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STANDARDS FOR COMPACTION OF DENSE ROADBASE MACADAM

by

W D Powell (Transport and Road Research Laboratory) and
D Leech (Asphalt and Coated Macadam Association)

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ABSTRACT

Research relating compaction to performance properties indicates that the benefits of better compaction are considerable. In order to improve compaction, modified rolling procedures have been formulated to ensure that greater compactive effort was applied before the material had cooled excessively. An improved method specification met with limited success. An alterantive way of achieving the necessary improvement in compaction is to set compaction targets but this requires a satisfactory means of assessing the end result. A refusal test which was originally developed to determine the scope for further compaction was found to offer considerable potential as a standard.

1. INTRODUCTION

In the United Kingdom, dense coated macadams[1] have been widely used for the past 15 years or so for roadbases and basecourses of roads carrying medium and heavy traffic. These materials were manufactured to a composition specification and the control of their compaction was by means of a very simple method specification in which no detailed description of rolling procedures was given.

In general, the performance of these materials was considered satisfactory. However, it was widely believed that better performance might be achieved by improving compaction and by changes in composition. In 1970 a co-operative programme of research between the Asphalt and Coated Macadam Association and the Transport and Road Research Laboratory was launched; it was planned to investigate the scope and benefits of improved compaction of dense roadbase macadams. At a later stage the Refined Bitumen Association and the British Tar Industry Association joined the co-operative research programme which widened to include the performance benefits derived from changes in composition, but compaction continued to play a prominent role.

The most important finding of the early work was that the level of compaction achieved at the centre of the laid width was about 3 per cent more than in the wheel paths. Since the structural performance of the whole pavement is largely governed by the level of compaction in the wheelpaths there was scope for improvement. Furthermore the work showed that better compaction would significantly improve structural performance. A paper to the 1974 ACMA Seminar described this early work[2].

For the heavily trafficked roads now being constructed, a high standard of compaction is essential if a long design life is to be assured. A modified method specification for compaction was therefore devised[3] and this met with some success[4] but there were problems inherent in controlling a method specification. Another way of achieving the necessary improvements in rolling practice that are required to ensure consistently high levels of compaction is to set compaction targets but this needs a satisfactory means of assessing the end result. There is clearly an advantage in using a nuclear gauge as a simple, quick and non-destructive device for measuring density but these gauges have not been widely accepted in the UK to date. Alternatively, the densities of cores can be measured.

The present paper summarizes the research findings regarding the relationship between compaction and structural performance in flexible pavements having dense coated macadam roadbases with 40 mm well graded crushed rock or blast furnace slag aggregate and 100 pen bitumen binder. It then describes more recent work directed towards improving compaction and establishing reliable methods of determining standard levels of compaction for these materials.

2. COMPACTION AND PERFORMANCE

Experiments using normal laying and compaction equipment have been carried out at TRRL in a pilot-scale test facility on a foundation of realistic stiffness; this has provided good control of experimental variables combined with realism. The laid materials were rolled with a 9 tonne tandem deadweight machine, the number of passes ranging from 3 to 40. The compacted materials were the source of cores, beams and slabs for laboratory tests to determine compaction level and to establish its relation to the material properties that influence performance in the road.

The load spreading ability of a bituminous basecourse and roadbase is defined by its dynamic stiffness. This provides a measure of the ability of these layers to reduce the stresses developed in the sub-base and subgrade by traffic loading. Dynamic stiffness of beams cut from macadams made with a granite aggregate and a wide range of bitumen contents was measured in both three point bending and uniaxial loading. The results plotted in Figure 1 show that a 3 per cent decrease in void content increases stiffness by 30 per cent, irrespective of binder content. Linear elastic analysis of a typical flexible pavement shows that with this increase in stiffness the vertical stress generated in the soil subgrade by a wheel load can be maintained at the same level with a bituminous layer whose thickness has been reduced by 8 per cent. Similar results have been obtained for wide ranges of test temperature and frequency and for different aggregate types.

Increasing the level of compaction also results in an increase in the repeated traffic loading required to initiate cracking at the bottom of the bituminous roadbase, this is mainly due to the increase in stiffness of the roadbase[5].

Much of the surface deformation of a pavement incorporating a bituminous roadbase and wearing course can take place in these two layers; their deformation characteristics are, therefore, important in determining pavement performance. To determine the deformation resistance of macadam roadbase, slabs of material were mounted on a rigid base and trafficked at $30^{o}C$ by a pneumatic tyre loaded to 20 kN[6]. Figure 2 shows that the deformation measured after 1000 load cycles decreased sharply with improved compaction; a 3 per cent decrease in void content reduced deformation by up to 50 per cent.

Improving compaction could, therefore, bring about significant improvement in load spreading, resistance to cracking and internal deformability of dense macadams.

3. IMPROVED COMPACTION

Improved compaction can be attained by increasing the compactive effort and, within limits, increasing the temperature at which compaction is carried out. Typical results for crushed rock materials are shown in Figure 3 where density expressed as a percentage of refusal density is plotted against the number of roller passes. The results illustrate the importance of both the number of roller passes and temperature of the material in determining the level of compaction achieved. Sufficient voids remain to avoid 'fatting up' of roadbase and most basecourse macadams compacted to the refusal density used in the derivation of Figure 3; this shows that there is considerable scope for improving compaction, particularly in the wheelpaths.

3.1 *Thick layer construction*

The ability of thicker layers to retain heat longer increases the time available after laying for effective compaction to be carried out. However, in a thick layer laid hot to counteract adverse wintry conditions, a skin of relatively cold and stiff material rests on a hot mass, giving rise to the danger of cracking of the surface material and of lack of stability of the mix under the roller. In a road experiment designed to investigate the possibility of laying materials in thick lifts[2] instability was encountered in precisely these circumstances and specifications regarding surface irregularity and level could not be met in layers of more than 200 mm thickness. Thus although it may appear desirable to increase the thickness of pavement layers to improve their compaction, reservations about riding quality have so far held back the use of the greater layer thicknesses common in other countries.

3.2 *More powerful compaction machinery*

Figure 3 shows that the density of the compacted material will continue to increase with number of passes of a conventional deadweight roller beyond the 30 pass level at virtually all practical rolling temperatures. According to weather conditions and the temperature of laying it is either difficult or impossible to complete this number of passes in the time available. More effective compaction machines than those currently used in the United Kingdom are required if compaction close to refusal is to be obtained consistently. Recent trials[7,8,9] have demonstrated the advantage of applying vibration when compacting dense bituminous macadams. The results obtained with three vibratory and one conventional roller are compared in Figure 4. Conclusive evidence has not been obtained that vibrating rollers always produce such beneficial effects as those shown in Figure 4 and the compaction process is not sufficiently well understood to allow the best level of centrifugal force, amplitude and frequency characteristics to be specified for each bituminous material. However, the results are encouraging.

3.3 *Modifying rolling procedures*

The temperature at which bituminous material is laid and the rate at which roller passes are applied are important in determining the level of compaction achieved. The interaction of these factors was examined and recommendations made to modify rolling procedures[10]. These recommendations led to a new method specification designed to increase the number of roller passes in the wheelpaths while the material was still hot enough to compact. The specification has been tried out on a number of sites on motorways[4] with the results shown in Figure 5; densities in the wheelpaths are compared with densities at the middle of the laid width for conventional and modified compaction procedures. Improvements in compaction of between 1 and 2 per cent were obtained in the wheelpaths, the improvement being greatest when observers from TRRL were present, but not controlling the compaction operation. The difference between densities in the wheelpaths and those at the centre of the laid width was generally reduced by the operation of the modified specification, reflecting the more effective use of rollers. However, the wide range of densities obtained by both procedures indicates considerable scope for further improvement in compaction. It is significant that, the highest densities were achieved in thicker layers of material and that the best compacted state of all was produced on a warm day when prolonged rolling was possible while the material was still hot.

