

Development of a Practical Method for Design of Hot-Mix Asphalt

K. E. COOPER, S. F. BROWN, J. N. PRESTON, AND F. M. L. AKEROYD

The development of a method for the design of hot-mix asphalt is traced. The design of gradations based on aggregate packing characteristics was found to be impractical for routine mix design. Measurement of elastic stiffness and assessment of resistance to permanent deformation was made possible with the development of the Nottingham asphalt mix tester. This development provided a method of designing mixes using relevant mechanical properties as design criteria. The percentage refusal density equipment was used to manufacture specimens at levels of compaction that should be achieved in practice. For a particular source of aggregate, the effect of binder content and aggregate gradation on volumetric composition and mechanical properties can be assessed. Certain volumetric and test criteria are applied to identify the mix or mixes that will perform satisfactorily. The final mix formulation can then be selected on the basis of certain practical and economic considerations.

As the end of the millennium approaches, there is increasing pressure to use more innovative highway construction materials that will result in greater economy, increased service lives, and less disruption to our environment. There have been advances in bitumen modification and significant improvements in the design of production and site plants. The results of research have highlighted the effect of mix variables on the mechanical properties of asphaltic mixes, and many engineers are willing to apply the results of this work. The principal obstacle to real progress is the lack of a reliable and practical method of mix design.

Since the publication of the results of earlier work on the development of a method of mix design for bituminous base-course and road base materials (1), work has continued at Nottingham on developing an improved method of mix design using relatively simple equipment. A preliminary version of the method and associated test equipment was presented to the Eurobitume Conference in Madrid in 1989 (2,3).

In the United Kingdom, no method of mix design for highway materials is used other than an adaptation of the Marshall method for the "skip" or gap-graded, hot-rolled asphalt wearing course mix that forms the surface of much of the major highway network. The aggregate in this material is normally not greater than 20 mm ($\frac{3}{4}$ in.), but road base mixes may contain sizes up to 37.5 mm ($1\frac{1}{2}$ in.); therefore, existing methods of mix design cannot be used because specimens prepared in relatively small molds are not representative. This constraint on the maximum aggregate size may have inhibited the use of mixes with large stone size in the United States.

The benefits of using larger stone sizes have been discussed recently (4).

Even with conventional 20-mm ($\frac{3}{4}$ -in.) down gradations, specimen preparation methods and equipment do not provide the means of producing materials representative of that laid in practice. Moreover, the tests used do not measure relevant mechanical properties. As a consequence, the premature failure of mixes designed using existing methods is becoming increasingly common as the volume of traffic and axle loads increases.

BACKGROUND WORK

Aggregate Packing Characteristics

Previous work (1) indicated that gradations could be quantified by the equivalent fines content (EFC), which is the percentage of aggregate passing a sieve with a mesh size 3 percent of that of the smallest sieve through which all the aggregate passes. The voids in mineral aggregate (VMA) and resistance to permanent deformation of a wide range of mixes were found to be related to EFC irrespective of maximum aggregate size.

Work on the compaction of uncoated aggregates suggested the possibility of designing gradings to a target VMA without the necessity of using bitumen in the first instance. Further investigations into the possibility of using spherical ballotini as a reference aggregate were commenced. It was believed that the packing of gradations of perfect spheres could be compared with that of real aggregates to provide an index of aggregate shape. Materials were compacted in a mold placed on a vibrating table. However, tests indicated that the degree of packing may depend on a relationship between aggregate size and frequency of vibration. It became obvious that a considerable amount of preliminary work would be necessary; as a result, the work on the packing of dry aggregates and spheres was discontinued.

Nottingham Asphalt Mix Tester

Work on the development of simple equipment for measuring mechanical properties continued in parallel with the investigation of aggregate packing characteristics. State-of-the-art techniques in digital interfacing were used so that control and data acquisition could be carried out using a conventional desktop computer and user-friendly software. Load was applied by a pneumatic system with the type of components

K. E. Cooper, S. F. Brown, J. N. Preston, Department of Civil Engineering, University of Nottingham, Nottingham, U.K. NG7 2RD. F. M. L. Akeroyd, Mobil Oil Company, Ltd., Mobil House, 54/60 Victoria Street, London, U.K. SW1F 60B.

commonly used for process control in manufacturing industries. Therefore, the user requires only mains electricity and a compressed air supply of about 7 bar (100 psi). The resultant apparatus is known as the Nottingham asphalt mix tester (NAT).

Currently, three types of test may be carried out using this device. The first is the repeated-load indirect tensile (RLIT) test, otherwise known as the resilient modulus test. The second is the uniaxial creep (UC) test, and the third is the repeated-load axial (RLA) test (also called dynamic creep). The user may first measure elastic stiffness (resilient modulus) of a material using the nondestructive RLIT test and then, using the same specimen, assess resistance to permanent deformation using either the UC or RLA test. Specimens may be 100 mm (4 in.), 150 mm (6 in.), or even 200 mm (8 in.) in diameter, and they may be laboratory molded or cored. The advantage of providing for the use of both molded and cored specimens is that the apparatus used for mix design can also be used for quality control and end product specification testing as well as failure investigation.

Figure 1 shows the NAT set up for the RLIT test. Figure 2 shows the same equipment configured for either the UC or the RLA test. Figure 3 shows schematic layouts of the equipment. NAT is normally situated in a temperature-controlled cabinet with a range of -10°C to 45°C .

