A LABORATORY INVESTIGATION OF THE COMPACTION OF DENSE GRADED ASPHALT CONCRETE

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ABSTRACT

This paper reports some of the results that have been obtained from a 3-year laboratory investigation of the compaction of dense graded asphalt concrete, that is being carried on by McAsphalt Engineering Services for the Airfield Section of the Canadian Department of National Defence.

The investigation is studying the influence of three important factors affecting pavement compaction that can be controlled in the field, compaction temperature, compaction effort, and paving mixture design.

Compaction temperatures of 275°F, 200 °F, and 150°F are employed to study the influence of temperature on compaction, while 100, 60, 20 and 6 blows of a Marshall double compactor provide variable compactive effort.

Paving mixture design includes the variables: normal, gap, and Fuller gradings; three levels of VMA, 13.5, 15.0 and 16.5 percent; three levels of air voids, 2.5, 4.0 and 5.5 percent; aggregate particle index; filler/bitumen ratio; various grades and sources of asphalt cements; and the influence of different aggregate gradings for the same VMA and air voids values.

The paper demonstrates that degree of compaction is greatly influenced by the temperature range for compaction, degree of compactive effort, and paving mixture design, and by means of a mathematical treatment it demonstrates the influence of each of these three factors quantitatively.

Generally speaking, asphalt paving mixtures with the highest asphalt contents tend to be most easily compacted.

There is no single temperature at which paving mixture compaction by rolling or by other means *suddenly* becomes ineffective.

The VMA of a paving mixture can be increased very easily by deviating the aggregate grading curve further from the corresponding Fuller curve.

Marshall stability is influenced by the particle index of the aggregate in the paving mixture, by the VMA of the paving mixture, and by its filler/bitumen ratio.

Cooling curves based on temperature measurements beginning immediately after a paving mixture has left the spreader, indicate that the time available for effective compaction is relatively short.

In addition to hot asphalt mixes, it is shown that a straight line relationship between compacted density and logarithm of compactive effort in the form of number of Marshall blows (semi-log plot), exists for many road building materials such as soil, sand screenings, soil asphalt, soil cement, and cold asphalt mixtures. Therefore, some of the findings of this paper can also be applied to the compaction of these materials.

Key Words:
Compactive effort, paving mixture temperature, paving mixture design, percent laboratory compacted density, aggregate gradation, VMA, air voids, particle index, filler/bitumen ratio, asphalt concrete.

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INTRODUCTION

This paper presents some of the results of a 3-year laboratory investigation of paving mixture compaction that is being conducted by McAsphalt Engineering Services for the Airfield Section DCEDE-6, Department of National Defence, Ottawa, Canada.

Although engineers and contractors have been aware for many years of differences in the ease or difficulty of compacting asphalt paving mixtures by rolling during construction, until quite recently this matter appears to have received very little study. In particular, the influence on paving mixture compaction of factors that can ordinarily be easily controlled, such as the temperature range employed for rolling, the rolling effort expended, and the design of the paving mixture itself, do not appear to have been systematically investigated.

Why should paving engineers be more concerned about the influence of factors that can make the compaction of paving mixtures to the specified minimum density more efficient and effective? This is answered very effectively by Figure 1, which provides the results of a study made by the U.S. Federal Highway Administration some years ago (1).* Engineers from FHWA went to a number of paving projects in the vicinity of Washington, D.C., and took samples from pavements immediately after rolling was completed. These samples were analysed for air voids, and the asphalt binder was extracted and its penetration at 77°F was determined. These same pavements were sampled each year for a number of years afterward, the asphalt cement was extracted, and its penetration at 77°F was measured, Figure 1 illustrates the results obtained after a period of only four years. The ordinate axis lists penetrations at 77°F of the asphalt cements after four years as percentages of their corresponding penetrations at 77°F immediately after construction. The abscissa indicates the percentage air voids in each pavement when construction was complete. The curve in Figure 1 demonstrates that high air voids in a pavement immediately after construction due to poor compaction by rolling results in rapid hardening of the asphalt binder. For example, in pavements which due to poor compaction had air voids of 12 and 14 percent immediately after rolling, the asphalt cement retained only 40 and 30 percent respectively, of the penetration at 77°F just after construction. On the other hand, in pavements that had been adequately compacted to just under 6 percent air voids during construction, after four years the asphalt cement still retained from 70 to 80 percent of its penetration immediately after construction. Pavement deterioration increases with increasing hardness of the asphalt binder, and the FHWA investigators state in their report that the two pavements with 12 and 14 percent air voids due to poor compaction were showing signs of deterioration after only two years of service.

Other studies have reached similar conclusions.

An insidious result of poor compaction is that its influence on pavement performance does not ordinarily show up until several years after construction in the form of shortened service life, higher maintenance expenditures, and the need for an early overlay. Unfortunately, the quite unnecessary high costs for these items are very seldom traced back to the primary cause, which is very often poor compaction during construction, although other factors may also sometimes contribute.

So far, studies of the problem of more effective pavement compaction by rolling during construction have been on a very limited basis. In 1960 Parker (2)

* Numbers in parenthesis denote references listed on page 406

investigated the effect of temperature on the density obtained for a single paving mixture when using a constant compactive effort of a 50-blow Marshall. In 1965, Heukelom (3) referred to the effect of 5-blow versus 50-blow compaction on the density of a paving mixture compacted at a single temperature. In 1968, Ruiz and Dorfman (4) published the results of a compaction study on two paving mixtures. They used the slope of the straight line obtained when paving mixture density is plotted versus the logarithm of number of Marshall blows on a semi-log chart, as the basis for a compactibility index. The steeper the slope of this line the greater would be the resistance to compaction. In 1969, Lefebvre and Robertson (5) showed that by using the Ruiz and Dorfman approach, to paving mixtures with the same ease or difficulty of compaction could receive different compactibility index ratings, merely because of differences in the specific gravities of the paving mixture components. To avoid this criticism, Lefebvre and Robertson proposed that paving mixture density for different compactive efforts should be expressed as percent of density for 50-blow or 75-blow Marshall compaction. In this case, either 50-blow or 75-blow Marshall would be given a rating of 100 percent of laboratory compacted density. When percent of laboratory compacted density is plotted versus logarithm of number of blows on a semi-log chart, a straight line relationship is obtained. Like Ruiz and Dorfman, Lefebvre and Robertson used the slope of this line as the criterion for the ease (flatter slope) or difficulty (steeper slope) of compaction.

In 1970, Fung (6) found that a straight line relationship occurs between density values for paving mixtures compacted at 280°F versus logarithm of compactive effort, whether the compactive effort is applied as number of blows of a Marshall hammer, number of tamps of the Hveem mechanical compactor, or the differences in static pressure when compaction is being exerted by a double plunger.

In a preprint of their paper for the 1975 annual meeting of AAPT, Lister and Powell (7) have shown that a straight line relationship exists between decrease in air voids (increase in pavement density) and the logarithm of the number of roller passes made over a paving mixture during its compaction.

Consequently, the straight line semi-log relationship obtained when increase in paving mixture density is plotted versus the logarithm of increasing compactive effort, has been amply documented.

SCOPE OF THE PRESENT INVESTIGATION

Reference to the work of previous investigators shows that in general, each has concentrated very largely on one phase of the problem of paving mixture compaction. The present study is very much more comprehensive, and consists of a laboratory investigation of the influence on paving mixture compaction of three important variables, temperature, compactive effort, and pavement design, each of which can be controlled in the field. Control can be exerted over the range of temperature to be employed for compaction; the amount and intensity of compactive effort can be prescribed; and the design of the paving mixture to be used can be selected.

