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The compaction of bituminous base and base-course materials and its relation to pavement performance

by

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TRANSPORT and ROAD RESEARCH LABORATORY
Department of the Environment
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DIGEST OF REPORT

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THE COMPACTION OF BITUMINOUS BASE AND BASECOURSE MATERIALS AND ITS RELATION TO PAVEMENT PERFORMANCE	
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N W Lister and W D Powell

(Paper presented at the Annual Meeting of the Association of Asphalt Paving Technologists, Phoenix, Arizona, USA in February 1975)

In the United Kingdom the compaction of dense coated macadam roadbases and basecourses is controlled using a loose method specification. The overall standard of compaction obtained tends to be determined by the need to meet specifications about levels of the pavement layers and, in the case of basecourses, of surface regularity. Contractors have had little difficulty in meeting the compaction specifications and in consequence relatively little is known of the state of compaction presently being achieved in dense coated macadams or therefore of the scope for improving the performance of these materials by improving their compaction. Methods for improving compaction using conventional plant and assessment of the potential benefit of doing so have been studied in a joint programme between the Transport and Road Research Laboratory and the Asphalt and Coated Macadam Association.

CONCLUSIONS

1. An appraisal of the state of compaction being achieved in current UK construction practice revealed that variation of binder content had a significant effect on the void content of the compacted material but not on the final achieved values of Voids in the Mineral Aggregate (VMA). Ninety per cent of the values of void content were between 2 and 8 per cent whereas the range of values of VMA was considerably narrower, from 13 to 16 per cent.

2. The non-uniform pattern of rolling results in a considerable variation in density across the laid width, with peak values in the centre of the laid width and not in the critical wheel-path zones which determine structural performance of the material under traffic. This variation in density still exists after many years of heavy traffic. The performance of the material is therefore determined by its initial properties at the time of construction and thus good compaction at that time is essential.

3. There is therefore considerable scope for improving compaction in the wheel-path zones; improved compaction in these areas has been achieved using a second roller to increase the compactive effort towards the edges of the laid widths. The temperature at which material is laid and the degree of urgency given to rolling have also been shown to be very important in determining the state of compaction.

4. Satisfactory compaction can be achieved using thick lift construction but at the expense of some loss of riding quality when the base and basecourse were combined in one lift. The superior heat-retaining ability of a thick lift, in many ways advantageous, can also present construction problems under certain circumstances.

5. Worthwhile extensions of pavement life, or alternatively, reduction in pavement thickness, should be obtained if compaction in the wheel paths is increased to the peak values now being obtained in the centre of the laid widths. In-situ measurements of

dynamic modulus and deflection on experimental pavements and laboratory measurements of dynamic modulus and resistance to deformation and fatigue cracking all show that improving the compaction of dense coated macadam improves pavement performance. The way in which the dynamic modulus, important because it is related both to the load-spreading ability and to fatigue resistance, increases with improved compaction is shown in Fig 16 of the report. Some indication of possible performance benefits have been assessed directly by the Laboratory's deflection approach and also in terms of load-spreading and fatigue resistance.

6. The possibility of developing cheaper base and base-course macadams having binder contents lower than currently used is attractive; preliminary results from full-scale road experiments show considerable promise.

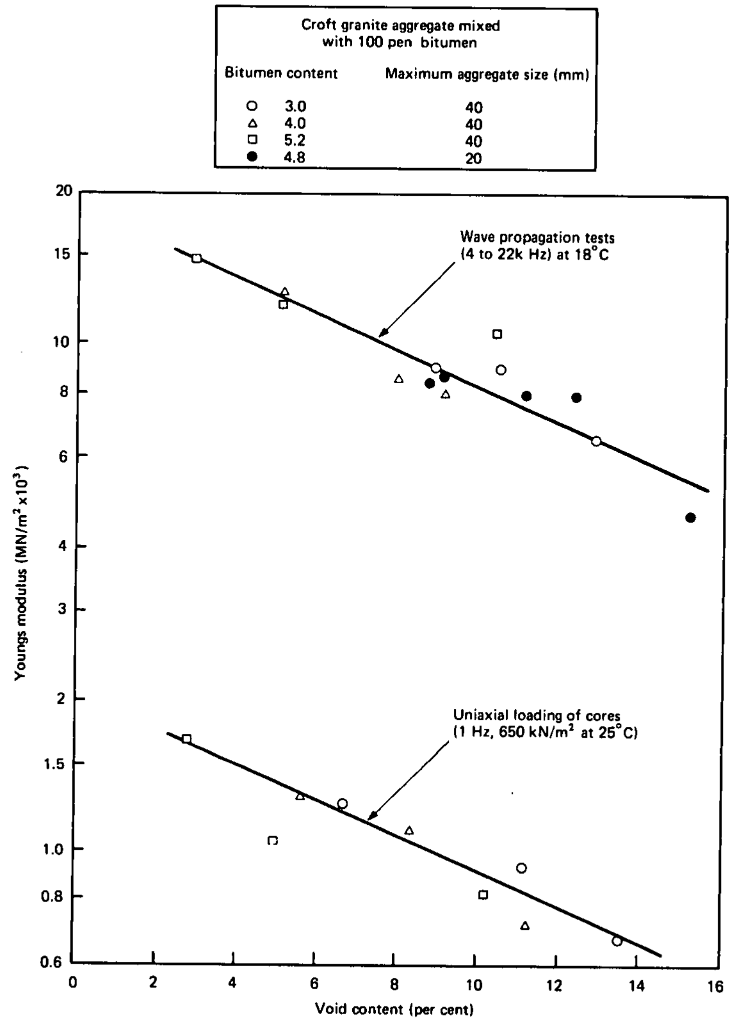

Fig.16 VARIATION OF DYNAMIC MODULUS WITH VOID CONTENT

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If this information is insufficient for your needs a copy of the full report, SR 260, may be obtained on written request to the Library, Transport and Road Research Laboratory, Old Wokingham Road, Crowthorne, Berkshire.

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SUPPLEMENTARY REPORT 260

THE COMPACTION OF BITUMINOUS BASE AND BASE-COURSE MATERIALS AND ITS RELATION TO PAVEMENT PERFORMANCE

by

N W Lister and W D Powell

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CONTENTS

THE COMPACTION OF BITUMINOUS BASE AND BASE-COURSE MATERIALS AND ITS RELATION TO PAVEMENT PERFORMANCE

ABSTRACT

An appraisal of the state of compaction of dense coated macadam bases and base-courses being achieved in current British construction practice reveals a considerable range of compaction levels and that the initial variation of density across the laid width persists after many years of intense commercial traffic. The effects of material composition, compactive effort, roller speed, rolling temperatures and stiffness of the working platform are analysed. An examination of the rolling procedures indicated that there is scope for increasing the level of compaction in the critical wheel path zone. Modified rolling procedures have been successfully used to improve compaction in the wheel paths.

A brief summary is given of British experience with thick lift construction including results from a full-scale road experiment. Good compaction was achieved at the expense of some loss of riding quality when the base and basecourse were combined in one lift.

The relation between performance of dense coated macadams and their compacted state has been studied in an associated programme of pilot scale and laboratory testing. Results show that worthwhile performance benefits are obtained if compaction in the wheel paths is increased to the peak values now being obtained in the centre of the laid widths.

The suitability of cheaper base and basecourse materials of binder contents lower than those currently used in the United Kingdom is also being studied and preliminary results showing considerable promise are presented.

1. INTRODUCTION

Full benefit from the use of bituminous materials in road construction and maintenance depends on achieving a satisfactory degree of compaction. Good compaction increases

a) the stiffness and strength of the material
b) the resistance to deformation
c) the durability of the mixture.

The relationships between compaction and these properties, which are important in controlling road performance, have not been established in quantitative terms. Durability in terms of resistance to weathering is of importance only in wearing courses. The study reported in this paper is concerned only with road base and basecourse materials and the dependence of the essential properties of these layers on compaction.

Specification of the method by which the layer is to be constructed is used for controlling compaction of bituminous road layers in the United Kingdom. In the USA the compaction process is frequently a three-phase activity: breakdown rolling, intermediate rolling and finish rolling[1]. Different types of roller are often specified for the separate phases of compaction. In contrast guidance in the current British Specification[2] is limited to definition of the type and overall weight of the roller to be used for the whole compaction process. The maximum permitted thickness of bituminous layers is 105mm and limiting values of temperature of the materials delivered on site and at the start of rolling are specified. The type of roller permitted for the compaction of all bituminous layers is an 8-10Mg smooth wheeled roller having a width of roll not less than 450mm or a multi-wheeled pneumatic tyred roller of equal weight. Surfacing courses must however be finished with a smooth wheeled roller.

In practice the three-wheel type is that most widely used for compaction of bases and basecourses in the United Kingdom. The material is rolled in a longitudinal direction from the sides to the centre of the laid width overlapping on successive passes by at least half the width of the rear roll. Although neither the number of rollers nor the number of passes is specified, materials must be compacted to meet other clauses in the Specification concerned with the levels of pavement layers in relation to the nominal finished road surface and, in the case of surfacing courses, to clauses regarding surface irregularity. The normal procedure therefore is for compaction to commence as soon as possible without causing undue displacement of the material and continues until all roller marks have disappeared.

British contractors have had little difficulty in meeting these Specifications, either for the traditional surfacing materials or for the dense bituminous bases the use of which has become widespread generally in the last few years, and the performance of bases and surfacings is considered to be generally satisfactory. In consequence little is known about the actual state of compaction being achieved particularly in the case of road bases. This is in contrast to the situation in countries where "end-product" specifications focus attention on the state of compaction and appear to provide incentive for contractors to use more sophisticated and expensive laying and compacting equipment than normally used in the United Kingdom. Lack of knowledge of what is being achieved, and therefore of the potential for improvement, prompted the Asphalt and Coated Macadam Association and the Transport and Road Research Laboratory to initiate a joint research programme in 1970 with a view to improving the efficiency and economy of bituminous construction. The programme included

a) establishment of compaction levels being achieved in current construction practice

b) studies of the factors affecting compaction in order to assess the potential for improving it in practice

c) development of practical methods of improving compaction

d) quantification of relationships between compaction and structural performance in order to establish the potential for reducing the thickness of better compacted bituminous materials.

Dense coated macadams are considered to be more difficult to compact than gap graded rolled asphalt, the other high quality bituminous material in common use; they also constitute a greater proportion of current output. Attention has therefore been concentrated on dense coated macadams.

2. COMPOSITION OF DENSE COATED MACADAM MATERIALS

The dense coated macadams generally used in the United Kingdom are continuously graded materials manufactured to a composition specification for both grading and binder-content. Table 1 gives a summary for dense bitumen macadam base and basecourse materials containing 40mm maximum size aggregate. There are also specifications for 28mm and 20mm maximum size aggregate and for tarmacadam materials.

3. DEFINITION OF THE COMPACTED STATE

Compaction results are quoted in terms of void content and percentage of voids in the mineral aggregate (VMA). Densities of compacted material have been determined primarily by scanning cores with gamma rays[3]. A gamma-ray backscatter gauge was also used to extend the information obtained from core scanning on a comparative basis.

Core scanning enables the profile of density through the compacted layer to be studied. Profiles of two different kinds of bituminous material in Fig 1, both show maximum density in the centre of the layer and minimum at the bottom and top surfaces. This characteristic distribution reflects the over-riding influence of temperature on the compaction process, and is a consequence of the surface layers always cooling more rapidly than the centre during rolling. Differences in the shape of the profile also reflect other factors such as aggregate shape and grading. Values of density and related parameters quoted in this paper are mean values taken over the whole profile depth.

4. PRESENT STANDARDS OF COMPACTION

A programme of coring was undertaken[4] at 12 road construction sites to determine typical levels of compaction of dense coated macadam bases and basecourses being achieved at the time of laying by present practice. At each site 12 cores were removed at 10m intervals along the centre-line of the nearside wheelpath assumed to be 0.9m from the nearside edge of the lane.

Figures 2 and 3 summarize the compaction results in terms of void content and VMA. The relatively narrow range of VMA values indicates that the compaction of the aggregate structure was similar in most layers. The much wider range of void contents is a consequence of the wide range of binder contents in the mixes studied: there are two distinct distributions within that shown in Fig 2 reflecting mixes to base and basecourse specifications. The effect of binder content and other construction factors is considered in detail later.

5. FACTORS DETERMINING THE LEVEL OF COMPACTION

To identify factors affecting the level of compaction obtained at the sites, the composition of materials used was analysed and laying and compaction procedures observed. The effect of several of these factors on compaction has also been studied under controlled conditions in pilot-scale trials in which the bituminous materials were compacted on a crushed stone sub-base and heavy clay subgrade of realistic stiffness. In the following each factor is considered separately.

5.1 *Aggregate type*

Figures 2 and 3 show that most of the layers measured contained limestone, reflecting the extensive use made of this aggregate in coated macadam in the United Kingdom. The few results for granite suggest that values of both void content and VMA about 2 per cent higher than for limestone and basalt are typical.

From the limited data available values of VMA for dense coated macadams produced from slag are also significantly higher than the overall average. The void contents for slag mixtures are also generally higher than those for other aggregates even though higher binder contents are specified for slag mixtures.

5.2 *Binder content*

The site studies showed that, over a wide range of practical binder contents, a change in binder content, although reflected by a corresponding change of void content, does not affect the final achieved values of VMA. This has been confirmed in pilot-scale trials in which dense coated macadams containing crushed Croft granite of 40mm maximum size mixed with 100 pen bitumen were compacted with an 8.5Mg tandem roller at temperatures between 100 and 105°C. Results are shown in Fig 4 for a range of binder contents wider than that permitted by the present specification and for widely differing compactive efforts. The binder fills the interstices in the aggregate matrix and affects the void content of the mix but does not influence the compacted state of the aggregate ie the VMA.

5.3 *Compactive effort*

The paving machines used at sites where paving was observed were Blaw-Knox machines driven on rubber tyres except at one site where a tracked Barber Greene paver was used. None of the pavers were fitted with vibrating screeds. The rollers used at the sites were the 8-10Mg three-wheel type except at one site where the second roller was an 8-10Mg tandem dead weight roller.

5.3.1 Definition of compactive effort: Any laid material is considered to be subjected to a roller coverage if some part of a roll comes into contact with it. Although the rear rolls of a three-wheel roller have a greater mass per unit width than the front roll, the pressure applied by the rear rolls is reduced in relation to its mass per unit width because of the greater roll diameter and consequent larger contact area with the material being compacted. In the absence of published information about the effect of roll diameter on compaction it has been assumed that front and rear-roll coverages of a three-wheel roller produce equal amounts of compaction; the number of roller passes may then be defined as half the sum of the number of front and rear-roll coverages. Tandem rollers do not present problems of definition of compactive effort. Comparison of results obtained by three-wheel and tandem rollers of similar mass suggests that the simple definition of roller passes given above is justified.

5.3.2 Correlation of roller passes with level of compaction: On site the rolling of the cooling bituminous material, whose compactability is therefore decreasing with time is intermittent and spread over a considerable period. This tends to mask relationships between density and roller passes. However, Fig 5 shows that systematic and significant results can be obtained; the data refer to dense bitumen macadam base and basecourse material rolled with 8-10Mg three wheel rollers.

