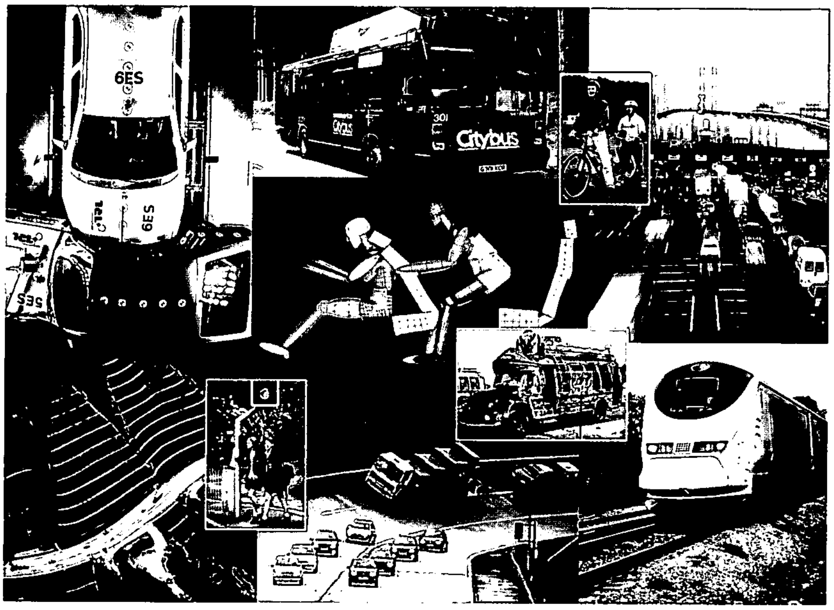

The characterisation of bituminous Macadams by indirect tensile stiffness modulus

by M E Nunn

TRL Report 160

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TRANSPORT RESEARCH LABORATORY
An Executive Agency of the Department of Transport

TRL REPORT 160

THE CHARACTERISATION OF BITUMINOUS MACADAMS BY INDIRECT TENSILE STIFFNESS MODULUS

by M E Nunn

This report describes work commissioned by the Road Engineering and Environmental Division of the Highways Agency under E082A/HM, Performance Related Standards for Comité Européen de Normalisation (CEN).

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EXECUTIVE SUMMARY

Over recent years, in the UK, much work has been gone into the development of economic and practical means of measuring the structural and performance-related properties of bituminous materials. The stiffness modulus is an important performance property of the roadbase and basecourse. It is a measure of the load-spreading ability of the bituminous layers and it controls the levels of traffic-induced, tensile strain at the underside of the roadbase which may be responsible for fatigue together with the stresses and strains in the subgrade that can lead to structural deformation. The indirect tensile test, defined by the British Standards Institution, BS DD 213 (1993), has been identified as a potential means of measuring this property.

The objectives of this report are to estimate the range of stiffness moduli applicable to standard materials used for the structural layers and to investigate concerns that have arisen from the use of the indirect tensile test (ITT). The more important of these are:-

- Calculation of stiffness modulus using the ITT.
- Determination of mean stiffness.
- Relationship between stiffness modulus measured using the ITT and measured using a more sophisticated test.
- Relationship between Poisson's ratio and temperature and/or stiffness.
- Equivalence of pulse and continuous sinusoidal loading.
- Effect of pulse shape.

The issues raised in this report will contribute to the current discussion on the standardisation of the ITT and provide guidance for the setting of target values of stiffness modulus for inclusion in an end-product specification for roadbase and basecourse materials. The most important of these is that the method of calculating the ITT stiffness modulus needs to be defined in the British Standards Institution Draft for Development.

The following recommendations are made:-

1. The points raised in this report concerning the use of the ITT should be resolved by the British Standards Panel B/501/1/WG2. Convening an expert panel may offer the best means of reaching a consensus decision.

2. The measurement of structural properties of bituminous roadbase materials in new road construction contracts, as part of the requirements of the Department of Transport, Specification for Highway Works (SHW) Clause 929, would aid setting end-product standards and lead to a better understanding of pavement behaviour. A database should be established to collect this data.

3. A second stage of performance trials should be undertaken, to build on experience gained from the earlier trials on the M53 and M56. In these trials, target values for the structural properties could be specified and the Contractor be required to demonstrate that his mix meets the requirements by testing material laid in a trial strip to Clause 929.

THE CHARACTERISATION OF BITUMINOUS MACADAMS BY INDIRECT TENSILE STIFFNESS MODULUS

ABSTRACT

The indirect tensile test (ITT) has been identified as an economic and practical means of measuring the stiffness modulus or load-spreading ability of bituminous roadbase. This test has been defined in a British Standards Institution (BSI) Draft for Development and it is considered to have the potential for inclusion in a future end-product specification.

The objectives of this study are to provide estimates of stiffness moduli applicable to standard roadbase and basecourse materials used in the UK and to investigate controversial points that have arisen from the use of the ITT. This report considers the definition of ITT stiffness modulus, the determination of mean stiffness, curing, comparison with a more sophisticated test, the selection of Poisson's ratio and the effect of load-pulse shape and its equivalent sinusoidal, loading frequency.

Estimates of the stiffness moduli of newly laid, standard macadams used in the UK have been determined and the specification of bituminous material by stiffness class is discussed. It is recommended that an expert panel is convened to resolve the issues raised in this report and that a data-base should be established to collect information on the performance properties of materials laid in UK road contracts.

1. INTRODUCTION

Over recent years, in the UK, much work has been gone into the development of economic and practical means of measuring the structural and performance related properties of bituminous materials. The stiffness modulus is considered to be a very important performance property of the roadbase and basecourse. It is a measure of the load-spreading ability of the bituminous layers and it controls the levels of traffic induced tensile strain at the underside of the roadbase which may be responsible for fatigue together with the stresses and strains induced in the subgrade that can lead to structural deformation. The indirect tensile test, defined by the British Standards Institution, BS DD 213 (1993), has been identified as a potential means of measuring this property.

The purpose of this report is to estimate the range of stiffness moduli applicable to standard roadbase and basecourse materials used in the UK and to investigate any related aspects that have arisen from the use of the indirect tensile test (ITT). The more important aspects considered are:-

- Calculation of stiffness modulus using the ITT.
- Determination of mean stiffness.
- Relationship between stiffness modulus measured using the ITT and measured using a more sophisticated test.
- Relationship between Poisson's ratio and temperature and/or stiffness.
- Equivalence of pulse and continuous sinusoidal loading.
- Effect of pulse shape.

The issues raised in this report will contribute to the current discussion concerning the standardisation of the ITT and provide guidance for the setting of target values for stiffness modulus for inclusion in an end-product specification for road base and basecourse materials. The route to the development of an end-product specification is also discussed.

2. BACKGROUND

For many years the standard means of measuring the stiffness modulus of bituminous materials involved the use of sophisticated test equipment. At TRL, a 3-point bending test was used that was capable of measuring the complex modulus of a beam of bituminous material over a range of frequencies and temperatures. Elsewhere, bending or push-pull tests, which perform a similar function, have been developed. The primary function of these machines is to investigate the fundamental properties of materials for research purposes. These methods are slow and expensive. For example, the TRL 3-point bending test can only test one specimen per day if results are required for a range of temperatures and frequencies. On the other hand, the indirect tensile test can be used to carry out up to 50 tests per day, using test specimens that are easily manufactured from 150 mm diameter cores.

In the late 1980's, a form of the indirect tensile test (ITT), the Nottingham asphalt tester (NAT), became commercially available (Cooper and Brown, 1989). This test was shown to be practical and economic and the measurements correlated well with those of the more sophisticated TRL, 3-point bending test (Nunn and Bowskill, 1992). Since then, research involving this test has continued at TRL and Nottingham University. The NAT has played an important role in the Nottingham University *LINK* programme that is jointly funded by the Department of Transport and by Industry (Brown, Gibb, Read, Scholz and Cooper, 1995). This research has been concerned with developing end-product tests and a methodology for mix design. At the same time, a collaborative research programme carried out at TRL, which is jointly funded by the Highways Agency (HA), British Aggregate and Construction Materials Industry (BACMI) and the Refined Bitumen Association (RBA), has examined the practicality of using this test in an end-product specification in a contract situation (Nunn and Smith, 1994). This work has demonstrated the benefits of an end-product specification and that the indirect tensile test has potential as a performance test.

Within Europe, work is underway in the Comité Européen de Normalisation (CEN) to produce harmonised European test methods. This requirement to harmonise standards in all countries within the Europe Union will accelerate the introduction of standards based on performance properties. The recognition that the indirect tensile test has potential to be a good performance test, has resulted in the British Standards Institution Panel B/510/1/WG2 (Sampling and examination of bituminous mixes) producing a Draft for Development for this test; British Standards Institution, BS DD 213 (1993). The Panel, together, with TRL have recently completed a standardisation trial involving 27 laboratories (Leech, 1995). The trial established the current precision of the test and identified possible ways in which it could be improved.

The ability to carry out a large number of tests, using the ITT, soon after material has been laid has helped to progress our understanding of the fundamental behaviour of bituminous materials. Work carried out as part of the HA/BACMI/RBA collaborative research programme established that the structural properties of bituminous materials change considerably from the time that they are first laid. This change, which is called curing, is initially rapid but slows down over the life of the road. Trials described by Chaddock and Pledge (1994) have demonstrated that the stiffness modulus of newly laid roadbase can increase by over 100 per cent in the first year, and measurements on materials taken from roads of approximately 20 years old, have indicated that the stiffness modulus may eventually attain a level 4 times its original value.

Curing has important fundamental implications for the behaviour of roads. Hitherto, researchers considered that the structural properties of bituminous materials remained essentially constant over the life of the pavement. Researchers have generally measured the properties of new bituminous materials and used these properties in mechanistic models to predict the future behaviour of the road. These properties were determined using test specimens that were often manufactured in the laboratory. At that time, protocols had not been developed to ensure the laboratory processes affected material in a similar way to those used on site. The fact that mechanistic models assume that the structural properties of bituminous materials are unaffected by the environment may be a large contributory factor for the generally poor agreement between observed performance and prediction. Also when test specimens were taken from road construction sites, they were very often stored in undefined laboratory conditions before they were tested. This, coupled with the natural variability of bituminous material and the fact that very few specimens could be tested using the sophisticated research methods, meant that phenomena such as curing went un-noticed.