It is recognized that other factors such as layer thickness, deflection characteristics or solidity of the base on which the pavement layer is being constructed, temperature of the underlying surface, etc., also influence the difficulty or ease of compaction, but these are usually outside the control of those who are actually constructing an asphalt pavement.

The scope of a major portion of the present investigation is indicated by the factorial design of Table 1, and includes the following:

1. The effect of paving mixture temperature on compaction was determined by using compaction temperatures of 275°F, 200°F and 150°F.
2. Differences in compactive effort are represented by differences in the number of blows of the hammer of a Marshall double compactor that were applied, 100, 60, 20 and 6.
3. The effect of paving mixture design was investigated:
   - (a) to determine the influence of aggregate gradation, normal, gap and Fuller gradings, were included, Figure 2 and Table 2.
   - (b) by employing VMA values of 13.5, 15.0 and 16.5 percent for each of the normal and gap gradings, and by determining VMA values associated with Fuller grading.
   - (c) by employing air voids values of 2.5, 4.0 and 5.5 percent with each VMA value, and with the fuller grading.
   - (d) an aggregate particle index of 11.5 was used for all paving mixtures in Table 1, because in general, this particle index provided paving mixtures with the minimum Marshall stability of 1500 pounds at 140°F specified by the Airfield Section DCEDE-6.
   - (e) the filler/bitumen ratio by weight was 0.9 for all mixtures in Table 1, filler being defined as mineral dust passing a No. 200 sieve.
   - (f) The consistency of the asphalt cement used with all paving mixtures in Table 1 was 150/200 penetration that was generously supplied by the Montreal Refinery of Imperial Oil Limited, and for which inspection data are listed in Table 7.

The paving mixtures of Table 1 were employed for Phase 1 of this investigation. In Phase 2, the influence of other variables are being investigated such as different aggregate particle indices, asphalt cements of other penetrations at 77°F, other filler/bitumen ratios, and various gradations for any given particle index value.

While the influence of wide variations in aggregate gradation has not been a direct variable in this investigation, it has been included indirectly because for any given particle index, changes in VMA can be obtained only by differences in aggregate gradation.

Asphalt content has not been a direct variable, but has been included indirectly since for any given VMA value, differences, in air voids values result very largely from differences in asphalt content.

Unless specifically stated to be otherwise, all paving mixtures referred to in this paper were made with aggregates having a particle index of 11.5, a filler/bitumen ratio of 0.9 by weight, and 150/200 penetration asphalt cement having a viscosity at 275°F of about 260 centistokes.

For this paper, VMA is based on the aggregate's ASTM bulk specific gravity, and air voids are determined from the bulk and theoretical maximum specific gravities of each of the paving mixtures. For practical reasons, VMA and air voids values within ± 0.2 percent of the target value were accepted. For example if the target VMA value was 15 percent, any value between 14.8 and 15.2 percent was considered to be on target.

TEST PROCEDURES

Each of the 21 paving mixtures listed in Tables 1 and 2 was designed to have a particle index of 11.5. The particle index test for aggregates, ASTM D3398, was developed by Professor E. Y. Huang (11, 12) to provide a measure of the influence of differences in aggregate particle shape and surface texture. A low particle index of 7 or 8 or less indicates rounded aggregate particles with relatively smooth surfaces. A high particle index of 15 or 16 or more is associated with angular particles with rough textured surfaces. The particle index test consists of compacting three layers of a single aggregate size, for example, 4 to 8, 30 to 50, etc. seive size, in a steel mold 6 inches in diameter by 7 inches high, with 10 blows on each layer provided by a 2 inch drop of a 5/8 inch steel rod 24 inches long, and repeating the test with 50 blows on each of the three layers. The voids for 10-blow and 50-blow compaction are determined, and from these values the particle index value for that aggregate size is read from a nomograph.

A constant aggregate particle index of 11.5 was employed in Phase 1 of the investigation to avoid uncertainties that would otherwise be introduced concerning the effect of differences in particle shape and surface texture whenever the grading of an aggregate was changed.

Figure 3 demonstrates that the resulting particle index can be calculated on the basis of simple proportions when two aggregates of the same size fraction but with different particle indices are blended. Consequently, by blending the same size fractions from two aggregates with particle indices, one below and one higher than the particle index desired, any particle index between them, for example 11.5 can be easily obtained.

For each of the 21 paving mixtures referred to in Table 1, each size fraction employed, 1/2 to 3/8, 3/8 to No. 4, 4 to 8, 8 to 16, 16 to 30, 30 to 50, 50 to 100, and 100 to 200, was prepared to have a particle index of 11.5, and each of these size fractions was weighed out separately for each Marshall briquette that was made. The mineral dust fraction (passing No. 200) for each mix came from the screenings from a gravel crushing operation. Sieve analysis and asphalt content for each of the 21 paving mixtures are given in Table 2.

The design for each of the 21 paving mixtures referred to in Tables 1 and 2 was based on 60-blow compaction at 275°F, in accordance with ASTM D1559 except that a Marshall double compactor was employed in place of hand compaction. After its design was worked out, Marshall briquettes for each of these 21 paving mixtures were prepared in triplicate for each compaction temperature 275°F, 200°F, and 150°F, and for each compaction effort, 100, 60, 20 and 6 blows, indicated in Table 1. The average bulk specific gravity and average Marshall stability for each set of conditions were measured, and these values are listed in Tables 3 and 4. This involved the testing of 11 duplicates of each of the original 21 paving mixture designs, or a total of 252 paving mixtures. The order in which these 252 paving mixtures were prepared and tested was randomized, since a statistically designed experiment requires factorial design and randomization of the order in which tests are performed.

In Table 4, specific gravity and Marshall stability data for *each* paving mixture at compaction temperatures of 275°F, 200°F, and 150°F and for compactive efforts of 100, 60, 20 and 6 blows Marshall, as listed in Table 3, have been expressed as corresponding percent of specific gravity or Marshall stability for 60-blow Marshall at 275°F.

DISCUSSION OF TEST DATA

1. General

When analyzing the data obtained from this investigation, least squares lines were drawn through the raw data for specific gravity versus logarithm of number of blows and through logarithm or raw Marshall stability data versus logarithm of number of blows. The data plotted for the various figures for this paper were taken from these least squares lines. This will explain the very good agreement between the points and the smooth lines drawn through them that will be observed in each of the figures.

Dr. J. C. Young of the Statistics Section of the Mathematics Department at the University of Waterloo advises that the correlation coefficient for the least squares line drawn through the plot of raw specific gravity data versus logarithm of number of blows shown in Table 3 is 0.98, and that the correlation coefficient for the least squares line drawn through the logarithm of the raw Marshall stability data versus logarithm of number of blows listed in Table 3 is 0.97. These correlation coefficients indicate excellent agreement between the actual raw data, and the least squares lines drawn through the data.

2. Influence of Compactive Effort and Compaction Temperature on Paving Mixture Compaction.

Figure 4 is a plot of percent of laboratory compacted specific gravity versus the logarithm of the compactive effort in the form of Marshall blows that have been applied. Figure 4 illustrates the influences of compactive effort and compaction temperature on the ease or difficulty of compacting paving mixtures. The lines in Figure 4 are the least squares lines through the pertinent specific gravity data in Table 4 for the 21 paving mixtures of Table 1. As would be expected, Figure 4 demonstrates that both temperature at the time of compaction and compactive effort have a great influence on the percent of laboratory compacted specific gravity that can be attained. Figure 4 also illustrates the compaction requirement of 97 percent of laboratory compacted specific gravity that many specifications stipulate.