The pilot-scale facility enabled rolling to be better controlled. The results of Fig 4 replotted in Fig 6 in terms of roller passes indicate that the level of compaction is approximately linearly related to the logarithm of number of roller passes up to the point of compaction refusal, established in a further trial as being 15 per cent VMA for granite aggregate to the specified grading.

Laboratory tests using powerful vibration have been developed at TRRL[6] to assess the compactibility of unbound aggregate and it is interesting to note that this predicted a minimum VMA of approximately 15 per cent. Further work is necessary with this test to assess its accuracy in predicting the refusal point for bituminous materials in general.

5.3.3 Distribution of roller passes across the laid width: The distribution of roller passes across a laid width of bituminous material is not uniform, more passes inevitably being applied towards the centre of the width; the non-uniformity is likely to be greater when a three-wheel roller is used. Because the performance of a road under traffic is largely determined by the behaviour of the pavement in the area of the wheel paths, areas which are not normally at the centre of the laid widths, a pilot scale trial was carried out to examine the degree of the non-uniformity of coverage and its consequences in terms of compaction.

The driver of an 8.5Mg three-wheel roller was encouraged to follow his normal rolling procedure in compacting a dense macadam containing Charnwood granite of 20mm maximum size and 4.3 per cent binder content at a mean temperature of 110^{o}C.

The extent of the variation of passes across the laid width shown in Fig 7 was surprisingly large with only 1 or 2 passes applied at its edges; the variation in the compacted state of the macadam was also considerable, the void content of just over 6 per cent recorded at the centre rising to values greater than 12 per cent at the edges.

Site studies have substantially confirmed the pattern of these variations; two examples are shown in Fig 8. Passes at the edge were 3 and 5 compared with 20 and 27 respectively at the centre, resulting in differential void contents of about 5 per cent in both cases.

Because the wheel paths are critical in determining pavement performance, the definition of the zone constituting the wheel path must be related to performance considerations. For this purpose it is not the relatively narrow width carrying the majority of the commercial vehicles but a rather wider zone that is most severely stressed by traffic. Its position on the road at any particular location will depend on the road's curvature and superelevation there. On Fig 8 it is shown as lying between 0.5 and 1.1m from the edge of the road, assuming that the edge of the road coincides with the edge of the laid width. This is probably conservatively narrow and on left hand bends the severely stressed area will certainly extend considerably closer to the edge of the road. It is therefore reasonable to assume that the pavement 0.5m from the edge of the road plays an important role in determining the road's performance. The void content at this point is typically 3 per cent greater than the minimum value between the wheel paths and there is clearly scope for improving compaction in this critical wheel path zone.

The limited evidence at present available suggests that peak values in the centre of the laid width obtained by current practice are close to refusal and these values therefore represent the likely limit of possible improvement in the compacted state of the wheel paths.

5.4 *Traffic*

To ascertain whether traffic could improve the compacted state and thereby possibly improve road performance, further coring after one year of traffic was carried out at sites where the compaction of dense coated macadam was initially studied during construction; the extent of surface rutting after this period was also determined.

Little or no densification occurred in most of the layers, the exceptions being at two sites where the materials were poorly compacted at the time of construction. At both sites a reduction in VMA of approximately 2 per cent was recorded for one base layer. These same two sites were also the only ones where any deformation in the nearside wheel path in excess of 3mm was observed. The traffic flow at both of these sites was less than 2000 commercial vehicles a day, considerably less than at some of the other sites where negligible densification was observed, indicating that the rutting was not primarily traffic associated.

That the variation in density of dense coated macadam layers across the lane width still exists after trafficking is confirmed by the results in Fig 9; these show the variation found at two full-scale road experiments after many years of traffic. The variation of density of the limestone basecourse and base material is typical of that in new construction. At one road experiment which had been subjected to a 4×10^6 standard axles of 8.2Mg (18,000 lb) the density variation was determined in both right and left-hand lanes. Assuming that peak densities were unaffected by trafficking a comparison of the peak densities of base layers measured in the two lanes show the right-hand lane to have been better compacted than the left-hand lane. The lower densities of the left-hand lane should have made it more susceptible to traffic compaction but the difference between peak density and density in the wheel path were the same in both lanes. Traffic therefore appears to have had no appreciable compactive effect on the dense macadam base.

At the other road experiment the gravel bound base was laid in three lifts the density of which again varied across the lane width. Traffic equivalent to 7.5×10^6 standard axles does not appear to have produced any significant densification in the base layers in the near side wheel paths except in the top layer where the base material was used experimentally as a basecourse material under a wearing course only 25mm thick.

These results indicate the importance of obtaining good compaction of dense coated macadam layers during construction: in roads of normal design no significant further compaction by traffic can be expected and the performance of the material is determined by the properties built into it at the time of construction.

Although rolled asphalt layers have not been studied to the same extent as dense coated macadam evidence from Fig 9 and from other sites shows that the variation in density across the lane width is less prominent for rolled asphalt than dense coated macadam. This is a reflection of the relative ease of compaction of rolled asphalt.

5.5 *Rolling speed*

Rolling speeds in the pilot-scale trials were of necessity normally limited to about 0.5m/sec whereas on site roller speeds are in the range 0.5 to 2.0m/sec. However a pilot scale trial established that speed of compaction in this range was unlikely to affect the compaction level significantly.

5.6 *Temperature of the material during rolling*

The temperature of the material determines the viscosity of the binder and is known to have an important effect on the compaction of bituminous materials. Minimum temperatures at the commencement of rolling therefore are specified for rolling hot bituminous materials in the UK, 80°C being the value for dense bitumen macadam containing 100 pen bitumen. Temperatures refer to those at the centre of the layer.

Fig 5 gives material temperatures at the commencement of rolling at 4 sites and demonstrates the great importance of temperature in determining the level of compaction achieved by any given compactive effort. The bitumen macadam rolled at 85°C is far more difficult to compact than that at 130°C: after 20 roller passes, the VMA of the cooler material is approximately 5 per cent higher than the corresponding value for the hotter material.

The effect of rolling temperature on compaction of dense bitumen macadam is presented more directly in Fig 10 over a range of temperature from 74 to 130°C. Material rolled at 95°C requires approximately 25 passes to attain the same VMA as material given 8 passes at 120°C.

Although Fig 10 indicates the trends to be expected when materials of different temperature are compacted, it cannot be used to predict accurately the compaction level obtained after a given number of roller passes. Factors such as the rate of cooling and the intermittent nature of rolling complicate the relationship.

It is of interest to consider the effect on compaction of the rate of cooling subsequent to commencement of rolling. Fig 11 shows the variation of temperature with time measured at two sites and also indicates the timing of roller passes applied 0.9m from the edge of the laid width. The material at both sites was dense bitumen macadam mixed with 100 pen bitumen. Conditions at these two sites were very different; at the first the material was laid as hot as restrictions on delivery temperature would allow and laid in warm, calm conditions; whereas at the second the temperature at commencement of rolling was just above the minimum specified and compaction took place in cooler and windy weather. Adverse ambient conditions cooled the material laid at the lower temperature almost as quickly as the much hotter material in more favourable conditions. Although rolling was carried out at roughly the same rate on both sites 12 passes were applied at temperatures above 80°C at the first site compared to only three at the second. The result in terms of compaction was that the hotter material was compacted to a VMA of 13.5 per cent whereas the corresponding value for the colder material was 18.5 per cent.

In adverse conditions, particularly in winter, the temperatures at the commencement of rolling are generally maintained well above the minimum specified and the conditions at the second site are not common. However the pattern of results presented in Figs 10 and 11 indicate that there should be scope for increasing compaction or improving its efficiency by increasing the number of roller passes at higher temperatures.

6. THICK LIFT CONSTRUCTION

Practice has been to lay bituminous materials in relatively thin lifts of 75mm or less; this facilitated control of levels of thin layers and hence that of the finished surface itself. It was also generally believed that better compaction was achieved by the use of thin lifts because of the higher stress concentration applied.

In limited trials some years ago both dense bitumen macadam and tarmacadam were however compacted satisfactorily in lifts up to 130mm thick, the thicker lifts retaining heat longer[7]. The satisfactory outcome of these trials prompted an increase in the maximum permitted thickness of lift to the current value of 105mm. A computer programme has been successfully developed at the Laboratory to predict the rate of cooling of bituminous layers from a knowledge of ambient conditions and physical properties of the material; this is similar in concept to work reported in the United States[8] and Germany[9]. The distribution of temperature through a thick lift and one of normal thickness 30 minutes after laying, when rolling should still be in progress, is predicted in Fig 12. Comparison of curves 1 and 2 and of 3 and 4 illustrate the superior heat retaining ability of thick lift construction under different conditions. Curve 5 represents the condition of a thick lift base laid hot to counteract the adverse wintry conditions. A skin of relatively cold and stiff material on the upper surface rests on an extremely hot mass, the centre temperature having only dropped by 2°C over a thirty minute period. A distinct danger of cracking the surface material and of lack of stability of the mix under the roller exists under these conditions.

Lack of stability was in fact encountered in precisely these circumstances in the thicker lifts of an experiment constructed by the Laboratory at the Sevenoaks By-pass on A21 to investigate the effect of thick lift construction in gravel asphalt on compaction, riding quality and accuracy of surface levels[7]. Good compaction was achieved in all thicknesses of asphalt employed. The specifications regarding surface irregularity and level could not be met on the thickest layer, a combined base and basecourse 240mm thick. The laying of the wearing course improved the final surface finish to within specification but under traffic the riding quality deteriorated more rapidly than that of the pavement containing base layers of conventional thickness. The most successful form of thick lift construction was the single life of base 175mm thick. The irregularities at its surface were reduced by the laying of conventional surfacing courses to give a final surface of acceptable regularity whose deterioration under traffic has been no worse than the pavement laid to a conventional thickness. Specified levels were also achieved without difficulty.

A pilot scale trial has since been carried out to determine whether the good compaction in thick lifts of gravel asphalt could also be achieved in macadam mixes of greater stability. 20mm Charnwood granite aggregate mixed with 4.3 per cent binder was compacted to thicknesses between 90 and 145mm by a 8.5Mg three wheel roller. Fig 13 shows that compaction of the 145mm thick lift was at least as good as that of a lift of conventional thickness. The experimental bay was too short to provide any meaningful measurement of surface irregularity; unacceptable irregularity is however less likely than on gravel asphalt.

The results of experiments in thick lift construction are therefore encouraging but further experience is required on the road before it can be recommended for general use.

7. POSSIBLE METHODS OF INCREASING COMPACTION IN THE NEARSIDE WHEEL PATH

One method of increasing compaction in the nearside wheel path, only possible where a hard shoulder is being constructed, is to lay the hard shoulder and left-hand lane in a single pass of a paver equipped with a wide screed; the position of the nearside wheelpath would then be near the centre of the laid width, that is, the area which receives the greatest number of roller passes.

An alternative approach capable of more general application is by modifying the pattern of rolling operations. A road trial has been carried out to investigate the effect of three alternative rolling procedures.

a) The conventional rolling procedure using 2 three wheel rollers, each of mass 8-10Mg for comparison with two modified rolling procedures.

b) The primary roller, an 8-10Mg three-wheel roller, was used in a conventional manner and was followed by the second roller, an 8-10Mg tandem deadweight roller, concentrating on compacting the edges of the laid width.

c) Two three wheel rollers were operated in tandem about 5m apart, so that more passes are made at higher temperatures. The approach was suggested by Lilja of the National Swedish Road and Traffic Research Institute[10].

A dense bitumen macadam containing limestone aggregate of 40mm maximum size and 4 per cent bitumen (100 pen), was compacted to a thickness of 85mm, the mean temperature at mid-depth during rolling being 95°C. Fig 14 summarizes the compaction results and also shows the distribution of roller passes across the laid width for the three procedures.

Procedure c) gave slightly better overall compaction than the normal procedure, probably because the total number of passages in the longitudinal direction, irrespective of lateral position, was greater. However the procedure proved difficult to operate and the aim of obtaining more passes at higher temperatures, at least in the wheel-paths, was not fulfilled and the variation of passes and compaction level across the laid width remains typical of that obtained by conventional rolling.

The edge rolling procedure b) increases the number of passes in the critical wheel-path zones at the expense of the passes between the wheel paths. Consequently, lower values of VMA were achieved in the wheel paths and the minimum value of VMA does not now occur at the centre of the laid width. This procedure produced better compaction in the wheel paths without any apparent detrimental effect on surface finish and further site studies are planned to confirm these promising results.

A further alternative, that of pre-heating the underlying layer to restrict the drop in temperature of the layer being compacted, as suggested in the work of Frenzel, Dickson and Corlew[11] and others[12] is presently under investigation.

8. THE RELATIONSHIP BETWEEN COMPACTION AND PAVEMENT PERFORMANCE

Attainment of higher densities in the neighbourhood of the wheel paths would be expected to result in improved performance of the pavement under traffic provided that the condition of zero voids is not reached or closely approached in so doing. There is little evidence relevant to British practice of the relationship between compaction and structural performance and the full scale road experiments conducted by the Laboratory have not included the state of compaction of bituminous materials as an explicit variable. Evidence of this nature is, however, required in order to assess whether the possible benefits in performance which should result from obtaining improved standards of compaction are sufficient to allow significant reductions in pavement thicknesses or extensions of design life to be made.

Parameters considered to be related to pavement performance have therefore been examined during the programme of pilot scale investigations into factors affecting the compaction of dense bitumen macadam.

Parameters which have been studied in detail are

a) the deflection of the macadam base and its foundation
b) the dynamic modulus of the macadam
c) the tracking of cores of macadam at elevated temperatures.

In addition limited numbers of laboratory fatigue tests and tracking tests on slabs have also been made. The conclusions regarding the relation between performance and the compacted state drawn from the study of any one parameter are not by themselves convincing for reasons which will be discussed. By considering the results of all three investigations as a whole broader based conclusions emerge.

8.1 *Deflection*

Deflection of the complete road pavement has been correlated with performance under traffic[13] and the inclusion of a sub-base and subgrade of realistic strength in the pilot-scale facility allows deflection of the experimental pavements to be used to examine the relation between performance and the compacted state.

Deflection measurements were taken on the top of the crushed stone sub-base and on the compacted macadam bases, the latter results corrected for the effects of temperature to an equivalent standard temperature of 20°C. Variations in foundation stiffness between experimental sections as reflected by deflections measured on the top of the sub-base were also allowed for. The considerably greater stiffness of the better compacted material is reflected in the relation between deflection and void content shown in Fig 15; the trend is readily distinguishable for individual binder contents. The same picture emerges when the results are plotted in terms of VMA.

The deflection of the finished road surface has been correlated with pavement performance under traffic. The deflections in Fig 15 have therefore been adjusted to allow for the effect of a 40mm and a 100mm thickness of rolled asphalt surfacing again using reference 13 and the results given on the same diagram. A decrease in void content from 13 to 3 per cent (the latter figure is close to refusal for the material) results in a decrease in deflection from 64 to 48 x 10^{-2}mm. The relation between deflection and performance in reference 13 indicates that this change would more than double the critical life of the pavement up to the point where overlaying is necessary.