Curing of the main structural layers can improve pavement performance, provided that the road is initially built strong enough to prevent over-stressing of the bituminous layers, by traffic, inhibiting the development of curing. Curing improves the load-spreading ability and deformation resistance of the roadbase as the road ages. This increase in stiffness modulus will result in a steady reduction in the traffic-induced tensile strains at the bottom of the roadbase, which are considered to be responsible for fatigue damage, and it will also reduce the stresses and strains in the subgrade that can cause structural deformation.

These developments raise questions concerning the measurement of stiffness modulus by the indirect tensile test for specification purposes.

3. MEASUREMENT OF STIFFNESS MODULUS

3.1 DEFINITION OF STIFFNESS MODULUS

It is first necessary to define stiffness modulus. Stiffness modulus is a function of the visco-elastic components of a material. Under sinusoidal, uniaxial loading it is generally defined as the ratio between the maximum stress and the maximum strain. This is often referred to as the complex modulus. Because of the viscous component in bituminous materials, the strain always lags behind the stress, and this lag is known as the phase angle. There is general agreement on how stiffness modulus should be calculated for a test specimen subjected to a simple stress system under sinusoidal loading.

However, the indirect tensile test differs in two respects. Firstly, a pulsed load is applied and, secondly, the stress system is complex and not easy to define. Tests, based on push-pull and beam bending, are basically uniaxial stress systems, whereas the stress system in the ITT is biaxial and each of these stresses varies continuously throughout the specimen. Consequently, the computation of stiffness involves reliance on an analysis of the stress system and an assumption of the value of Poisson's ratio.

Because the ITT uses a pulsed load, the definition of stiffness modulus is open to different interpretations. An ITT test has been used for a number of years in the USA and the ASTM D 4123 (1987) defines two methods for computing stiffness modulus. The NAT method of calculation, which is built into the NAT software, is again different. The ASTM method uses the resilient or recoverable component of deformation over a loading cycle, whereas the NAT method uses a measure that is close to the maximum deformation induced by the load pulse. These methods are illustrated in Fig 1.

The ITT method described in BS DD 213 (1993) does not define a method of calculation, this clearly needs to be remedied. The ASTM is an established method, whereas that used in the NAT is not. In spite of this, the NAT method appears to have technical advantages over the ASTM method and these are discussed in more detail in Appendix A and the relative merits of the two methods are summarised in Table 1.

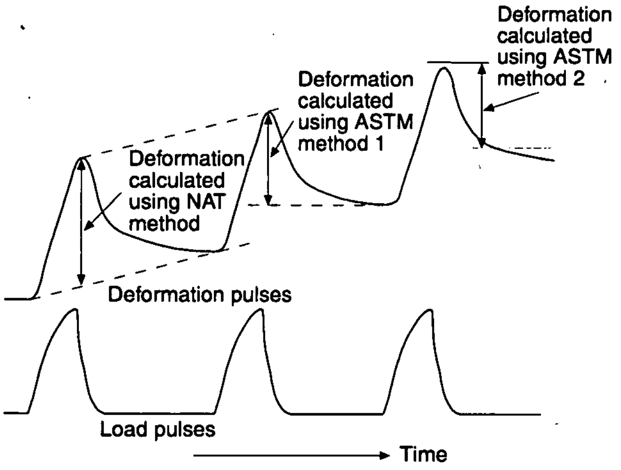

Fig 1 ITT Load and deformation pulses

Throughout this report the ITT stiffness modulus has been calculated using the NAT method.

3.2 CALCULATION OF MEAN STIFFNESS MODULUS AND MATERIAL VARIABILITY

The most appropriate calculation of mean stiffness modulus is determined by its statistical distribution. The available evidence suggests that the logarithm of stiffness modulus is normally distributed. This was concluded from measurement of stiffness modulus of improved macadams reported by Nunn et al (1987). More recently an analysis of data for a standardisation trial of the ITT reached the same conclusion (Leech, 1995).

The evidence for the distribution being log normal is that the standard deviation of the logarithm of stiffness is independent of the level of stiffness. The measured standard deviations of materials laid in seven TRL test pavements (Chaddock et al, 1994) and in trials of an end-product specification carried out as part of two motorway contracts (Nunn et al, 1994) are plotted in Fig 2.

The test pavements were constructed in a number of sections using a range of penetration grade binders, aggregate types and different levels of compaction. The stiffness of many of the test sections were measured on a number of occasions as part of the curing investigation. Over 2,000 individual measurements were made to determine 184

TABLE 1

Advantages and disadvantages of the methods

	NAT Method	ASTM Method
Advantages	1. Less sensitive to pulse shape. 2. Deformation components are more representative.	1. Established method.
Disadvantages	1. Not defined in any standard.	1. More sensitive to pulse shape. 2. Negative component of irrecoverable deformation.
Comments	1. A shorter pulse load would help to produce a deformation response more representative of a wheel load travelling at a realistic speed. 2. The negative component of irrecoverable deformation, given in Table A1, raises the question of what is the physical significance of the resultant stiffness determination by the ASTM method.	

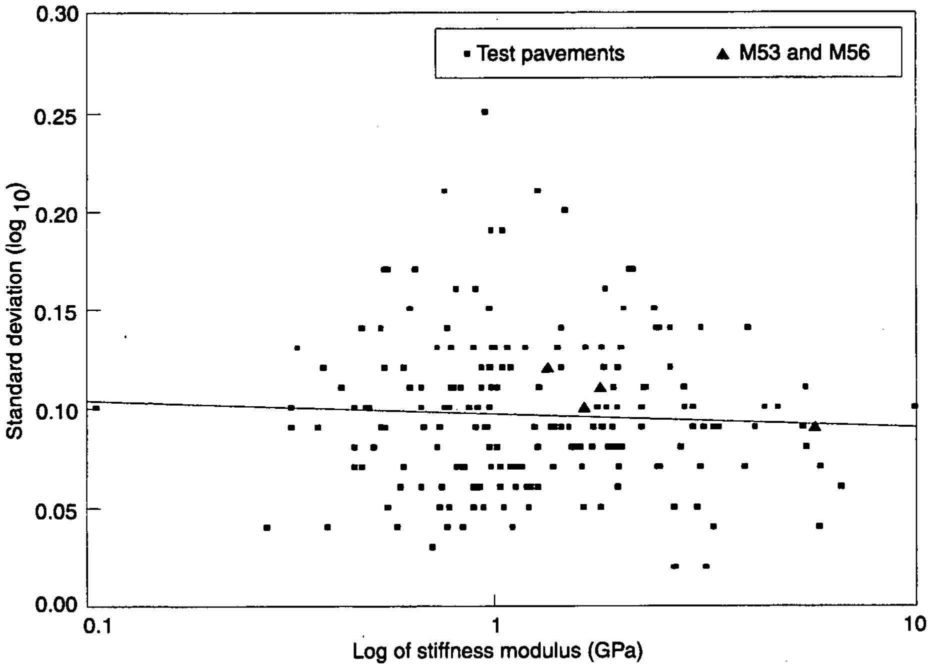

Fig 2 Standard deviation of measured stiffness moduli as a function of stiffness

mean stiffnesses of bituminous material. The results from the motorway trials involved a further 1,065 individual stiffness measurements.

The best fit line to the data is shown in Fig 2 to be almost horizontal. This illustrates that the standard deviation of the logarithm of stiffness modulus is independent of the level of stiffness modulus and is essentially constant at 0.10. The results from test pavements are more scattered about the best fit line than the 4 results from the motorway construction contracts because the standard deviations were derived from smaller samples. The standard deviations for the sections of test pavement were derived using between 6 and 20 individual measurements, whereas those for the motorway trials involved between 210 and 375 measurements.

These standard deviations for the test pavements were determined from measurements on samples from a relatively small area; a typical test section was approximately 25 m long by 2 m wide. A further feature of the distribution is that, so long as more about than a few square metres are sampled, the standard deviation of the logarithm of stiffness modulus is close to 0.10, provided that the mix ingredients are from the same source and the material is mixed, laid and compacted under nominally identical conditions. The same standard deviation is obtained even if the sample area covers a whole construction contract.

This can be illustrated by considering the distribution of stiffness measurements in the M53 and M56 end-product specification trials. Here material was laid on a much larger scale than in the TRL test pavements. Four areas of between 14,000 and 25,000 m^2 were laid and between 210 and 375 stiffness measurements were made in each area. The standard deviations for each of these areas was 0.12, 0.10, 0.11 and 0.09, which are similar to those of the smaller test sections of the TRL test pavements. Furthermore, each area of the motorway trials was divided into between 14 and 25 sample areas of 1,000 m^2 and 15 stiffness measurements were made for each of these sample areas. The average standard deviation of the logarithm of stiffness of these much smaller sample areas was again 0.10.

However, if material is sampled from a very small area of a few square metres, the distribution of results reduces slightly. For example, in each sample area of the M53 and M56 trials, 5 cores were cut for testing along three evenly spaced transverse lines and the average standard deviation of the logarithm of these 5 measurements was about 0.06. The reason for this reduced variability may be because the material sampled from this very small area was produced in a single batch by the mixing plant. Leech (1995) sampled material from a somewhat larger area of about 8 m^2 for the standardisation trials of the ITT and, although care was taken to obtain uniform material, the measurements reported again have a standard deviation of about 0.10.

The results indicate that the mean logarithm of stiffness modulus, which is often referred to as the geometric mean, should be used to characterise material. In the remainder of this report the logarithm to the base 10 of the stiffness modulus will be quoted, followed, where applicable, by the absolute value of stiffness modulus in brackets.