To carry out a test, the operator merely responds to questions on the computer screen by typing in specimen dimen-

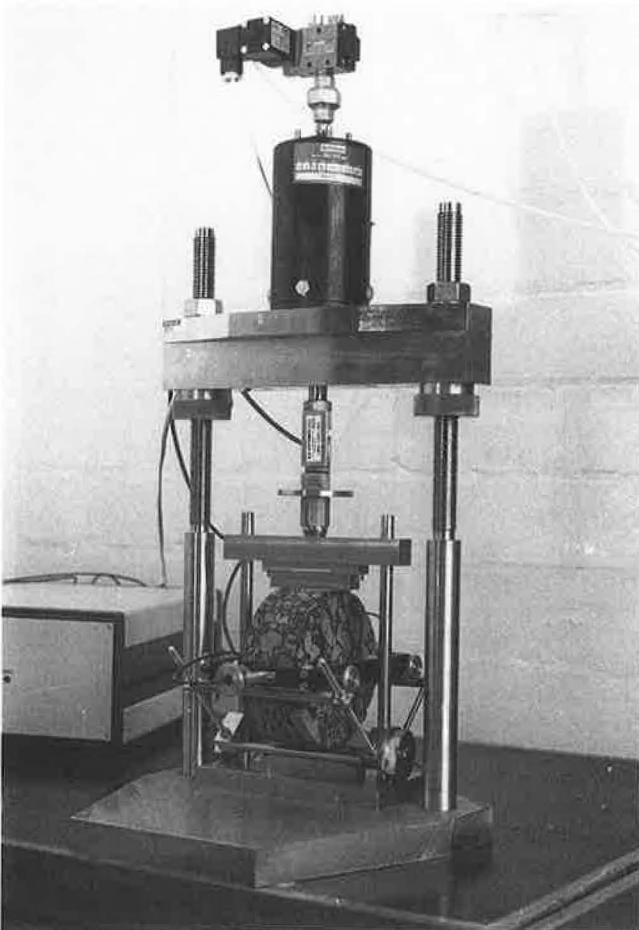


FIGURE 1 NAT set up for repeated-load indirect tensile test.

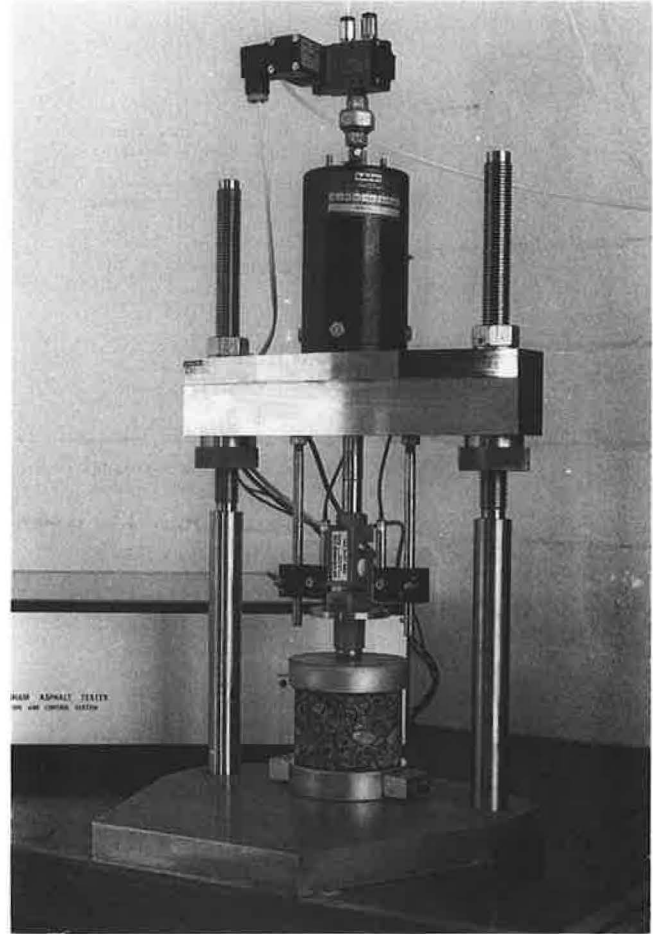


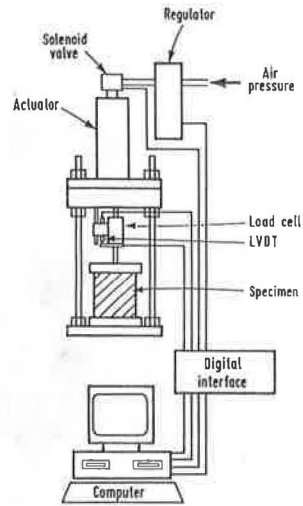
FIGURE 2 NAT set up for uniaxial creep or repeated load axial test.

sions and test conditions. The computer provides information on the steps involved in setting up the specimen and then automatically carries out the test, calculates the results, and presents the data in graphical or tabular form. Alternatively, data can be stored for analysis using spreadsheet software. NATs are currently used in six countries.

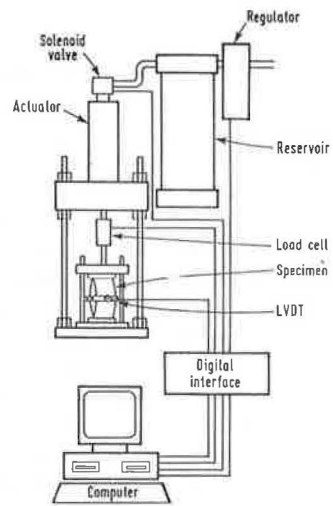
For the RLIT test, the software enables the operator to select the magnitude of vertical load to be applied and the rise time of the load pulse within the ranges of which the equipment is capable, for example, load up to 3 kN and rise time typically 0.06 to 0.15 sec. Figure 4 shows the output from a typical RLIT test. The dimensionless plots of vertical load and horizontal deformation reflect any errors in specimen setup and indicate the effect of any electrical interference on the results.

Figure 5 shows typical relationships between axial strain and time for the UC test. Currently, the software provides for the following test conditions:

1. An optional 10-min conditioning period during which 10 percent of the test load is applied,
2. A 60-min test period, and
3. An optional 15-min relaxation period during which axial strain is monitored.



(a) Uniaxial creep and repeated load axial test configuration



(b) Repeated load indirect tensile test configuration

FIGURE 3 Schematic layout of NAT.