Figure 5 demonstrates that for the 21 paving mixtures in Table 1, for the same compaction temperature of 275°F, those with 2.5 percent air voids have the flattest slope and are therefore most easily compacted. These are followed in order of increasing difficulty of compaction by paving mixtures with 4.0 and 5.5 percent air voids. Figure 5 also indicates that the average asphalt contents for mixes with 2.5, 4.0 and 5.5 percent air voids are 5.9, 5.3 and 4.7 percent respectively. Throughout the analysis of data from this investigation it has been apparent that when other conditions are equal, the higher the asphalt content of a paving mixture the greater is its ease of compaction.

In Figures 6 and 7, the data of Figure 4 has been plotted on arithmetic charts which may be more easily understood. Figure 6 is a plot of percent laboratory compacted specific gravity versus compaction temperature. While Figure 7 is a graph of percent laboratory compacted specified gravity versus compacted effort. The following comments can be made on Figures 6 and 7:

1. Contrary to some published statements that have been made, there is no single paving mixture temperature such as 175°F or 200°F where compactive effort *suddenly* becomes ineffective.
2. The lower the compaction temperature, the greater is the compactive effort required to attain a specified percentage of laboratory compacted specific gravity. For example, 19 blows provide 97 percent of laboratory compacted

density at a paving mixture temperature of 275°F, where 29 and 48 blows are needed to obtain the same density at temperatures of 200°F and 150°F, respectively.

3. Consequently, the least compactive effort is required to satisfy the pavement density specified, if the paving mixture is compacted as quickly as possible at the high temperatures that prevail just after it has left the spreader.

4. Figure 6 demonstrates that for any given compaction temperature the difficulty of compaction increases as the paving mixture density is increased. For example, at a compaction temperature of 275°F, the 14 blows between 6-blow and 20-blow compaction increases pavement density from 93.8 to 97.2 percent = 3.4 percent; from 20 blows to 40 blows, the increase in pavement density is from 97.2 to 98.9 percent = 1.7 percent, while from 40 blows to 60 blows the increase in pavement density is only from 98.9 to 100.0 percent = 1.1 percent.

Remembering that the steeper the slope of the line the more difficult a paving mixture is to compact, Figure 8 demonstrates that at each compaction temperature of 275°F, 200°F and 150°F, paving mixtures with Fuller gradings are more difficult to compact than those with normal gradings. Figure 8 indicates that the average asphalt content for paving mixtures with normal gradings was 5.4 percent while the average asphalt content for paving mixtures with Fuller gradings was only 3.9 percent. This is another example of a finding referred to earlier, that when other conditions remain the same, the higher the asphalt content of a paving mixture the greater is the ease of compaction. Therefore, it is not posible to state at present how much of the greater difficulty of compacting Fuller graded paving mixtures is due to the Fuller grading, and how much is due to the lower asphalt content of these paving mixtures.

Gap graded and normal graded paving mixtures of the same design had approximately the same compaction characteristics and Marshall stabilities for any given compaction temperature and compaction effort. Therefore, this paper concentrates on data for normally graded and Fuller graded paving mixtures.

3. Influence of Aggregate Particle Index on a Paving Mixture.

Figure 9 illustrates the influence that the particle index of the aggregate has on the Marshall stability of paving mixtures that have been compacted at 280°F. For a portion of Phase 2 of this investigation, 150/200 penetration asphalt provided through the courtesy of Husky Oil Operations Ltd., Lloydminster, Saskatchewan, was employed. For the standard compaction viscosity of 280 centistokes, ASTM D1559, a compaction temperature of 280°F was required when this asphalt cement was used. Inspection data for this asphalt cement are listed in Table 7.

Each of the three paving mixtures referred to in Figure 9, was designed to have a VMA value of 15 percent and an air voids value of 4 percent. Figure 9 demonstrates that at 100 percent of laboratory compacted density, the paving mixtures with particle indices of 15.0, 11.5 and 8.0 have Marshall stabilities of 3050, 1675, and 880 pounds, respectively.

On the other hand, Figure 10 demonstrates that the paving mixture containing an aggregate with a particle index of 15 would have the greatest resistance to compaction, while the mixture made with aggregate with a particle index of 8 would be most easily compacted. Nevertheless, for any given compactive effort, for example 20-blow Marshall, the following table shows that in spite of its greater resistance to compaction, as illustrated in Figure 10, and its lower percent of laboratory compacted specific gravity, the paving mixture with the highest particle index would still have the highest Marshall stability.

Particle Index	% Lab. Comp. Spec. Grav. for 20-blow Marshall	Marshall Stability
15.0	96.15	1275 lb.
11.5	97.10	725 lb.
8.0	97.90	410 lb.

4. Influence of Different Particle Indices for Coarse and Fine Aggregate Fractions.

For all of the data recorded in Tables 3 and 4, with the particle index of each size fraction was 11.5, and the overall particle index for the aggregate as a whole in each paving mixture was therefore also 11.5. However, in the field, it is not uncommon to combine a crushed highly angular coarse aggregate having a high particle index, with a natural sand having a much lower particle index, and vice versa. Figure 11 illustrates the effect on Marshall stability of a paving mixture by combining a coarse aggregate with a particle index of 15 with a fine aggregate with a particle index of 8, by combining a coarse aggregate with a particle index of 8 with a fine aggregate with a particle index of 15, and by combining a coarse aggregate with a particle index of 11.5 with a fine aggregate having a particle index of 11.5. In each of these three cases, the coarse and fine aggregates were blended in proportions that would result in an overall aggregate particle index of 11.5. Each of the three paving mixtures was designed to have a VMA value of 15.0 percent, and an air voids value of 4.0 percent.

Figure 11 demonstrates that insofar as Marshall stability is concerned, the highest stability is provided by the paving mixture containing the aggregate blend consisting of coarse aggregate with a particle index of 8.0 with fine aggregate showing a particle index of 15.0. The lowest Marshall stability occurs for the paving mixture made with an aggregate blend consisting of a coarse aggregate with a particle index of 15.0 and a fine aggregate with a particle index of 8.0. The following table indicates the Marshall stabilities for paving mixtures containing each of these three aggregate blends at 97 percent and at 100 percent of laboratory compacted Specific Gravity.

Aggregate Blend	Marshall Stability	
	97% Comp.	100% Comp.
Coarse P1 = 8.0, Fine P1 = 15.0	1160 lb.	2250 lb.
Coarse P1 = 11.5, Fine P1 = 11.5	715 lb.	1675 lb.
Coarse P1 = 15.0, Fine P1 = 8.0	610 lb.	1550 lb.

Figure 11, therefore, indicates very effectively that the particle index of the fine aggregate has a much greater influence on the Marshall stability of an asphalt paving mixture than the particle index of the coarse aggregate.

With regard ot ease or difficulty of compaction, the plot of specific gravity versus logarithm of number of blows for the three paving mixtures of Figure 11, is quite similar to Figure 10, with the combination of coarse aggregate with a P1 of 8 and fine aggregate with a P1 of 15 having the steepest slope and being the most difficult to compact, followed in turn by the combination of both coarse and fine aggregate with a P1 of 11.5, and by the combination of coarse aggregate with a P1 of 15 and fine aggregate with a P1 of 8, the last of these having the flattest slope and therefore being the easiest to compact.