4. THE REFUSAL TEST

Controlling rolling procedures by an improved method specification has met with only limited success. The general view now is that realistic compaction targets and a satisfactory means of assessing the end result would be a more effective way of achieving the necessary improvements in rolling practice that are required to ensure consistently high levels of compaction. First it is necessary to select a suitable measure of compaction. It is desirable that this measure is not sensitive to changes in binder properties or angularity of the aggregate but can be related to a standard that reflects these influences. The simplest method appeared to be to relate the density of a sample taken from the road to the density brought about by applying a standard compactive effort as in the Marshall test.

Marshall tests[11] were carried out on a wide range of aggregate types, with gradings adjusted to give material of 20 mm maximum size because the specified 100 mm diameter mould is unsuitable for use with material containing aggregate of larger size. For a given compactive effort, the compacted state expressed as VMA, voids in the mineral aggregate, was found to vary significantly with binder content; this was in marked contrast to the results of full-scale trials[12]. Moreover other evidence suggests that performance parameters of bituminous macadams compacted in a mould differ substantially from those measured on material compacted to the same VMA by full-scale compaction equipment[13].

In an attempt to overcome these deficiencies of the Marshall test a standard of compaction was established in terms of the maximum compaction attainable in a refusal test carried out on cores cut from actual roadbases where the particle orientation of aggregate is the same as that of material compacted in the road. The equipment needed to carry out a refusal test is illustrated in Plates 1 and 2.

In preparation for the test each 150 mm diameter core is dried in an oven at 40°C for 16 hours. If the core has more than one layer, these are separated by working a knife around the circumference of the core. The core is then cooled and weighed before coating with paraffin wax to seal the surface. When the wax has hardened, the core is reweighed, in air and water, and its initial density is calculated. The wax is then removed with a pallet knife, checking that it has been completely removed by reweighing the core.

The core is then inserted into a split mould with the flatter of the two ends uppermost. The mould is tightened, placed in an oven at 140°C for 3 hours and on removal retightened.

The mould is immediately placed on a firm, level surface and the core is compacted to refusal using a 750 watt 50 Hz vibrating hammer with a 100 mm tamping foot. The tamping foot is moved around the mould giving a few seconds compaction at each of eight equispaced, diametrically opposite positions: the tamping foot is moved from one position to the next before material pushes above its edge. After 2 minutes of continuous compaction a 145 mm tamping foot is used to smooth irregularities on the surface of the core. For cores longer than 80 mm the core is then turned over, pushed into the mould using the 145 mm tamping foot and compacted for two minutes as before.

After two hours the core is cool and can be removed from the mould and weighed in air and in water to determine its refusal density. Percentage refusal density (PRD) is then the initial density expressed as a percentage of the refusal density.

5. AN EVALUATION OF THE REFUSAL TEST

The refusal test has been studied in the laboratory to determine its sensitivity to test and material variables and also to estimate the variability of test results on identical samples. In this work the refusal test was carried out mainly on core samples cut from pavement layers which had been laid and rolled with full-scale plant. Some additional tests were done on samples of loose material taken from behind the paver. These were put in cans and heated to the test temperature in the oven together with assembled moulds tightened to their test condition. Sufficient material was then transferred to each mould to provide a compacted sample of depth about 70 mm and the refusal test carried out in exactly the same way as for the core samples.

5.1 *Effect of test temperature, sample depth and compaction time*

The results in Figures 6 and 7 from tests on samples having a similar composition and initial VMA, show that test temperature and sample depth have little effect on final VMA in the ranges investigated. The small change in final VMA with temperature means that control of test temperature need not be precise. The test temperature recommended is that corresponding to a viscosity of approximately 4 poise for the nominal penetration of binder used, ie 140°C for 100 pen bitumen. At higher temperatures there would be a danger of binder draining from materials of high binder content. Noting the results shown in Figure 7 and bearing in mind the possibility of less compactable materials being laid in the future the depth of samples subjected to the refusal test carried out on only one end of the sample should be limited to 80 mm. Where the test is carried out on both ends of the sample it would appear possible to raise the limit and further work has shown that the test gives valid results on samples up to 150 mm deep, which is the maximum depth of sample that can be tested in the present moulds. The test is therefore capable of dealing with cores cut from any single layer of roadbase or basecourse macadam laid in the UK without the necessity of cutting the core to reduce the sample depth. Studies of many compaction-time characteristics like those shown in Figure 8 allowed the compaction time in the refusal test to be set at 2 minutes for a single ended test or 2 x 2 minutes for a double ended test.

5.2 *Segregation, orientation and degradation of aggregates*

Five pairs of loose samples of dense bitumen macadam containing blast furnace slag were taken from immediately behind the paver. One set of samples was analysed for grading whilst the other was subjected to the refusal test before determining gradings. The aggregate gradings of untested and tested loose material showed no significant difference indicating little or no degradation of the low density blast furnace slag, the aggregate most likely to break down in the refusal test. It is important that the test does not bring about appreciable degradation of the aggregate because this would give misleading results of refusal density.

Four cores were removed from rolled material of identical composition and the results of refusal tests on these cores were compared with those obtained with the loose material. The refusal VMA of the loose samples was 18.8 per cent compared with 15.4 per cent for the core samples; a difference significant at the one per cent level. This result confirms the necessity of basing a compaction standard on cores cut from the road rather than samples of material compacted in a mould.

To provide a further check another set of eight samples of loose material taken from basecourse containing basalt were tested. The refusal VMA of the loose material was 12.8, compared to 11.3 per cent for the cored samples. Again no significant difference was found between the gradings of the untested and tested samples.

5.3 *Initial compaction, binder content and aggregate*

Figure 9 gives the individual results of tests carried out on cored samples containing slag and limestone aggregates with wide ranges of bitumen contents, and a different limestone aggregate with a tar binder. The results are plotted to show the effect of the initial compaction of the samples on the final density achieved in the refusal test: initial compaction and binder content are seen to have little or no effect on refusal VMA. The samples were cut from four areas, each compacted to a different extent by 3, 9, 25 and 40 passes of a 9 tonne tandem roller. The associated range of compaction levels is therefore much greater than would be expected from site work and variation in initial compaction would be expected to have negligible practical effect on refusal VMA. Some cores were removed from areas compacted by a vibrating roller but this had no discernible effect on refusal VMA. Figure 9 confirms that a real point of refusal is being reached in the test, a point at which further compactive effort will make no significant reduction in VMA. Furthermore it shows that the test result is not affected by a change of operator.

The effect of binder content has been studied for cores of material containing partly crushed flint gravel. Samples having bitumen contents of 3, 4 and 5 per cent were tested; the refusal levels of compaction were 11.3, 11.5 and 11.5 per cent VMA respectively. These results and those of Figure 9 show that binder content has little or no effect on refusal VMA for all aggregates tested.

Although the effect of aggregate grading has not been studied systematically, refusal levels of VMA have been determined for samples covering a range of gradings that is typical of normal site work. The effect on refusal VMA of these grading differences represents the main component of variability when testing nominally identical samples of a material.

The range of aggregate types studied included granite, blast furnace slag, limestone, basalt and gravel, all of nominally the same grading. There were large differences between the refusal compaction levels of materials containing different aggregate types. For example, in Figure 9, results for slag differ markedly from those for limestone. In the present studies, the highest values of refusal VMA, around 14 per cent, were found with slag and the lowest figures of about 9 per cent with limestone. It is evident that the nature of the aggregate has a significant effect on VMA in the refusal test but the same is also true in rolling; Figure 10 shows the variation of VMA with roller passes. There is good agreement between results for crushed limestone and granite. The rate of decrease in

VMA for slag is about equal to that for crushed rock but absolute values are 3 or 4 per cent higher. Differences between the VMAs obtained for a given compactive effort on crushed rock and slag are likely to be a consequence of the very different surface roughness of the two classes of aggregate and not of their effective compacted state. When Figure 10 is replotted in Figure 11 in terms of PRD, there are no apparent differences. The results obtained using the refusal test, therefore, are seen to provide a valuable standard against which to measure the compacted state of different materials. More recently[6] it has been found that performance properties too are closely related to PRD.

Work has so far concentrated on 40 mm nominal size dense coated macadam but there would appear to be no difficulty in applying the test to 28 mm or 20 mm nominal size dense material. Further work would be required before considering the application of the test method to rolled asphalt or other materials.