4. STIFFNESS MODULUS OF STANDARD BITUMINOUS ROADBASE

The materials most commonly used in the UK are dense bitumen macadam made with 100 penetration grade binder (DBM) and 50 penetration grade binder (DBM50) and heavy duty macadam (HDM) containing 50 pen binder and additional filler. In an end-product specification, the properties of these materials will be specified and it will be the responsibility of the supplier to provide a material to his own design that achieves these properties.

4.1 SOURCES OF INFORMATION

In defining target values of stiffness modulus to be specified in a future end-product specification, the properties of materials currently in common use need to be considered. At the present time, the information on these materials is sparse. Although a number of materials have been laid in TRL test pavements by leading UK surfacing contractors, they were laid for research purposes, and many were either lightly compacted or specified to be outside the relevant compositional specification. However, the TRL test pavements contained 13 suitable materials whose stiffness modulus was measured soon after they were laid. The results obtained from the end-product specification trials, on the M53 and M56, can also be added to this list. The stiffness moduli of these materials measured within a few days of laying, are reproduced in Table 2.

More comprehensive data are available on DBM, therefore a stiffness modulus that characterises typical DBM can be estimated with more assurance. The mean log stiffness of the 14 DBM results given in Table 2 is 0.192 (1.56 GPa) and the standard deviation of the individual means is 0.11. With a sample of this size, there is a 95 per cent probability that the population mean will lie between 0.254 (1.79 GPa) and 0.140 (1.38 GPa). This gives a measure of the reliability of the best estimate.

Here again, it should be noted that the standard deviation of the mean stiffness modulus of nominally the same material from different sources is approximately 0.10, similar to the standard deviation of individual measurements made on samples from the same source.

TABLE 2

Stiffness modulus of macadams

Pavement*	Material code**	Nominal penetration of binder (0.01mm)	Stiffness modulus (GPa)	Stiffness modulus (Log_{10})	Standard deviation (Log_{10})	Pen of recovered binder (0.1mm)	Voids content (V/V%)	Filler content (M/M%)	Binder content (M/M%)	PRD (%)	Aggregate type
Materials laid in TRL test pavements											
TP2	E	100	1.23	0.090	0.21	61	3.56	4.4	3.2	96.8	Limestone
TP2	E	100	1.06	0.025	0.12	77	5.21	4.4	3.2	96.4	Limestone
TP2	G	100	1.87	0.271	0.11	77	1.80	4.4	3.7	99.2	Granite
TP2	G	100	1.60	0.204	0.13	63	4.24	4.4	3.7	98.6	Granite
TP3	J	100	1.04	0.017	0.13	101	6.36	5.5	3.4	95.1	Limestone
TP4	X	100	2.05	0.312	0.09	51	5.67	7.4	3.7	-	Limestone
TP5	LS	100	2.38	0.376	0.07	71	5.13	8.0	3.3	95.8	Limestone
TP5	LS	100	1.87	0.271	0.08	71	6.52	8.0	3.3	93.0	Limestone
TP5	SL	100	1.39	0.143	0.14	70	-	5.9	4.1	94.7	Slag
TP5	SL	100	1.34	0.127	0.07	70	-	5.9	4.1	93.0	Slag
TP7	M	100	1.97	0.294	0.08	61	5.38	6.0	4.0	-	Granite
TP3	K	50	2.76	0.441	0.16	48	9.29	5.7	3.4	-	Limestone
TP4	Y	50	3.24	0.510	0.09	52	4.96	6.4	3.3	-	Limestone
Materials laid in end-product specification trials											
M53	Area 1	100	1.30	0.114	0.12	80	2.54	8.8	4.5	97.5	Limestone
M53	Area 2	100	1.59	0.201	0.10	68	3.45	8.8	4.2	96.1	Limestone
M56	Area 1	100	1.74	0.241	0.11	80	2.20	8.2	3.9	100.0	Limestone
M56	Area 2	50	5.69	0.755	0.086	38	2.40	7.2	3.4	100.0	Limestone

* TP refers to a test pavement laid at TRL.

** The alphabet code refers to a particular material laid in a TRL test pavement.

For other materials such as DBM50 and HDM, the data is less extensive and therefore any estimate of their typical properties will be less reliable. Other data does exist, for example from the earlier trials of improved macadams reported in TRL Research Report RR 132 (Nunn et al, 1987). However, curing had occurred in these materials, which were tested approximately 6 months after laying and after storage in the laboratory at a temperature of between 20°C and 25°C.

Nevertheless, relationships have been obtained in this and other work that can be used to estimate the stiffness modulus of materials with a harder binder. These are listed below:

Equation 4 was derived by combining all the data in Table 2. In all the relationships, the penetration of the recovered binder was the most significant variable. Other mix variables may affect stiffness modulus but, in most of the data sets, their variation was not sufficient to obtain a relationship. These equations yield the stiffness moduli given in Table 3 for DBM50; the stiffness moduli for DBM50 materials given in Table 2 have also been included.

The limited data available on DBM50 shown in Table 3 gives a mean log stiffness of 0.54 (3.47 GPa) with a standard deviation of 0.12. Equation 3, which was based on stiffness measurements of 12 materials from 5 construction sites, predicts that the addition of 3% extra filler would increase the stiffness by 30%. This would give a mean stiffness for HDM of 0.66 (4.57 GPa). Although more confident predictions will be possible as more information becomes available, the stiffnesses given in Table 4 are probably close to the best estimates that can be made with current information.

These stiffnesses, which apply to measurements on newly laid material, may need to be adjusted when more information becomes available and they will certainly need to be adjusted if the method of calculating indirect tensile stiffness modulus or the test protocol is redefined. Table 4 also illustrates that there is a large scatter in the means of stiffness moduli of materials using a nominally identical grade of binder and that the distributions overlap. For example, the upper 5 percentile for DBM50 is estimated to be 5.06 GPa and the lower 5 percentile for HDM is 3.13 GPa.

M53: $\text{Log}_{10}(E) = 0.75 - 0.0072P - 0.247V_c$ $R^2 = 0.76$ 1.
M56: $\text{Log}_{10}(E) = 1.15 - 0.0112P$ $R^2 = 0.96$ 2.
RR132: $\text{Log}_{10}(E) = 0.81 - 0.0066P + 0.039F$ $R^2 = 0.94$ 3.
Table 2: $\text{Log}_{10}(E) = 0.91 - 0.0097P$ $R^2 = 0.60$ 4.

Where,
E = Stiffness modulus (GPa)
P = Penetration of recovered binder (0.01 mm)
V_c = Air voids content (V/V%)
F = Filler content (M/M%)
R = Correlation coefficient

TABLE 3

Stiffness moduli of DBM50

Site/source	Stiffness modulus (Log_{10})	Stiffness modulus GPa)	Comments
TP3 (K)	0.44	2.76	
TP4 (Y)	0.51	3.24	Sections of TRL pilot-scale test pavements.
M56 Phase 2	0.76	5.69	End-product specification trial.
M53	0.50	3.15	Derived from equation 1.
RR132	0.43	2.72	The stiffness of DBM50 relative to DBM, obtained using Equation 3, was multiplied by the mean stiffness of DBM given in Table 2.
Table 2	0.57	3.71	Equation 4. This value was predicted by combining the data in Table 2.
Mean	0.54	3.47*	* Geometric mean

TABLE 4

Estimate of stiffness moduli of standard macadams

Material	Mean stiffness modulus (Log$_{10}$) Lower 5 percentile	Mean	Upper 5 percentile
DBM	0.026 (1.06 GPa)	0.19 (1.56 GPa)	0.354 (2.26 GPa)
DBM50	0.376 (2.38 GPa)	0.54 (3.47 GPa)	0.704 (5.06 GPa)
HDM	0.496 (3.13 GPa)	0.66 (4.57 GPa)	0.824 (6.67 GPa)

Although stiffness classes in an end-product specification could be specified to match the properties of materials currently used in the UK, it may be more convenient to define a number of stiffness classes of roadbase and basecourse materials with equal divisions. Table 5 illustrates possible stiffness classes based on the estimate of the stiffness values of typical standard materials given in Table 4 with each stiffness class being 1.6 times that of the lower class. The terminology used for the stiffness classes refers to the generic classification of asphatic concrete (AC), to be adopted by CEN.

The supplier would need to pay more careful attention to the design of some DBMs to ensure that they exceeded the minimum requirement given in Table 5. There would be no problem with current DBM50 and HDM materials fitting into one or other of the stiffness classes. Four classes are suggested in this Table but further classes could be added if this was considered necessary.

The two highest stiffness classes can be compared with the mean stiffness moduli of some HDM and high modulus base (HMB) materials, shown in Table 6 that have been laid as part of road contracts and pilot-scale trials monitored by TRL. Also included are stiffness measurements on enrobé à module élevé (EME) a French high modulus material (Nunn and Smith, 1994).

This Table shows that all but one of the HDM materials would fall into the third stiffness class and all the HMB and EME materials would fall into the highest stiffness class listed in Table 5.

The implications for pavement design are discussed more fully in Appendix B and in Appendix C trials to aid the development of an end-product specification for bituminous roadbase are discussed.

4.2 CURING

The curing behaviour of bitumen macadams have been studied by Chaddock and Pledge (1994). These studies showed that the modulus can change considerably over the life of a road and that, although the voids content has an affect, it is not possible to predict curing from the composition variables of the mix. Furthermore, it has been demonstrated that curing of the structural layers can have a beneficial effect on the load spreading ability, deformation and fatigue resistance of the pavement (Nunn, 1994).

Curing also means that the pavement is most vulnerable to structural damage in its early life, while the performance properties of the roadbase and basecourse are still developing. The recent experience from the Norwich Bypass is an illustration of this effect (Haydon, 1994). Sections of the Norwich Bypass (A47) exhibited excessive deformation in the basecourse and roadbase layers under construction traffic. Material sampled 2 years later showed significant improvements in the stiffness modulus and dynamic creep modulus compared with measurements on the new material.

TABLE 5

Recommended stiffness modulus classes

Stiffness class	Current equivalent	Stiffness modulus lower limit (Log$_{10}$)
AC$_1$	DBM	0.1 (1.25 GPa)
AC$_2$	DBM/DBM50	0.3 (2.0 GPa)
AC$_3$	DBM50/HDM	0.5 (3.2 GPa)
AC$_4$	HDM/HMB*	0.7 (5.0 GPa)

* High modulus base.