The decrease in deflection brought about by raising the compacted state of the base in the wheel paths by 3 per cent to that of the peak value is between 7.5 and 9.5 per cent for a pavement with a 40mm rolled asphalt surfacing, the actual percentage depending on the initial state of the compacted material. The corresponding increases in pavement life are 30 and 35 per cent, equivalent to reductions in the combined thickness of the bituminous surfacing and base of about 5 per cent. With the thicker 100mm surfacing the reductions in deflection are rather smaller but correspond to reductions in thickness of the order of 6 per cent.

The above analysis has been carried out on results obtained on experimental areas in which the same weight of material per unit area was laid and compacted. The quantified improved behaviour is therefore not attributable to the presence of more material in a better compacted layer and no adjustment of benefit to allow for better compaction is required.

The results suggest that a significant reduction in the thickness of dense-bitumen macadam bases could therefore be the consequence of consistently achieving a compacted state in the nearside wheelpath similar to the peak values already being achieved in between the wheelpaths.

The deflection approach can be criticised on the grounds that the stiffness of the foundation varied considerably between the test sections, and that the relation between deflection and performance used was not explicitly derived for pavements with bituminous bases of different compacted states. However a second analytical approach ignoring the effects of foundation stiffness yielded a similar relation to that shown in Fig 15 and examination of limited data from pavements with rolled asphalt bases at Alconbury Hill indicated that the state of compaction did not appear to affect the deflection-performance relationship.

8.2 *Dynamic modulus*

The dynamic moduli of the bitumen macadam base and basecourse laid in the pilot scale trials were measured in-situ using a wave propagation technique[14]. Low level sinusoidal loading was used to generate flexural waves in the base over a range of frequencies between 4 and 22 kHz and their velocity of propagation measured. The relation between velocity and wavelength depends on the density and modulus of the base; for the purposes of comparison the modulus was evaluated in terms of the velocity approaching zero wavelength.

The common relation obtained between Young's Modulus and void content for the four materials studied is given in the top half of Fig 16; a substantial increase in material stiffness results from better compaction, a three per cent reduction in voids bringing about a 26 per cent increase in the modulus of an initially well compacted (5 per cent voids) macadam. The relation of stiffness to compactive effort in terms of roller passes is illustrated in Fig 17 where Young's Modulus is plotted against VMA.

Because of the unrealistically high frequency employed in the test method values of moduli obtained are much larger than those relevant to the road situation. A limited number of cores taken from the experimental pavements were tested in the laboratory at Nottingham University using more realistic stress levels and loading frequency[15]. The results are given in the lower half of Fig 16 and confirm the rate of change of stiffness with void content, the actual values of moduli being about one decade smaller.

The possible consequences of stiffer base materials on road performance are considered below.

8.2.1 Fatigue behaviour: Increasing the modulus of the base increases the flexural stresses within the base. For a simple pavement considered as a single elastic layer of thickness h and modulus E_1 on a soil foundation of modulus E_2 the maximum tensile stress at the bottom of the base has been shown to be proportional to[16]

$$\log\left(\frac{E_1}{E_2}\right)$$

Increasing the modulus of the pavement will therefore increase the stresses generated within it by a relatively small amount, the increase depending on the temperature of the bituminous material and on the stiffness of the road foundation. On the other hand the tensile strain level at the bottom of the base, generally accepted as being the parameter which determines the resistance of bituminous materials to cracking under traffic, is related to moduli by an expression of the form

$$\varepsilon \propto \left(\frac{1}{h}\right)^{1.8} \cdot \log\left(\frac{E_1}{E_2}\right) \cdot \left(\frac{1}{E_1}\right) \qquad \text{.............} (1)$$

The tensile strain in the base decreases with increasing pavement stiffness for all practical circumstances. Fatigue life is related to the level of the transient strain (ε) by the expression $N = A \left(\frac{1}{\varepsilon}\right)^m$.

where N is the number of repetitions of strain to cause cracking and A and m are material constants; m is quoted as having a value of about 4 for dense bitumen macadam[17]. A small increase in modulus of the base therefore results in a considerable increase in life as a consequence of the decrease in strain in the material.

A limited number of laboratory fatigue tests have been carried out, primarily to establish whether increased fatigue life resulted directly from a better compacted state, as distinct from the consequence of the stiffening discussed above. The results summarised in Fig 18 show that for the leaner material (3 per cent binder) an appreciable improvement results from decreasing the VMA from 18-20 per cent to the virtually fully compacted state of 15 per cent.

The richer mix with a binder content of 5.2 per cent demonstrated superior resistance which, however, is independent of the compacted state in the range 15-21 per cent VMA. Improving compaction of this material results in greater stiffness and therefore a longer life without effectively further increasing the value of parameter A.

The apparent promise of greatly improved fatigue performance in the road from better compacted materials has however to be considered in relation to the fact that there is virtually no evidence in the United Kingdom of failure by fatigue cracking of bituminous base materials to present specifications. If there were, the percentage increase brought about by better compacted and therefore stiffer materials would depend greatly on temperature used to characterize the pavement in the analysis.

Equation 1 indicates that the highest strain levels are obtained with low values of pavement modulus and this is confirmed in strain measurements made on experimental pavements shown in Fig 19; warm and hot weather conditions would control fatigue behaviour. Under these conditions equation 1 indicates that a reduction in the thickness of a pavement made of the stiffer material to give the same value of tensile strain as that of a material of lower stiffness (with 3 per cent greater voids) is in the range 3 to 8 per cent.

8.2.2 Load spreading capacity: In this country deterioration of pavements with bituminous bases is manifested by the development of deformation in the wheelpaths, with cracking of the surface taking place only at a late stage. Deformation is seasonal, taking place primarily in warm weather when the bituminous materials have a low modulus and particularly in the late spring when water table levels are often still high[18]. Fig 20 shows these characteristics in a section of the full scale road experiment at Conington Lodge; all pavement layers and the subgrade contribute to the developing deformation. The stresses transmitted to the sub-base and sub-grade are therefore sufficiently large for any improvement in the load spreading ability of the bituminous base to be beneficial to pavement performance.

The magnitude of vertical stress zz at the formation level should be related to the likelihood of deformation taking place in the sub-grade. Using the same nomenclature as before[16],

$$zz \propto \left(\frac{1}{h}\right)^{1.85} \cdot \left(\frac{E_2}{E_1}\right)^{0.64} \qquad \text{............. (2)}$$

Increasing the modulus of the macadam by 25 per cent reduces zz by 16 per cent and from Equation (2) reduction of the pavement thickness by about 10 per cent will give the same value of stress zz under the stiffer pavement. There is little evidence as to which sub-grade parameter is most directly related to the fatigue resistance of the sub-grade; using vertical sub-grade strain as the relevant parameter a similar conclusion is however reached.

8.3 *Wheel tracking*

Fig 20 indicates that up to half the surface deformation of a pavement incorporating a bituminous base and surfacing takes place in these two layers; their deformation characteristics are therefore important in determining pavement performance.

The wheel tracking test[19] was used to study the stability of base and basecourse materials. The tests were on 150mm cores cut from the experimental sections and were carried out at the standard test temperature of 45°C. This is approximately the highest temperature ever reached at the top of the basecourse in the United Kingdom; a limited number of tests were therefore also made on base material at 32°C, more typical of the highest temperatures recorded in the middle of the base layer. Results expressed in terms of the depth of track at the centre of the specimen after 40 minutes operation are given in Fig 21.

The few measurements made on base material at 32°C gave a similar trend and absolute values for the better compacted material lower than values obtained at 45°C.

The results presented indicate the desirability of attaining the maximum possible level of compaction. Of the three different experimental approaches, the tracking test, although valuable from the point of view of its convenience and speed, is the furthest removed from the reality of the road. In particular the regime of applied stress is unrealistic; the flexural stresses present under traffic are absent in the wheel tracking test.

In an attempt to overcome this a limited number of more realistic tracking tests were carried out on slabs of macadam base material mounted on a resilient artificial foundation and trafficked at 42°C by a pneumatic tyre loaded to 20 kN. The results confirmed the dependence of deformation resistance on the compacted state, the slope of the relation being greater than that shown on Fig 21.

9. BITUMEN MACADAMS OF LOW BINDER CONTENTS

The work reported has all been carried out on crushed natural rock to the present grading specification with binder contents not less than the lower limit of the specification for dense macadam base materials.

The way in which deflection, modulus and deformation resistance change with binder content suggest an alternative approach to the construction of more economic macadam bases. For a given VMA increasing the binder content decreases the deflection and improves performance assessed on an empirical basis. The increase in modulus with binder content improves the load spreading ability by decreasing stress levels in the sub-base and subgrade and also improves fatigue resistance. Deformation resistance of the material appears to change little over the range of binder content examined although it is possible to question this conclusion because of the experimental approach used. On the other hand it has been shown that improving the compacted state improves all these aspects of performance. Equal performance from bases of lower binder content, better compacted in the wheel path areas, should therefore be possible. This is an attractive approach in view of the recent unprecedented rise in the price of bitumen which has resulted in the cost of binder approaching half that of the laid material as compared to compaction costs which are only about one per cent of the total.

Macadams having a range of binder contents between 2 and 3 per cent were in fact incorporated in the full scale road experiment built by the Laboratory in 1963 on Wheatley By-pass[20]. The eight sections included three to the present grading Specification and five to two coarser gradings, all using Charnwood granite aggregate; details are given in Fig 22. No particular difficulties in compacting the bases were experienced at the time of construction. The compacted state of the various bases is at present under investigation.

Table 2 shows that the performance of the sections with bases of low binder content expressed in terms of their surface deformation is generally at least as good as the sections containing the richer mixes; this is also reflected in the deflections of the sections. However the pavement thickness employed in the experiment corresponds to a design life of about 30×10^6 standard axles compared with traffic of 4.5×10^6 standard axles carried so far by the sections over a 10 year period; both deformations and deflections are, as could be expected, correspondingly small and it must be therefore concluded that all the sections are very far from any condition approaching failure. Thus, evidence in terms of full scale road performance for the employment of bases of low bitumen content, although encouraging and supported by a similar pattern of behaviour in a parallel group of tarmacadam sections in the same experiment, is inconclusive.

10. CONCLUSIONS

1. The study of levels of compaction of dense coated macadam achieved during construction revealed that variation of binder content had a significant effect on the void content of the compacted material but not on the final achieved values of VMA. Ninety per cent of the values of void content were between 2 to 8 per cent whereas the range of values of VMA was considerably narrower, from 13 to 16 per cent.

2. Although dense macadam bases and basecourses are currently being laid to a satisfactory standard, the non-uniform pattern of rolling results in a considerable variation in density across the laid width, with peak values in the centre of the laid width and not in the critical path zones, zones which determine structural performance under traffic.

3. The variation in density of dense coated macadam bases across the lane width still exists after many years of heavy traffic. The performance of the material is determined by its initial properties at the time of construction and thus good compaction is essential.

4. Although peak values are close to refusal there is considerable scope for improving compaction in the wheel path zones. Improved compaction in these areas has been achieved using a second roller to increase the compactive effort towards the edges of the laid widths. The temperature at which material is laid and the degree of urgency given to its rolling are also important in determining the state of compaction.

5. Satisfactory compaction can be achieved in thick-lift construction but its superior heat-retaining ability, in many ways advantageous, can also present construction problems under certain circumstances.

6. Worthwhile extensions of pavement life, or alternatively, reduction in pavement thickness, should be obtained if compaction in the wheel paths is increased to the peak values now being obtained in the centre of the laid widths. Investigations of the dynamic modulus, of tracking of cores, of resistance to fatigue and of deflection all show that improving the state of compaction of dense bitumen macadam is beneficial to pavement performance.

7. Dense macadams of low binder content appear to be promising paving materials particularly if compacted to peak values.

11. ACKNOWLEDGEMENTS

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TABLE 1

Composition of 40mm nominal size dense bitumen macadam (base and base-course)

Aggregate Grading

B.S. sieve size	Aggregate: crushed rock, slag or gravel
mm	percentage by mass passing
50	100
37.5	95-100
28	68-92
14	55-75
6.3	44-60
3.35	31-45
μm	
300	7-21
75	2-8

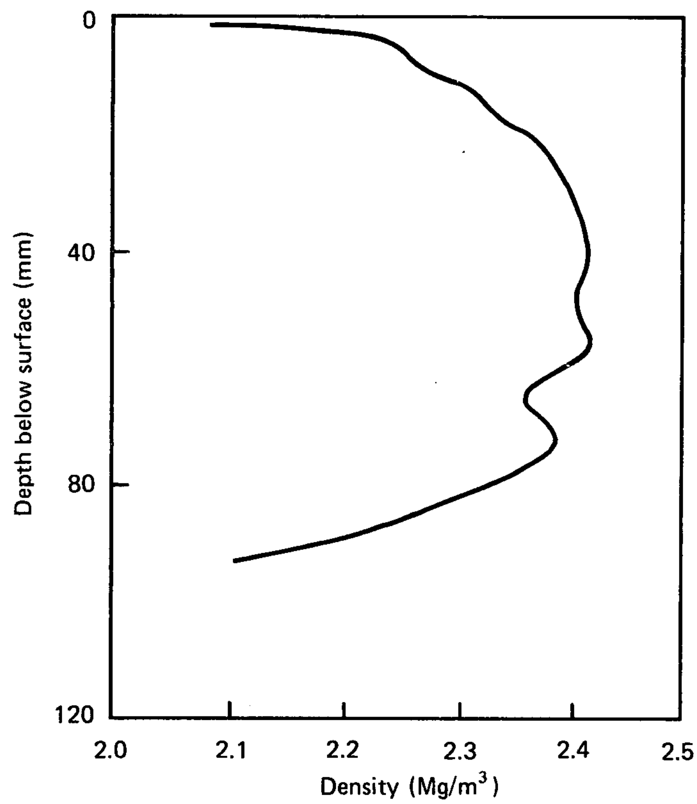
Binder Content

Aggregate	Bitumen per cent by mass of total mixture		
	Base	Base-course	
	100 pen grade	100 pen grade	200 pen grade
Crushed rock, steel slag or electric furnace slag	3.5 ± 0.5	4.5 ± 0.5	4.0 ± 0.5
Blast furnace slag Bulk density kg/m^3			
1440	4.0 ± 0.5	5.2 ± 0.5	4.7 ± 0.5
1360	4.2 ± 0.5	5.5 ± 0.5	5.0 ± 0.5
1280	4.5 ± 0.5	5.8 ± 0.5	5.3 ± 0.5
1200	4.8 ± 0.5	6.2 ± 0.5	5.6 ± 0.5
1120	5.1 ± 0.5	6.6 ± 0.5	6.0 ± 0.5
Gravel	4.5 ± 0.5	4.8 ± 0.5	4.5 ± 0.5