5.4 *Variability in the refusal test*

In the refusal test the initial density of the core is expressed as a percentage of the refusal density (PRD). An initial assessment has been made of the repeatability of the test and its reproducibility. The reproducibility study is based on an unsatisfactorily small amount of work but is offered here as indicative of the sort of results which might be expected to emerge from the more comprehensive reproducibility work necessary before the test can be applied.

5.4.1 Repeatability of test (r): Repeatability is a quantitative expression of the random error associated with a single test operator in a given laboratory obtaining successive results with the same apparatus under constant operating conditions on identical test material. It is defined as that difference between two such single results as would be exceeded in the long run in only one case in twenty in the normal and correct operation of the method. Mathematically, repeatability (r) is expressed by $r = 2.77\ \sigma_1$ where σ_1 is the standard deviation associated with a single operator repeating the same test on identical material in a given laboratory. In the work reported it was not possible to obtain identical samples because composition of material and distribution of aggregate vary between cores of nominally identical material, giving rise to different values of initial and refusal density. Analysis of many test results indicates the repeatability of the test to be about 1.9 PRD but much of this figure could be attributed to sample variability rather than errors in determining the initial and refusal density of samples.

5.4.2 Reproducibility of test (R): Reproducibility is defined as the random error associated with test-operators working in different laboratories, each obtaining single results on identical test material when applying the same test method. It is the difference between two such single and independent results as would be exceeded in the long run in only one case in twenty in the normal and correct operation of the test method. Mathematically, reproducibility (R) is expressed by

$$R = 2.77\sqrt{\sigma_1^2 + \sigma_2^2} \qquad \text{. . . . . (1)}$$

where σ_1 is the standard deviation of test results in an estimate of repeatability and σ_2 is the standard deviation associated with all other sources of variability introduced when different operators in different laboratories are compared. As with repeatability it is not possible to obtain identical samples and any trials carried out to measure the reproducibility will result in an over-estimate. A pilot reproducibility study carried out between TRRL and two independent laboratories was designed to minimize the effect of material variability by taking sets of six closely spaced cores from a motorway reconstruction contract through three layers of dense bitumen macadam. Individual determinations of PRD for each of four different positions of coring were normalised by subtracting the corresponding means of the sets. The mean and standard deviation of the distribution indicates a figure of 1.9 PRD for the reproducibility of the test: this is no worse than the repeatability value given in the previous section and means that there was little additional variability introduced by using the test in three different laboratories. Reproducibility may be further improved by comparing means of pairs rather than single results; using means of pairs no more than one in twenty differences is likely to exceed 1.1 PRD.

5.4.3 Inter-laboratory variability: The results from each of the three laboratories are given in Figure 12 in terms of PRD of cores representing the range of conditions on the contract. The largest difference of 0.3 per cent between the means of laboratory A and B is just statistically significant but of negligible practical significance in comparison with the variation of PRD being measured. It has to be borne in mind that results from three laboratories are insufficient to determine reproducibility. A more extensive study is needed before the test can be put into practice; this study in accordance with BS 5497[14] is in hand.

6. APPLICATION OF REFUSAL TEST

The Department of Transport is faced with the urgent problem of recommending designs for very heavily trafficked roads, where a high standard of compaction is essential if a long design life is to be achieved. An interim specification has been written for these roads that involves the use of initial trial lengths rolled to an improved method specification to establish the density levels to be attained in the contract. Cores are taken during the remainder of the contract to check that the density is at least 99 per cent of that achieved in the trial areas. Although conventional rollers are stipulated for the trial areas the contractor is free to select the type of compaction plant and the manner of use thereafter.

Contracts in which the interim specification has been used, offered an opportunity to assess its effectiveness and examine the advantages of specifying field densities in relation to the standard density established by a refusal test, rather than in a trial bay. It also offered an opportunity to examine the difficulties of setting a fair and realistic compaction target that would allow for the wide range of materials and conditions of laying in the UK.

6.1 *Results of field trials of the refusal test*

Table 1 summarises the refusal test results obtained on two recent contracts (A and B) that have incorporated the interim end-result specification with target densities established in trial lengths at the start of the contract. Included for comparison are results from a third contract (C) where compaction was controlled by a method specification. A total of 189 cores were tested.

The trial areas established a target density which in terms of PRD may be seen to be four per cent lower in Contract A than in Contract B. Not surprisingly the mean PRD achieved on site was less in Contract A than in Contract B where the contractor found some difficulty in compacting to the high target levels set in the trial length.

The compaction levels achieved at these three sites may be augmented by results from other contracts where there are less intensive coring and Table 2 compares the level of compaction obtained on contracts using different specifications.

TABLE 1

Summary of refusal test results

	Contract A crushed rock fines	Contract B		Contract C crushed rock fines
		crushed rock fines	sand fines	
Mean refusal density (Mg/m^3)	2.564	2.564	2.490	2.494
Standard deviation	0.019	–	0.023	0.023
DTp Interim specification target density (PRD)	91.8	–	95.7	–
Mean density achieved on site (PRD)	93.6	96.0	96.1	95.3
Standard deviation	1.5	–	1.0	1.8

PRD – percentage of refusal density

TABLE 2

Comparison of refusal test results

Site		Average compaction level (PRD)	
Method specification			
Nately Scures A30 (11 sections)	TRRL full-scale experiments	94.7	wheel path zones
Alconbury by-pass A1 (6 sections)	TRRL full-scale experiments	95.5	wheel path zones
Wheatley by-pass A40 (2 sections)	TRRL full-scale experiments	95.0	wheel path zones
Denny by-pass A81 (8 sections)	TRRL full-scale experiments	95.1	wheel path zones
Contract C		95.3	wheel path zones
TRRL LR 891 site		93.5	wheel path zones
Improved method specification (TRRL LR 891)			
Modified specification, no observers		94.4	wheel path zones
Modified specification, observers		95.7	wheel path zones
DTp interim end-result specification			
Contract A		93.6	(target of 91.8)
Contract B		96.1	(target of 95.7)

6.2 *Achieving uniformly high compaction*

The purpose of applying a compaction specification to the construction of bituminous pavements is to ensure that a high and uniform level of compaction is maintained throughout the work so that the full performance potential of the materials may be realized as either a saving in the material used or a longer pavement life. In terms of the refusal test this means a high PRD with little variability about the mean. Given the mean value of PRD and its standard deviation the proportion of test samples expected to fall below any particular level of compaction may be estimated using published statistical tables: for example, approximately 5 per cent of all samples would be expected to be below the mean by more than 1.65 standard deviations. The limited results given in Tables 1 and 2 and in

Figure 11 suggest that a mean PRD of 95 per cent would not be too difficult to achieve. A standard deviation of 1.5 per cent is considered to be representative; if this is confirmed by further measurements, it would mean that no more than one result in 20 would lie below a PRD of 92.5. With more extensive observations of compaction levels and variability achieved in practice, quality control schemes can be developed to suit the requirements of contractor and client.

7. CONCLUSIONS

It has been shown that better compaction of roadbase and basecourse macadams would significantly improve their structural performance; furthermore, there is considerable scope for improving compaction in the critical wheel-path zones.

Initially the results of rolling trials were used to formulate improved procedures which would ensure that greater compactive effort was applied in the wheelpaths before the material cooled excessively. An improved method specification for compaction was tried out on four motorway construction contracts but it met with only limited success, probably because of the inherent problems of controlling a method specification. The general view now is that an end-result specification would provide a better check on the level of compaction being achieved.

Before an end-result specification can be implemented it is necessary to relate compaction to an acceptable standard. The Marshall test proved an unsuitable means of assessing the level of compaction of roadbase and base-course macadams but a refusal test, which was originally developed to determine the scope for further compaction, was found to offer considerable potential as a standard. The test uses cores taken from the compacted pavement layers, which ensures that the material tested is in every way representative of that in the road pavement. Moreover performance properties have been found to be closely related to the level of compaction determined in the test. The test has been developed for roadbase and basecourse material with crushed rock or slag aggregate; further work would be needed to extend it to uncrushed or partly crushed gravels.