TABLE 6

Moduli of HDM and HMB materials

Site (GPa)	Stiffness moduli	Material	Comments
A23	6.2 (upper layer) 5.6 (lower layer)	28 mm HDM	Roadbase materials. The measured mean void content was 1.9%.
M1	3.3	20 mm HDM	Basecourse
	2.6	28 mm HDM	Basecourse
	3.6	40 mm HDM	Basecourse
	3.3	40 mm HDM	Roadbase
PTF	5.7	28 mm HDM	
	4.6	28 mm HDM	Roadbase materials laid as test sections in the TRL Pavement Test Facility (PTF).
TRL	9.3	28 mm HMB	Basecourse with nominal 10/20 pen binder.
	7.2	28 mm HMB	Roadbase with nominal 10/20 pen binder.
	7.5	20 mm EME 1	Enrobé à module élevé class 1.
	6.0	20 mm EME 2	Enrobé à module élevé class 2.
A	6.3	20 mm EME 2	These measurements were made on materials sampled from 4 separate road contracts in France.
B	8.2		
C	8.2		
D	6.5		

Table 7, which gives measurements of the stiffness of material sampled from some older pavements, illustrates the degree of curing that occurs. These pavements were constructed using a DBM with a nominal 100 penetration grade binder.

Comparison of the stiffnesses in Table 7 with those in Table 2 demonstrates that the stiffnesses of dense macadam materials can increase by a factor of 4 or more over 20 years.

Ideally an end-product specification should stipulate both the initial stiffness and the future stiffness of a material. Attempts to define a laboratory accelerated curing test by Chaddock et al (1994) showed that it was potentially possible but much more work would be required to demonstrate the robustness of a test for a wide range of materials.

The most practical solution may be to base an end-product specification solely on the initial properties of the structural layers. The rationale is that the road is most vulnerable at this stage and, provided that the traffic growth is not excessive, the developing structural properties are likely to be sufficient to meet the future demands of the road. The initial design thickness could be conservative as a safeguard against a material that does not cure. This is unlikely to lead to the specification of excessive pavement thicknesses, because a roadbase layer 20 per cent thicker would have the same load spreading ability as the layer with double the stiffness.

4.3 END-PRODUCT SPECIFICATION FOR ROADBASE

The indirect tensile test would play an important role in the development of an end-product specification. However, safeguards will be required to prevent premature cracking and rutting to ensure that the roadbase is durable. The first trials on the M53 and M56 (Nunn and Smith, 1994) demonstrated the practicality of the indirect tensile test and pointed the way to the development of a full end-product specification. It was envisaged that this process will consist of a series of stages in which trials will be carried out under contractual conditions, and each step will depend on experience gained from the previous step and move closer toward the ideal of a full performance based specification. An approach of this type will enable all interested parties to take a part in the formulation of an end-product specification and it will ensure that the final product is acceptable, practicable and cost effective.

The experience gained from the M53 and M56 trial showed that detailed performance testing throughout a contract was time consuming and expensive. A preferred method would be to obtain approval for a *job-mix* based on testing material from a trial strip at the start of the contract. A further set of trials, similar in nature to those carried out on the M53 and M56, in which roadbase material is defined in a *job-mix* trial is therefore considered as the next stage. A possible

TABLE 7

Stiffness moduli of DBM from older pavements

Pavement	Age (years)	Layer	Mean stiffness modulus (GPa)	Comments
A500	20	Roadbase 1	4.8	
		Roadbase 2	4.5	Mean of 8 measurements for each layer.
		Roadbase 3	6.0	
A5103	20	Roadbase 1	4.3	Mean of 4 measurements for each layer.
		Roadbase 2	5.7	
A4091	35	Roadbase 1	6.5	
		Roadbase 2	5.4	Mean of 4 measurements for each layer.
		Roadbase 3	12.4	
M50	25	Roadbase 1	15.6	
		Roadbase 2	14.1	Mean of 4, 7 and 3 measurements.
		Roadbase 3	15.9	
M53	1	Basecourse	1.6	This is an increase of 30 per cent over the initial stiffness.
A47 Norwich Bypass	2	Basecourse and roadbase	4 to 7	The initial stiffness was in the range 2 to 5.5 GPa.

staged programme for progressing the work towards implementation could consist of:

Stage 1: Demonstrate the practicality of an end-product specification in road construction.

Stage 2: The *job-mix* approach using initial elastic stiffness and supporting tests described in Appendix C.

Stage 3: Further develop Stage 2 by inclusion of more performance testing.

Stage 4: By the end of Stage 3 the balance of the requirement will have moved away from the recipe to performance. However completion of a full end-product specification may need a further stage to investigate safeguards against durability problems and cracking if practical tests can be developed.

Appendix C describes a possible plan for a Stage 2 trial to follow-on from the Stage 1 trials carried out on the M53 and M56.

5. COMPARISON BETWEEN ITT AND 3-POINT BENDING TEST

The 3-point bending test has been used by TRL as the basic test to study the stiffness modulus of bituminous materials. This test, although well suited for fundamental research, is slow and expensive to operate. However, the stress system in the 3-point bending test is simple and amenable to analysis. The ITT enables data, albeit of a lower quality, to be collected quickly. The stress system in the ITT is biaxial in which the stresses vary continuously throughout the test specimen and, consequently, the computation of stiffness modulus relies on the use of linear elastic theory to relate the stiffness modulus to the deformation induced by the applied load. It can be argued that the ITT measures a quantity that is similar, but not the same as the stiffness modulus measured by the 3-point bending test.

Apart from the different nature of the stress system, there are two variables that are assumed in the calculation of ITT stiffness. These are Poisson's ratio and the effective frequency of the ITT load pulse.

5.1 POISSON'S RATIO

A direct comparison between the ITT and the TRL 3-point bending test was carried out on one of the first NATs to be made commercially available in 1988 and reported by Nunn and Bowskill (1992). The sinusoidal loading frequency equivalent to a rise time of 125 ms and Poisson's ratio was determined to give the optimum agreement between stiffness measurements using the ITT and the TRL 3-point bending test. The analysis indicated that the ITT load pulse was equivalent to a sinusoidal frequency of approximately 2.5 Hz and that Poisson's ratio was a function of temperature with values of 0.45, 0.35 and 0.25 at 30, 20 and 10°C respectively. Using these values a correlation coefficient of 0.95 was obtained between stiffness measurements on 22 materials using the ITT and 3-point bending test.

The weakness of this approach was that values obtained for the equivalent frequency and Poisson's ratio are not unique and any error in selection of the equivalent frequency will lead to errors in the determination of Poisson's ratio. For example, a choice of a lower equivalent frequency will result in lower predicted stiffness using the 3-point bending test and consequently, to obtain agreement with this test, a lower value for Poisson's ratio will be needed to calculate the stiffness using the ITT.

Since 1988, both the software and hardware in the NAT have been modified by the manufacturer. More recently in 1994 another comparison between the two tests was carried out. This comparison is illustrated in Fig 3 using the values of Poisson's ratio referred to above.

This shows that, while there is still a good correlation between the two tests, the results are not evenly scattered about the line of equivalence. In the latest comparison, the indirect tensile stiffness moduli are about 20% higher than those of the 3-point bending test. There are several possible reasons for this difference, ie:-

- hardware and software changes made to the test, by the manufacturer, since the earlier comparison.
- Poisson's ratio is lower.
- equivalent frequency is higher.
- deficiencies in the theory used to determine the ITT stiffness modulus.
- difference in test temperature between the two tests.
- a combination of the above.

Clearly what is required to settle this issue, is an independent determination of Poisson's ratio over a range of temperatures and materials.

Some light may be thrown on the variation in Poisson's ratio over a range of stiffness and frequencies by computing the values of Poisson's ratio required to make the ITT results, obtained in the two comparisons, agree with the results obtained with the 3-point bending test. These are plotted in Fig 4.

This figure shows that Poisson's ratio correlates weakly with stiffness modulus and that, it generally lies in the range

