A PROPOSED DESIGN METHOD FOR LARGE-STONE ASPHALT AND THE IMPLEMENTATION THEREOF IN THE REHABILITATION OF AN AIRPORT PAVEMENT

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SUMMARY

In the current scenario of increasing traffic volumes and loads, 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 benefits in terms of economic analysis.

This paper addresses the development of a design procedure for large-stone asphalt, the implementation thereof in two sets of trial sections, the correlation of engineering properties obtained in the laboratory with field properties, the constructability of these mixes and the performance of these trials under Heavy Vehicle Simulator (HVS) testing. Specific elements of the proposed method are discussed.

The proposed design method was also put through the test of a full scale rehabilitation effort at Jan Smuts airport. The results were satisfactory and some of the findings resulting from this work are discussed in this paper.

OPSOMMING

In die huidige scenario van toenemende verkeersvolumes en belastings, het beide die Suid-Afrikaanse Padowerhede en die Suid-Afrikaanse Asfaltindustrie die behoefte aan 'n ondersoek na Swaardiens-asfaltplaveisels ("HDAPs") uitgewys. Die hoofdoelwitte van hierdie projek was om die vermoë van "HDAPs" te bepaal om baie swaar verkeer te kan dra, om mengsel-ontwerpmetodes te ontwikkel, hulle boubaarheid te ondersoek en hulle ekonomiese voordele te evalueer.

Hierdie referaat behandel die ontwikkeling van 'n ontwerpmetode vir grootklip-asfalt, die toepassing daarvan in twee stelle proefseksies, die korrelasie tussen laboratorium- en veldeienskappe, die boubaarheid van hierdie mengsels en die gedrag van mengsels onder Swaarvoertuignabootser-toetse. Spesifieke elemente van die voorgestelde ontwerpmetode word bepreek.

Die voorgestelde ontwerpmetode is ook ge-evalueer tydens 'n volskaalse rehabilitasiepoging by Jan Smuts lughawe. Die resultate was bevredigend en sommige van die bevindings wat uit hierdie werk voortvloei, word in hierdie referaat bepreek.

INTRODUCTION

Increasing traffic volumes and loads in South Africa have resulted in traffic loading beyond the current design classes. Therefore, 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 three-year HDAPs project, sponsored by SABITA, the Department of Transport and the Natal Roads Department, has to date focused on the use of large-stone asphalt as a solution to the above-mentioned problem.

The benefits of large-stone asphalt fall into two categories, namely, improved structural capacity and improved economy. The economic considerations include both the savings in binder costs due to the lower bitumen content required and the savings resulting from a more economical crushing of the aggregate. Improved performance further enhances the savings in the life-cycle cost of the asphalt.

However, it is well known that conventional mix design procedures (Marshall and Hveem) do not make provision for mixes containing stones larger than 26,5 mm. The shortcomings of these conventional methods are, due to their empirical nature, well documented. The modern asphalt mix design scenario, which includes large-stone asphalt, modified binders and increased traffic loading, requires a more analytical approach.

This paper highlights specific elements of the HDAPs project to illustrate the development of the proposed design method from initial laboratory studies through to the Much Asphalt trials and finally the Dundee trials. It gives a brief overview of the proposed design method and evaluates the use of large-stone asphalt as a rehabilitation option at Jan Smuts airport.

THE HDAPs PROJECT

The HDAPs project, conducted over a period of three years, included a number of laboratory and field studies(1,2). The aims of this project were to assess the ability of large-stone asphalt to carry very heavy traffic(3), to investigate their constructability(4) and to develop design procedures for such mixes(5). Only specific elements of the HDAPs project are further highlighted.

Laboratory procedures

In the early stages of the work a number of laboratory-compaction methods were evaluated. Both the Marshall and Hugo methods were adapted to be used with 150 mm diameter moulds to make provision for the large stones(6). Based on the concept of applying the same amount of energy per volume of asphalt, the compaction effort was increased by using a larger falling weight (10,438 kg) and more blows per side (110). For the large Hugo hammer (see Figure 1), the depth of the indents was increased to 6 mm. The initial laboratory study 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.