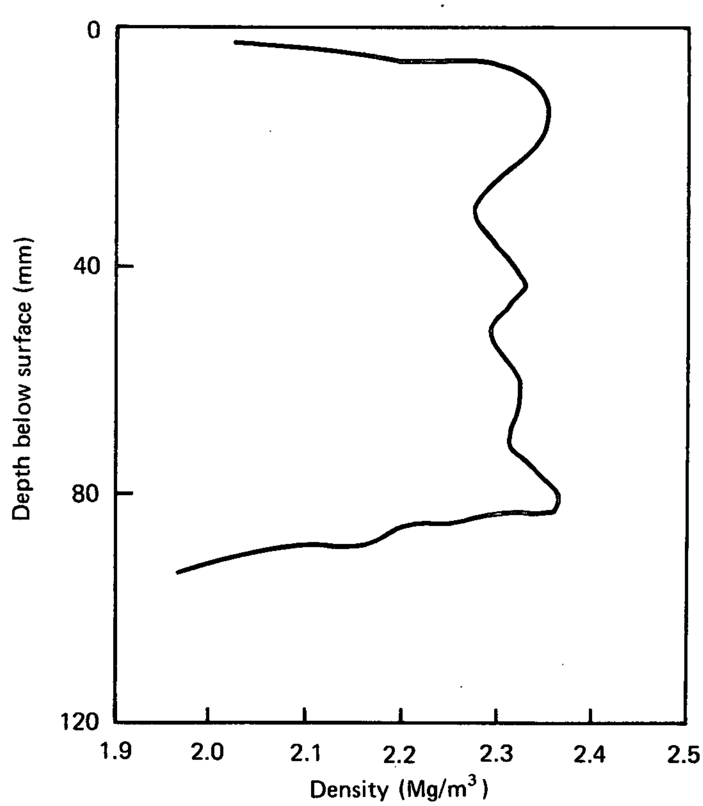
TABLE 2

Permanent deformation of sections with bitumen macadam bases at Wheatley Bypass after 4.5 x 10^6 standard axles

Grading	Bitumen content (per cent)	Permanent deformation (mm)
1	2.0	4.3
	3.5	5.2
2	2.5	3.4
	3.5	5.5
	5.0	5.8
3	3.0	4.6
(present	4.0	3.1
specification)	5.0	7.7



