. The semi-gap graded mix appears to be very sensitive to binder content and some segregation occurred when the binder content was slightly below the design target. The semi-open graded mix exhibited significant segregation.

The effect of constructability on engineering properties of the mix is of major importance. A constructability index based on the visual observation of factors such as ease of production, segregation, pavability and compactibility was defined. The mixes were rated on a three point scale for each of the factors and the index defined as the sum of the ratings. Figure 10 shows a correlation of this index with the difference between field and laboratory properties for the Cape Town sections. The figure shows that the mixes which rated poorly in terms of constructability also exhibited relatively worse engineering properties than that predicted in the laboratory.

Figure 9 shows that the dynamic creep moduli of the cores were significantly higher than the laboratory obtained values. Furthermore, even though the semi-open mix exhibited significant segregation its dynamic creep modulus was still higher than the laboratory obtained values which was not the case in the Cape Town sections where a different field compaction method was used. This is indicative of the fact that the field compaction method has a significant influence on the engineering properties which may have to be taken into account in the design phase by selecting the laboratory compaction effort to be compatible with the field compaction method.

The above work indicated that the constructability of large-aggregate asphalt need not be an obstacle in their use and South African contractors are optimistic in using these mixes. However, factors such as grading and binder content can influence the constructability and therefore they need to be addressed during the design phase.

CONCLUSIONS

The reported work provided the foundation for a newly proposed analytical design procedure for large-aggregate asphalt mixes. It is based on the analysis of laboratory samples compacted with a modified Marshall hammer (which brings about kneading/impact compaction) as well as criteria based on relevant engineering properties.

The study has led to the development of new procedures as well as the improvement of existing laboratory procedures for evaluating asphalt. An improved measurement technique for the Indirect Tensile Test, which allows the determination of strain at maximum stress and which improved the accuracy of the determination of Poisson's ratio and asphalt stiffness was used. Furthermore, the dynamic creep test was modified to accommodate large-aggregate samples and a variety of aggregate gradings.

Field verification of the work was done through the design and construction of thirteen trial sections and accelerated trafficking of three sections with the Heavy Vehicle Simulator. The results were very promising, in particular, the prediction of rutting based on the dynamic creep modulus and the prediction of stiffness based on a new Indirect Tensile Test.

Contrary to previous misgivings by constructors, the above mixes constructed with relative ease. However, constructability effects may have a significant effect on the engineering properties of the materials.

The economic advantages of using large-aggregate asphalt combined with the additional structural capacity obtained is well known. The above design procedure will enable the South African roads industry to use this material with increased confidence. Currently this procedure is being implemented in the rehabilitation design of the taxiways of the Jan Smuts airport in Johannesburg.

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KEYWORDS

Large-stone asphalt mixes, asphalt mix design.

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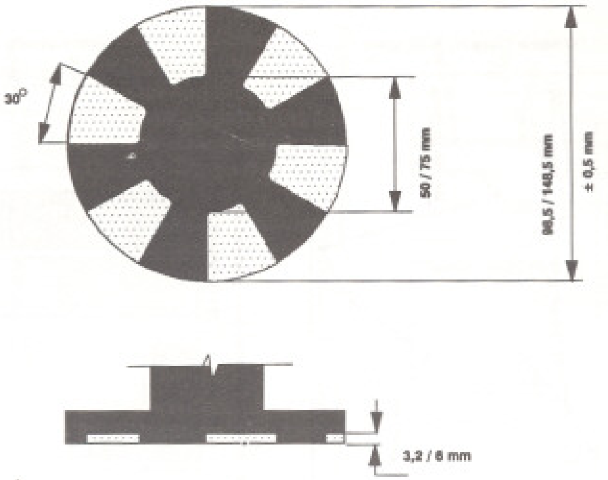