5. Marshall Stability Versus Density Changes due to Changes in Either Compactive Effort or Compaction Temperature.

Figure 12 demonstrates that when plotting Marshall stability versus paving mixture specific gravity, a single curve results whether the specific gravity changes are due to changes in compactive effort or to changes in compaction temperature. This is probably to be expected, since a change in the specific gravity of a paving mixture can result from a change in either compaction temperature or compactive effort, as Figure 4 clearly indicates.

6. Increase VMA by Deviation Away From Corresponding Fuller Grading Curve.

Figures 13 and 14 demonstrate very clearly that to obtain paving mixtures with higher and higher VMA values it is necessary to blend coarse and fine aggregates in proportions that result in grading curves that have been made to deliberately deviate farther and farther from the corresponding Fuller curve, when the air voids value and aggregate particle index remain constant, in this case at 4 percent and 11.5, respectively. Figures 13 and 14 show that this can be achieved in at least two ways. In Figure 13, the grading curves for VMA values of 13.5, 15.0 and 16.5 percent lie farther and farther to the left of the corresponding Fuller curve which has a VMA value of only 11.3 percent, and represent what have been termed "normal" mixes in this investigation. This has happened without exception for the 21 paving mixtures listed in Table 1. In Figure 14, part of the fine aggregate portion of each of the grading curves for VMA values of 13.5, 15.0 and 16.5 percent lies below the corresponding Fuller grading curve, to provide what is referred to as "Odd Grading," because this is the only time that this form of grading has been used in this investigation. Figures 13 and 14 demonstrate therefore, that VMA values of13.5, 15.0 and 16.5 percent can be obtained by keeping the fine aggregate portion either to the left and above the corresponding Fuller curve, or partly below this Fuller curve.

Table 5 lists the sieve analysis, asphalt contents and other pertinent data for each of the paving mixtures illustrated in Figures 13 and 14, and Table 6 contains the specific gravity and Marshall stability data obtained for each mixture. All paving mixtures were compacted at 275°F. For each pair of VMA values listed in Table 5, it should be noted that the quantity of coarse aggregate retained on the No. 4 sieve is the same, for example, 35 percent is retained on the No. 4 sieve for 15 percent VMA for both normal and odd gradings. The particle index employed for both sets of mixes was 11.5. However, because of the low percent passing No. 200, the filler/bitumen ratio was 0.4 for the odd grading illustrated in Figure 14, but was 0.9 for those of normal grading illustrated in Figure 13.

For comparative purposes, the specific gravity data from Table 6 have been plotted on Figure 15, and the Marshall stability data on Figure 16.

Figure 15 indicates that in general, the "odd" paving mixtures of Figure 14 are somewhat more difficult to compact (steeper slope) than the corresponding "normal" mixes from Figure 13. From Figure 8, this might be expected since the paving mixtures of Figure 14 are closer to the corresponding Fuller curve than those of Figure 13.

Figure 16 demonstrates that the Marshall stability values for the "odd" paving mixtures in Figure 14 tend to be somewhat less than those for corresponding "normal" mixes in Figure 13, particularly for paving mixtures that have been compacted to less than 100 percent of laboratory compacted density.

Consequently, both from Marshall stability and ease of compaction viewpoints, each "normal" paving mixture of Figure 13, is somewhat superior to its corresponding "odd" paving mixture in Figure 14.

The VMA value of a paving mixture is important because the VMA provides the only void space between the aggregate particles in a compacted paving mixture that is available to hold the volume of asphalt binder needed for a durable pavement plus the minimum volume of air voids that are required to avoid pavement flushing or bleeding. If the VMA value is too low, either the asphalt binder or the air voids or both are deficient.

Figure 17 is an Asphalt Institute chart that indicates minimum VMA values for paving mixtures made with aggregates having various nominal maximum particle sizes. For the ½ inch nominal maximum particle size employed for the paving mixtures of Table 1, Figure 17 indicates that the minimum VMA should be 15 percent.

A well designed and properly constructed asphalt pavement should have a service life of at least 20 years under normal heavy traffic.

As a result of a survey reported in 1971 by the US Federal Highway Administration, it was concluded that the average life expectancy of asphalt concrete pavement on highways in the United States, is only 15.0 years (8).

A study made sometime ago by Krchma, an outstanding asphalt authority in the USA, indicated that one-half the expected service life of an asphalt pavement can be lost if its asphalt content is only one-half percent less than the optimum normally required (9, 10).

Some years ago, one of the authors of this paper drove by car from Toronto to San Francisco and back to attend a technical meeting. He travelled to San Francisco by major highways across the Middle of the United Sates and returned via the southern U.S.A. Throughout this trip, he was primarily interested in the performance of asphalt pavements. He had driven all the way to San Francisco and part way back before he encountered the first section of hot-mix asphalt that was flushing or bleeding.

For pavement construction in Canada, governments of the provinces normally purchase the asphalt cement and furnish it to paving contractors. Consequently, it is not an item of expense to the contractor, who adds asphalt cement to the paving mixture as directed, and several years ago particularly, one did not have to drive very far before seeing a section of flushed or bleeding pavement.

In the USA, quite contrary to Canadian practice, it is common procedure for contractors to purchase the asphalt cement they use. Asphalt cement has always cost from ten to twenty times or more per pound than the aggregate in a paving mixture. Because of its high cost, contractors would quite naturally not use any more asphalt in a paving mixture than required, and pavements would therefore tend to be underasphalted rather than overasphalted.

The observed absence of pavement flushing or bleeding on the trip to San Francisco by one of the authors, the fact that in general, contractors in the USA purchase the asphalt cement they use, and Krchma's finding that reducing the asphalt content of a paving mixture one-half percent below the optimum could shorten a pavement's service life by one-half, would appear to fit together and explain the short average asphalt pavement service life in the USA of only 15 years that was reported by the Federal Highway Administration.

To provide paving mixtures that will have enough room between the aggregate particles after thorough compaction, for the volume of asphalt needed for durability, plus the volume of air void space required to avoid flushing or bleeding, the minimum VMA requirements of Figure 17 must be satisfied. Consequently, any engineer who deliberately reduces the VMA of a paving mixture in order to decrease the quantity of asphalt required, may save on original pavement cost, but eventually very much more than this so-called saving will be paid out in the form of greatly increased pavement maintenance, shortened service life, and asphalt concrete overlays.

Figure 13 demonstrates that a very simple method for obtaining a VMA value of 15 percent or more, is by a pronounced bulge in the fine aggregate portion of the grading curve. Furthermore, it should be emphasized that the VMA requirements of Figure 17 are based on the ASTM bulk specific gravity of the aggregate.

Figure 18 illustrates Ontario's grading band for surface course paving mixtures. Because of the bulge it contains in the fine aggregate portion, the shape of this grading band makes it relatively easy to satisfy the VMA requirements of Figure 17. However, based on the present investigation, the broken line additions to the grading band indicate how this could be further facilitated.

For many years, one of the authors of this paper has used the principle of deviating farther from the corresponding Fuller curve to obtain increased VMA values for paving mixture designs.