When applied to roadbase and basecourse macadams the refusal test is insensitive to material variables other than level of compaction: results are negligibly affected by sample thickness, sample temperature and binder content. Crushed rock and slag aggregates vary in the ease with which they may be compacted to a given VMA but they are all equally compactible in terms of percentage of refusal density (PRD). This is apparent in the unique relation between PRD and the number of roller passes, and allows a common target level of compaction to be specified for all crushed rock and slag aggregates in terms of PRD.

The research has led to the development of a test which may provide the basis for an end-result specification. Preliminary results suggest that an average compaction level of 95 PRD could be achieved in the wheelpath zones for any roadbase or basecourse macadam containing crushed rock or slag. The inherent variability of both the compaction process and of materials of construction will have to be allowed for in the satisfactory application of the test.

8. ACKNOWLEDGEMENTS

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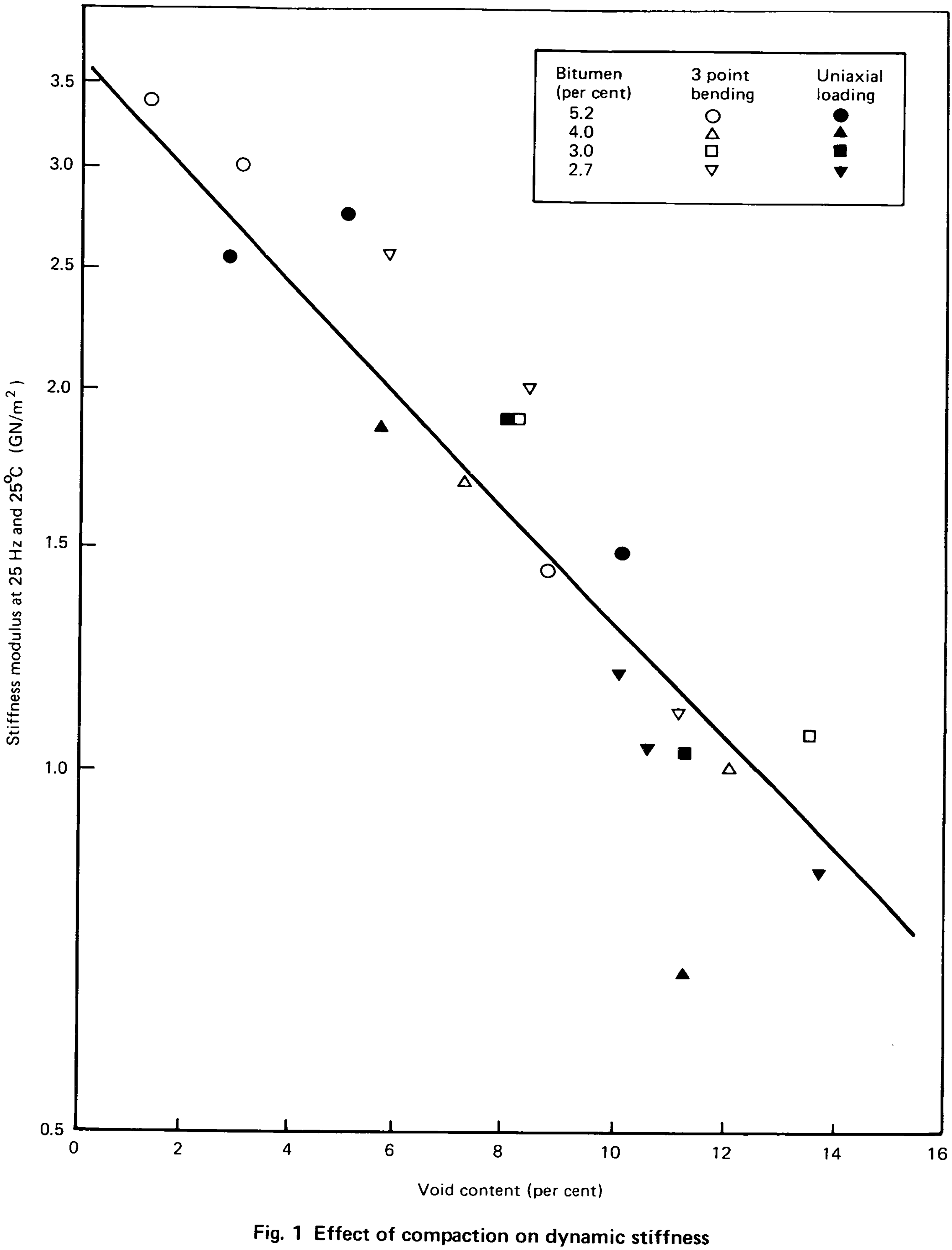