During the HDAPs project a number of testing methodologies have also been developed or adapted(6). Materials testing was limited to the evaluation of the following engineering properties, namely, stiffness (resilient modulus); indirect tensile strength (ITS); strain at maximum stress, and creep modulus (static and dynamic).

The indirect tensile test was used to measure the first three properties. The test had, however, been improved by the positioning of the lateral measurement device directly onto the sample(6). This new way of measuring the horizontal displacement enabled the measurement of the strain at maximum stress.

The dynamic creep test which applies a uniaxial compression loading has gained wide acceptance in the UK and was used to assess the permanent deformation characteristics of the samples by using a 0,5 Hz square wave with a maximum stress of 100 kPa and a duration of two hours (3 600 loading cycles)(7). The dynamic creep test is preferred over the static creep test because it simulates dynamic loading and shows a better correlation with field rutting.

Much Asphalt trials(6)

The Much Asphalt trials were based on the construction of a series of 10 mixes, using various combinations of maximum stone sizes (37,5 mm and 53 mm); gradings (continuously-graded, semi-gap-graded, stone filled and sand filled); type of binders (conventional and modified), and various bitumen contents. Material used included crushed Hornfels and a 60/70 penetration grade bitumen. Laboratory testing on cores from these sections was complimented by means of testing laboratory samples compacted by both the modified Hugo and Marshall hammers, using fresh plant mixes, reheated plant mixes and laboratory mixes (hand mixing).

These trials made a major contribution to the development of the proposed design method and provided valuable insights regarding the constructability and behaviour of large-stone mixes. The most important findings are discussed below.

The **density** attainable is influenced by the compaction method, but more significantly by the mix production method. The use of plant-prepared mixes in preparing samples yields densities much closer to that of the field cores than when laboratory-prepared mixes are used.

The **permanent deformation characteristics** of the asphalt were significantly influenced by the laboratory compaction method. Figure 2 clearly indicates that the modified Hugo compaction method simulates construction compaction more accurately than the Marshall method in terms of the dynamic creep modulus obtained.

Laboratory samples compacted by using **reheated** plant-produced mixes yield **ITS and stiffness** values far higher than laboratory-prepared samples or field cores. These differences in certain properties due to reheating must be carefully considered when using reheated mixes for quality control.

Visual assessment of the **constructability** of the mixes used in the Much Asphalt Trials, indicated that the 37,5 mm continuously-graded and semi-gap-graded mixes constructed with relative ease. Even the continuously-graded mix with 53 mm maximum stone size exhibited no significant production and construction problems. In the case of the stone-filled and sand-filled gradings significant segregation was observed particularly where 53 mm size stones were used.

Dundee trials(2)

The main objective of this phase was to verify and improve the interim mix design procedures and criteria (as based on the Much experiment) by correlating laboratory test results of both cores and laboratory-prepared samples with field performance under the Heavy Vehicle Simulator (HVS). The interim design procedure was used in the design and construction of three 100 metre long large-stone asphalt sections at Dundee. A maximum stone size of 37 mm was used in the sections with the aggregate gradings being continuous, semi-gap and semi-open graded. Binder contents of 3,5 per cent, 3,5 per cent and 4,0 per cent were used respectively. The materials used were crushed dolerite and a 60/70 penetration grade bitumen.

The **accelerated testing** (HVS testing) was conducted in two stages. Firstly a series of rapid tests, using high wheel loads (100 kN) over a short period of time, were conducted on all three trial sections, followed by an extensive test, using more realistic loads on the most promising section. The rut rate within the asphalt base is summarized in Table 1.