7. Influences of Differences in Percent of Coarse Aggregate.

At the No. 4 seive, current ASTM tolerances permit a range of ±7 percent from the grading curve representing the job mix formula for a paving mixture. Therefore, the influence of a range of ±10 percent at the No. 4 sieve was investigated for the normal paving mixture illustrated in Figure 19, which had 35 percent passing the No. 4 sieve. For the three paving mixtures referred to in Figure 19, each had a VMA value of 15 percent, an air voids content of 4 percent, and each aggregate had a particle index of 11.5. As might be expected, the grading curve for the paving mixture with the highest content of coarse aggregate, 45 percent retained on No. 4, also had the largest bulge in the fine aggregate portion of the grading curve in order to achieve a VMA value of 15 percent.

Figure 20 demonstrates that there was very little difference between the Marshall stability values for the three paving mixtures with the gradings illustrated in Figure 19. This would seem to imply that provided specified particle index, VMA, and air voids restrictions are maintained, substantial differences in gradation can be tolerated without significant effect on Marshall stability.

The difference in ease or difficulty of compacting these three paving mixtures was also small.

8. For a Constant VMA Value Marshall Stability is Unaffected By Differences In Air Voids.

Figure 21 demonstrates that when the VMA value of a paving mixture is held constant, the Marshall stability is not affected significantly by changes in the air voids values of 2.5, 4.0 and 5.5 percent. The VMA value employed for Figure 21 was 16.5 percent, but similar charts are obtained when corresponding data are plotted for paving mixtures with other VMA values. Figure 21 shows that this holds true even though the asphalt contents for the mixes with 2.5, 4.0 and 5.5 percent air voids range from 6.7 to 6.2 to 5.7 percent, respectively.

While Figure 21 shows that for a constant VMA value, Marshall stability is not affected by changes in air voids, Figure 22 indicates that for a compaction temperature of 275°F, for the same paving mixtures, the mixture with 2.5 percent air voids is most easily compacted, while the paving mixture with 5.5 percent air voids is the most difficult to compact. This is in agreement with Figures 5 and 8 which show that paving mixtures with the highest asphalt contents are most easily compacted.

9. For a Constant Air Voids Value Marshall Stability Increases With a Decrease in VMA Value.

Figure 23 illustrates that when the air voids value remains constant, the Marshall stability values for a paving mixture increase as the VMA value of the paving mixture is decreased. In Figure 23, for any given percent of the laboratory compacted specific gravity, the highest Marshall stability results from Fuller grading for which the VMA of the paving mixture is only 11.4 percent, and the Marshall stability decreases in order as the VMA value of the paving mixture is increased from 13.5 to 15.0 to 16.5 percent.

There is a wide difference in ease or difficulty of compacting the four paving mixtures illustrated in Figure 23, with the Fuller grading being the most difficult to compact, followed in order by the paving mixtures with 13.5, 15.0 and 16.5 percent VMA.

10. Influence of Grade and Source of Asphalt Cement.

Figure 24 illustrates the influence of grade and source of asphalt cement on Marshall stability of a given paving mixture for a wide range of compactive effort. The four asphalt cements being compared were 150/200 penetration furnished by Husky Oil, Lloydminster, 150/200 penetration from Imperial Oil's Winnipeg Refinery and 85/100 and 300/400 penetration from Imperial Oil's refinery at Montreal, Table 7.

All mixes were designed to have the same asphalt content of 5.5 percent by weight, a VMA value of 15 percent, and an air voids value of 4 percent. The same aggregate gradation and a particle index of 11.5 were employed for all mixes.

As shown by Figure 24, the mix containing 85/100 penetration asphalt cement had the highest Marshall stability for all compactive efforts. Although substantially less, mixes made with Lloydminster and Winnipeg 150/200 penetration, and with Montreal 300/400 penetration differed very little in Marshall stability for any compactive effort.

There was very little difference in the ease or difficulty of compacting these paving mixtures at their compaction temperatures. This should not be unexpected since the asphalt content of each paving mixture was the same, and because each mix was compacted at the temperature at which its asphalt cement had a viscosity of approximately 280 centistokes as required by ASTM D1559.

11. Influence of Percent Passing No. 200 Sieve.

The filler/bitumen ratio for all mixes in Table 1 was 0.9 by weight. As shown by Table 2, this restricted the percent passing the No. 200 sieve in each mix to a single value. Because the mineral dust passing a No. 200 sieve in paving mixtures in the field can range quite widely, for Phase 2 of this investigation, for two paving mixtures from Table 1, Mix No. 5 and Mix No. 20, the influence of 2 percent and of 8 percent of mineral filler passing No. 200 seive was also studied.

As shown by Figure 25, for Mix No. 20, the Fuller grading was maintained down to the No. 100 sieve, but the mixes for 2.0, 3.65 and 8.0 percent passing No. 200 were designed for 4.0 percent air voids.

Figure 26 demonstrates that as expected, the Marshall stabilities of the mixes with the gradings illustrated in Figure 25, increase quite substantially with an increase in percent passing the No. 200 sieve.

Figure 27, on the other hand, illustrates no increase in Marshall stability as the percent passing No. 200 sieve increases from 2.0 to 5.14 and to 8 percent.

This is explained by the grading curves for Mix No. 5 illustrated in Figure 28. In every case, the grading curves of Figure 28 provide paving mixtures with 15 percent VMA and 4 percent air voids. Figure 27 indicates that the Marshall stabilities of mixes with the three aggregate gradings of Figure 28 are the same, because the increasing bulge in the fine aggregate portion of the mixes containing 5.14 and 8.0 percent passing No. 200, reduces the Marshall stability by the same amount that it is increased by the increasing percent passing the No. 200 sieve.

Consequently, when designing paving mixtures for constant values of VMA and air voids, the Marshall stability will be increased by an increase in percent passing the No. 200 sieve, only if this stability increase is greater than the loss in Marshll stability that is occasioned by the larger bulge in the fine aggregate portion of the grading curve that is required to maintain the VMA value specified.

12. The Mathematics of Efficent and Effective Compaction of Asphalt Concrete.

(a) *General*

Evidence from this investigation and from other sources (2, 3, 4, 5, 6 and 7) support the conclusion that for any given compaction temperature, a straight line relationship exists when percent of laboratory compacted specific gravity or density is plotted versus the logarithm of the compactive effort that is exerted. Figures 4, 5, 8 and 22 demonstrate that these straight lines have different locations and slopes for different paving mixtures and for different compaction temperatures.

As illustrated by Figure 29, the general equation for any one of these straight line relationships is

$$D = m \log B + c \qquad (1)$$

where

D = percent of laboratory compacted specific gravity or density
B = number of Marshall blows (or other units of compactive effort).
m = The slope of the straight line relationship
c = the intercept made by the straight line with a compactive effort of 1 blow.

The compaction line for an average "normal mix" from Table 4, and for a compaction temperature of 275°F has been reproduced in Figure 29. The slope m for this line can be easily calculated.

Let Dm be the percent of laboratory compacted specific gravity for 1 blow, 89.00 percent, and let Dn be the percent of laboratory compacted specific gravity for 100 blows, 101.38 percent. (These specific gravity values for Dm and Dn can be read from the line in Figure 29 by visual inspection).

Then to evaluate m, the slope of the compaction line:

$$Dn - Dm = 101.38 - 89.00 = (m\log 100 + c) - (m\log 1 + c) = 2m$$
$$2m = 12.38$$
$$m = 6.19$$

The value of the intercept or constant c in Equation (1) can be quickly evaluated. From Figure 29, if B = 1 blow, D = 89.00

Substituting these values in Equation (1)

$$89.00 = m\log 1 + c$$

from which $c = 89.00$

After the constants c and m have been evaluated for any compaction line, which as illustrated by Figures 30 and 31 can change either with paving mixture design or with paving mixture temperature, or with both, either the percent of laboratory compacted specific gravity D, or the number of Marshall blows B, or similar units of compactive effort, can be quickly evaluated by Equation (1), when the other is known. For example, for the compaction line in Figure 29, what percent of laboratory compacted specific gravity corresponds to 50-blow Marshall and how many Marshall blows correspond to 99 percent of laboratory compacted specific gravity?