Fig. 1 Effect of compaction on dynamic stiffness

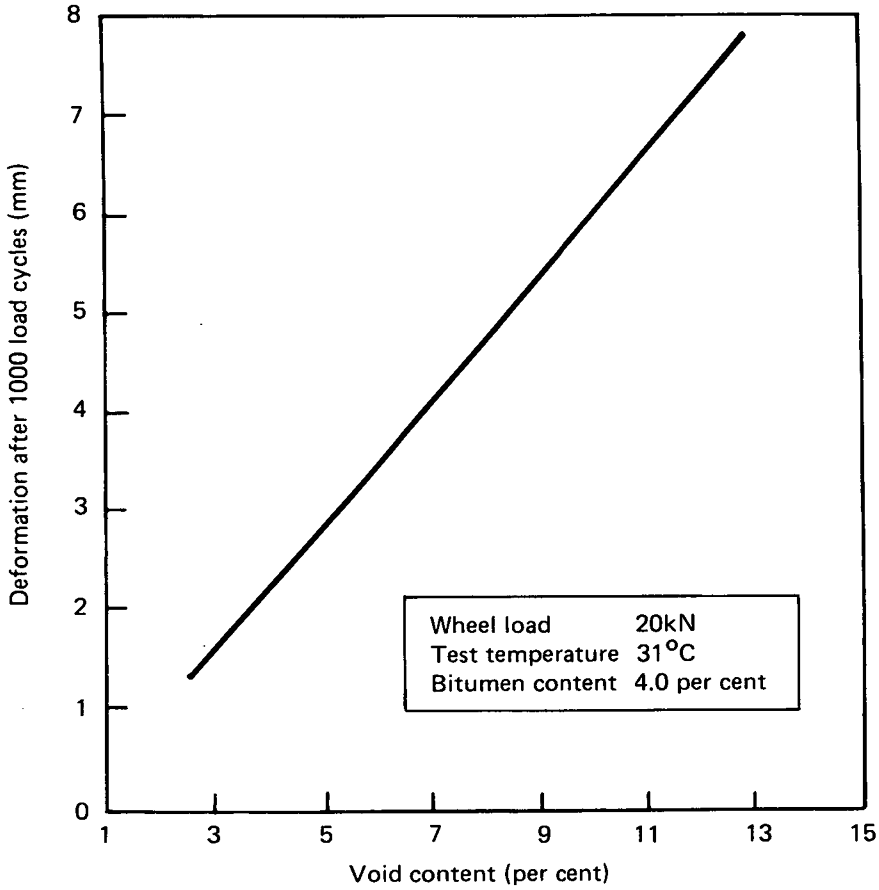


Fig. 2 Effect of compaction on deformation

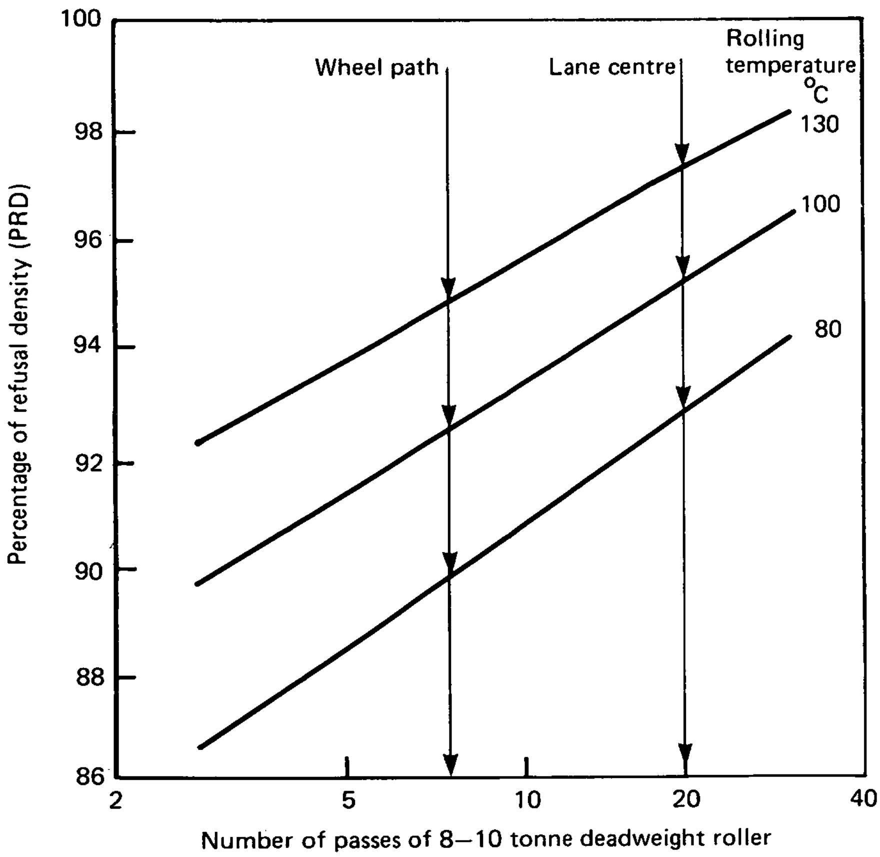


Fig. 3 Effect of rolling temperature on compaction

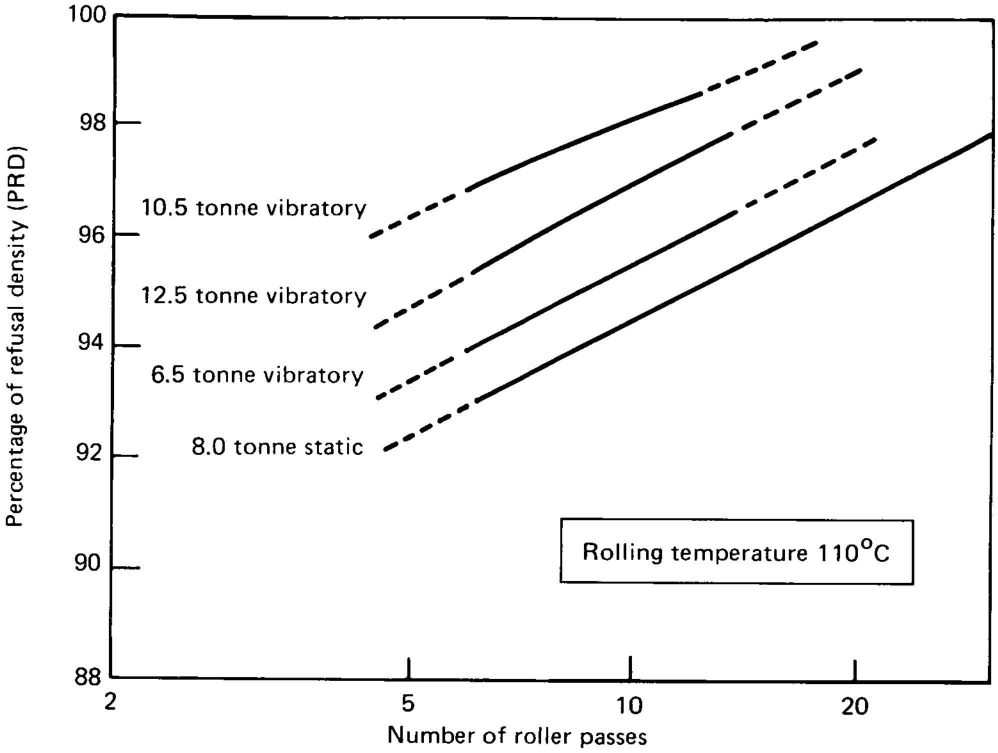


Fig. 4 The potential for increasing compaction using heavy vibratory rollers

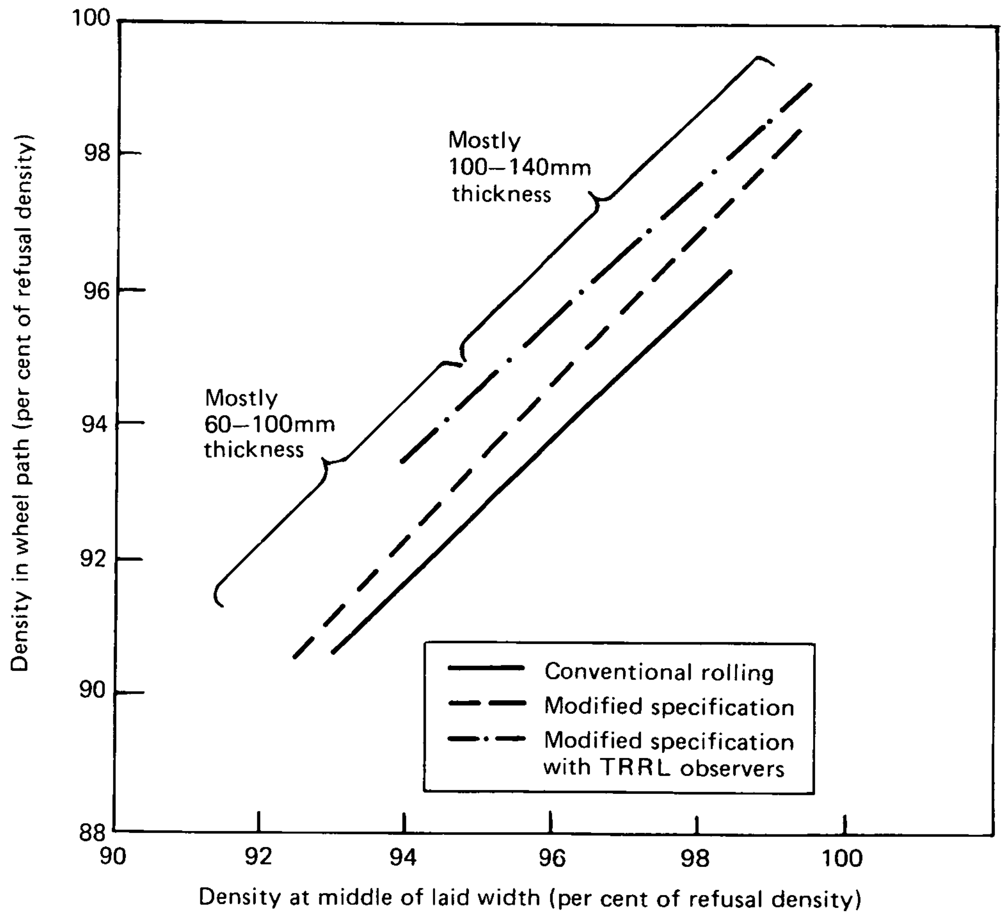


Fig. 5 Relationships between the degree of compaction in the wheel path and that at the middle of the laid width