Type of grading	**Load (kN)**	**Temperature (C)**	**Rate of deformation (mm/10^5 repetitions)**	**Dynamic creep modulus(Hugo)**
Semi-gap	100	20°C and less	1,810	7,0 MPa
Semi-open	100	20°C and less	0,910	10,6 MPa
Continuous	100	20°C and less	0,530	12,4 MPa
Continuous	40	15°C to 30°C	0,027 over 2,2x10^6 reps	12,4 MPa
			0,040 over last 1,4x10^6 reps	" "
Continuous	40	40°C to 50°C	0,034 over last 1,4x10^6 reps	" "

Table 1 : Rates of deformation and dynamic creep moduli of various base mixes.

If the rate of **permanent deformation** within the continuously and semi-open-graded asphalt bases tested above is extrapolated, indications are that these mixes should be able to carry traffic well in excess of 50 million standard axle loads without failure in terms of rutting (even at elevated temperatures). The surface rut rates of the continuously-graded mix using a range of loads are considerably less (at least 100 per cent) than any previous HVS test on similar pavement structures. Although subgrade rutting and surface deflection increased during the heating of the continuously-graded mix, it did not influence the permanent deformation behaviour significantly.

The **dynamic creep** moduli obtained during the design phase (Hugo-compacted samples) correlate well with the actual field rutting using 100 kN loads (see Table 1). Contrary to the Much Asphalt trials, where cores were removed after construction compaction, the dynamic creep moduli of the Hugo-compacted samples underestimated the dynamic creep moduli obtained from the cores taken after two months of traffic compaction. This phenomenon can be related to the effects of traffic compaction and time- dependent effects such as the ageing of the binder.

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 for various temperatures and speeds. Table 2 shows that the **stiffness** of both the core and Hugo-compacted samples, as measured with the improved ITT test, correlates reasonably well with the back-calculated field moduli.

Temperature 25°C	Back calculated modulus (± 20 km/h)	ITT test Cores (10 Hz)	ITT test Hugo/Field mix (10 Hz)	ITT test Hugo/Lab mix (10 Hz)
Semi-gap	1136 MPa	1298 MPa	1369 MPa	1505 MPa
Semi-open	1360 MPa	1380 MPa	1470 MPa	1477 MPa
Continuous	1138 MPa	1318 MPa	1381 MPa	1543 MPa

Table 2 : Comparison of field and laboratory measurements of stiffness.

As part of the Dundee rehabilitation project, a continuously-graded mix with 26 mm maximum size stone was called for. The **economic benefits** of large-stone asphalt mixes were clearly demonstrated in the Dundee trials. For the continuously-graded mixes, the use of 37 mm maximum stone grading resulted in a 96 per cent increase in the dynamic creep modulus in comparison to that of a 26,5 mm maximum stone grading. Furthermore, the lower optimum binder content (due to the larger stone) resulted in a 43 per cent saving in binder content (3,5 per cent vs 5,0 per cent).

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 appeared 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.

PROPOSED LARGE-STONE MIX DESIGN METHOD

A large-stone asphalt mix design method has been developed for continuously and semi-gap-graded mixes with a maximum stone size of 37,5 mm(1). This method is analytically based and is in line with international developments(8). Specific elements of this method are discussed below.

The **design methodology (see Figure 3)** is essentially an elimination process, starting with the gradings achievable with the quarry blends. Using these blends, laboratory samples are prepared at specified bitumen contents and their volumetric properties are determined. Only the bitumen/filler/grading combination that passes the voids criterion is subjected to further testing. The next series of testing includes ITS, stiffness and strain-at-maximum-stress and the bitumen/filler/grading combinations that pass this criterion, are subjected to dynamic creep testing.

Asphalt mix design is the selection of mix components in order to achieve a desirable balance between the different properties of asphalt. Therefore the final selection is based on the following: performance and behaviour requirements (e.g. fatigue life vs resistance to deformation); specific constructability aspects, and an economic analysis.