**NOTTINGHAM ASPHALT TESTER
REPEATED LOAD INDIRECT TENSILE TEST
(calibration factors reviewed on 24 May 90)**

Date is 8 Jun 90 -
Temperature = 20 Celsius
Specimen dia. = 100 mm
Poissons ratio = 0.35
No. cond pulses = 5
Pressure scale = 7 Rise time scale = 5

Specimen is PVC
Specimen thickness = 50 mm

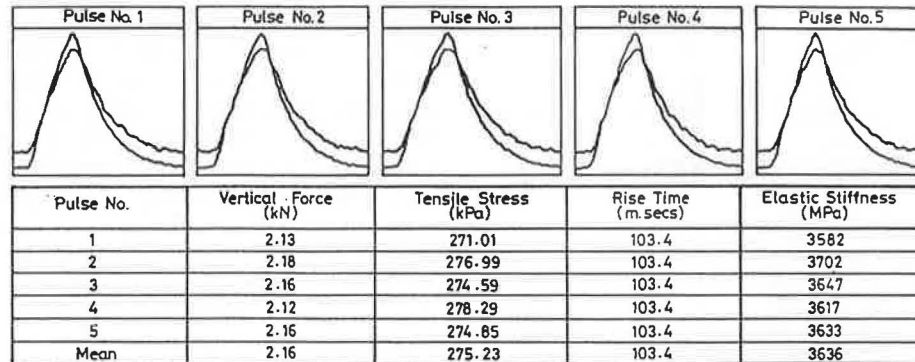


FIGURE 4 Typical output from No. 11 asphalt mix tester (elastic stiffness test).

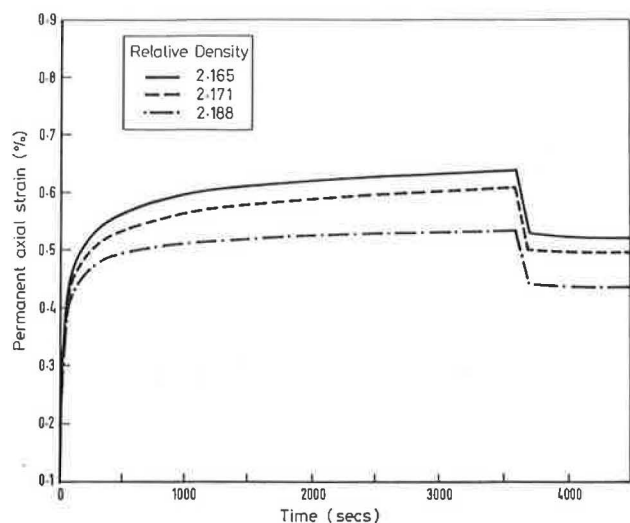


FIGURE 5 Results from typical uniaxial creep tests on bitumen emulsion mixes at 40°C and 100-kPa axial stress.

Software to provide the user with a greater choice of test conditions is being prepared.

Figure 6 shows typical relationships between axial strain and number of load pulses for the RLA test. In this test the specimen is subjected to alternate load applications and rest periods each 1 sec long.

Currently, the software provides for the following test conditions:

1. An optional 10-min conditioning period during which 10 percent of the test load is applied, and
2. A test period of up to 3,600 cycles (2 hr).

Software is being written to allow the user more choice of pulse and rest period length, with the opportunity of applying block periods of pulsed loading followed by rest periods of varying length.

For both the UC and RLA tests, the NAT is capable of applying a maximum vertical force of 3.5 kN.

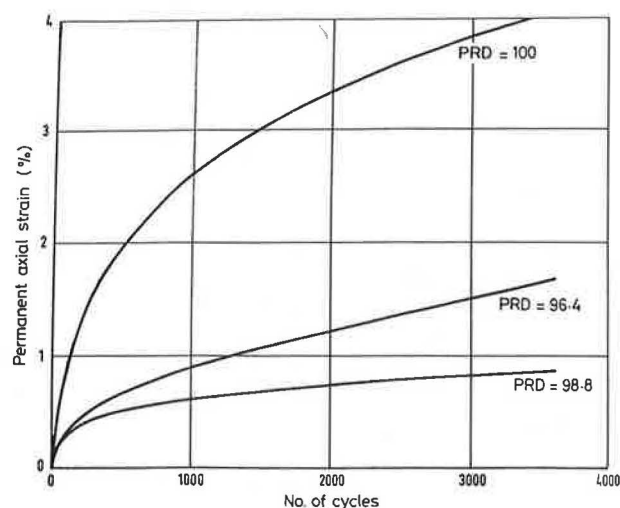


FIGURE 6 Results from typical repeated-load axial tests on hot-mix asphalt specimens at 40°C and 100-kPa axial stress.

Specimen Manufacture

The Nottingham roller compactor was considered for use in the manufacture of slabs from which test specimens could be cored. Some work was carried out with this equipment, but, although the roller compactor is similar to site compaction equipment, it was believed that the device would not be suitable for the routine manufacture of specimens necessary for a widely acceptable method of mix design. Involvement in a project on the problems of Marshall mix design in the Middle East resulted in the use of an alternative method of specimen preparation. The asphaltic concrete rutted seriously soon after the highway was opened to traffic. Investigation showed that good-quality aggregate had been used, the binder contents and gradations were close to those specified, and the bitumen had a penetration of less than 60. Although the mix designs were generally acceptable, the material in the wheel paths of the trafficked highway was found to have virtually zero void content in many cases.

To determine the susceptibility of the mix to overcompaction and subsequent flow under the action of repeated loading, the percentage refusal density (PRD) apparatus was used for specimen compaction (5). The PRD test is widely used in the United Kingdom for determining the degree of compaction of materials laid on site. Routinely, 150-mm (6-in.) cores are cut from newly compacted base materials. These cores are dried and coated with wax for density determination. The wax is then removed and the core is placed in a 150-mm-diameter, split PRD mold and put in an oven at 160°C for 3 hr. An electric vibrating hammer with a foot 100 mm (4 in.) in diameter is used to compact the material for 2 min on both ends of the sample. The foot is moved around the mold during compaction to achieve a kneading action. At the end of each 2-min compaction period, a foot 150 mm (6 in.) in diameter is used to flatten the ends of the sample. The density of the material at refusal is then measured. The density of the original core should not be less than a certain percentage of refusal (e.g., 93), otherwise the material from which the cores have been taken should be removed.