DENSE BITUMEN MACADAM



ROLLED ASPHALT

Fig. 1 TYPICAL DENSITY/DEPTH PROFILES

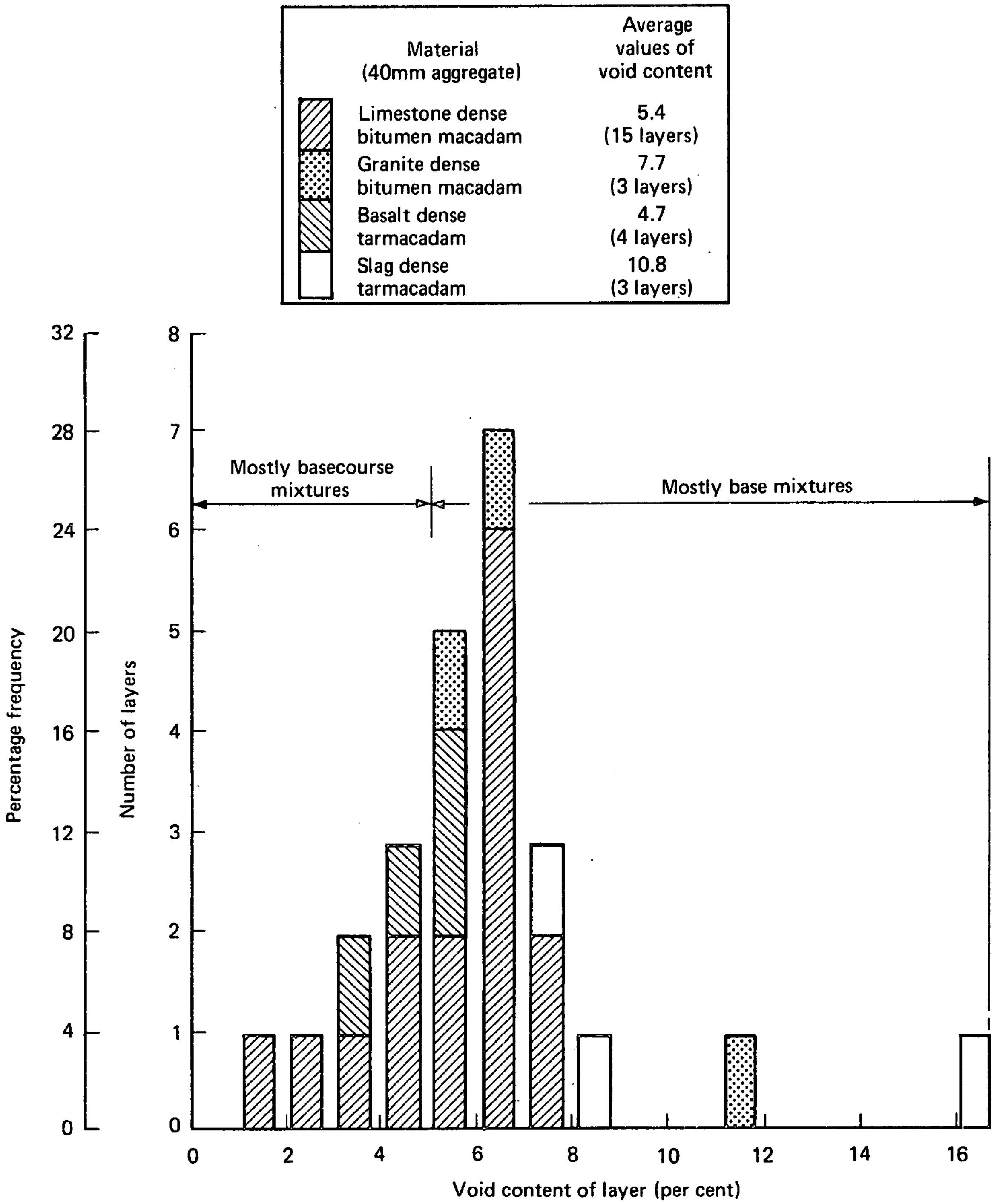


Fig. 2 FREQUENCY DISTRIBUTION OF VALUES OF VOID CONTENT IN DENSE COATED MACADAM

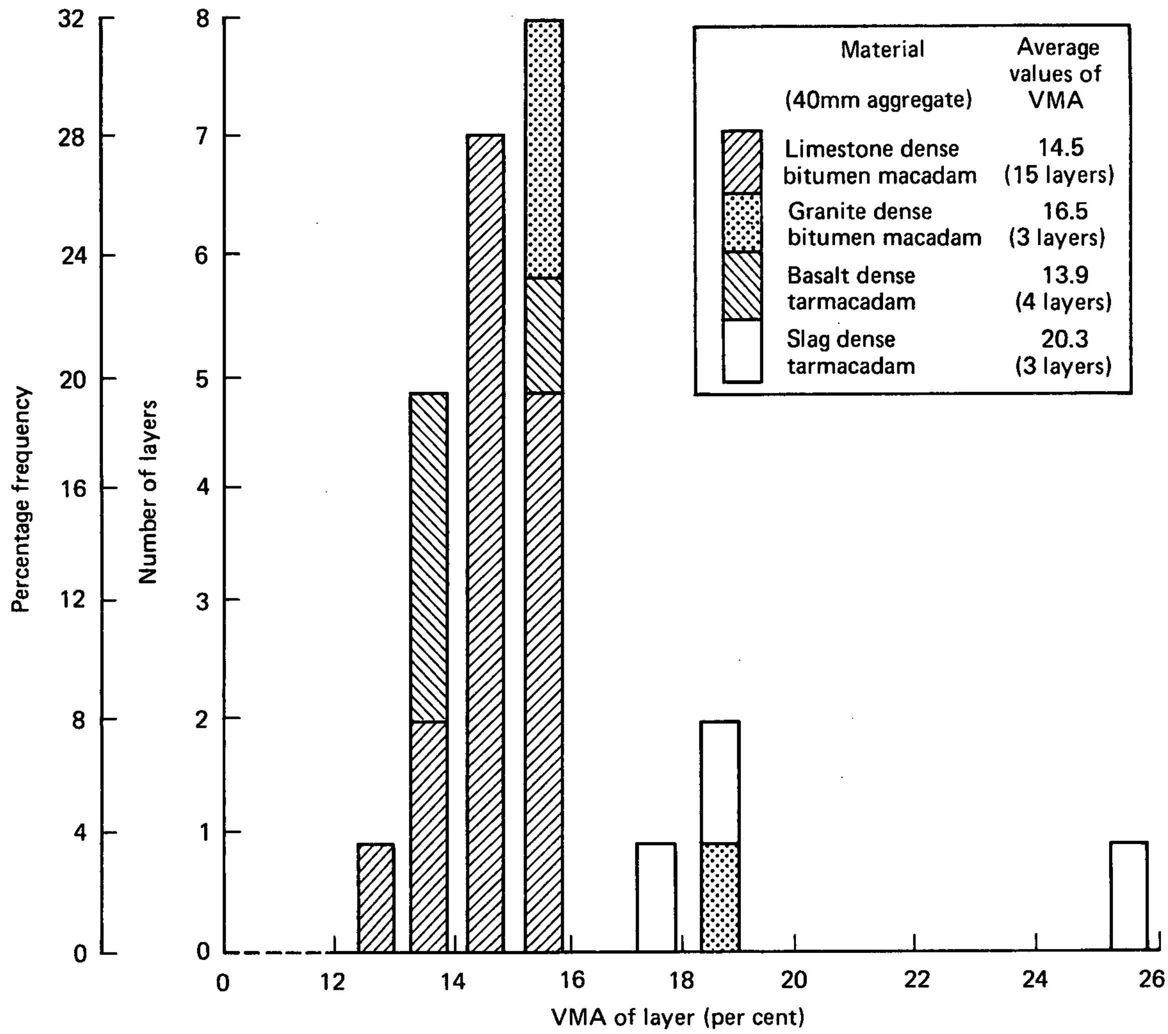


Fig. 3 FREQUENCY DISTRIBUTION OF VALUES OF VMA IN DENSE COATED MACADAM

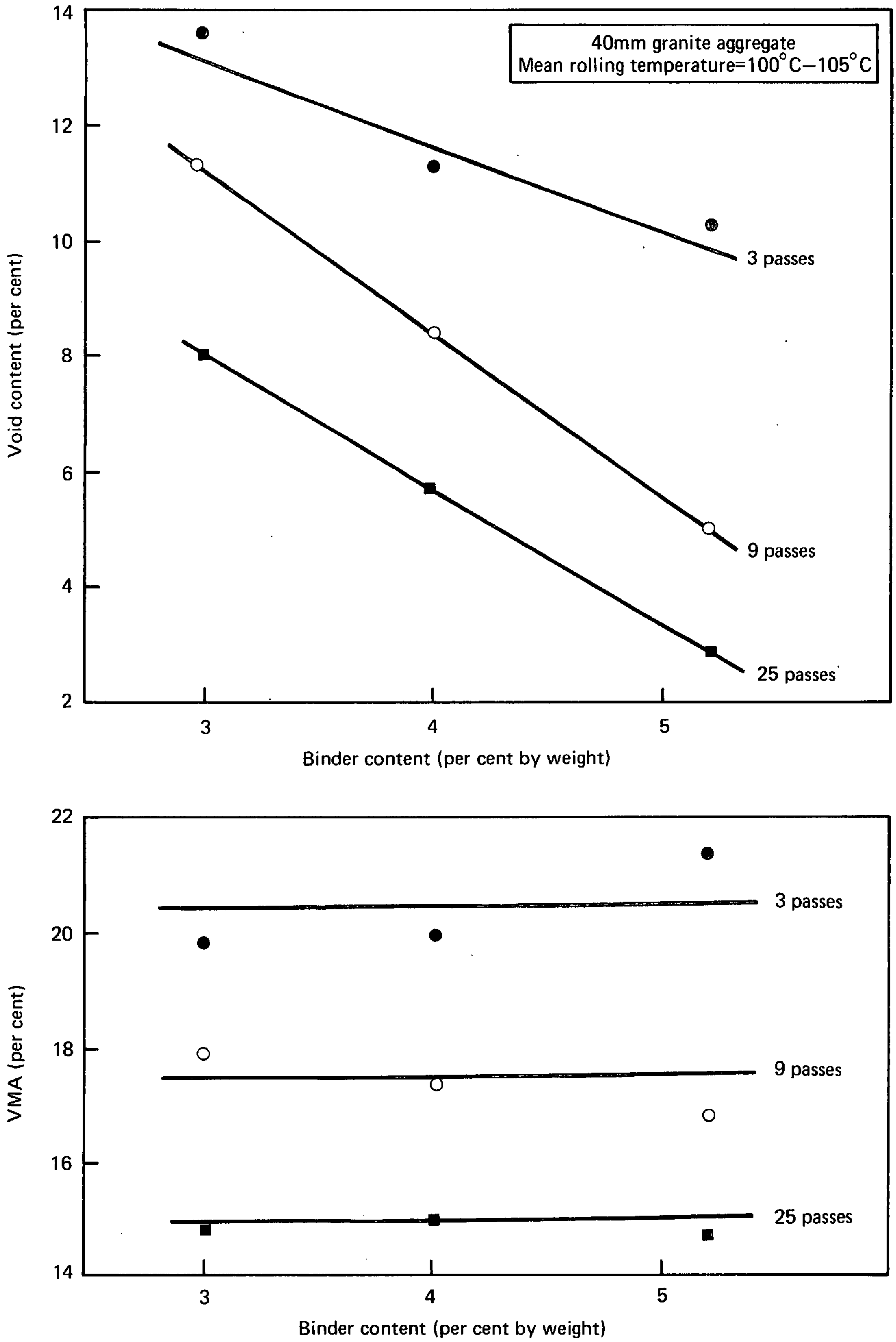


Fig. 4 VARIATION OF VOID CONTENT AND VMA WITH BITUMEN CONTENT AT DIFFERENT STAGES OF COMPACTION OF DENSE BITUMEN MACADAM

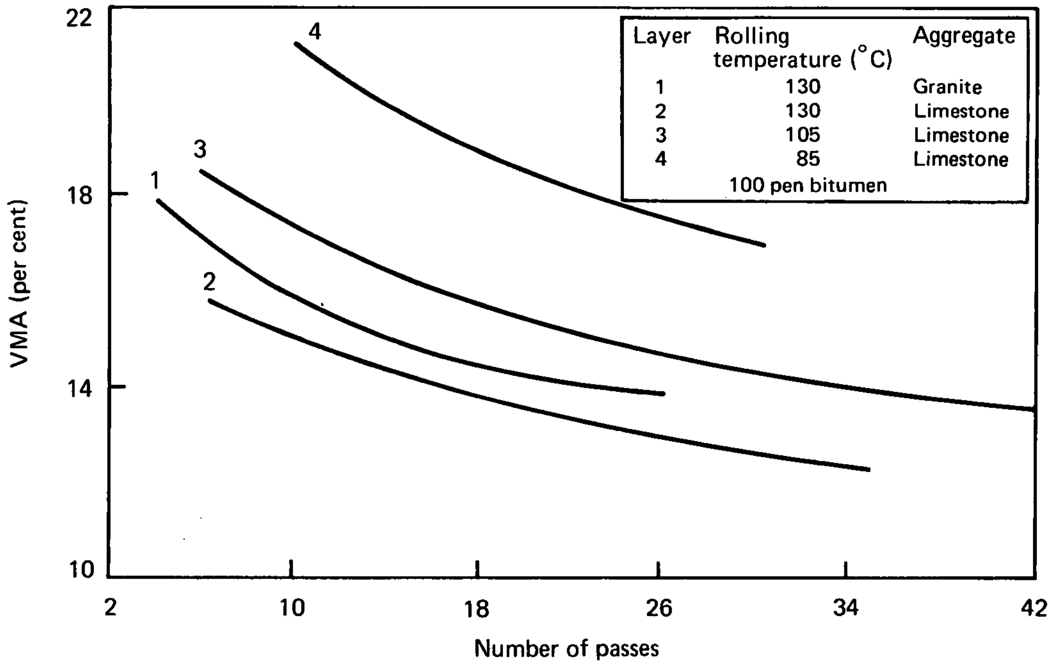


Fig.5 VARIATION OF VMA WITH ROLLER PASSES FOR DENSE BITUMEN MACADAM

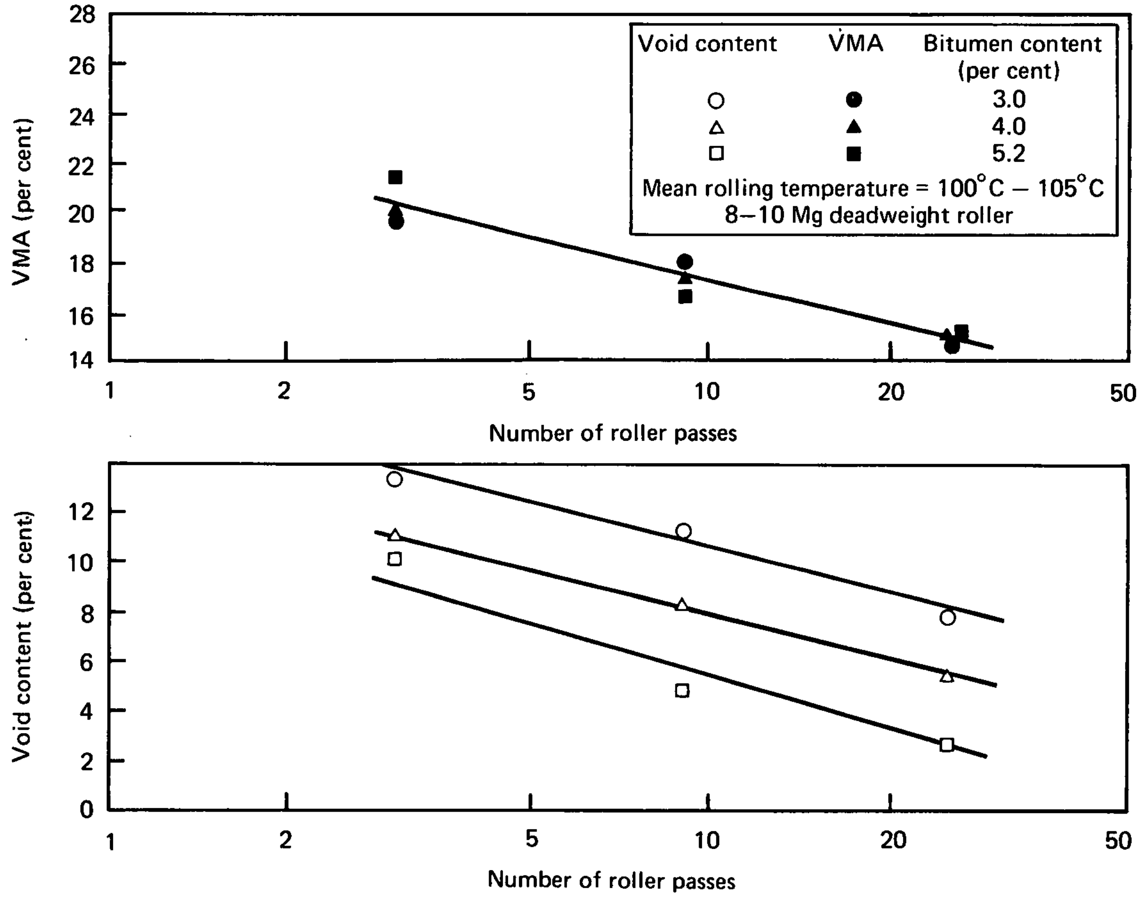


Fig.6 VARIATION OF VOID CONTENT AND VMA WITH ROLLER PASSES FOR DENSE BITUMEN MACADAM

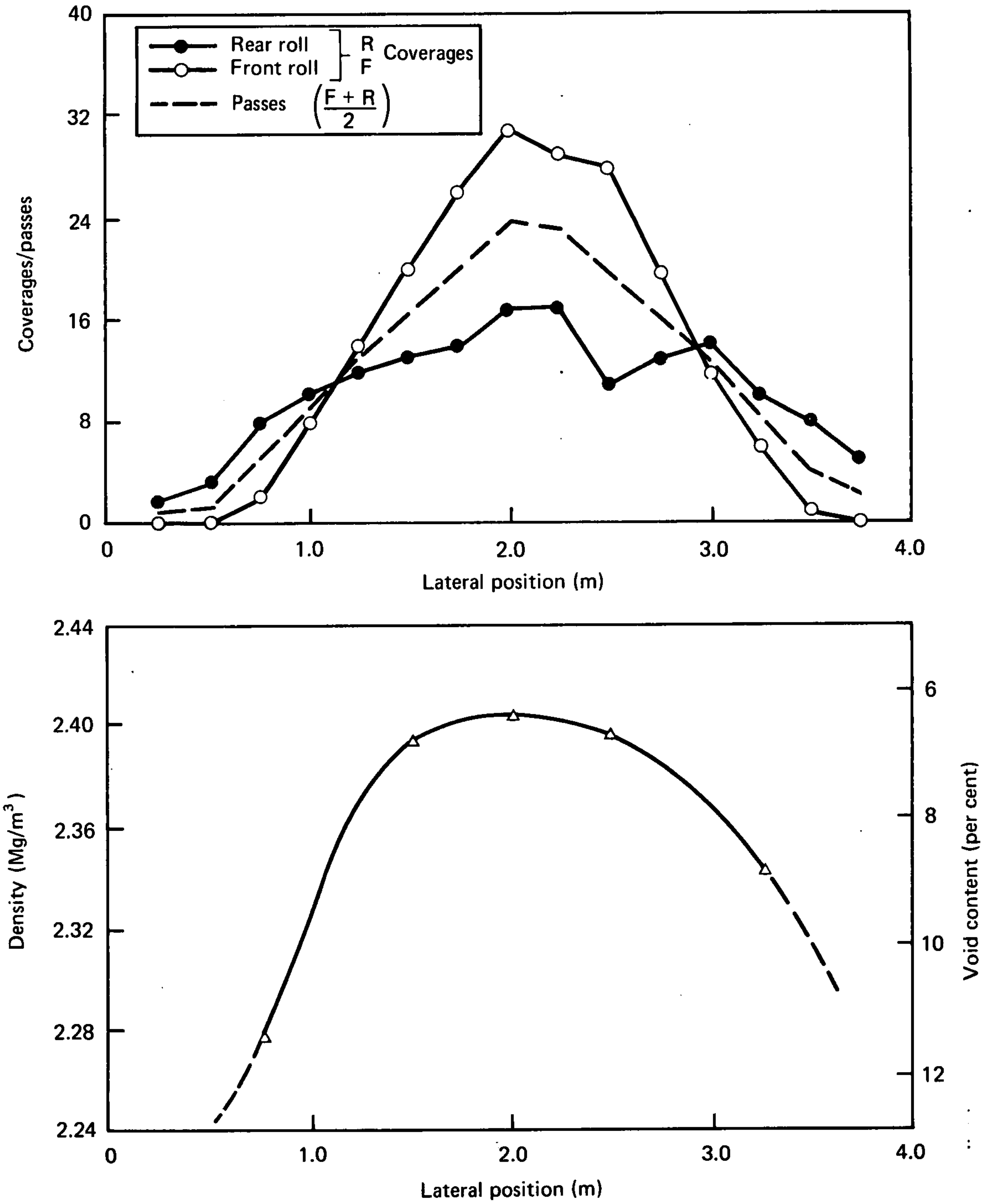


Fig.7 DISTRIBUTION OF DENSITIES AND ROLLER PASSES ACROSS THE LAID WIDTH FOR DENSE BITUMEN MACADAM (PILOT-SCALE TRIAL)