In the case of a continuous grading, the target grading is derived from a modified Fuller curve and can be calculated by using the following formula(7):

$$P = \frac{(100 - F)(d^{n} - 0{,}075^{n})}{(D^{n} - 0{,}075^{n})} + F \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

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 (5 per cent and 8 per cent) is recommended (see Figure 4). With a small modification, the same formula can be used to determine the shape of semi-gap grading curves. The modification involves the introduction of a 10 to 15 per cent addition of the minus 0,30 mm and plus 0,15 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.

Laboratory samples should be compacted with the 150 mm **Hugo compaction method** which simulates the kneading action of field compaction. After the determination of the volumetric properties, the engineering properties of the asphalt samples need to be determined where applicable. These mechanical tests (with engineering properties) include:

- dynamic indirect tensile test (stiffness);
- indirect tensile split test (tensile strength and strain-at-maximum-stress), and
- dynamic uniaxial test (dynamic creep modulus).

Table 3 gives the design criteria for selecting the bitumen/filler/grading combination which should be used in conjunction with specific constructability parameters and economic analysis. The **behaviour and performance** of the proposed mixes can be controlled through these criteria complimented by proper engineering judgement. Engineering properties that are addressed, include the following:

- stiffness (controlling of subgrade rutting);
- resistance to fatigue cracking;
- resistance to low-temperature cracking;
- durability (e.g. moisture damage), and
- resistance to permanent deformation.

PROPERTY	CRITERION
Voids	min - 2 % max - 6 %
Maximum binder content	aim for dry side of minimum VMA vs binder curve
VMA	min - 12 %
Vbe	aim for minimum of 75 % and maximum of 85 %
Film thickness	aim for minimum of 8 microns
Stiffness @ 25°C/10 Hz	1) For stiff layer : min - 2000 MPa 2) For flexible layer : min - 1500 MPa max - 2500 MPa
ITS @ 25°C	min - 800 kPa
Dynamic creep modulus @ 40°C	min - 10 MPa

Table 3: Design criteria for the proposed mix design method

LARGE-STONE ASPHALT AS A REHABILITATION OPTION AT JAN SMUTS AIRPORT

Requirements

The first practical implementation of the proposed asphalt mix design method was conducted on one of the taxiway pavements at Jan Smuts Airport. A pavement comprising 100 mm asphalt and a 250 mm crushed stone base was required to be reconstructed within a limited time period with material which had to provide an improvement on the combined stiffness of the existing pavement. A further requirement of the material was a high resistance to rutting under aircraft wheel loads (typical 200 kN with 1 500 kPa tyre pressures). It was also necessary that it should be usable by such aircraft within hours of construction. This requirement later proved to be of lesser importance because the construction area of 6 000 m^2 became available for an uninterrupted time period of 13 days, during which, all work could be completed with ease.

Alternatives

The alternative rehabilitation options considered, included the recycling and stabilization of the existing base course material and the construction of a concrete pavement. Both options were, however, ruled out due to the curing time requirement in relation to the time constraint. Roller compacted concrete was considered as a viable alternative but the concern for shrinkage cracking over a relatively wide area also ruled out this option. The most suitable option considered appeared to be an asphalt base, and taking the particular requirements into consideration, a choice was made for a large stone continuously-graded mix.

Specifications

In order to minimize the risk of segregation and also to enhance the workability of the mix, the maximum stone size was limited to 37,5 mm. The trial sections at Much-Asphalt, as well as those at Dundee have proved that a 60/70 penetration grade bitumen binder could be used for the required stiffness and rutting resistance rather than a higher viscosity binder.

A project specification included the following proposed design criteria: void content, stiffness, indirect tensile strength and dynamic creep modulus. The specification also required the contractor to provide the material for the mix design to enable the engineer to conduct the mix design. The CSRA grading envelope for a dense gravel asphalt base was specified and the contractor supplied the engineer with an aggregate sample of crusher-run conforming to the specified grading. The grading could, however, be regarded as fine with an n-value varying between 0,4 and 0,45 (Eq 1).