At refusal the material is considered to be at the ultimate state of compaction that can be achieved in practice. Refusal density should not be confused with maximum theoretical density, which is calculated on the basis that void content is zero. The advantage of refusal density is that it reflects the compactability of the mix, which depends on a variety of factors including aggregate shape, gradation, binder content, and layer thickness.

The PRD equipment was used to make samples of the deformation-susceptible material. To achieve a range of levels of compaction from 100 PRD to about 93 PRD, compaction temperatures and times were adjusted. This adjustment simulated the causes of variable compaction in the field where low material temperatures and insufficient roller passes can result in poor compaction.

The specimens were about 100 mm (4 in.) high after compaction. From each PRD specimen, a core 100 mm (4 in.) in diameter was cut; this core was trimmed to a height of 70 mm using a diamond-tipped masonry saw blade. Table 1 shows the volumetric proportions and level of compaction obtained for one of the asphalt mix gradations used. Mechanical testing was carried out in the NAT. The elastic stiffness of the cores

TABLE 1 VOLUMETRIC PROPORTIONS OF ASPHALTIC CONCRETE AT DIFFERENT BINDER CONTENTS AND LEVELS OF COMPACTION

Specimen No.	Mb (%)	Voids (%)	VMA (%)	VFB (%)	PRD (%)
1	4.3	1.9	13.2	85.8	100.0
2	4.3	3.8	15.0	74.3	98.0
3	4.3	4.7	15.7	70.0	97.1
4	4.3	5.7	16.6	65.6	96.1
5	4.3	7.1	17.8	60.2	94.7
6	4.3	9.2	19.7	53.4	92.6
7	3.8	4.1	14.0	70.8	100.0
8	3.8	6.9	16.5	58.3	97.1
9	3.8	9.4	18.7	49.8	94.4
10	4.8	1.3	13.9	90.5	100.0
11	4.8	3.6	15.9	77.3	97.7
12	4.8	6.6	18.6	64.2	94.6

Note: PRD = percentage refusal density; Mb = mass of bitumen; VFB = volume filled with bitumen

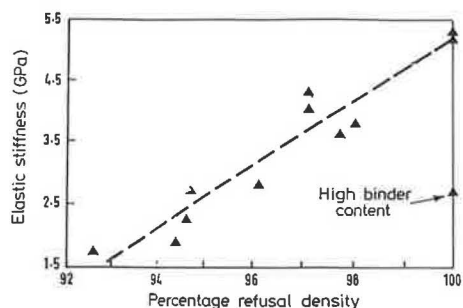
was measured using the RLIT test; the relationship between elastic stiffness and degree of compaction (PRD) is shown in Figure 7a, which indicates that, in general, higher elastic stiffness is achieved with well-compacted materials. At the high level of compaction, however, one mix with a high binder content did not follow this trend. The resistance to permanent deformation of the cores was then assessed using the RLA test (Figure 7b). The results generally reflect those of the elastic stiffness tests: higher levels of compaction result in lower levels of permanent deformation. There is a suggestion, however, that overcompaction could result in deformable mixes, as shown in Figure 6.

MIX DESIGN

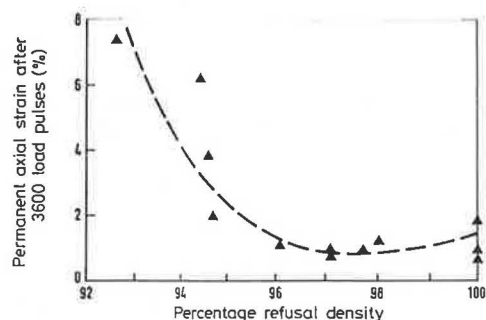
Earlier work (6) demonstrated the effect on the mechanical properties of bituminous materials of the interaction of gradation, binder content, and compaction. Therefore, the new mix design method was based on these three parameters by providing the means of examining their effect for a particular aggregate source. This would then enable the engineer to determine the best gradation and binder content for optimum mechanical properties at a target level of compaction.

Gradation

It was decided to concentrate on continuous gradations in the first instance because the use of this type of gradation for the structural layers is widespread. To define the target gradation, a modification of the widely known power law (7) was used. The modification allowed gradation and the fines content to be varied while filler (sub-200 mesh) material was maintained at a preselected and practical level. The grading equation is as follows:



(a) Relationship between PRD and elastic stiffness (temperature = 20°C, load rise time = 0.1 secs)



(b) Relationship between PRD and resistance to permanent deformation measured in the repeated load axial test (temperature = 40°C, repeated axial stress = 100 kPa)

FIGURE 7 Effect of compaction level on mechanical properties of asphaltic concrete.

$$P = \frac{(100 - F)(d^n - 0.075^n)}{(D^n - 0.075^n)} + F$$

where

- P = percentage passing a sieve of size d (mm),
- D = maximum aggregate size (mm),
- F = filler content (sub-200 mesh material), and
- n = exponent between 0 and 1.

Figure 8 shows the effect of varying the exponent n from 0.2 to 0.7 for 28-mm gradations with a filler content of 6.0 percent. The gradation with an exponent of 0.45 approximates the gradation that is generally acknowledged to have maximum density. Experience has shown that such gradations may be too dense, with insufficient void space to accommodate the binder. The solution generally adopted is to increase VMA by moving the gradation away from the maximum density curve. This move may be accomplished by reducing the exponent and, consequently, making the mix finer. This results in a higher binder content caused by the increased surface area of the graded aggregates and, in many cases, increased susceptibility to deformation. An increase in VMA may also be achieved by increasing the exponent and making the gradation coarser. This approach was adopted for the design of the road base and basecourse materials considered in this project; preliminary tests showed that exponents of 0.5, 0.6, and 0.7 were the most appropriate for mixes of this type.