For the first:

$$D = 6.19 \log 50 + 89.00 = (6.19)(1.69897) + 89.00$$
$$= 10.52 + 89.00 = 99.52 \text{ percent}$$

For the second:

$$99.00 = 6.19 \log B + 89.00$$

from which:

$$\log B = \frac{99.00 - 89.00}{6.19} = \frac{10.00}{6.19} = 1.61551$$

and:

$$B = 41.26 \text{ blows}$$

Suppose that the first pass of the roller increases the density of the paving mixture illustrated by the compaction line in Figure 29 by 2 percent, that is from 89.00 to 91.00 percent giving Dm = 89.00 and Dn = 91.00.

Then

$$Dn - Dm = 91.00 - 89.00 = 2.00 = (m\log Bn + c) - (m\log Bm + c)$$

from which

$$\log \frac{Bn}{Bm} = \frac{2}{6.19} = 0.32310$$

$$\text{and } \frac{Bn}{Bm} = 2.11 \text{ (to two decimal places)}$$

Therefore, if Bm = 1 blow Marshall, Bn = 2.11 blows Marshall, that is if the density Dm was 89.00 percent for Bm = 1 blow Marshall, and if the first roller pass increased the pavement density to Dn = 91.00 percent, the corresponding total number of Marshall blows required would be Bn = 2.11 blows.

Consequently, for this particular roller, the compactive effort provided by each roller pass is equivalent to 2.11−1.00 = 1.11 blows Marshall, since the paving mixture had already been compacted by 1 blow Marshall before the first roller pass was applied.

To increase the density of the paving mixture by another 2 percent, that is from Dm = 91.00 to Dn = 93.00 percent:

$$Dn-Dm = 93.00-91.00 = 2.00 = (m\log Bn + c)-(m\log Bm + c)$$

from which

$$\text{Log}\frac{Bn}{Bm} = \frac{2.00}{6.19} = 0.32310$$

and

$$\frac{Bn}{Bm} = 2.11$$

This time, since Bm corresponds to 2.11 blows Marshall (for 91.00 percent laboratory compacted specific gravity), Bn = 2.11 × 2.11 = 4.45 blows or $(2.11)^2$ blows marshall. However, compaction began after 1-blow Marshall had been applied, so that the blows actually applied are 4.45−1.00 = 3.45. Since each roller pass is equivalent to 1.11 blows Marshall, the corresponding number of roller passes required to increase paving mixture density from 91.00 to 93.00 percent = $\frac{3.45}{1.11}$ = 3.11.

To increase the paving mixture density by an additional 2 percent, that is from Dm = 93.00 to Dn = 95 percent:

$$Dn-Dm = 95.00-93.00 = 2.00 = (m\log Bn + c)-(m\log Bm + c)$$

from which

$$\log\frac{Bn}{Bm} = \frac{2.00}{6.19} = 0.32310$$

and

$$\frac{Bn}{Bm} = 2.11$$

This time, because Bm = 4.45 blows Marshall (for 93.00 percent of laboratory compacted specific gravity), and Bn = 4.45 × 2.11 = $(2.11)^3$ or 9.39 blows Marshall. Again since compaction began after 1 blow Marshall had been applied, the compactive effort actually applied to increase the paving mixture density from 93.00 to 95.00 percent = 9.39−1.00 = 8.39, and the corresponding number of roller passes = $\frac{8.39}{1.11}$ = 7.55.

Finally to increase the paving mixture density to 97.00 percent of laboratory compacted specific gravity as called for by many specifications, that is from Dm = 95.00 to Dn = 97.00 percent

$$Dn-Dm = 97.00-95.00 = 2.00 = (m\log Bn + c)-(m\log Bm + c)$$

from which

$$\log\frac{Bn}{Bm} = \frac{2.00}{6.19} = 0.32310$$

and

$$\frac{Bn}{Bm} = 2.11$$

In this case, since Bm = 9.39 blows Marshall, Bn = 9.39 × 2.11 = 19.82 or $(2.11)^4$ blows marshall. Again the number of Marshall blows actually applied = 19.82−1.00 = 18.82, and the corresponding number of roller passes = $\frac{18.82}{1.11}$ = 16.95.

The total number of Marshall blows required to increase the percent of laboratory compacted density from 89.00 to 97.00 can also be obtained indirectly from Equation (1).

$$97.00 = 6.19 \log B + 89.00$$

$$\text{Log } B = \frac{97.00-89.00}{6.19} = 8.00 = 1.29241$$

$$B = 19.82 \text{ blows.}$$

The number of Marshall blows actually applied = 19.82−1.00 = 18.82 and the corresponding number of roller passes required = $\frac{18.82}{1.11}$ = 16.95. However, this simple application of Equation (1) does not give the insight into the mechanism of compaction that is provided by the above step by step solution which is also illustrated in Figure 29.

The step by step solution that has just been worked out is summarized in the following table which provides additional usefull data.

Successive Equal Increments in Paving Mixture Specific Gravity	Corres-ponding No. of Marshall Blows	No. of Mar-shall Blows Actually Applied	Corres-ponding No. of Roller Passes	No. of Roller Passes for Each Successive Increment in Paving Mixture Specific Gravity
(1)	(2)	(3) (2) − 1.00	(4) (3) ÷ 1.11	(5)
89.00 to 91.00 percent	2.11	1.11	1.00	1.00 = 1.00
91.00 to 93.00 percent	4.45	3.45	3.11	2.11 = 2.11
93.00 to 95.00 percent	9.39	8.39	7.56	$4.45 = (2.11)^2$
95.00 to 97.00 percent	19.82	18.82	16.95	$9.39 = (2.11)^3$

The right hand column indicates the following mathematical equation for providing the number of roller passes required for each of successive equal increments in paving mixture specific gravity up to the specified compaction requirement:

Number of roller passes required to attain 97 percent of laboratory compacted specific gravity $= 1 + X + X^2 + \text{-----} X^n + \left[\frac{K-1}{X-1}\,(1 + X + X^2 \text{-----} X^n)\right]$ (2)

where:

X = is the ratio of the number of Marshall blows representing the **total** compactive effort that had been applied to the paving mixture at the end of the first roller pass, to the number of Marshall blows representing the **total** compactive effort that had been expended on the paving mixture before the first roller pass was applied. In Figure 29 for example, 1 blow Marshall represents the **total** compactive effort, Bm, that had been applied to the paving mixture before the first roller pass, while 2.11 Marshall blows represents the **total** compactive effort, Bn, that had been applied to the paving mixture at the end of the first roller pass. In this case, $X = \frac{Bn}{Bm} = \frac{2.11}{1} = 2.11$

n = the power of X that provides the number of roller passes that does not exceed the specified minimum percent of laboratory compacted specific gravity, In Figure 29, n = 3

K = the **total** number of Marshall blows that provide the specified minimum laboratory compacted specific gravity. In Figure 29, K = 19.82.