Figure 1 : The hammerface of the Hugo compaction method

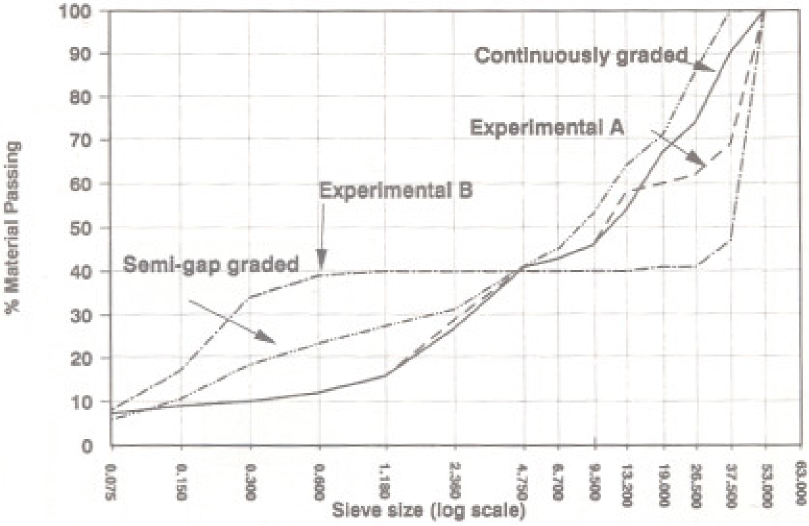

Figure 2 : The types of gradings used at the Cape Town trials

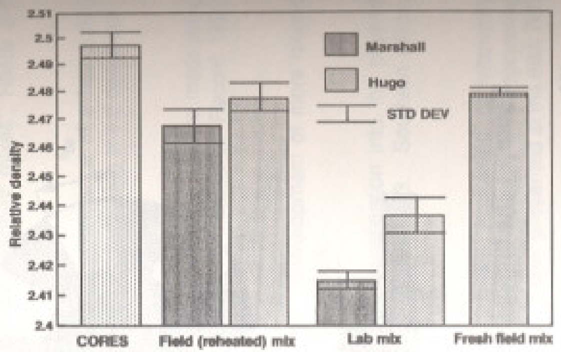

Figure 3 : Densities obtained using various preparation methods

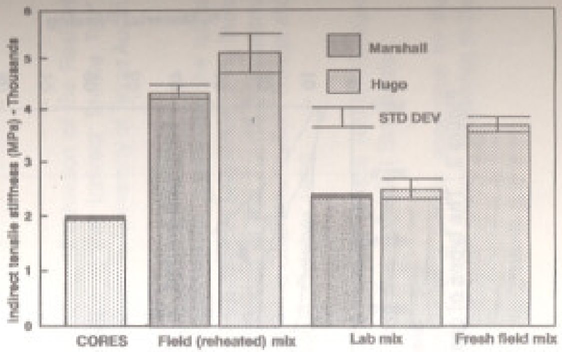

Figure 4 : Stiffness values obtained using various preparation methods

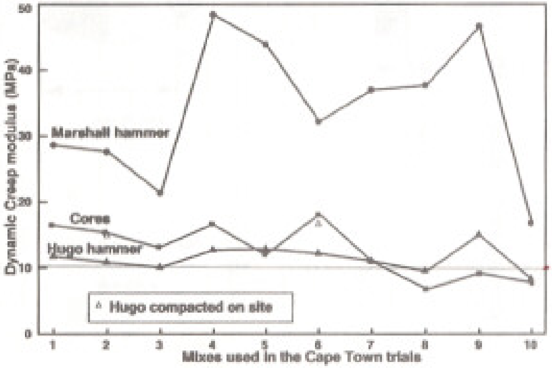

Figure 5 : The effect of compaction method on dynamic creep modulus - Cape Town trials

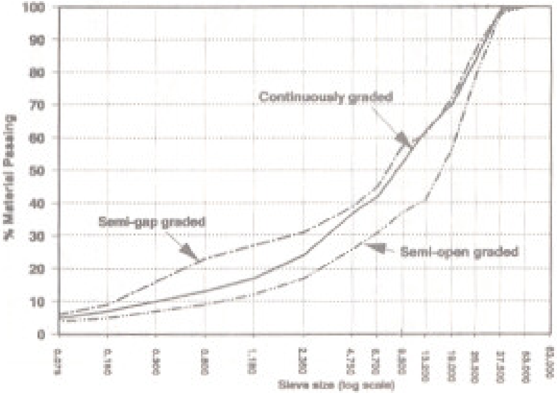

Figure 6 : Gradings used in the Dundee trial sections.

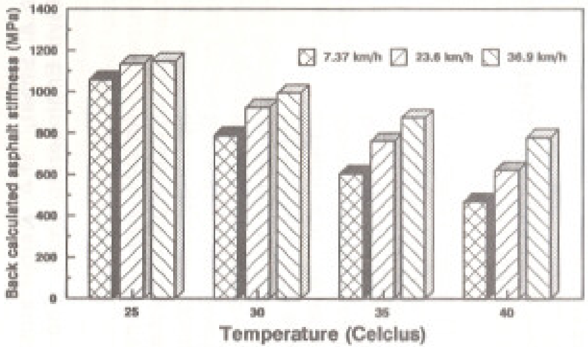

Figure 7 : The effect of temperature and vechicle speed on the stiffness of the Semi-open graded mix used in the Dundee trials

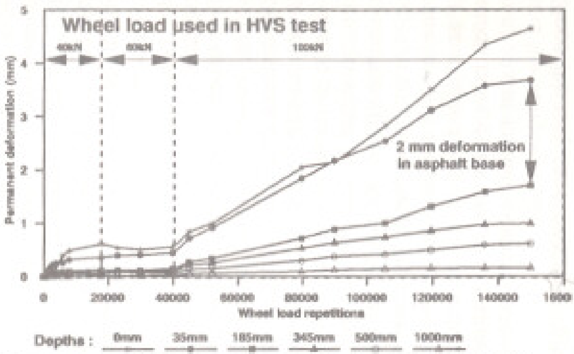

Figure 8 : Permanent deformation measured at various depths with the MMD - Semi-gap graded mix (Dundee trials)

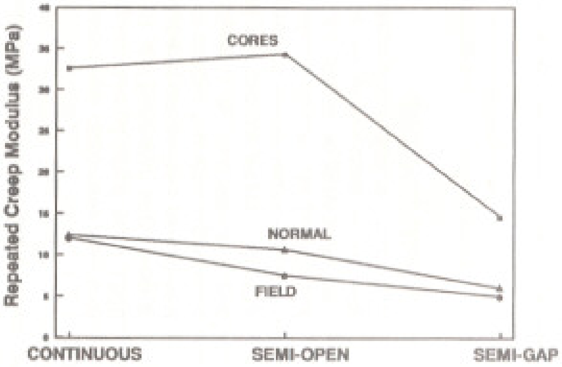

Figure 9 : Repeated creep results for all methods and mixes used at Natal.

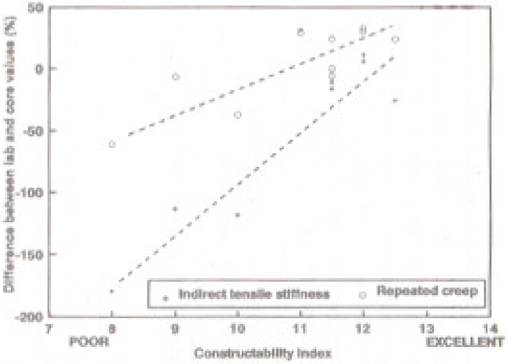

Figure 10 : The effect of constructability on engineering properties (Cape Town trials)