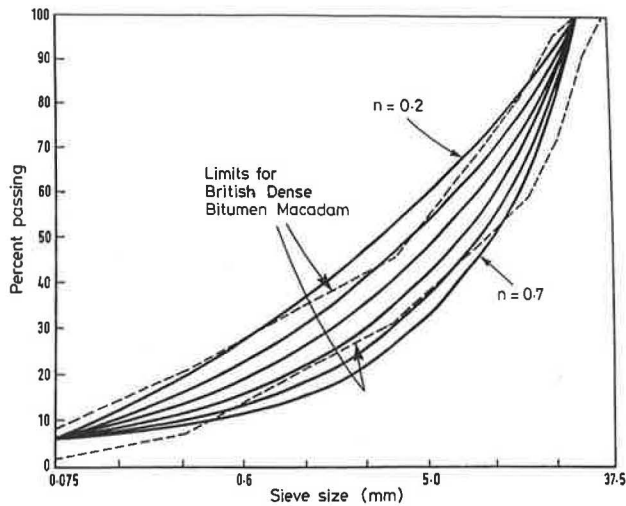


FIGURE 8 Typical grading curves based on Equation 1.

Figure 9 shows the effect of grading exponent on resistance to permanent deformation measured by the RLA test. It can be seen that, for a certain binder content, aggregate type, and level of compaction, there is an optimum grading exponent for maximum resistance to permanent deformation.

It would not be possible to expect that the aggregate sizes from a particular source could be combined to exactly fit a gradation defined by a theoretical relationship. A simple computer program, however, can be used to determine the blend that minimizes the difference between the theoretical and practical gradations.

Compaction

The compaction was carried out using the PRD equipment to provide three compaction levels. The compaction conditions were as follows:

Compaction Level (approximate value)	Compaction Time (sec)	Compaction Temperature (°C)
1 (100 PRD)	120	SP + 92
2 (97 PRD)	60	SP + 50
3 (93 PRD)	30	SP + 40

Compaction time is for each end of the specimen, and SP is ring-and-ball softening point (°C).

The 100 PRD level is necessary as a datum for the other levels of compaction. It is also useful because the void content of a mix compacted to refusal reflects the ability of a material to perform adequately in severe conditions, such as the high temperatures combined with very heavy axle loads that occur in the Middle East. A mix with a void content of at least 2 percent at refusal may well be the best for such conditions. For Compaction Level 1, the temperature was that considered ideal for compaction in the field and represents something of an extrapolation assuming typical temperature susceptibilities. For modified bitumens, a more detailed definition of temperature would have to be used. For Compaction Levels 2 and 3, temperatures and compaction times were established by carrying out trials.

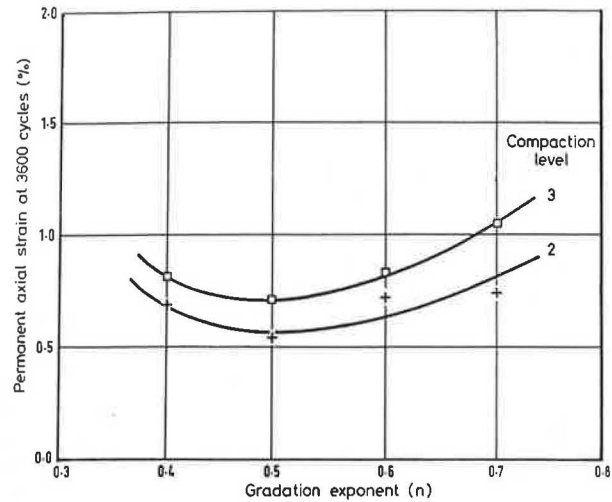


FIGURE 9 Effect of grading exponent *n* on resistance to permanent deformation measured in repeated-load axial test (granite aggregate with 4.1 percent binder).

The target level of compaction in practice is generally 95 PRD, with 93 PRD being the minimum acceptable. For the purposes of mix design, therefore, 95 PRD is the most appropriate level of compaction.

Binder Content

In the United Kingdom, the binder content of continuously graded basecourse and road base mixes is generally within the range of 3.5 to 4.7 percent of the total mix. These two binder contents, together with the midrange value of 4.1 percent, provide the three levels of binder content that are used in the mix design procedure for the structural layers. For wearing course mixes, however, a finer gradation and higher binder content may be necessary to provide an impermeable, level running surface.

Basis of Mix Design Procedure

The mix design procedure involves an investigation of the effect of gradation, compaction, and binder content for a particular aggregate source. As discussed, three levels of each of the parameters were selected, resulting in nine mix compositions at three levels of compaction (i.e., 27 different mixes).

Specimen Preparation

To simplify the specimen-preparation process, the practice of cutting 100-mm-diameter cores from the PRD samples to produce test specimens was discontinued. Instead, the ends of the PRD specimens were cut, using a diamond-tipped masonry saw, to provide test specimens 70 mm high and 150 mm in diameter.

Volumetric Analysis

The first stage of the design procedure is the measurement and assessment of volumetric proportions when materials that

do not have volumetric proportions within the target ranges can be screened out. Densities are determined from gravimetric measurements without using wax to waterproof the specimens.

For road base and basecourse materials, the mix with a grading exponent of 0.5 and a binder content of 3.5 percent and compacted to 100 PRD is selected as a datum. The void content of this mix reflects the compactability of the aggregate and enables the appropriate volumetric chart (Figures 10–12) to be selected. In each of these charts, an area is defined by constraints on void content, VMA, and binder volume. These constraints are based on experience, practical considerations, and the volumetric proportions at 100 PRD. With the continuously graded basecourse and road base mixtures considered in this work, properly compacted materials have void contents in the range of 3 to 8 percent, as specified to ensure adequate fatigue resistance. Mixes falling within the defined area are considered to be candidates for the measurement of mechanical properties for mix design purposes. Those mixes outside the defined area are rejected, although test data on these materials could provide valuable information in the event of materials' being laid out of specification in practice.