Mix design

The proposed mix design method was used to determine the optimum binder content for the given aggregate, and no alteration to the filler content or the grading was thought to be necessary if the required design criteria could be achieved. Compaction of the test samples was done in 150 mm diameter moulds using the Hugo compaction method. Three asphalt briquettes of each of four binder contents (3,5% to 5,0%) were manufactured, and of those complying with the void content criteria, three more briquettes were prepared. A second test involving three briquettes for each binder content was performed on the indirect tensile testing apparatus. Indirect tensile strengths (ITS) and stiffness values were determined. The dynamic creep modulus was then determined for that binder content which complied with all the other design criteria.

Table 4 gives the average asphalt property values for three test samples as they were determined during the mix design process.

Bitumen content %	Bulk density (kg/m^3)	Voids (%)	ITT Stiffness (MPa) @ 25 °C	ITS (kPa) @ 25 °C	Dynamic creep modulus (MPa) @ 40 °C
3,5	2 448	4,1	2 550	1 250	10,4
4,0	2 451	3,2	2 700	1 150	9,8
4,5	2 468	1,8	2 350	1 100	-
5,0	2 452	1,0	-	-	-

Table 4 : Design test values for Jan Smuts karge-stone asphalt

Preference was given to a binder content of 4,0% because of a higher stiffness and lower % voids ratio than for 3,5%. The small difference in dynamic creep was not believed to be significant.

Construction

The overall opinion of the construction process was satisfactory. Compaction was done with ease in layer thicknesses of up to 120 mm and field densities achieved varied between 95% and 97% of theoretical maximum density. The contractor managed to pave, on average, 120 tonne of asphalt per hour with a maximum of 160 tonne per hour. Compaction was done with a 25 tonne and 18 tonne pneumatic roller and an 8 tonne steel wheel roller. The asphalt was paved at a temperature of approximately 140°C which cooled down to 75°C within 80 minutes after off-loading. This proved that large-stone asphalt mixes can be used like any other asphalt where pavements need to be trafficable immediately after construction. The construction process, however, also had its setbacks and the following main problems were initially encountered :

(a) Segregation : The first day's work was marked with high variations in grading with a tendency to be on the coarse side of the grading curve.

(b) Instability : The first batches of asphalt proved difficult to compact, and movements under compaction equipment occurred for quite some time. This was attributed to a higher than specified bitumen content (+ 1%) and the finer grading achieved on the first day. The required densities and other specified criteria were, however, achieved when tested.

The design criteria were also tested on 100 mm diameter cores of the more acceptable material after construction, and a comparison between the design and constructed asphalt is shown in Table 5.

Bitumen content (%)	Bulk density (kg/m^3)	Voids (%)	ITT Stiffness (MPa) @ 25 °C	ITS (kPa) @ 25 °C	Dynamic creep modulus (MPa) @ 40 °C
Constructed 4,15%	2 437	3,63	2 800	1 040	10,7
Design 4,0%	2 451	3,2	2 700	1 150	9,8

Table 5 : A comparison between the design and constructed asphalt properties.

The grading was found not to be as consistent as would normally be preferred. This was probably due to the fact that the materials were obtained as is from a rock crushing process and no extra blending took place. However, at the asphalt plant the stockpiled material was first divided on a screenbed into four different fractions and then recombined to minimize the risk of segregation. The average grading for a lot fell well within the required CSRA specified envelope for the target grading, but individual test samples differed from the target grading by as much as 12% for the coarse and 5% for the fine fraction of the aggregate. As can be seen from the property test results in Table 5 it does not appear that the fluctuation in the grading has influenced the quality of the product significantly.

CONCLUSIONS

An analytically based design procedure for large-stone mixes is proposed. This method is based on laboratory compaction with a modified Hugo hammer (which brings about kneading/impact compaction) as well as criteria based on relevant engineering properties.

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

The experience with large stone asphalt in a full scale rehabilitation effort has revealed the following:

(a) The recommended design procedure by means of the Hugo compaction method and the 150 mm diameter mould proved to provide accurate predictions of expected field performance after construction (see Table 5).