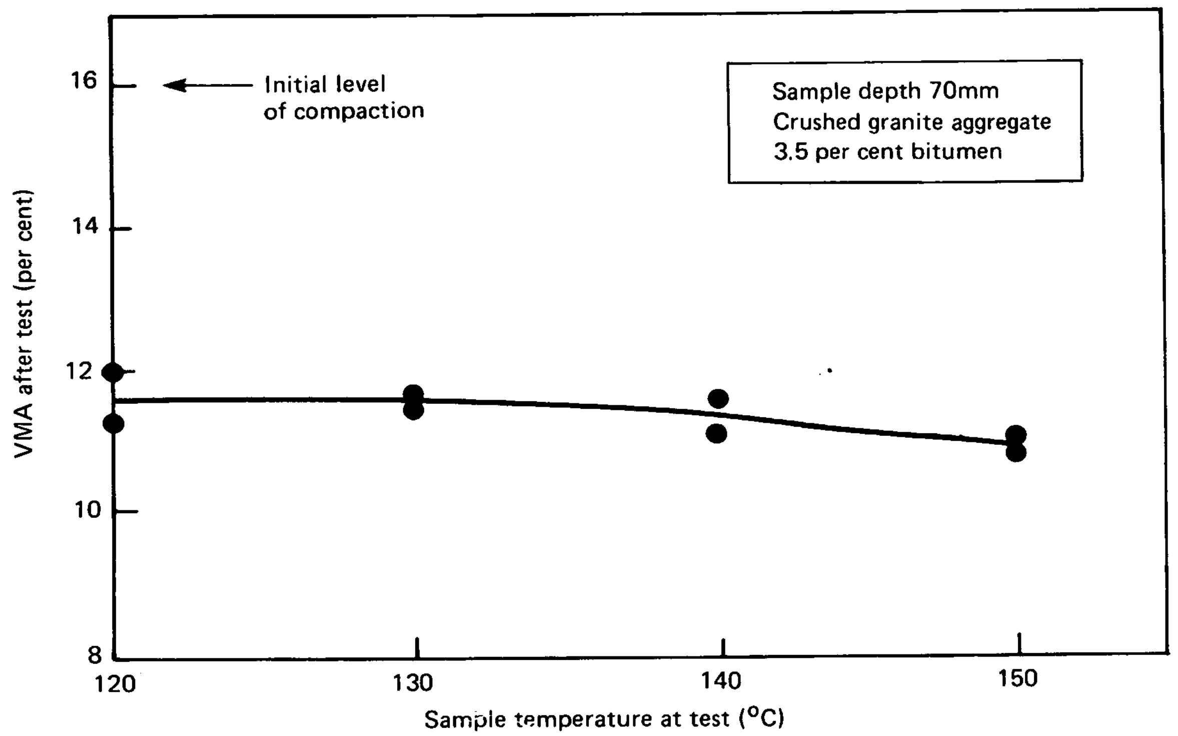


Fig. 6 Effect of temperature on the compaction achieved in the refusal test

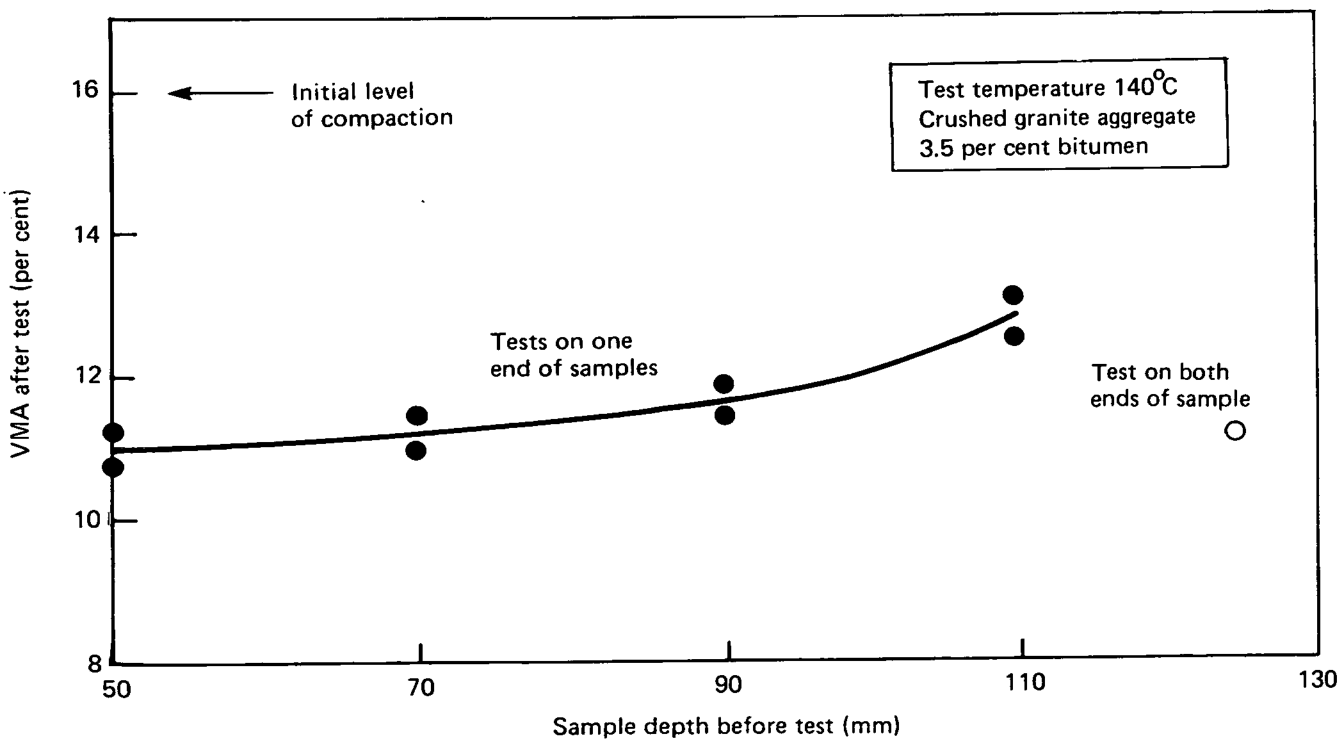


Fig. 7 Effect of sample depth on the compaction achieved in the refusal test.

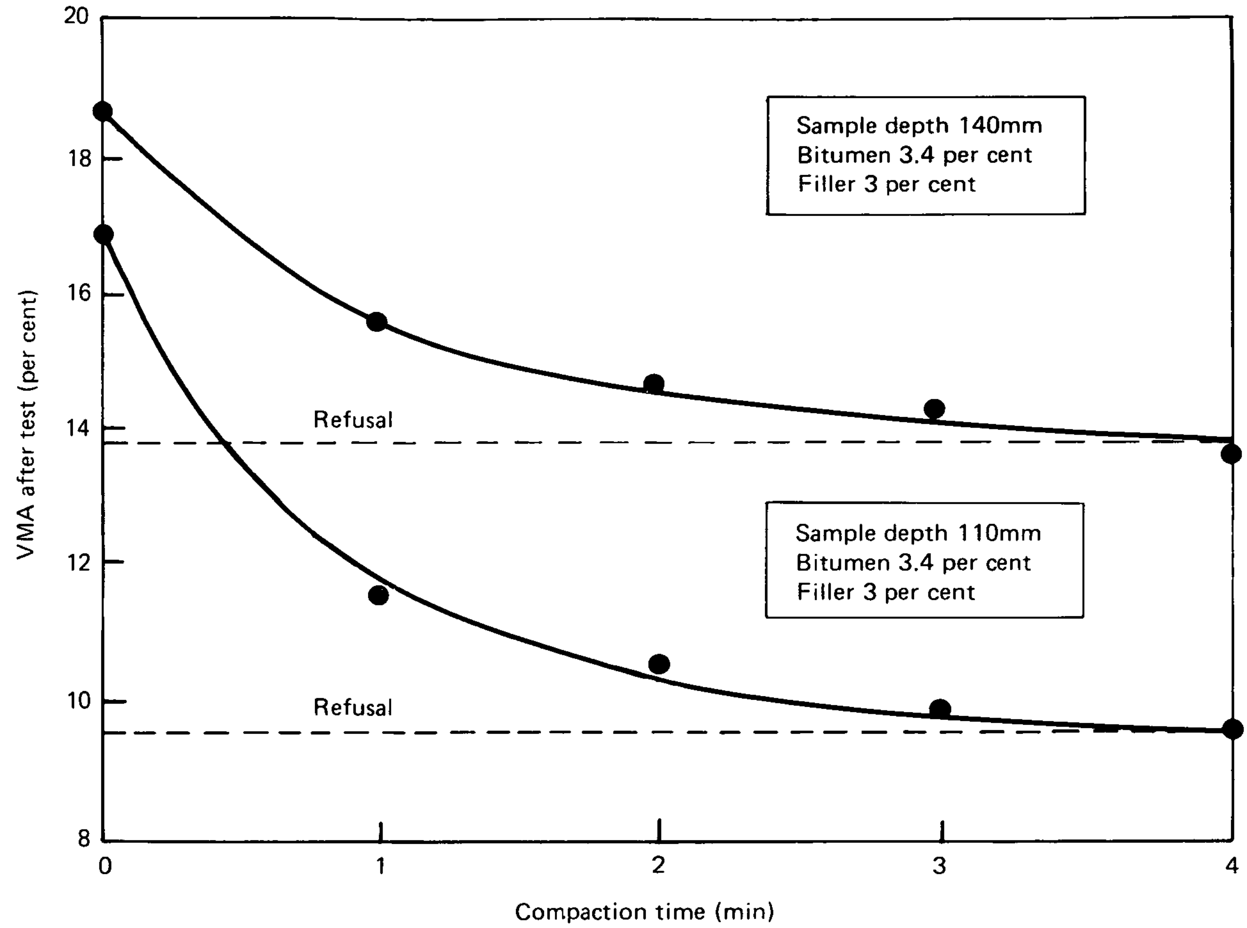


Fig. 8 Effect of compaction time on the compaction of samples with granite aggregate