Measurement of Mechanical Properties

NAT measures the elastic stiffness using the RLIT test configured for 150-mm-diameter specimens. The test temperature is 20°C and the rise time is about 120 msec (where rise time is the time between the start and the peak of the load pulse).

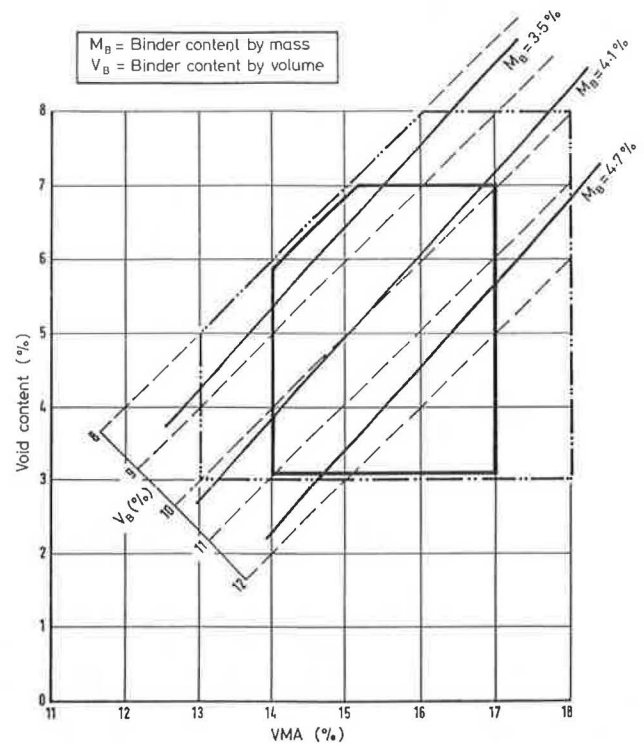


FIGURE 11 Volumetric criteria chart (2 percent voids at 100 PRD).

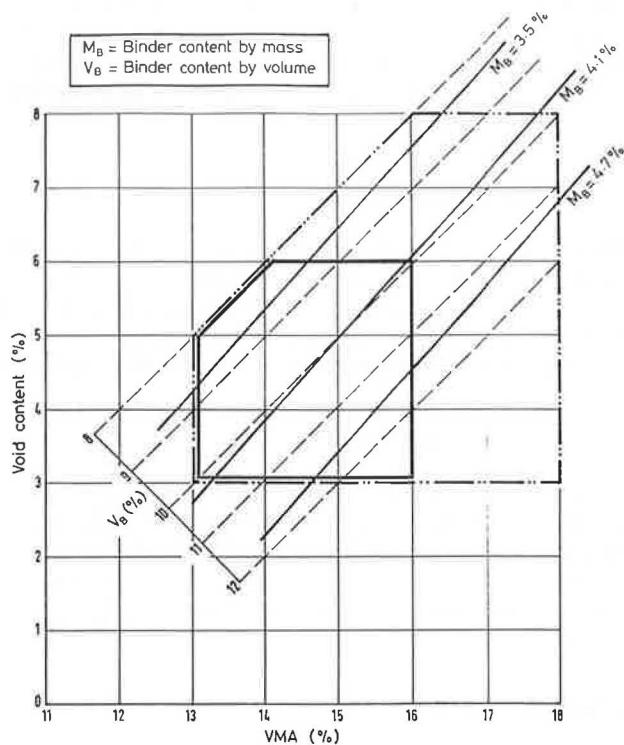


FIGURE 10 Volumetric criteria chart (1 percent voids at 100 PRD).

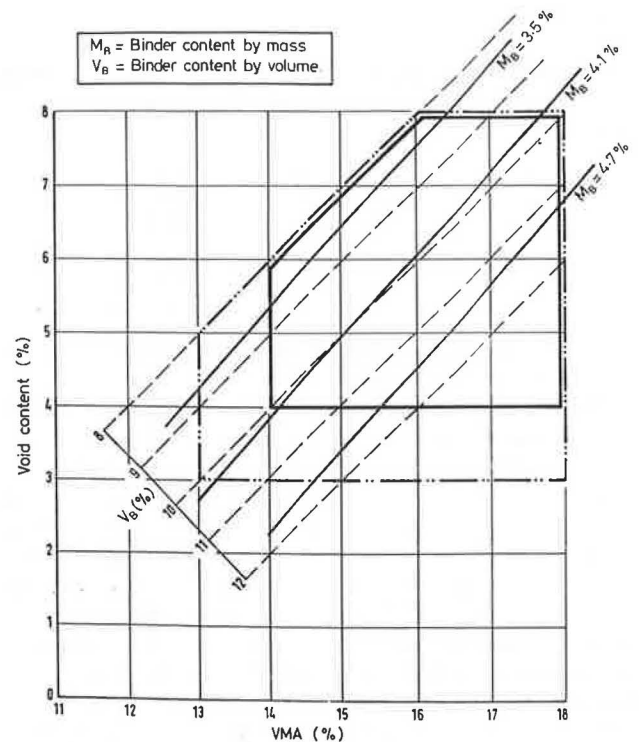


FIGURE 12 Volumetric criteria chart (3 percent voids at 100 PRD).

NAT then assesses resistance to permanent deformation using the RLA test, which, because it uses a pulsed axle load, is considered more simulative of in situ conditions than uniaxial creep. In this test, the 150-mm-diameter specimens are loaded axially between 100-mm-diameter platens as shown in Figure 13. The 25-mm-wide annulus of material outside the directly loaded part of the specimen is considered to impart a degree of lateral constraint that is related to the strength of the material. The test temperature is 40°C and the axial load waveform is virtually square with alternate load and rest periods each 1 sec long. The peak axial stress is 100 kPa and the specimen is normally subjected to 3,600 load pulses, which takes 2 hr. If modified bitumens are to be evaluated, the RLIT test should be carried out at more than one temperature to determine the temperature susceptibility of elastic stiffness.