(b) Segregation can be a problem but with proper stockpiling operations (the sandwich method is preferable), mixing procedures and loading methods, this could be minimized. It was also found that improper sampling methods could result in inaccurate grading results and the steel plate method by which a section of the placed pavement layer is sampled before compaction, is recommended. It seems as though large-stone asphalt is a highly forgiving material with regard to grading and small variations in grading can be accommodated.

(c) The crusher-run is a most economical aggregate and could be used with success in the production of large-stone asphalt. A coarse grading ($n > 0,5$) is however preferable but it should be remembered that special crushing procedures or blending might increase the cost of asphalt.

(d) The apparatus required for the large-stone asphalt design is currently not freely available yet and should be taken into consideration when specifying this type of asphalt. The method of quality control is limited to density, binder content and grading, but this was found to suffice in controlling the quality of the product. Trial sections are recommended.

(e) The ease with which compaction was achieved indicates that specified densities can be even higher than required by the CSRA standard specification.

(f) Successive layers can be constructed within two hours of each other because of the relative high rate of cooling that was experienced. The rate of cooling could, however, be influenced by the type of aggregate used, which in this case happened to be quartzite, and the prevailing ambient temperature.

(g) Large stone asphalt can be an economical solution in many rehabilitation projects, especially where thick layers with high bearing capacity are required. The economical advantage of large-stone asphalt over finer asphalt certainly lies in the low binder content and the thicker layers which can be laid at a time. The cost of the product in this case was slightly more than R100/t or R250/m^3 which compares very favourably with the price of concrete pavements.