Substituting the values from the above table in Equation (2):

Number of roller passes required to attain 97 percent of laboratory compacted specific gravity = $1 + 2.11 + 4.45 + 9.39 + \left[\frac{19.82-1}{2.11-1} - (1 + 2.11 + 4.45 + 9.39)\right]$ 9.39)]

$= 16.95 + (16.95-16.95) = 16.95$ or 17.00

In this example, the sum of the terms up to X^3 provides the exact number of roller passes needed to attain 97 percent of laboratory compacted specific gravity. Consequently, the final term which includes K in Equation (2) is zero in this case, which is the exception as later sample calculations will show.

It must be emphasized that Equation (2) can be used to provide compaction information only in situations like those illustrated in Figures 29, 30, and 31, where the paving mixture has received compactive effort equivalent to 1 blow Marshall before the first roller pass is applied. Nevertheless, it is very usefull for the comparisons that are made in parts (b) and (c), and (d) of the present section of this paper.

The more general Equation (1) can be used to provide compaction information for all situations.

(b) Influence of More Effective Compaction Equipment

If a more effective roller were employed in connection with the compaction line in Figure 29, for which the first roller pass whould increase the paving mixture specific gravity by 3.00 percent from 89.00 to 92.00 percent of laboratory compacted specific gravity, a substantially smaller number of roller passes would be required to attain a specified 97.00 percent of laboratory compacted specific gravity, as illustrated below:

$$Dn - Dm = 92.00 - 89.00 = 3.00 = (m\log Bn + c) - (m\log Bm + c)$$

from which

$$\log \frac{Bn}{Bm} = \frac{3.00}{6.19} = 0.48465$$

and

$$\frac{Bn}{Bm} = 3.05$$

Since Bm = 1.00 blow Marshall, Bn = 3.05 × 1.00 = 3.05 blows Marshall. Consequently, the total number of Marshall blows corresponding to the first roller pass, that is needed to increase the paving mixture specific gravity by 3.00 percent from 89.00 to 97.00 percent of laboratory compacted specific gravity is 3.05. However, the paving mixture had received the equivalent of 1 blow Marshall before the first roller pass was applied. Therefore, the first roller pass is equivalent to 3.05 − 1.00 = 2.05 Marshall Blows.

The number of roller passes required to increase paving mixture specific gravity in successive steps, each of 3.00 percent, from 89.00 to 97.00 percent of laboratory compacted specific gravity, can be determined from Equation (2):

$$1 + X + X^2 + \text{-----}X^n + \left[\frac{K-1}{X-1} - (1 + X + X^2\text{-----}X^n)\right]$$

where X = 3.05

To Increase Paving Mixture Density		Number of Roller Passes Required
from 89.00 to 92.00 percent	1	1.00
from 92.00 to 95.00 percent	X	3.05
from 95.00 to 97.00 percent		
$\frac{K-1}{X-1} - (1 + X) = \frac{19.82-1}{3.05-1} - 4.05$		
$= 9.18 - 4.05 =$		5.13
Total No. of Roller Passes Required =		9.18

Therefore to increase paving mixture density from 89.00 to 97.00 percent of laboratory compacted specific gravity with this more effective roller, with which the increase in paving mixture density for the first roller pass is 3.00 percent, requires 9.18 or 10 roller passes. This is roughly only 60 percent of the 17 roller passes that were required for the same increase in paving mixture density from 89.00 to 97.00 percent, when using the roller for which the increase in paving mixture density for the first pass was only 2 percent.

This demonstrates the importance of using the most effective compaction equipment available when compacting hot mix paving mixtures.

Suppose that three passes of a breakdown roller that increases the density of the paving mixture illustrated in Figure 29 by 2.00 percent in its first pass, is followed by an intermediate roller that would have increased paving mixture density by 3.00 percent in its first pass over newly spread paving mixture. How many passes of the two rollers are required to increase the density of the paving mixture represented by Figure 29 from 89.00 to 97.00 percent of laboratory compacted specific gravity ?

From what has already been presented, three breakdown roller passes are equivalent to

$$3 \times 1.11 = 3.33 \text{ blows Marshall}$$

In turn 3.33 blows Marshall are equivalent to $\frac{3.33}{2.05} = 1.62$ passes of the intermediate roller.

It has already been demonstrated that to increase paving mixture density from 89.00 to 97.00 percent of laboratory compacted specific gravity using the intermediate roller would require $\frac{18.82}{2.05} = 9.18$ roller passes. Therefore the number of roller passes required for intermediate rolling

$$= 9.18 - 1.62 = 7.56 \text{ passes.}$$

Consequently the total required rolling effort becomes:

Breakdown rolling	3 passes
Intermediate rolling	7.56 passes
Total	10.56 or 11.00 passes

This indicates that if one type of roller were used for breakdown rolling, and a more effective roller for intermediate rolling, this combination of rollers would substantially reduce the number of roller passes that would have been required if the first roller only had been employed throughout the compaction operation. The comparison is 11.00 versus 17.00 roller passes. The reverse could be true, if the roller being employed for intermediate rolling were less effective per pass than the roller used for breakdown rolling.

(c) Influence of Range of Compaction Temperature.

For Figure 29, it was assumed that the paving mixture remained at a constant temperature of 275°F throughout the compaction period. In actual practice, paving mixtures cool quite rapidly after leaving the spreader. In Figure 30, which reproduces the compaction lines of Figure 8 and Figure 29 for "normally" graded paving mixtures, the upper dashed line indicates that during compaction the paving mixture cooled from 275°F to 200°F, while the lower dashed line indicates cooling of the paving mixture from 275°F to 150°F during compaction. Both dashed lines have been terminated at 97 percent of laboratory compacted specific gravity, since this is a normal specification requirement for hot mix compaction.

If both the upper dashed line representing compaction of the paving mixture as it cooled from 275°F to 200°F, and the solid line representing compaction at a constant temperature of 200°F, had been shown to intersect the horizontal line representing 97 percent of laboratory compacted specific gravity at the same point, this would have indicated that the same compactive effort in terms of number of Marshall blows, 27.5, would have been required for compaction applied at a uniform rate starting at 275°F and ending at 200° F as for compaction at a constant temperature of 200°F. This is not reasonable. A similar situation exists concerning compaction over a cooling range from 275°F to 150°F represented by the lower dashed line in Figure 30, with respect to the solid line indicating compaction at a constant temperature of 150°F. Therefore, the upper dashed line in Figure 30, representing compaction over the cooling range from 275°F to 200°F must intersect the horizontal broken line indicating 97 percent of laboratory compacted specific gravity, at a compactive effort (number of Marshall blows) between the points of intersection of this line with the solid lines indicating compaction at constant temperatures of 275°F and 200°F, and the lower dashed line representing compaction over the cooling range from 275°F to 150°F, at a compactive effort between the points of intersection with the solid lines representing compaction at constant temperatures of 275°F and 150°F, but where between these two points in each case?

The number of Marshall blows at the intersection of the upper dashed line in Figure 30 with the line representing a compaction requirement of 97 percent of laboratory compacted specific gravity is given by the geometric mean of the 19.61 blows required to compact this particular normally graded paving mixture to this density value at a constant temperature of 275°F and the 27.72 blows needed for the same purpose at a constant compaction temperature of 200°F. That is:

Number of Marshall blows at the intersection of the upper dashed line in Figure 30 with the line representing 97 percent of laboratory compacted specific gravity $= \text{antilog} \dfrac{(\log 19.61 + \log 27.72)}{2}$

$= \text{antilog } 1.36764 = 23.32$ blows.