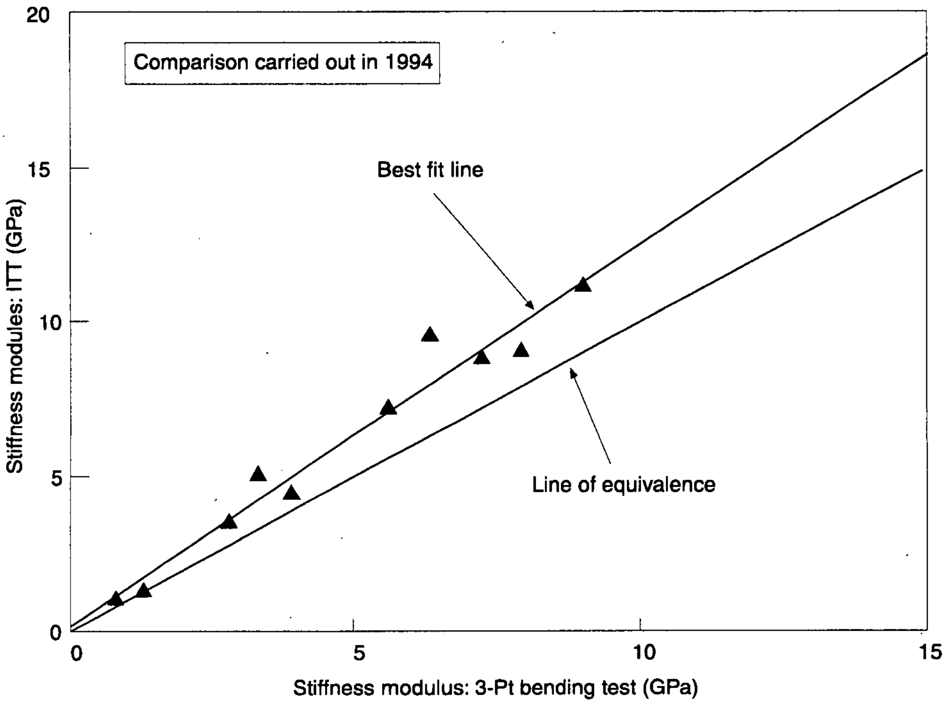

Fig 3 Comparison of ITT and 3-point bending test

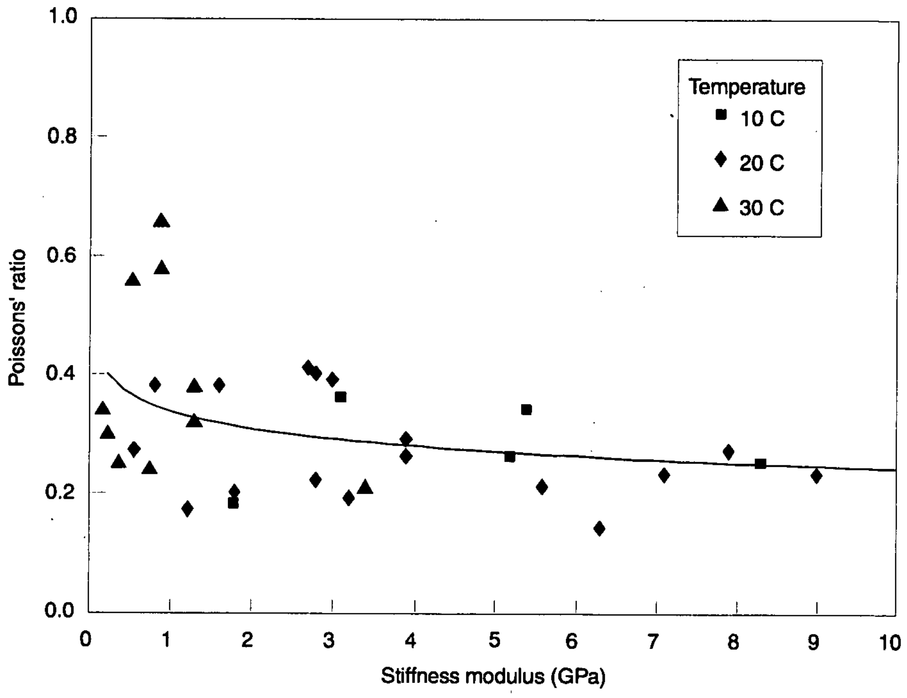

Fig 4. Poisson's ratio versus stiffness modulus

0.2 to 0.4. It does appear to be somewhat higher at low stiffnesses. However, these low stiffnesses were obtained by increasing the test temperature and consequently there is no way of determining whether the effect is related to higher temperature or lower stiffness.

5.2 FREQUENCY

It has already been mentioned that the frequency estimated to be equivalent to the pulse load of the ITT is debatable. The equivalent frequency can be defined as the frequency under sinusoidal loading that gives the same value of stiffness modulus as under the pulsed load of the ITT. If pulsed and sinusoidal loads were applied in the same test system this equivalence would be easy to determine. However, the concern has been to determine the equivalent frequency of the TRL 3-point bending test. There are two factors that have to be considered, namely:

a.) the different natures of the two test systems and,

b.) the equivalence between sinusoidal and pulse loading.

In the absence of a precise theoretical understanding of how the materials behave while being tested, the first factor can only be resolved empirically. The second factor can be resolved for loads applied to the same test system. This is examined in Appendix A.

If the definition given above is used, the equivalent frequency will depend on how the ITT stiffness modulus is defined. For example, the ASTM D 4123 method ignores the irrecoverable component of deformation at the end of the load pulse cycle and therefore gives a higher stiffness than the NAT method. An estimate of equivalent frequency based on the ASTM method would therefore be higher than that based on the NAT method.

What is apparent is that the ITT using the NAT method and the ASTM method and the 3-point bending test, all give measurements of a slightly different quantity. This is also explored in Appendix A.

Empirically, the equivalent frequency of the ITT with a rise time of 0.125 s has been shown to be approximately 2.5 Hz (Nunn et al, 1992). Appendix A shows that, using rheological model devised by Burgers (1935), the ITT pulse load is equivalent to a sinusoidal load of frequency 1.9 Hz for the NAT method of calculation, and 3.6 Hz for the ASTM method. The difference between 1.9 Hz and 2.5 Hz for the empirical comparison may be due to the different nature of the ITT and 3-point bending test systems and it is possible that a different equivalent frequency would be obtained for a comparison between the ITT and another test system, for example a sinusoidal push-pull test.

5.3 LOAD PULSE SHAPE

Different shapes of the load pulse are often observed in the indirect tensile test. The effect of the pulse shape is explored in section A.3 using a Burgers' model. This demonstrated that for the examples of pulse shape occurring in the standardisation trial (Leech, 1995) the measurement of stiffness modulus can differ by about 10% using the NAT method of calculation. The predicted differences will be even larger if the ASTM method is used.

The analysis shows that it is decay characteristics of the load pulse that has a strong influence on stiffness modulus as determined using the ASTM method. Whereas the NAT method is relatively insensitive to this.

6. CONCLUSIONS

1. The method of calculating the indirect tensile test stiffness modulus needs to be defined in the BS Draft for Development, BS DD 213.

2. The mean Log_{10} (stiffness modulus) offers the best way of expressing the mean stiffness.

3. The standard deviation of the Log_{10} (stiffness modulus) is approximately 0.10 for materials with the same ingredients and mixed, laid and compacted under nominally the same conditions. This standard deviation is the same irrespective of whether individual measurements, sampled from several square metres or from a whole contract, are considered or whether the mean values for materials from different sources are being considered. The standard deviation may be less than 0.10, if the sample area is reduced to a few square metres.

4. Estimates of the stiffness moduli of standard roadbase materials are given based on the limited data currently available. These estimates can be updated as more information comes available.

5. At the present time, it is not practical to include curing in a performance based specification. Materials should be specified in terms of their initial properties. Uncertainties about curing can be taken into account by specifying conservative design thicknesses.

6. Empirical comparisons between the indirect tensile test with a pulsed load and the TRL 3-point bending test using a sinusoidal load depend on assuming a value either for Poisson's ratio or the equivalent frequency of the pulsed load. The comparisons indicate that, if Poisson's ratio is approximately 0.35, the equivalent frequency is about 2.5 Hz.

7. The deformation response of a bituminous material under load, depends on elastic, irrecoverable and delayed-elastic responses within the material. Burgers' model shows that the relative proportion of these responses will depend on the shape of the load pulse and its frequency.

8. Burgers' model suggests that the ITT pulse load is equivalent to a sinusoidal load of 1.9 Hz, using the NAT method of calculating stiffness, when these different forms of loading are applied to the same test system. The difference between this and the 2.5 Hz obtained from an empirical comparison between the ITT and the TRL 3-point bending test is likely to be due to the different nature of the two stress systems involved. The equivalent frequency for the ASTM method is somewhat higher.

7. RECOMMENDATIONS

1. The points raised in this report concerning the method of determining stiffness modulus using the ITT and selection of Poisson's ratio should be resolved by the British Standards Institution Panel B/501/1/WG2. Convening an expert panel may offer the best means of reaching a consensus decision.

2. The structural properties of bituminous roadbase materials should be measured as part of the requirements of Clause 929 (Department of Transport et al, 1994) and a database should be established to collect this data. This would help in the development of performance standards and it would lead to improvements in the understanding of pavement behaviour.

3. A second stage of performance trials should be undertaken, to build on experience gained from the earlier trials on the M53 and M56 and reported by Nunn et al (1994). In these trials, target values for the structural properties should be specified and the Contractor should be required to demonstrate that his mix meets the requirements by laying a trial strip to SHW Clause 929.

8. ACKNOWLEDGEMENTS

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APPENDIX A: EQUIVALENCE BETWEEN SINUSOIDAL AND PULSE LOADING

The following analysis deals with a pulse and sinusoidal loading applied to the same test configuration. A bituminous material reacts to an applied load in a phenomenologically similar manner to the rheological model of viscous dashpots and elastic springs, known as Burgers' model (Burgers 1935), illustrated in Fig A1.

Ignoring, inertial effects, the same time dependent force F(t) is transmitted to the dash-pot, η_1 (irrecoverable component), the spring, k_1 (elastic component), and the spring and dash-pot in parallel, η_2+k_2 (delayed-elastic component), therefore the resultant deformation, x, is the sum of the deformation of all three elements given by the equations:-

$$F(t) = \eta_1 \frac{dx_1}{dt} \tag{A1}$$

$$F(t) = k_1 x_2 \tag{A2}$$

$$F(t) = \eta_2 \frac{dx_3}{dt} + k_2 x_3 \tag{A3}$$

$$x = x_1 + x_2 + x_3 \tag{A4}$$

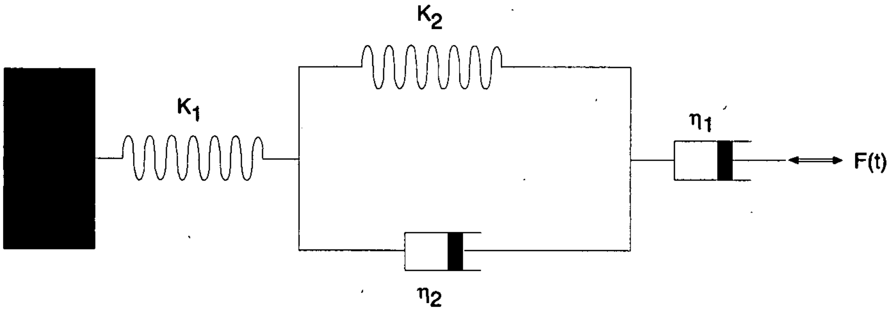


Fig A1 Burgers' model

These equations can be solved for a continuous sinusoidal loading, when:

$$F(t) = F_0 \sin(\omega t) \qquad \text{A5}$$

Where: ω is the angular frequency
F_0 is the load applitude

or for a load wave form similar to that applied by the ITT, in which case:

For $0 < t < 0.125$ s

$$F(t) = F_0 (1-e^{-\alpha t}) \qquad \text{A6}$$

For $t > 0.125$ s

$$F(t) = F_0 (1-e^{-0.125\alpha t})\, e^{-\beta t} \qquad \text{A7}$$

Where α and β are time constants for the rise and decay of the load pulse.