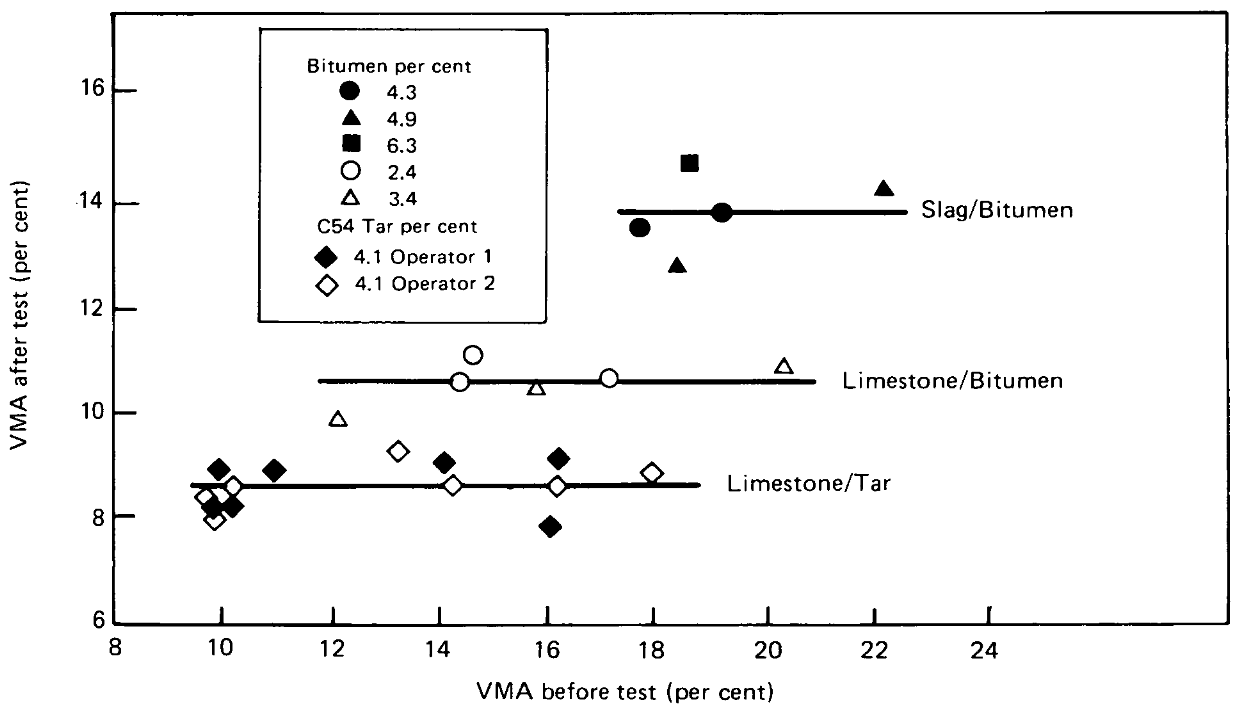


Fig. 9 Variability of the compacted state at refusal

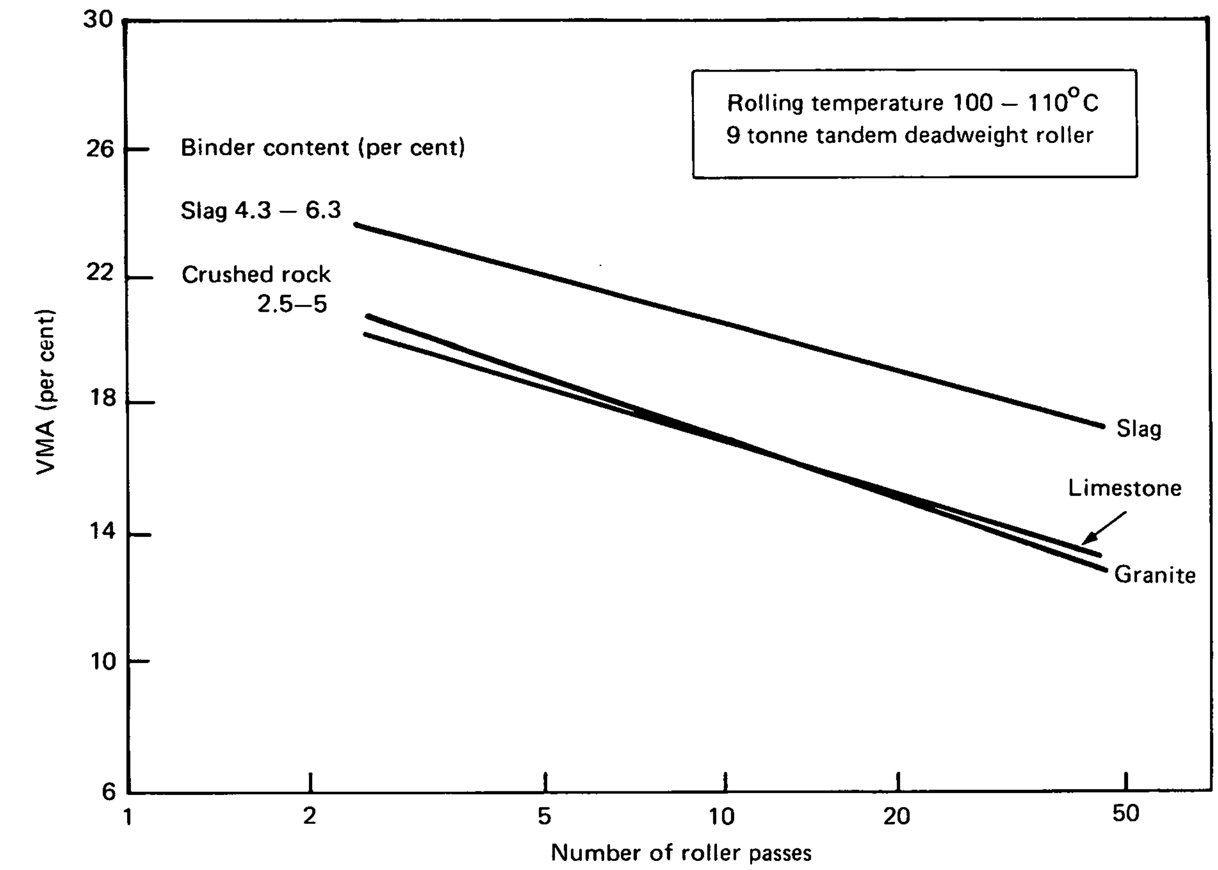


Fig. 10 Variation of VMA with number of passes

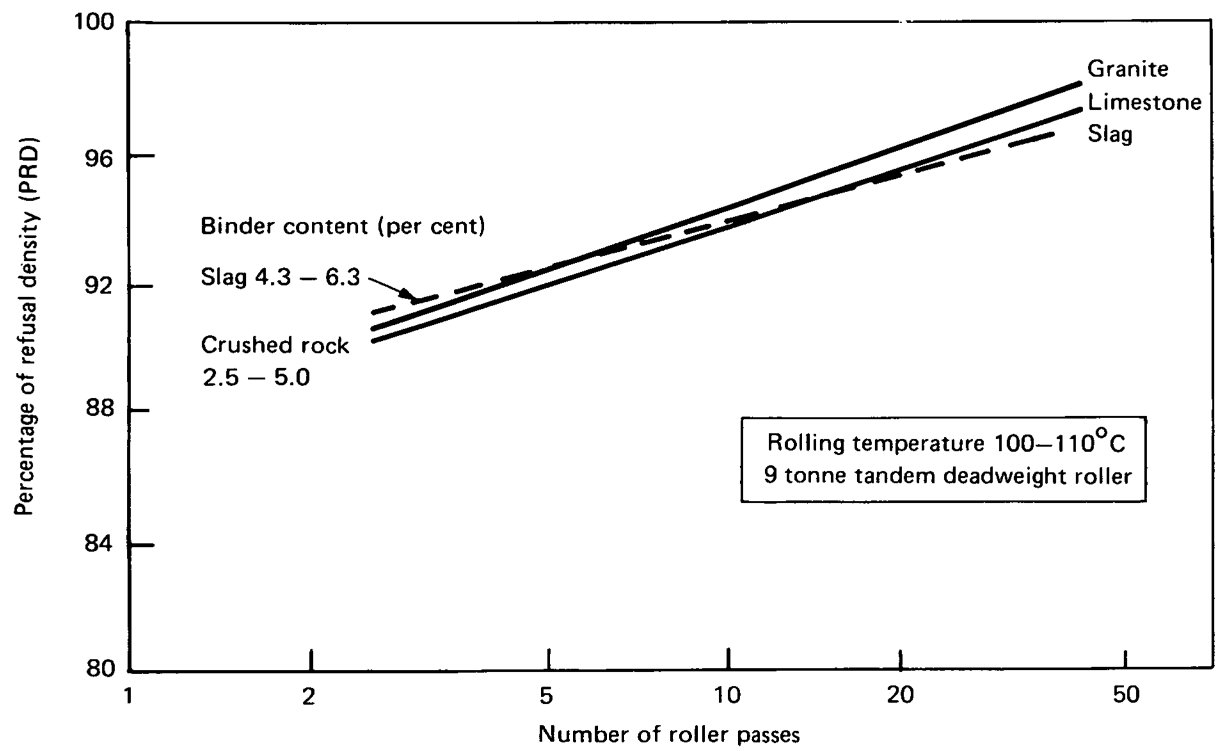


Fig. 11 Effect of roller passes on compaction level expressed as percentage of refusal density (PRD)

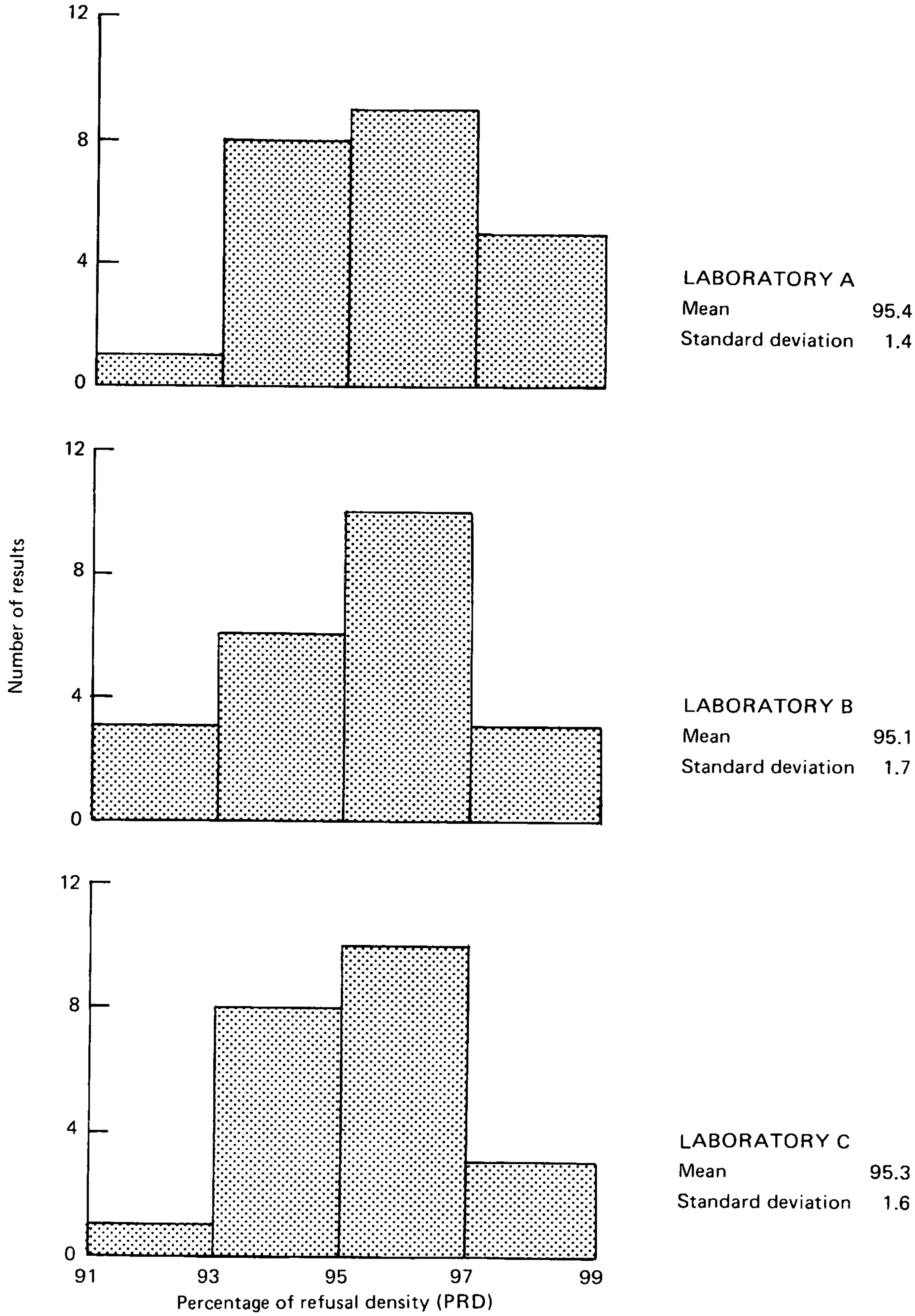