Additional durability aspects that should be assessed, particularly for surface courses, are water sensitivity and the effects of aging. Measurements of elastic stiffness before and after soaking or freeze-thaw cycling would provide relevant information. New developments in accelerated aging, which involve forcing oxygen-rich air through a mix, could allow ready assessment of the effect of aging on mechanical properties.

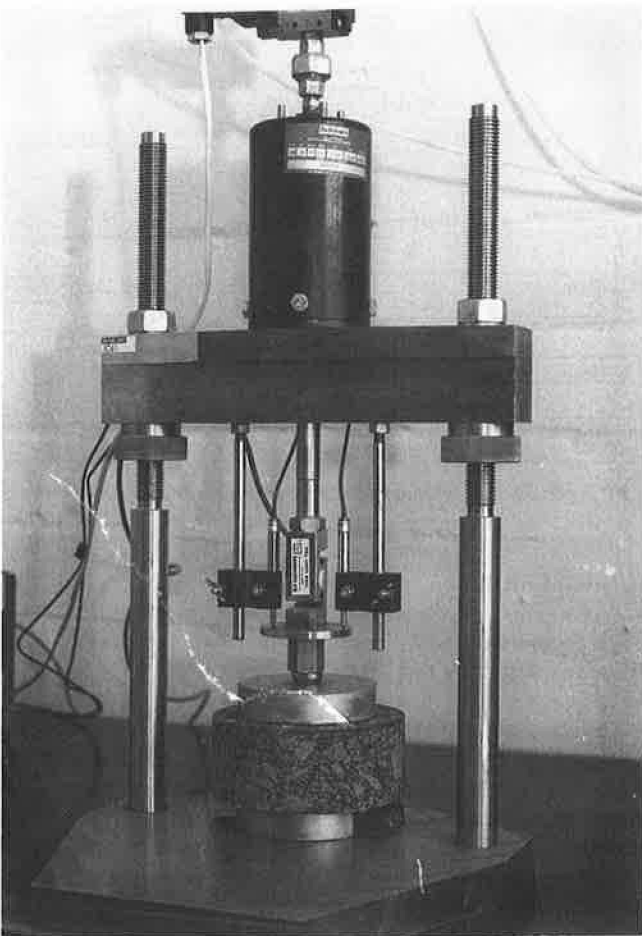


FIGURE 13 Repeated-load axial tests on 150-mm-diameter specimens using 100-mm-diameter platens.

Design Criteria

The development of a new method of mix design has three main problems. The first problem is the method of sample preparation; the second is the test methods; and the third is the selection of design criteria. With this phase of the work, which is primarily concerned with basecourse and road base mixes, the design criteria will be somewhat different from those used for wearing courses. In this project, it was decided not to determine optimum mix proportions for maximum mechanical properties but to specify certain minimum performance levels. This decision enables the engineer to determine the best mix on the basis of additional self-imposed criteria such as workability, the availability of materials, and, inevitably, the associated economic considerations. It is difficult to draw cut-off lines that rule out all materials that fall below, however marginal the shortfall. It is essential to be prudent, however, and ensure that the selected mix exceeds the criteria so that normal variances in composition and compaction do not mean that material is unnecessarily condemned and removed from the works.

For basecourse and road base mixes, the important mechanical properties are resistance to fatigue cracking, resistance to permanent deformation, and elastic stiffness, which reflects the load-spreading ability of the material. Other criteria concerned with volumetric proportions are dealt with in the volumetric charts (Figures 10–12) discussed previously.

Currently, the assessment of resistance to fatigue cracking involves more specimen preparation and testing than is considered practical for routine mix design work. In addition, the test equipment and techniques are generally too complex for a normal materials laboratory. For pavement constructions, which use relatively thick lifts of road base materials made with unmodified bitumens, prediction methods based on mix proportions and bitumen properties (8) are considered adequate. The current work on Strategic Highway Research Program Contract A003A may provide the means of assessing fatigue resistance more readily.

For resistance to permanent deformation measured using the RLA test, the criterion currently used is a maximum of 1.0 percent axial strain after 3,600 applications of an axial stress of 100 kPa at 40°C. The strain level was chosen because it appears to form a boundary between those mixes that become stable with a decreasing rate of permanent strain, and those mixes in which strain rate shows no sign of decreasing. Typical results are shown in Figure 14, which also shows the volumetric compositions of the materials used. It is interesting to note, from Figure 14, that overcompaction results in materials that are susceptible to permanent deformation.

For elastic stiffness measured by the RLIT test, the criterion is a minimum of 2500 MPa at 20°C with a load rise time of approximately 0.12 sec. The criterion was based on calculated levels of elastic stiffness related to pavement layer thickness and a background of extensive test data. Table 2 shows typical volumetric compositions and elastic stiffnesses for a particular aggregate type. The results have been sorted on the basis of the magnitude of elastic stiffness. The tabulated results show that, for the aggregate source investigated, higher values of elastic stiffness result from high levels of compaction and the consequently low levels of VMA and void content. In general, higher binder contents result in lower values of elastic stiffness.