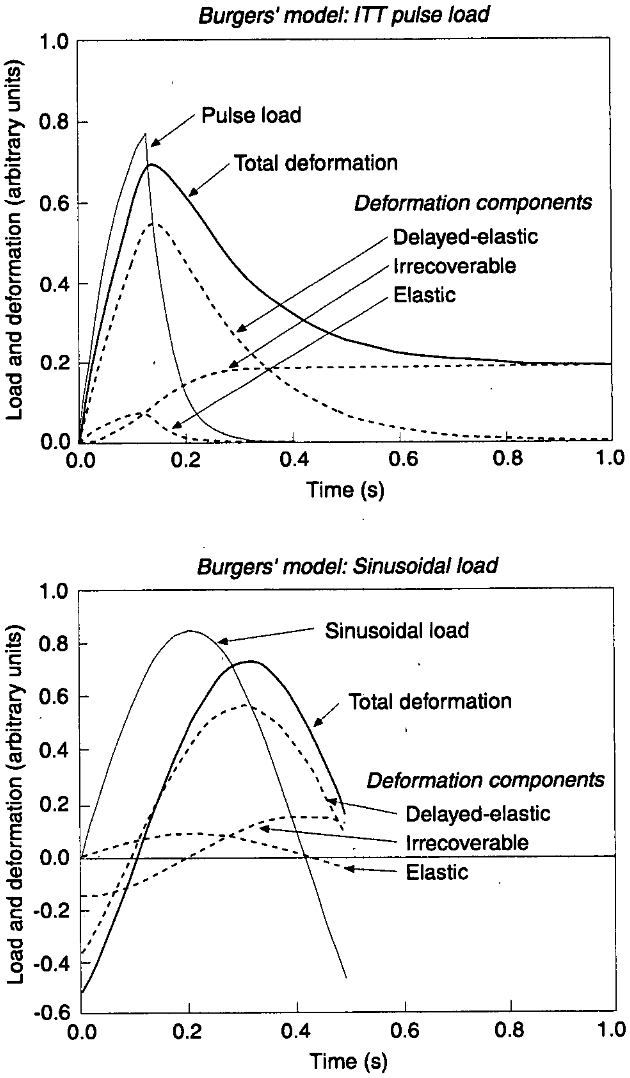
By assigning appropriate constants to the viscous dash-pots and the elastic springs the deformation behaviour of this system can be matched to the strain or deformation behaviour of a test system.

Figs A2 show the deformation response of a test specimen to pulse and sinusoidal loading, together with the deformation components due to the elastic, viscous and visco-elastic components. The visco-elastic and viscous contributions are often referred to as the delayed-elastic and irrecoverable components. The time between pulses in the ITT is 3 seconds.

A.1 EQUIVALENT FREQUENCY

The equivalent frequency of a pulsed load was defined in section 5.2 as the frequency under sinusoidal loading that gives the same value of stiffness modulus as under the pulsed load of the ITT. The effect on frequency of moving from the ITT system to a 3-point bending test can only be determined empirically. The equivalence between a pulse and sinusoidal load applied to the same test system is rather easier to determine using the above definition and assuming Burgers' model can be used to represent the behaviour of bituminous material. The equivalent frequency, using typical parameters in Burgers' model, is 1.9 Hz for the NAT method of measuring stiffness and 3.6 Hz for the ASTM method.

Comparisons of stiffness modulus measured using the ITT and the TRL 3-point bending test suggest that the effect of moving from the ITT stress system to the 3-point bending test stress system further increases the equivalent frequency. A sensible comparison could not be obtained between the ITT and the 3-point bending test at 1.9 Hz while maintaining a plausible value for Poisson's ratio.



Burgers' model: ITT pulse load

Burgers' model: Sinusoidal load

Fig A2 Response of Burgers' model to different load forms

A.2 METHOD OF MEASUREMENT

The result of a test to measure stiffness modulus depends upon the type of loading applied. This is illustrated in Figure A2, which shows that the predicted deformation responses due to a pulsed load and a sinusoidal load. The resultant deformation consists of delayed-elastic, elastic and irrecoverable components. The mix of these components changes as the measurement system or pulse shape changes. Table A1 gives the relative proportions of these components for different loading conditions and methods of determining stiffness modulus.

In this Table, the ITT deformation components, measured using the ASTM method, appear to be unrealistic with a negative contribution from the irrecoverable component. This is because when the deformation reaches a peak, the relative mix of the components is similar to that of the NAT method, but after the peak has been reached the irrecover-

TABLE A1

Components of measured deformation

Test system	Components of deformation (%) Delayed-elastic	Elastic	Irrecoverable
ITT NAT method	48	38	14
ITT ASTM method	63	49	-12
Sinusoidal load (1.9 Hz)	60	32	8
Sinusoidal load (3.6 Hz)	49	47	4
Sinusoidal load (5.0 Hz)	43	55	2
Sinusoidal Load (8.0 Hz)	33	66	1

able deformation component continues to increase because there is still a positive decaying load on the specimen, as illustrated in Fig A2. The irrecoverable deformation that accrues as the load is applied and then removed is subtracted from the peak deformation. The final irrecoverable deformation will, of course, be greater than the irrecoverable deformation when the total deformation is at its maximum value and the subtraction of this from the peak value will produce the negative component in Table A1. The elastic component will become zero when the load is removed and the delayed-elastic component will decay to a very small value at the end of the 3 s load cycle.

As the frequency increases the relative contribution from the irrecoverable component reduces and at the reference frequency of 5 Hz, used for pavement design purposes in the UK, only a small portion of the total deformation is due to the irrecoverable component. A decrease in the rise-time of the ITT load pulse will reduce the irrecoverable component and produce a mix of deformation components that more closely match those induced by a 5 Hz sinusoidal load.

This still leaves unanswered the question of what is the best means of measuring stiffness modulus using the ITT? The NAT and ASTM methods of determining stiffness produce a different mix of deformation components compared to those exhibited by 3-point bending at 5 Hz. The NAT method appears to be more representative than the ASTM method, which introduces a negative irrecoverable component. The load-spreading ability is controlled principally by the elastic and delayed-elastic components of the material and both methods would make a similar type of error in this measurement. To cancel out the irrecoverable component would require subtracting a proportion of the permanent deformation at the end of each load cycle, with the proportion depending on the decay characteristics of the load pulse. However, this resultant deformation would still not have the same mix of elastic, delayed-elastic and irrecoverable components as testing, for example, at 5 Hz with a continuous sinusoidal load. Therefore some compromise will be necessary if the ITT is adopted.

A.3 EFFECT OF DIFFERENT PULSE SHAPES

The standardisation trials reported by Leech (1995) showed that the shape of the load pulse could vary between different indirect tensile tests, in particular between the NAT and the MATTA. Burgers' model allows the effect of the pulse shapes on deformation and hence stiffness modulus to be estimated. There are a number of reasons why the pulse shape should vary. For example the amount of air required to pressurise the load actuator will affect the pulse shape. This in turn will depend on the position of the actuator relative to the test specimen. If it is set high, the actuator piston will be in a low position and the actuator with require a larger quantity of air to activate it. Also a high amplitude load pulse will have a different shape to a low amplitude pulse. Fig A3 gives two pulse shapes, that represent the range experienced in the standardisation trials, together with the predicted deformation responses.

Although the two pulses in Fig A3 are shown to have the same amplitude, this is unlikely. Pulse shape A has a faster initial rise-time which slows down as it reaches its peak. This pulse shape is more likely to arise for a high load amplitude where the pressure in the actuator is approaching that of the air supply reservoir. This pulse also decays fairly

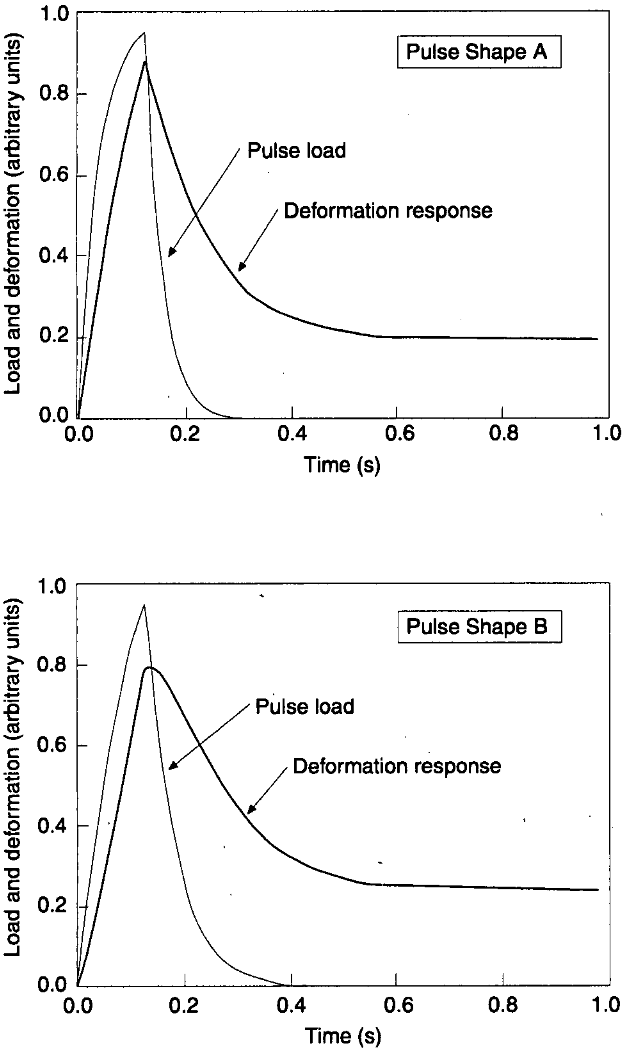


Fig A3 Comparison of responses to ITT pulse shapes

rapidly because the exhaust rate will depend on the pressure difference within the actuator and the atmosphere. Pulse shape B would be more typical of a lower amplitude load. Where the rise-time is more steady and the air will exhaust from the actuator more slowly because of the smaller pressure difference between the atmosphere and the air within the actuator.