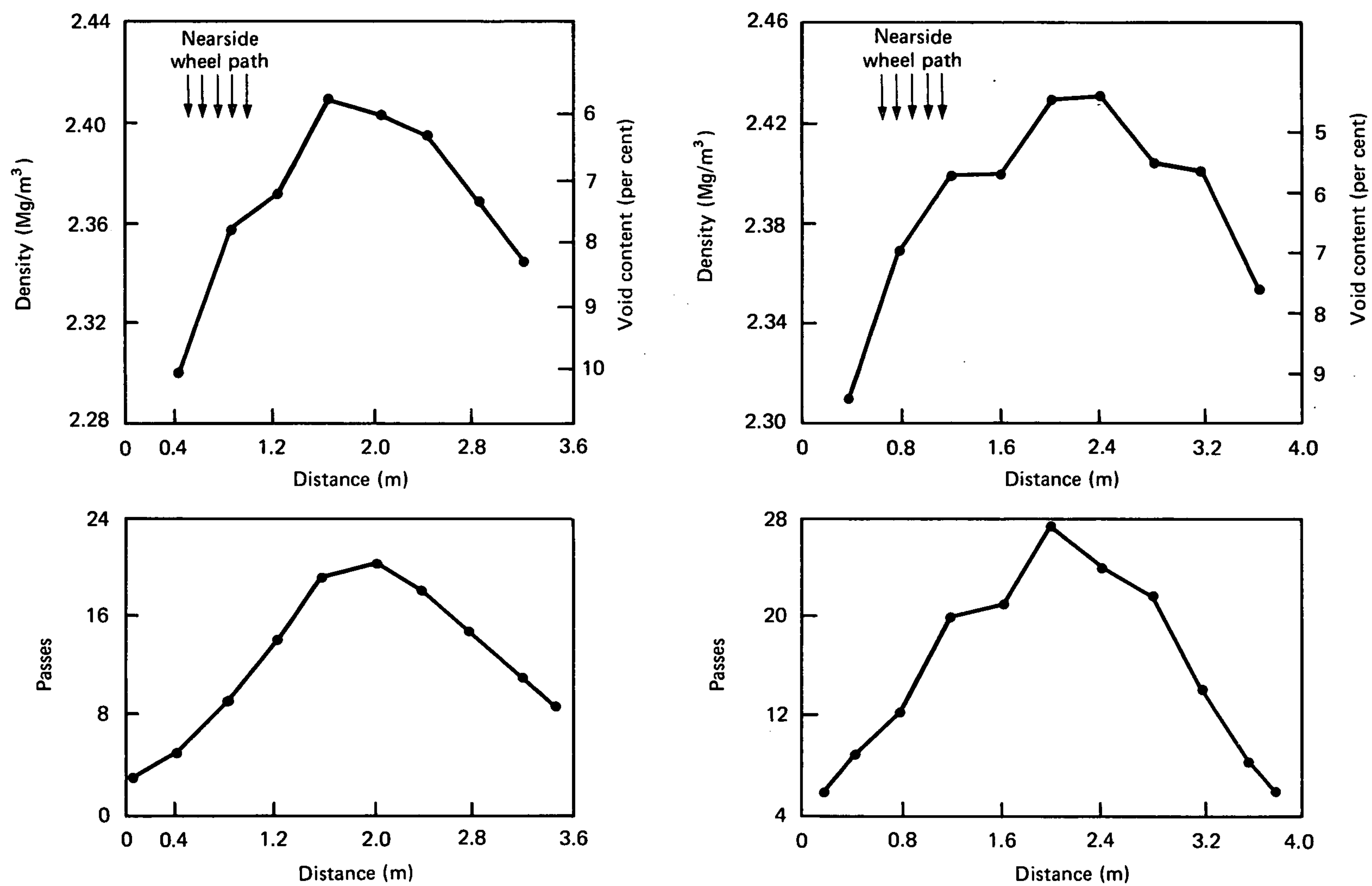


Fig. 8 VARIATION OF DENSITY AND ROLLER PASSES ACROSS THE LAID WIDTH OF DENSE BITUMEN MACADAM ROAD BASE AT 2 SITES

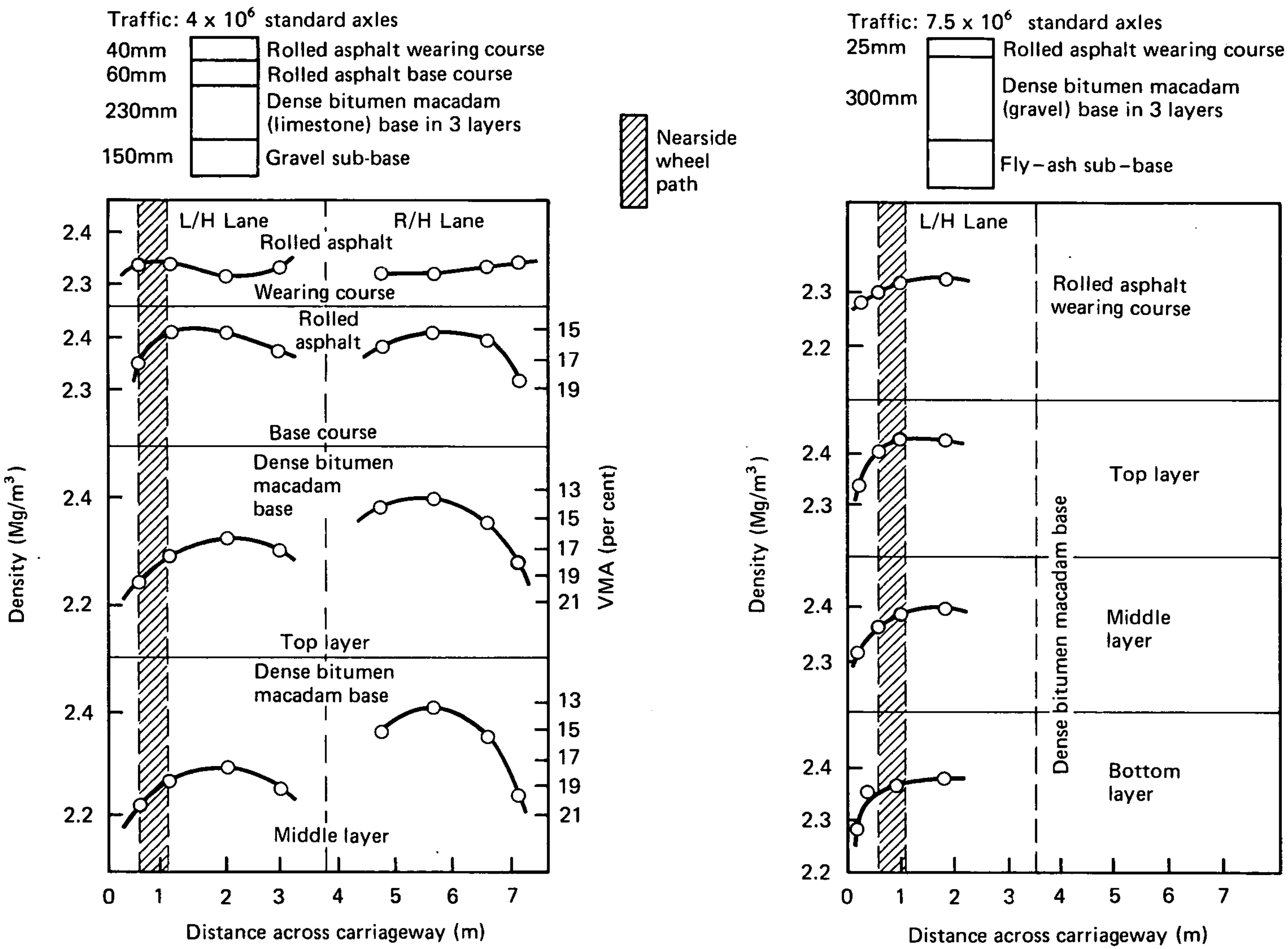


Fig.9 VARIATION OF DENSITY ACROSS THE LANE WIDTHS AFTER TRAFFICKING AT TWO FULL SCALE ROAD EXPERIMENTS

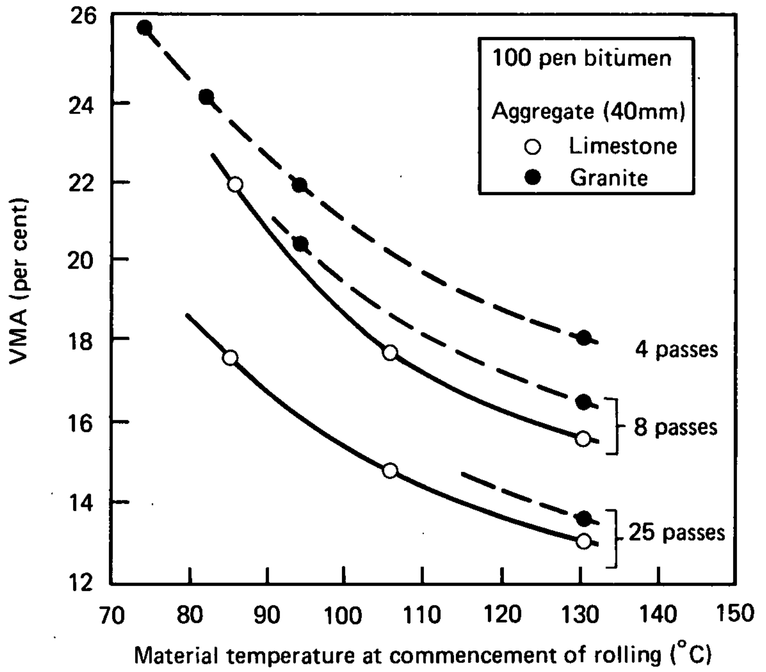


Fig.10 VARIATION OF VMA WITH ROLLING TEMPERATURE FOR DENSE BITUMEN MACADAM

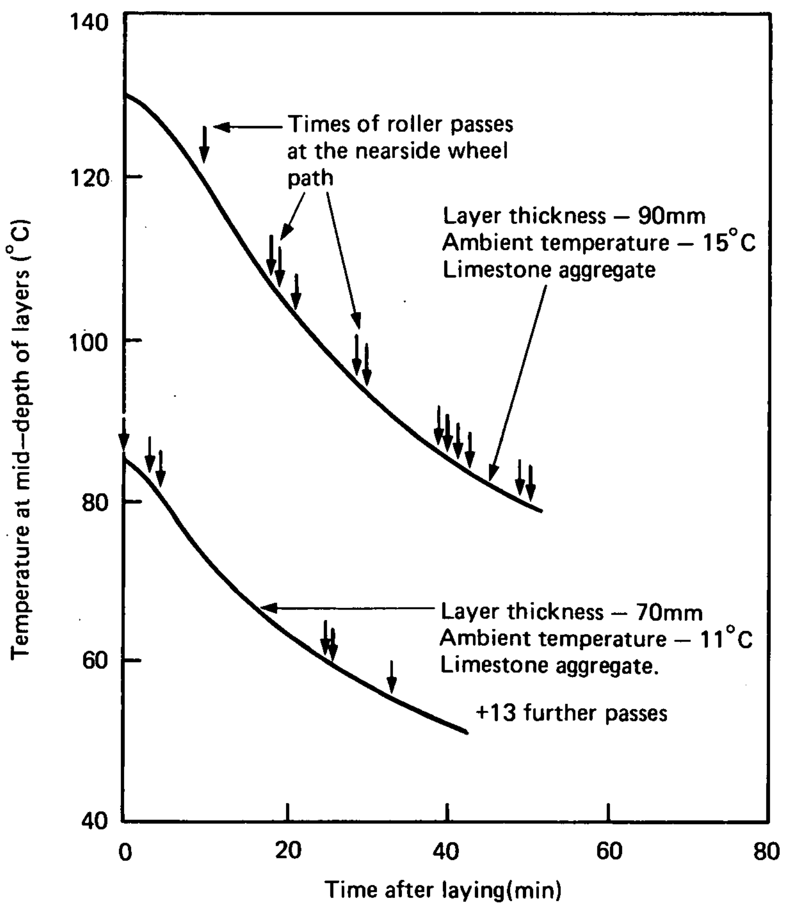
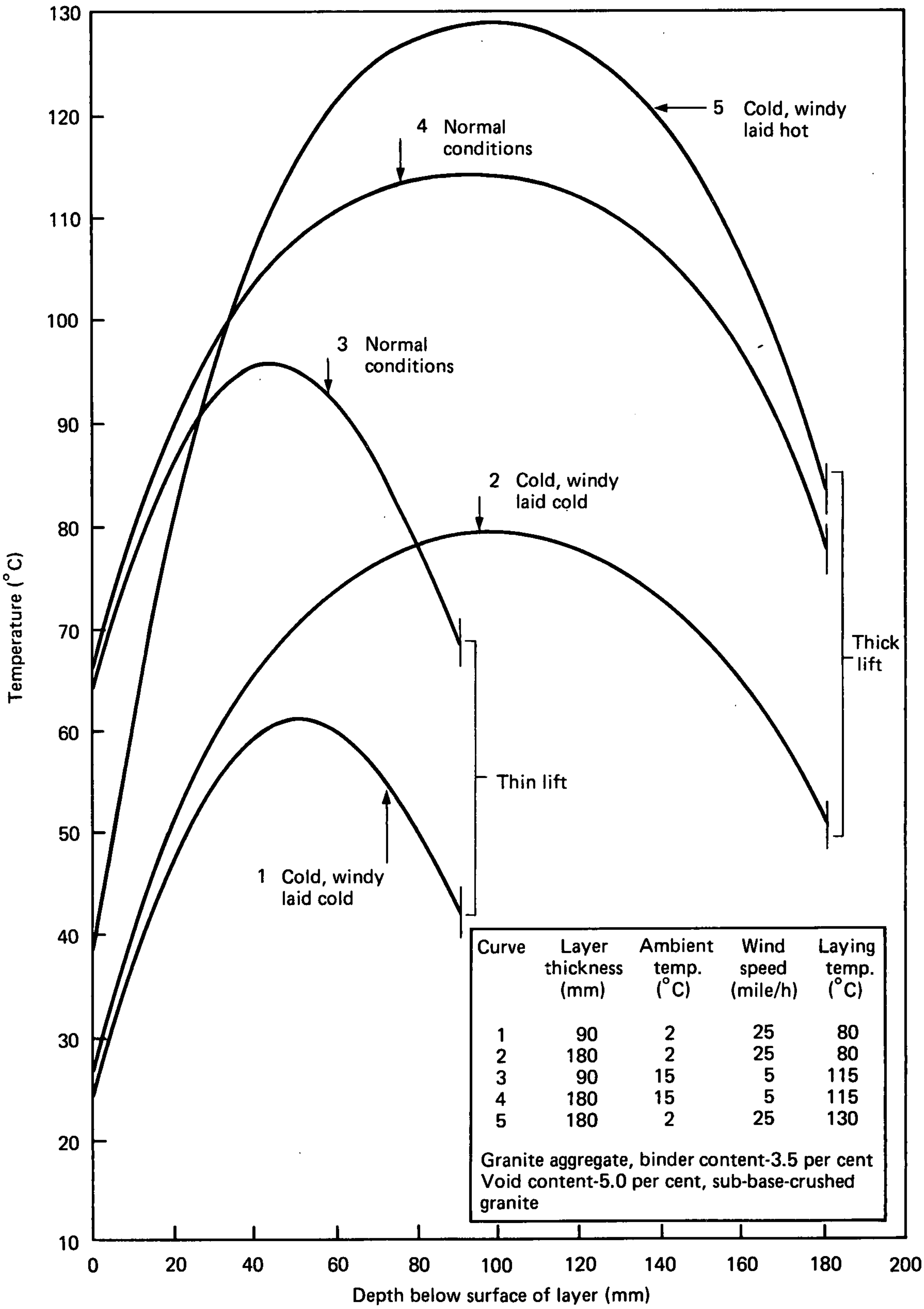


Fig.11 VARIATION OF TEMPERATURE OF DENSE BITUMEN MACADAM LAYERS WITH TIME RELATED TO PASSES OF A ROLLER IN THE WHEEL PATH POSITION



Curve	Layer thickness (mm)	Ambient temp. (°C)	Wind speed (mile/h)	Laying temp. (°C)
1	90	2	25	80
2	180	2	25	80
3	90	15	5	115
4	180	15	5	115
5	180	2	25	130

Granite aggregate, binder content-3.5 per cent
Void content-5.0 per cent, sub-base-crushed granite