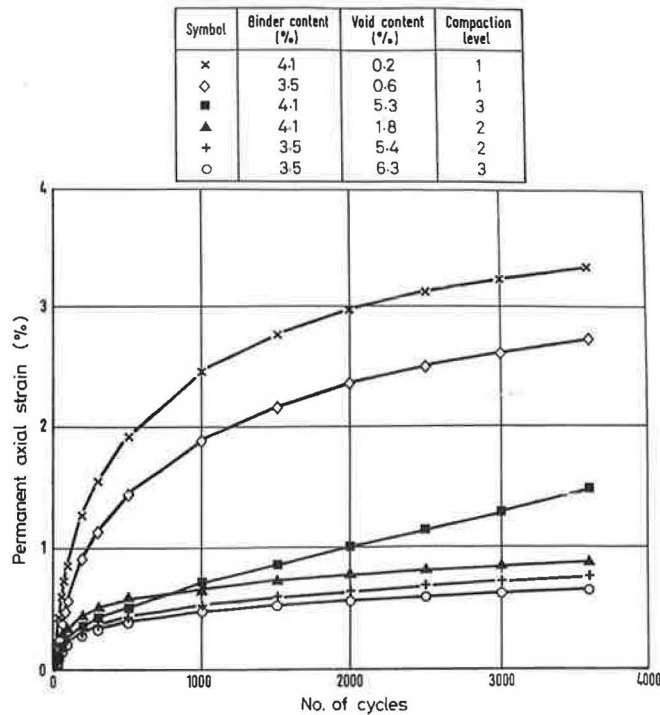


FIGURE 14 Repeated-load axial results for limestone aggregate specimens with gradation exponent $n = 0.5$.

TABLE 2 VOLUMETRIC COMPOSITIONS AND ELASTIC STIFFNESS OF MIXES MADE WITH CRUSHED LIMESTONE AND 100 PENETRATION BITUMEN

Grading Exponent n	Binder Content (%)	Compaction Level	Voids (%)	VMA (%)	PRD (%)	Elastic Stiffness (MPa)
0.7	3.5	1	0.6	9.6	100.0	5300
0.6	3.5	1	1.2	10.2	100.0	5200
0.5	3.5	1	0.6	9.6	100.0	5100
0.5	4.1	2	1.8	12.1	98.4	4400
0.7	4.1	1	0.1	10.6	100.0	4000
0.6	3.5	2	4.9	13.5	96.3	3700
0.6	3.5	3	6.8	15.3	94.3	3500
0.5	3.5	3	6.3	14.8	94.2	3300
0.5	4.1	1	0.2	10.7	100.0	3300
0.5	3.5	2	5.4	13.9	95.2	3300
0.7	4.7	1	-0.3	11.7	100.0	3300
0.7	3.5	2	4.8	13.4	95.8	3200
0.6	4.1	1	0.3	10.8	100.0	3200
0.5	4.7	1	-0.0	11.9	100.0	3000
0.6	4.7	1	-0.4	11.6	100.0	3000
0.5	4.7	2	1.3	13.0	98.8	2800
0.7	4.1	2	3.8	13.9	96.2	2800
0.6	4.7	2	0.6	12.4	99.4	2800
0.6	4.1	2	4.2	14.2	96.2	2600
0.7	3.5	3	6.9	15.3	93.7	2500
0.6	4.1	3	4.1	14.2	96.2	2400
0.5	4.7	3	3.7	15.1	96.4	2200
0.5	4.1	3	5.3	15.3	94.9	2200
0.7	4.7	2	2.2	13.9	97.8	2000
0.6	4.7	3	3.5	15.0	96.5	1700
0.7	4.7	3	5.3	16.6	94.7	1500
0.7	4.1	3	6.9	16.7	93.2	1400

(Results sorted in order of magnitude of elastic stiffness)

Summary

The basis of a mix design procedure has been established. Relevant volumetric and mechanical properties are used as design criteria. It is envisaged that the complete mix design procedure will take the form represented by the flow chart shown in Figure 15. A complete mix design example is available elsewhere (9).

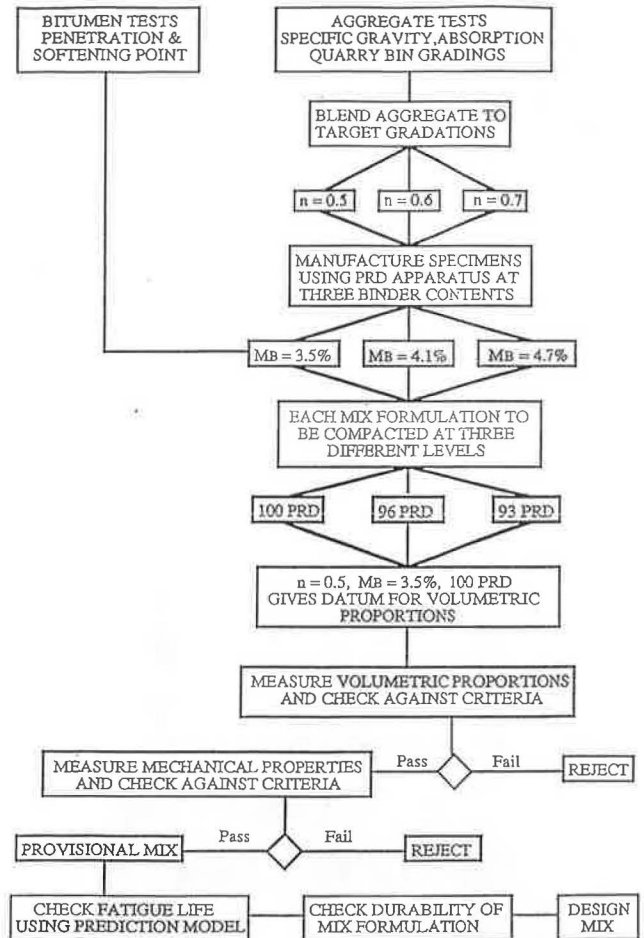


FIGURE 15 Flow chart of mix design procedure.

CONCLUSIONS

The conclusions drawn from this phase of the development of a mix design method are as follows:

1. The compaction of uncoated aggregates to develop appropriate gradations is impractical for routine mix design work.
2. The Nottingham asphalt mix tester provides a convenient method of measuring the elastic stiffness and resistance to permanent deformation of asphalt mixes. The equipment can be used for mix design and has potential for quality control and end product specification.
3. The percentage refusal density equipment enables asphalt mixes to be compacted in the laboratory to a range of densities typical of those achieved in practice.

4. The framework of a mix design method for road base and basecourse mixes has been established. Design criteria are based on relevant volumetric proportions and mechanical properties. The method is to be developed to take into account flexibility, water sensitivity, and the effect of aging.

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