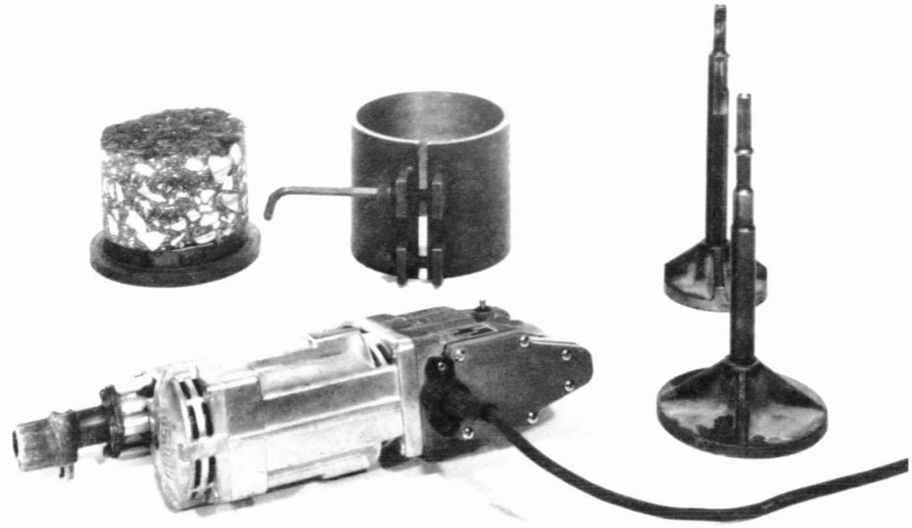


Fig. 12 Comparison of PRD measurements at different laboratories



Neg. no. B133/79

Plate 1 Test equipment and sample prior to assembly

Neg. no. B131/79

Plate 2 Sample in assembled mould at test temperature being compacted to refusal

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