The deformation response for pulse A is greater than for pulse B. This results in the stiffness modulus measured with pulse B being about 10% greater than that measured with pulse A using the NAT method of determining stiffness. On the other hand, if the ASTM method is used the difference will be over 20%. This is because not only is the deformation response lower with pulse B but because the load decays more slowly, the irrecoverable deformation at the end of the pulse cycle is higher. Both these factors will increase the stiffness modulus with pulse B relative to pulse A. Because of this it does seem that the ASTM method of determining stiffness produces a result that is more sensitive to pulse shape than the NAT method. Also, the way in which the load decays has a strong influence on the stiffness modulus determined using the ASTM method. Whereas, with the NAT method, it is relatively insensitive to the decay of the load pulse.

A.4 REFERENCES

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APPENDIX B: SPECIFICATION OF ROADBASES BY STIFFNESS MODULUS

B.1 INTRODUCTION

In this Appendix the implications for pavement design of specifying roadbases by modulus classes are considered. The modulus classes specified in Table 5 are based largely on measurements carried out using TRL's NAT and therefore the results will take into account the repeatability of this machine. The recently completed standardisation trial (Leech, 1995) has shown that the reproducibility of the test needs to be improved before absolute values of stiffness modulus can be specified with confidence.

There is also uncertainty about the relationship between the representative in-service stiffness of material and the initial stiffness of newly laid material before curing has occurred. Measurements from older roads has shown that standard dense bitumen macadam, containing a nominal 100 penetration grade binder, can increase in stiffness by a factor of 4 or more over 20 years, but there is less information on the curing behaviour of macadams that use a harder binder. It is plausible that these high modulus base materials do not cure to the same extent. However, in the foregoing discussion it is assumed that the curing behaviour of all classes of bituminous roadbase is similar. Nevertheless, this discussion should be considered in a conceptual manner because of the uncertainties regarding precision and curing.

B.2 DESIGN INDIRECT STIFFNESS MODULI

The characteristic stiffnesses of continuously graded asphaltic concretes given in Table 6 refer to the indirect tensile test stiffness moduli of materials soon after they are laid. Whereas the stiffness moduli specified by the analytical design method (Powell et al, 1984), that forms the basis for Department of Transport (1994) design standards, uses values of stiffness that are considered to be representative of roadbase material under in-service conditions and takes into account curing. Furthermore, measurements to determine representative in-service moduli were made using the TRL, 3-point bending test operating at a loading frequency of 5 Hz. Under these conditions the effective in-service stiffness was estimated to be 3.1 GPa for standard DBM with 100 penetration grade binder. This can be compared with 1.25 GPa, for the lowest stiffness class given in Table 5, determined from measurements carried out at a lower equivalent load frequency of 2.5 Hz on new, uncured material. These values suggest that the effective in-service stiffness measured at 5 Hz is 2.5 times that of new material measured using the ITT. The stiffness classes given in Table 5, using this factor, are adjusted to equivalent design stiffnesses in Table B1:

B.3 DESIGN THICKNESSES

The design thicknesses of fully flexible pavements using the design stiffnesses given in Table B1 are illustrated in Figure B1.

Specifying material by elastic stiffness modulus classes opens up the possibility of introducing an end-product specification for bituminous roadbase. This will give the supplier the incentive to produce more commercially attractive, lower cost materials to his own design. However, an end-product specification will require more than just a stiffness modulus criterion. A specification will need to be supported by a comprehensive range of tests to ensure that the material is durable and not susceptible to premature deformation and cracking (Nunn et al, 1994; Loveday, 1995; Curtis, 1995).

End-product specifications are used in many branches of civil engineering, for example concrete strength is assessed by crushing a cube and the grade of concrete is specified by its characteristic strength. This is defined as - *the value of strength below which 5 per cent of the population of all possible strength measurements of the specified concrete are expected to fall* (British Standards Institution; BS 5398, 1990). The British Standards Institution also defines a designed mix as - *a mix for which the purchaser is responsible for specifying the required performance and the purchaser is responsible for selecting the mix proportions to produce the required performance.* This technique can be used to specify bituminous roadbase by a characteristic elastic stiffness modulus class. These aspects are addressed more fully in Appendix C where it is suggested that the Contractor should demonstrate that he can achieve the mix design design requirements at the 5 per cent level of significance.

An advantage of this approach is that suppliers who do not have good quality assurance may have to aim for a higher target stiffness than suppliers with good quality assurance. This is illustrated in Figure B2.

TABLE B1

Proposed design stiffnesses

Stiffness class	ITT stiffness modulus at 20°C. (Log_{10})	Equivalent in-service design stiffness at 20°C and 5 Hz. (GPa)
AC_1	0.1 (1.25 GPa)	3.1
AC_2	0.3 (2.0 GPa)	5.0
AC_3	0.5 (3.2 GPa)	8.0
AC_4	0.7 (5.0 GPa)	12.5

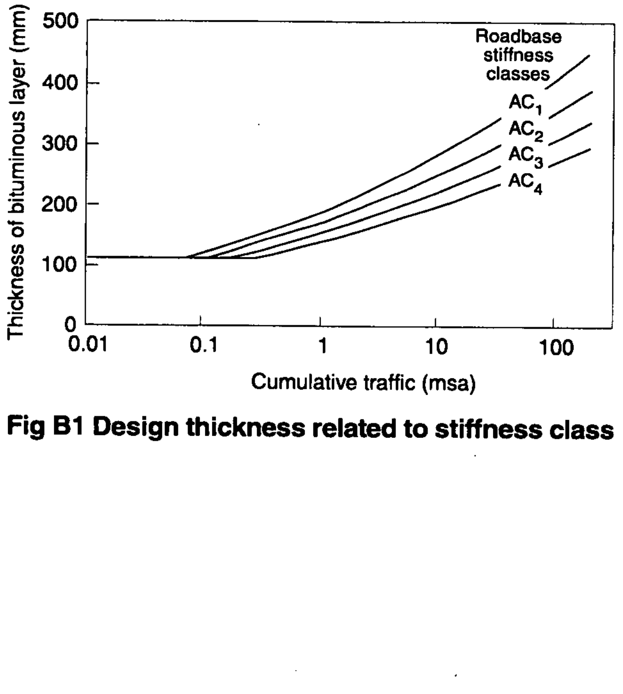

Fig B1 Design thickness related to stiffness class

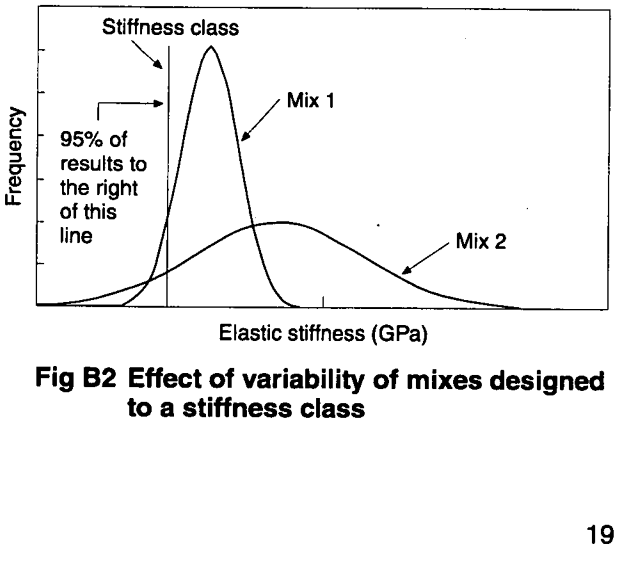

Fig B2 Effect of variability of mixes designed to a stiffness class

The curves are standardised normal distributions. Mix 1, which has the smallest variance, also has the lowest mean stiffness. Mix 1 is also likely to be more cost effective, from the suppliers point of view, than Mix 2 which may require a harder binder to produce the much higher target stiffness.

By using design charts similar to those illustrated in Figure B1, it would be possible for the pavement designer to state the design traffic required and the supplier would select the characteristic stiffness of the roadbase mix to be used. Costs would then depend on the layer thickness and the quality of the material to be used. This approach would be attractive to design, build and operate contracts, where the contractor has to consider maintenance aspects

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APPENDIX C: END-PRODUCT SPECIFICATION: STAGE 2 TRIAL

C.1 INTRODUCTION

The trials carried out as part of road construction contract on the M53 and M56 demonstrated that an end-product specification will provide an improved quality of material and that there are potential benefits for both the Client and the Contractor (Nunn and Smith, 1994). The study recommended a staged programme of trials for progressing end-product specification towards implementation. An approach of this type will ensure that the resultant method is acceptable, practical and cost effective.

The detailed performance testing in the earlier trials was time consuming and expensive. A preferred method would be to obtain approval for a *job-mix* based on testing material from a trial strip prior to laying for the main contract. During the contract, compliance would involve less onerous measurements of composition with some elastic stiffness testing. When more experience has been accrued, it may be possible to move towards a certification process that will dispense with the need for a trial strip at the start of each contract.

It is proposed in this Appendix that an end-product specification trial should be carried out as a part of a road construction contract in which target properties of a basecourse or roadbase material will be specified. The Contractor will be free to design the mix but he will be required to demonstrate that it achieves the target properties by testing material laid in a trial strip.

The target values suggested, are based on limited information. These target values may need to be adjusted as more information becomes available in the future. Also it will be necessary to take into account the precision and any other limitations of the performance tests.

C.2 OBJECTIVES

The objectives will be similar to the earlier Stage 1 trials carried out on the M53 and M56. The Stage 2 trial will examine a more practical method of specifying material based on an *agreed job-mix.* The Contractor will demonstrate that the mix has the required performance properties by testing material from a trial strip.