Fig.12 VARIATION OF TEMPERATURE WITH DEPTH OF BITUMINOUS LAYER 30 MIN AFTER LAYING

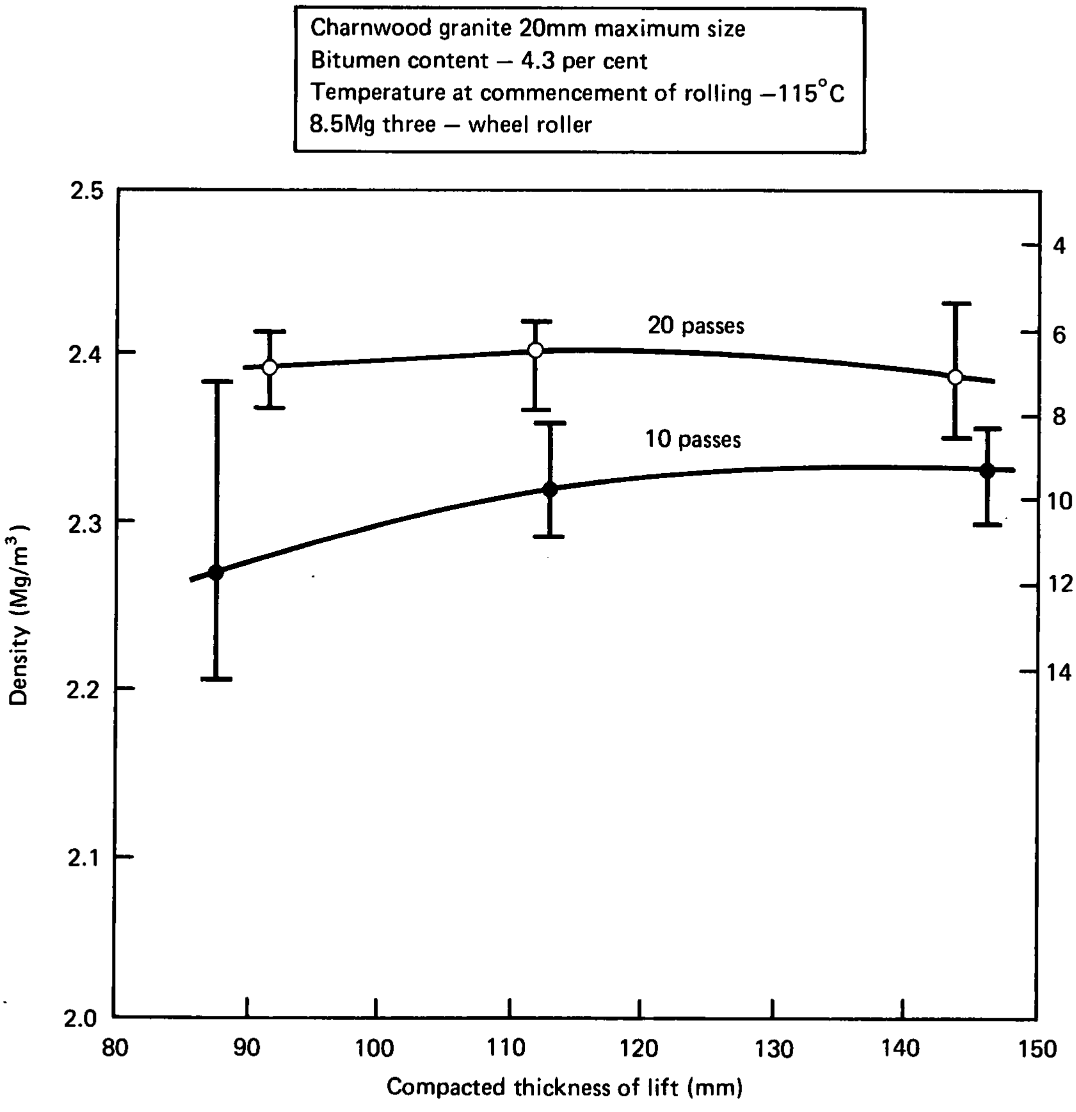


Fig.13 VARIATION OF COMPACTED STATE WITH LIFT THICKNESS

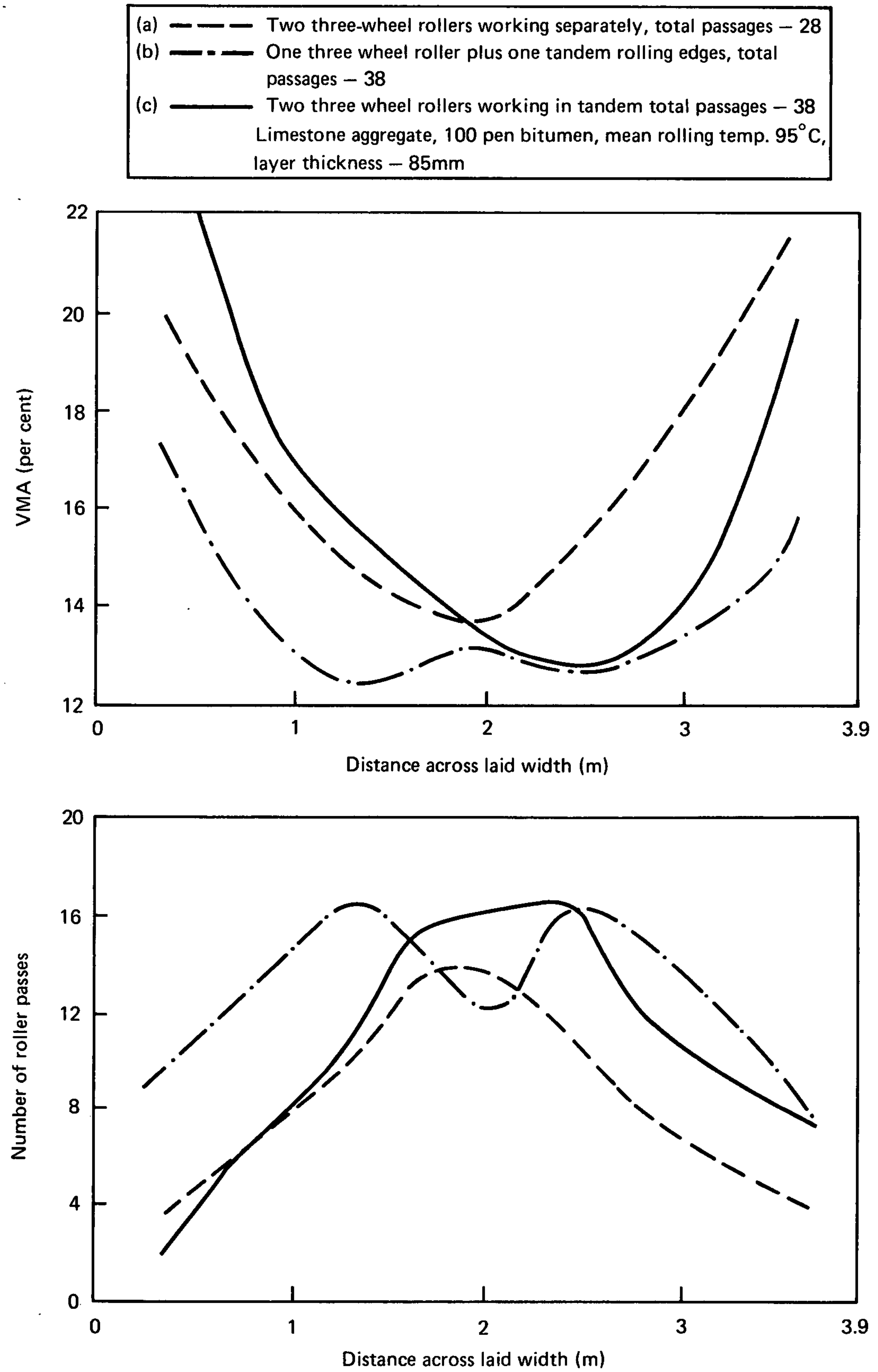


Fig.14 VARIATION OF COMPACTION OF DENSE BITUMEN MACADAM ACROSS THE LAID WIDTH FOR DIFFERENT ROLLING PROCEDURES

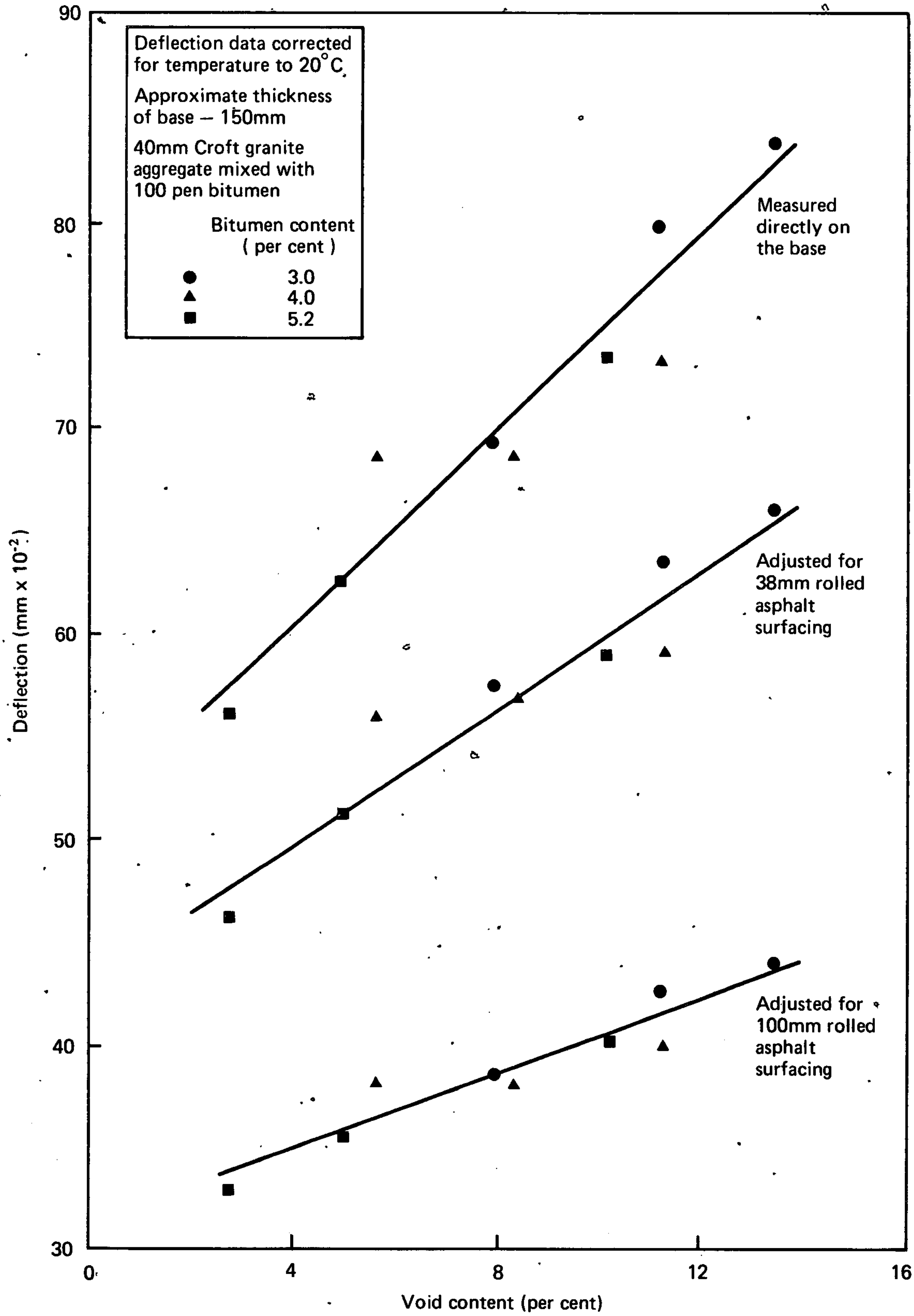


Fig.15 VARIATION OF DEFLECTION WITH VOID CONTENT OF BASE LAYER

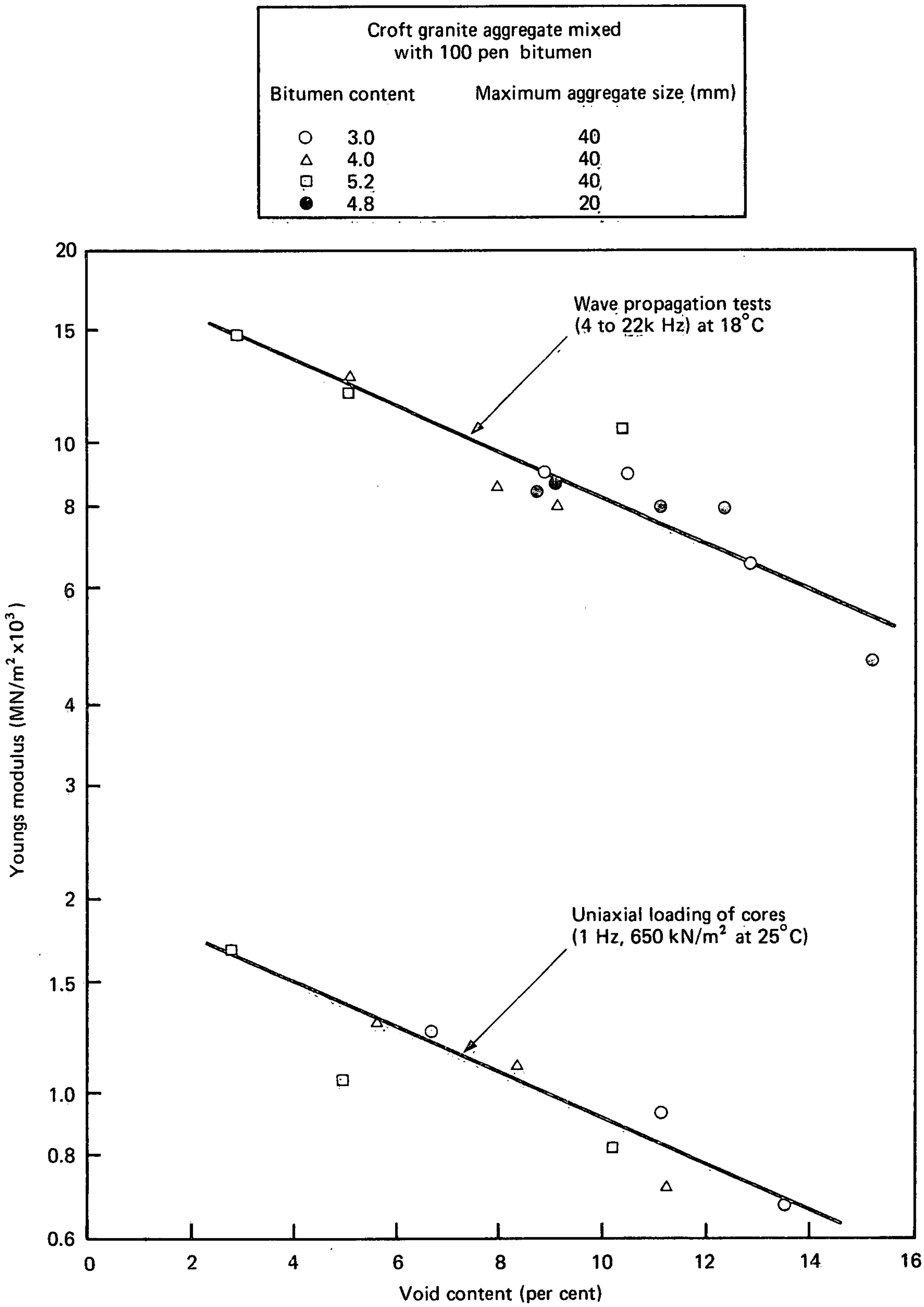


Fig.16 VARIATION OF DYNAMIC MODULUS WITH VOID CONTENT

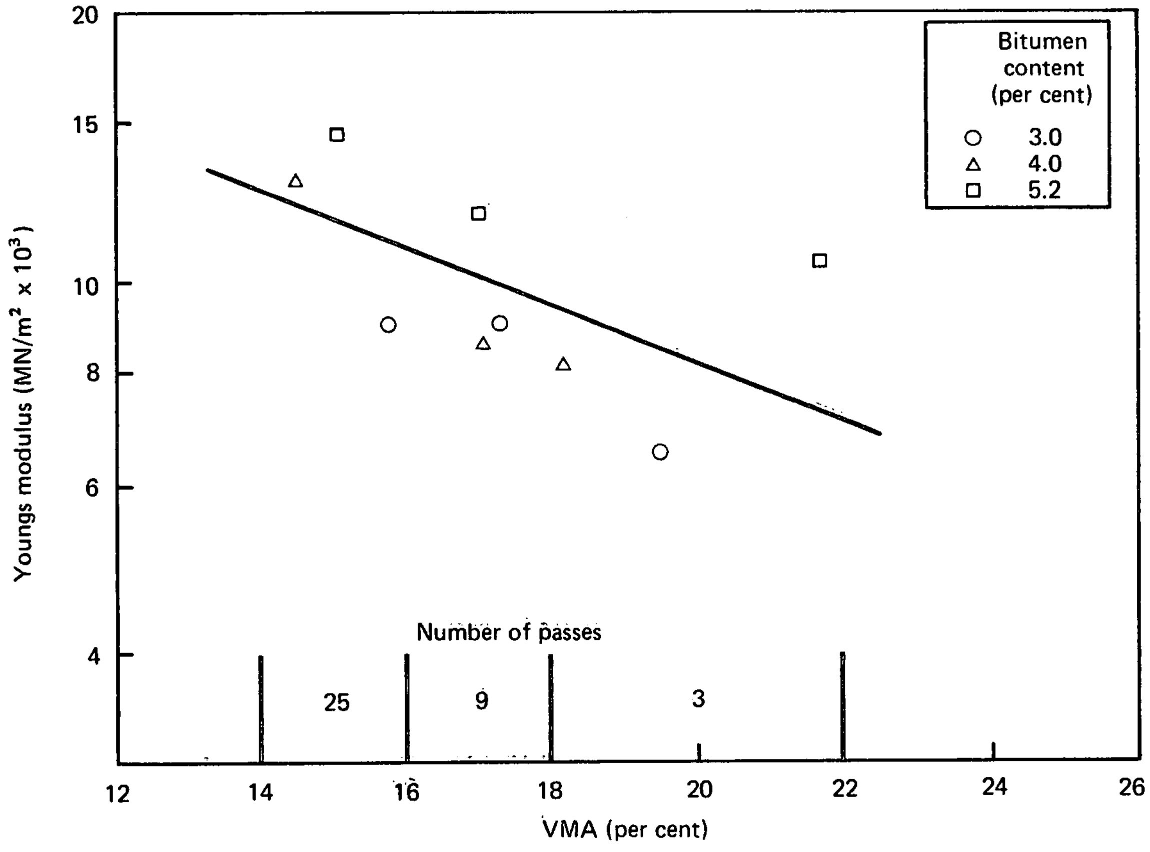


Fig.17 VARIATION OF DYNAMIC MODULUS WITH V M A

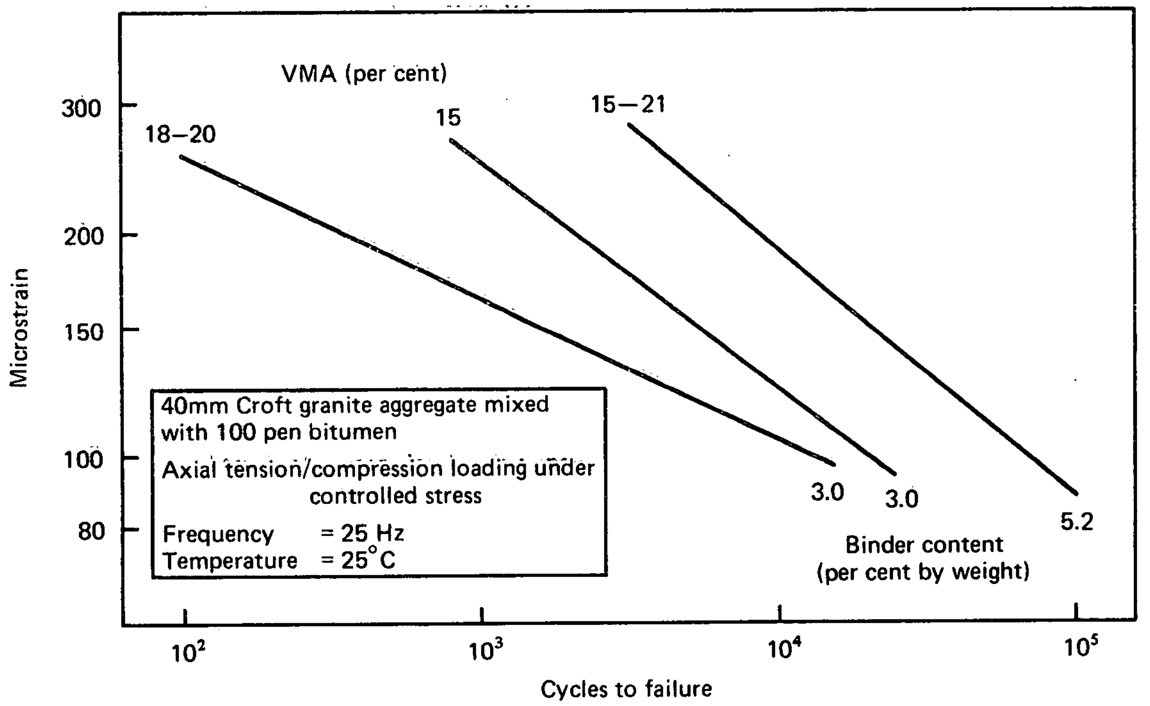


Fig.18 EFFECT OF COMPACTION AND BINDER CONTENT ON FATIGUE PERFORMANCE OF DENSE BITUMEN MACADAM

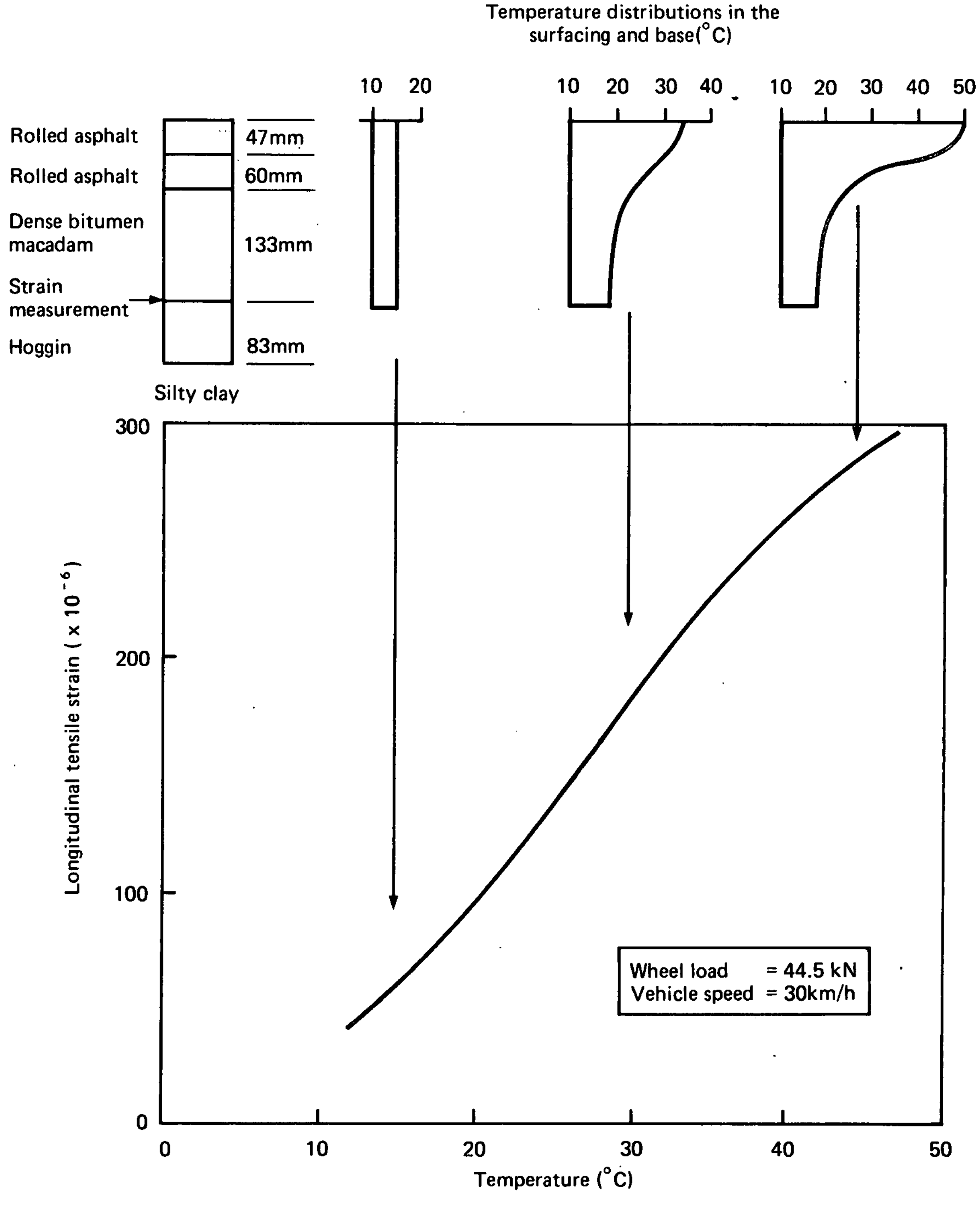


Fig.19 VARIATION OF LONGITUDINAL STRAIN AT THE BOTTOM OF A D.B.M. BASE WITH TEMPERATURE OF THE SURFACING (WEARING COURSE/ BASE COURSE INTERFACE)

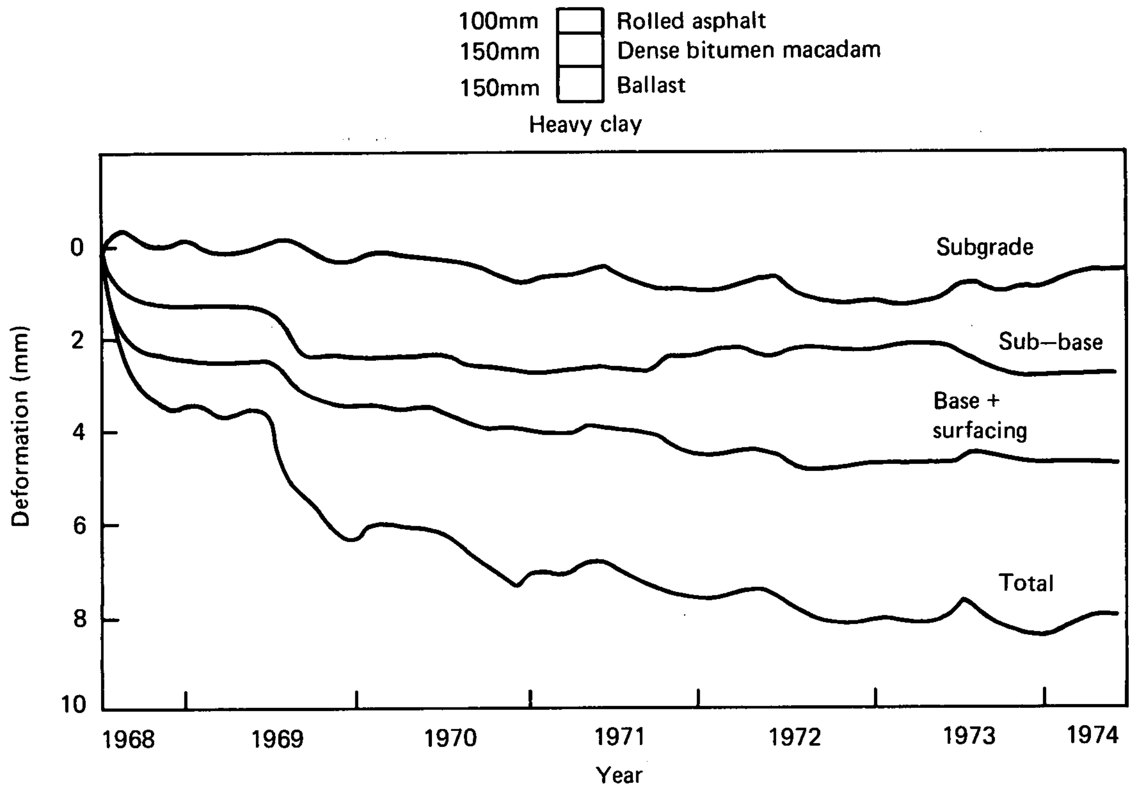


Fig.20 DEVELOPMENT OF PERMANENT DEFORMATION IN THE PAVEMENT LAYERS AND SUBGRADE IN A PAVEMENT WITH A DENSE BITUMEN MACADAM BASE

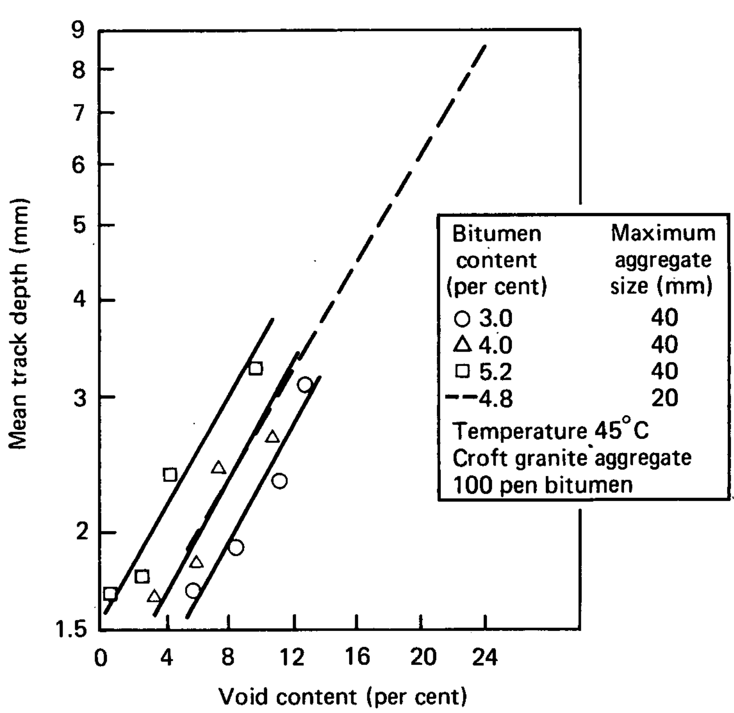
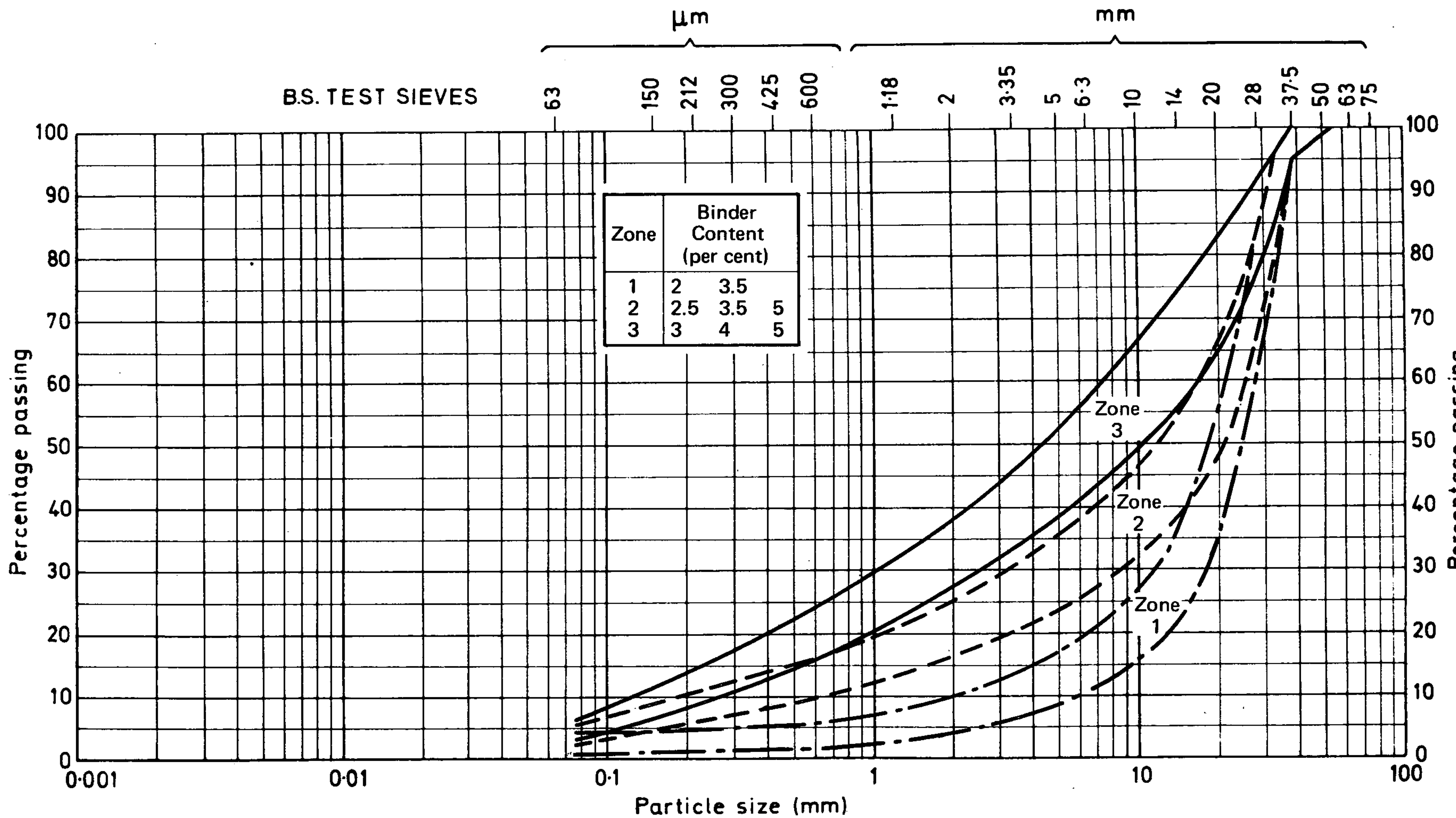


Fig.21 EFFECT OF VOID CONTENT AND BINDER CONTENT ON MEAN VALUES OF TRACK DEPTH



Zone	Binder Content (per cent)		
1	2	3.5	
2	2.5	3.5	5
3	3	4	5

Fig.22 GRADING ZONES FOR BITUMINOUS BASE MATERIALS AT WHEATLEY BYPASS

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ABSTRACT