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J E Grobler

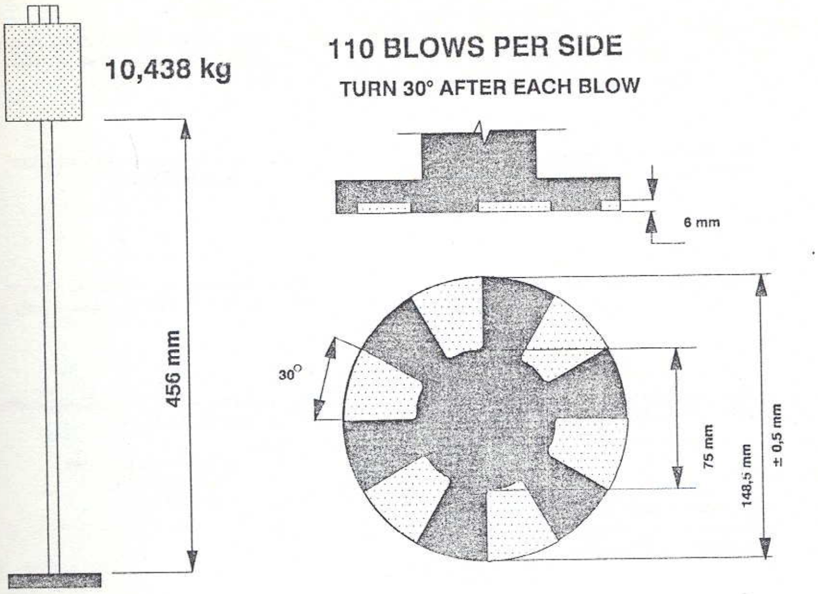

Figure 1: The Hugo laboratory compaction method

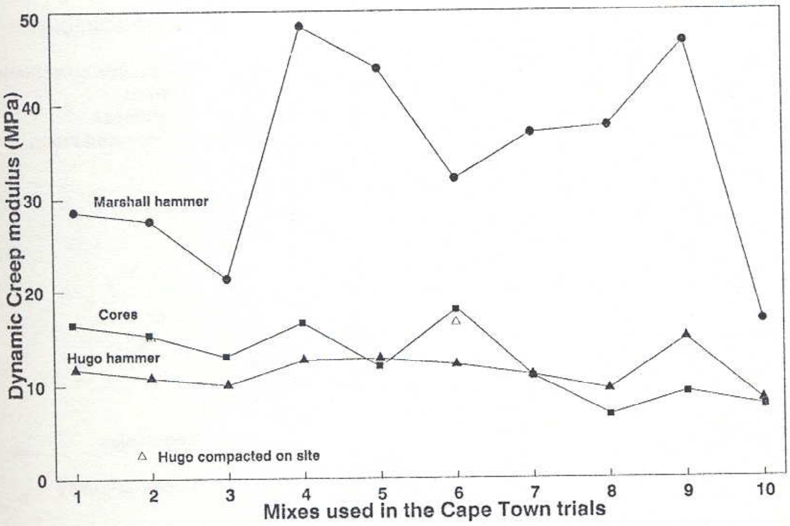

Figure 2: The effect of compaction method on dynamic creep modulus - Much trials

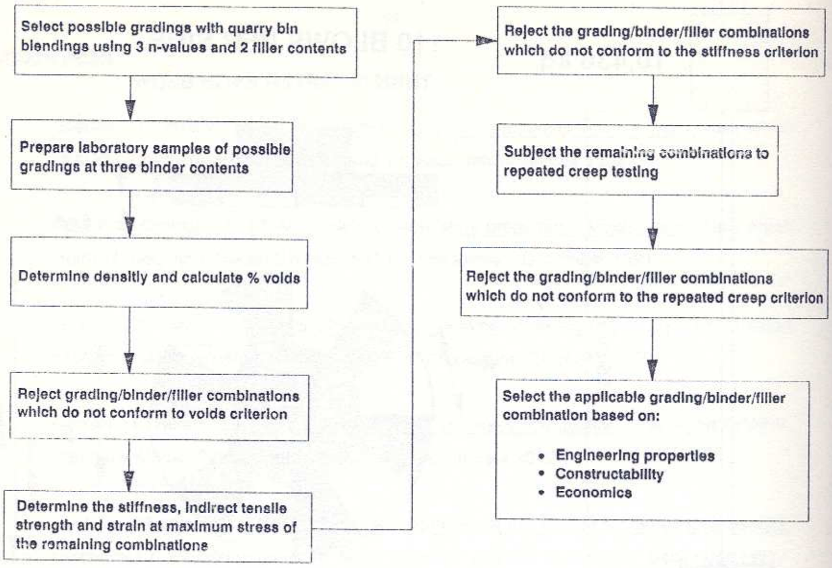

Figure 3 : Outline of suggested mix design method

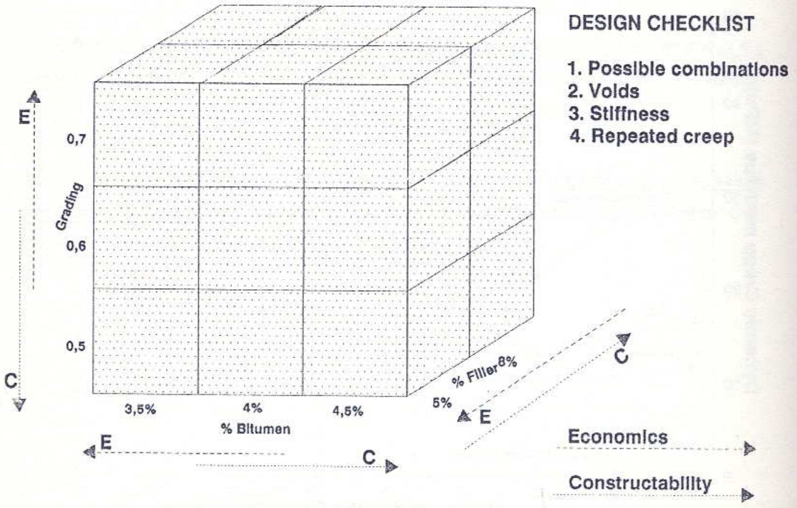

Figure 4 : Design matrix for selection of components