C.3 TRIAL STRIP

The concern that deformation prone mixes can be produced as a result of voids being over-filled with binder and filler has led to the introduction Clause 929 into the Specification for Highway Works (Department of Transport, 1994); *Design of DBM roadbase and basecourse, including HDM and DBM50.* This clause requires that the Contractor proposes a target mix composition and, by evaluating a trial strip, demonstrates that his target mix meets the performance related requirements of the specification. If this demonstration trial is satisfactory, the material becomes the *job-mix* and tolerances are fixed and the material is used as a conventional composition compliance specification for the remainder of the contract.

It is proposed that this approach is extended to the second stage trial of an end-product specification. A trial strip should be laid and, in addition to the requirements of Clause 929, the properties of the recovered binder, indirect tensile stiffness modulus and the creep stiffness should be measured. The testing required under Clause 929 is listed in Table C1 together with the additional testing for the trial of an end-product specification.

TABLE C1

Testing of Trial Strip

Test	Sampling	Comments
Clause 929 Testing		
Core Density (ASTM D2726)	6 x 150mm cores	3 core pairs in accordance with Clause 901.19
Air voids content (BS 598:Pt 104. Use bulk density by ASTM D3202	"	" "
PRD (Clause 901.19)	"	" "
Theoretical Max. SG (ASTM D2041)	3 samples of loose mixture	Taken at evenly spaced locations (BS 598:Pt 100)
Additional testing		
Indirect tensile stiffness modulus (BS DD 213)	18 x 150 mm cores	18 additional cores to be cut.
Core density (as above)	"	" "
Air voids content (as above)	"	" "
Dynamic creep stiffness (BS DD 185)	3 x 150 mm cores	
Properties of recovered binder	Combine 3 cores	

C.4 TARGET PROPERTIES IN MAIN CONTRACT

The Contractor will be required to demonstrate his capability of achieving the properties given in Table C2 in the main contract by first laying a trial strip. This will be followed by at least 2 lane kilometres (8,000 m^2) of the agreed *job-mix*. A minimum volume of binder is specified to ensure that the material produced is not too lean and lacking in durability. The trial would be a more convincing demonstration of the Contractor's ability to control his materials, if material of two, or preferably three, characteristic stiffness classes were laid.

AC$_1$ is used as an example in the following discussion in which the Contractor will be required to demonstrate his ability to achieve a stiffness modulus of greater than 1.25 GPa in the main contract at the 5 per cent level of significance.

C.5 PROPERTIES OF MATERIAL IN THE TRIAL STRIP

The material laid in the trial strip must satisfy the requirements of Clause 929. In addition the individual values of stiffness modulus, the mean log stiffness modulus and its standard deviation shall be reported together with density, measured composition and creep stiffness.

The trial strip required by Clause 929 is relatively small, and therefore the Contractor will only be able to demonstrate a probability that he will be able to achieve the required levels in the main contract. The trial strip becomes more representative as its size increases, but it also becomes less practical. To demonstrate statistically to a high level of significance that the Contractor's material is, say, just above the minimum requirement would, in effect, necessitate the whole contract becoming the trial strip.

To overcome this difficulty it is proposed that a pragmatic approach is adopted and that 4 criteria are applied to the measurement of stiffness modulus of the trial strip. These criteria are, firstly that if the Contractor demonstrates that the material has a high probability (95%) of exceeding the minimum requirement, the material of the trial strip would become the *job-mix*. The two intermediate criteria would apply to material that is likely to exceed the minimum requirement but further evidence is required. The forth criterion would be to reject material that is unlikely to achieve the minimum requirement. The four conditions listed in Table C3 are suggested and the decision process is illustrated in Fig C1.

The criteria and decisions listed in Table C3 are arbitrary. They are not very arduous, bearing in mind, that for the estimated mean stiffness modulus of conventional DBM, based on current information, is expected to be in the region of 0.19 (1.56 GPa) which very similar to criterion 1.

TABLE C2

Material Properties

Clause 929		
Measurement	Requirement	
Air voids (V/V%)	≤ 8%	
Air voids at refusal (V/V%)	≥ 1%	
Percentage Refusal Density	In accordance with Clause 901.19	
Additional Requirements		
Stiffness class	ITT stiffness modulus	
	Log$_{10}$(E)	E (GPa)
AC$_1$	≥ 0.1	≥1.25
AC$_2$	≥ 0.3	≥ 2.0
AC$_3$	≥ 0.5	≥ 3.2
AC$_4$	≥ 0.7	≥ 5.0
Nominal maximum aggregate size	Minimum binder volume (V/V%)	
40 mm roadbase	7.0	
28 mm roadbase	8.2	
40 mm basecourse	9.4	
28 mm basecourse	9.8	
20 mm basecourse	9.8	

TABLE C3

Criteria for acceptance

Criterion	Condition for mean stiffness modulus of trial strip	Decision
1	≥ 0.20 (1.58 GPa)	Contractor has demonstrated that he has a probability of over 95% of achieving the minimum requirement. His target material can become the basis of an *agreed job-mix* for the main contract.
2	≤ 0.20 (1.58 GPa) ≥ 0.14 (1.38 GPa)	Contractor has demonstrated that he has a probability of between 75% and 95% of achieving the minimum requirement. An additional trial area the same size as the trial strip shall be laid andif the mean stiffness of this area is greater than 1.25 GPa then the mix can become the basis of an *agreed job-mix* for the main contract.
3	≤ 0.14 (1.38 GPa) ≥ 0.10 (1.25 GPa)	Contractor has demonstrated that he has a probability of between 50% and 75% of achieving the minimum requirement. An additional trial area twice the size of the trial strip shall be laid and tested as though it were two trial strips. If the mean stiffness of each of these is greater than 1.25 GPa then the mix can become the basis of an *agreed job-mix* for the main contract.
4	≤ 0.10 (1.25 GPa)	Contractor has failed to demonstrate that he is likely of achieving the minimum requirement. Remove trial strip and repeat.

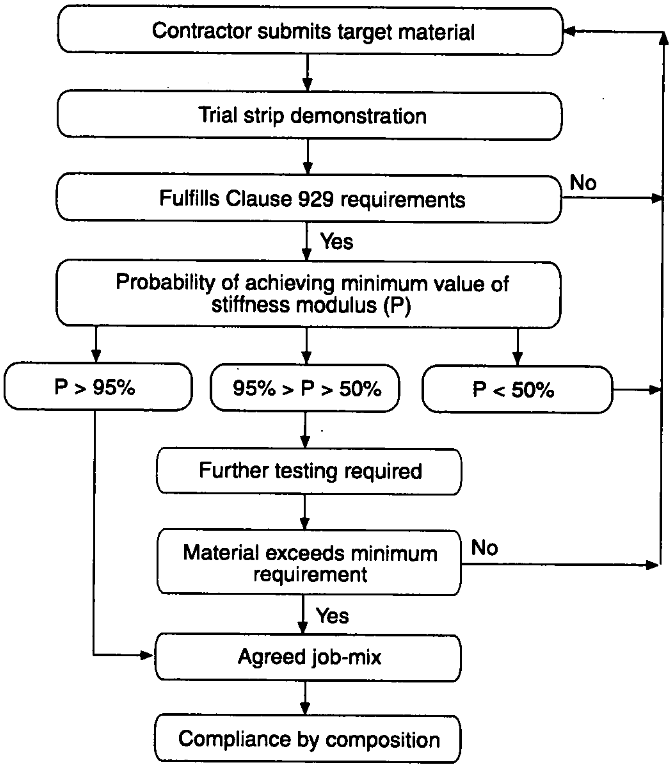

Fig C1 Flow chart for end-product specification trial

The added expense of further testing or laying additional test areas, to give greater assurance, act as an incentive to the Contractor to lay a good material at his first attempt.

C.6 TESTING IN THE MAIN CONTRACT

Conventional composition compliance testing should apply to the *agreed job-mix* for the remainder of the contract. However additional testing will be required to monitor the effectiveness of this form of specification. It would also be useful to investigate whether the indirect tensile test has a role in compliance testing. The indirect tensile stiffness modulus test is a moderately quick and easy test to conduct. Stiffness modulus is likely to be a good proxy for composition and the test is much easier and quicker than, for example, the PRD test.

The tests listed in Table C4 are proposed, for each 1,000 m^2 of laid material for each roadbase layer.

C.7 STIFFNESS MODULUS MEASUREMENTS FROM STAGE 1 TRIAL

The M53 and M56 trials provide the most information on the variability of measurements of stiffness modulus of nominally the same material laid throughout a contract. The trial sections of these contracts were divided into a number of sample areas and 15 indirect tensile tests were carried out in each area. These trials showed that the means of the 15 measurements from each sample area had a standard deviation of 0.06. If the measurements from each sample area were the same as taking 15 measurements at random from the whole Contract, this standard deviation would be 0.10/ 15 or 0.026. The fact that it is not, demonstrates that a small trial strip cannot be regarded as a representative sample of the main contract. It has been assumed that the standard deviation of the mean stiffness modulus of a trial strip is 0.06, the same as for the sample areas in the M53 and M56 end-product specification trial. This was used to establish the criteria in Table C3.

C.8 REFERENCES

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ASTM D3203 (1988). Standard test method for percent air voids in compacted dense and open bituminous paving mixtures. Washington DC.

TABLE C4

Testing in main contract

Material property	Test method	Sampling
Stiffness modulus	BS DD 213	9 x 150mm cores cut at regular spacing throughout test area.
Creep stiffness	BS DD 184	Cores 3, 6 and 9 (for information).
Density	ASTM D2726	All cores.
Max density	ASTM D2041	Loose samples of material taken close to cores 2, 4 and 6.
Composition	BS	As above
Properties of recovered binder	BS	Combine cores 1, 4 and 7 for every other trial strip. If the mean stiffness modulus of any test area departs substantially from the running mean after the first four areas are tested, then its recovered binder properties shall be measured.
Cores 2, 5 and 8 from each test area shall be stored on a flat surface in a cool place and delivered to TRL within 14 days of laying.		

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MORE INFORMATION FROM TRL

TRL has published the following other reports on this area of research:

TRL158	Standardisation trials of performance tests for bituminous materials. (1996). D Leech. Price Code J
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