THE COMPACTION OF BITUMINOUS BASE AND BASE-COURSE MATERIALS AND ITS RELATION TO PAVEMENT PERFORMANCE: *N W Lister and W D Powell:* Department of the Environment, Department of Transport, TRRL Supplementary Report 260: Crowthorne, 1977 (Transport and Road Research Laboratory). An appraisal of the state of compaction of dense coated macadam bases and base-courses being achieved in current British construction practice reveals a considerable range of compaction levels and that the initial variation of density across the laid width persists after many years of intense commercial traffic. The effects of material composition, compactive effort, roller speed, rolling temperatures and stiffness of the working platform are analysed. An examination of the rolling procedures indicated that there is scope for increasing the level of compaction in the critical wheel path zone. Modified rolling procedures have been successfully used to improve compaction in the wheel paths.

A brief summary is given of British experience with thick lift construction including results from a full-scale road experiment. Good compaction was achieved at the expense of some loss of riding quality when the base and basecourse were combined in one lift.

The relation between performance of dense coated macadams and their compacted state has been studied in an associated programme of pilot scale and laboratory testing. Results show that worthwhile performance benefits are obtained if compaction in the wheel paths is increased to the peak values now being obtained in the centre of the laid widths.

The suitability of cheaper base and basecourse materials of binder contents lower than those currently used in the United Kingdom is also being studied and preliminary results showing considerable promise are presented.

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