Similarly, the number of Marshall blows at the intersection of the lower dashed line in Figure 30 with the line denoting 97 percent of laboratory compacted specific gravity, is provided by the geometric mean of the 19.61 blows needed to compact this particular paving mixture to 97 percent of laboratory compacted specific gravity at a constant temperature of 275°F, and the 44.67 blows required to compact the paving mixture to the same density at a constant compaction temperature of 150°F. That is:

Number of Marshall blows at the intersection of the lower dashed line of figure 30 with the line representing 97 percent of laboratory compacted specific gravity $= \text{antilog}\left(\dfrac{\log 19.61 + \log 44.67}{2}\right)$

$= \text{antilog } 1.47125 = 29.60$ blows.

Therefore the upper dashed line in Figure 30, representing cooling during compaction from 275°F to 200°F intersects the line marking compaction to 97.00 percent of laboratory compacted specific gravity at 23.32 blows, and the lower dashed line in Figure 30, denoting cooling during compaction from 275°F to 150°F, intersects the line representing the same degree of compaction at 29.60 blows.

Figure 30 shows that the slopes of the two dashed lines are increasingly flatter than the slope of the line marking compaction at a constant temperature of 275°F to 200°F, can be calculated as follows from Equation (1):

$$97.00 = m \log 23.32 + 89.00$$

$$m = \frac{97.00-89.00}{\log 23.32} = \frac{8.00}{1.36764} = 5.85.$$

In part (b) above, it was shown that to increase the density of the paving mixture of Figure 29 by 3.00 percent (from 89.00 to 92.00 percent of laboratory compacted specific gravity) by the first pass of the roller, corresponded to a **total** compactive effort of 3.05 blows Marshall. However, the paving mixture had received the equivalent of 1 blow Marshall before the first roller pass was applied. Therefore, the first roller pass was equivalent to 3.05 − 1.00 = 2.05 blows Marshall.

For the dashed line in Figure 30, denoting compaction at a uniform rate over a cooling temperature range from 275°F to 200°F, Equation (1) can be employed to determine the pavement density provided by a total compactive effort of 3.05 blows Marshall or the first roller pass:

$$D = 5.85 \log 3.05 + 89.00 = 5.85(0.48464) + 89.00 = 2.84 + 89.00$$

$$= 91.84 \text{ percent.}$$

The number of roller passes needed to increase the paving mixture density in successive steps, each of 2.84 percent, from 89.00 to 97.00 percent of laboratory compacted specific gravity, as the paving mixture referred to in Figure 30 cools from 275°F to 200°F can be calculated by means of Equation (2), where X = 3.05.

To Increase Paving Mixture Density		Number of Roller Passes Required
from 89.00 to 91.84 percent	1	1.00
from 91.84 to 94.68 percent	X	3.05
from 94.68 to 97.00 percent $\dfrac{K-1}{X-1} - (1 + X) = \dfrac{23.32-1)}{3.05-1} - 4.05$ $= 10.89 - 4.05 =$		6.84
Total No. of roller passes required =		10.89

Consequently, the number of roller passes required to increase the density of the paving mixture of Figure 30 from 89.00 to 97.00 as the compaction temperature cools from 275°F to 200°F is 10.89 or 11 passes.

For the lower broken line in Figure 30 pertaining to compaction over a cooling temperature range from 275°F to 150°F, its slope m can be calculated by means of Equation (1) as follows:

$$97.00 = m \log 29.60 + 89.00$$

$$m = \frac{97.00-89.00}{\log 29.60} = \frac{8.00}{1.47125} = 5.44$$

For the lower dashed line in Figure 30, Equation (1) indicates that the first roller pass, or a compactive effort of 3.05 blows Marshall, will increase the paving mixture density from 89.00 to:

$$D = 5.44 \log 3.05 + 89.00 = 5.44\,(0.48465) + 89.00 = 2.64 + 89.00 = 91.64 \text{ percent.}$$

Utilizing Equation (2), where X = 3.05 blows Marshall, the numbers of roller passes required to increase the paving mixture density in successive steps, each of 2.64 percent from 89.00 to 97.00 percent of laboratory compacted specific gravity, as the paving mixture of Figure 30 cools from 275°F to 150°F, can be calculated:

To Increase Paving Mixture Density		Number of Roller Passes Required
from 89.00 to 91.64 percent	1	1.00
from 91.64 to 94.28 percent	X	3.05
from 94.28 percent to 96.92 percent	X^2	9.30
from 96.92 to 97.00 percent	$\frac{K-1}{X-1} - (1 + X + X^2)$	

$$= \frac{29.60 - 1}{3.05 - 1} - (1 + 3.05 + 3.05^2)$$

$$= \frac{28.60}{2.05} - (13.35) = 0.60$$

Total number of roller passes required 13.95

Consequently, when during compaction, the temperature of the paving mixture referred to in Figure 30 cools from 275°F to 150°F, as indicated by the lower dashed line, to increase the paving mixture density from 89.00 to 97.00 percent of laboratory compacted specific gravity requires 13.95 or 14 passes of this particular roller.

Therefore, if compaction of the normally graded paving mixture referred to in Figure 30 were to take place at a uniform rate over the following temperature ranges:

Range of Temperature During Compaction	No. of Roller Passes to Increase Paving Mixture Density from 89.00 to 97.00 Percent
Constant at 275°F	10
from 275°F to 200°F	11
from 275°F to 150°F	14

This demonstrates the benefit, in terms of the reduced compactive effort required, that results from compacting paving mixtures at the highest possible temperature after thay have left the spreader.

(d) Influence of Paving Mixture Design.

From Figures 5 and 8, it is apparent that different paving mixture designs have a marked influence on the steepness or flatness of slope of the compaction line, and therefore on the amount of compactive effort that must be applied to attain any specified paving mixture density. While other comparisons could be made, these differences in required compactive effort due to variance in paving mixture design will be illustrated by the differences in the number of roller passes required to achieve 97.00 percent of laboratory compacted specific gravity for the Fuller graded paving mixtures of Figure 31 versus those needed for the correspondingly "normally" graded paving mixtures of Figure 30. The solid compaction lines for the Fuller graded paving mixtures at different temperatures, 275°F, 200°F, and 150°F, illustrated in Figure 31, are a reproduction of the same compaction lines for paving mixtures with Fuller gradings shown in Figure 8.

The same problem now arises that was described in part (c) above. At what numbers of Marshall blows do the dashed lines in Figure 31 representing compaction over the cooling temperature ranges from 275°F to 200°F, and from 275°F to 150°F, intersect the horizontal broken line representing 97 percent of laboratory compacted specific gravity?

Employing the principles described in part (c) above:

Number of blows at the intersection of the **upper** dashed line of Figure 31 with the line representing 97 percent of laboratory compacted specific gravity =

$$\text{antilog}\left(\frac{\log 24.44 + \log 37.43}{2}\right) = \text{antilog } 1.48071$$

$$= 30.25 \text{ blows.}$$

and

Number of blows at the intersection of the **lower** dashed line of Figure 31 with the line representing 97 percent of laboratory compacted specific gravity =

$$\text{antilog}\left(\frac{\log 244.44 + \log 62.92}{2}\right) = \text{antilog } 1.59349$$

$$= 39.22 \text{ blows.}$$

Consequently, the **upper** dashed line in Figure 31, representing cooling during compaction from 275°F to 200°F intersects the horizontal line denoting compaction to 97 percent of laboratory compacted specific gravity at 30.25 blows, while the lower dashed line in Figure 31 indicating cooling during compaction from 275°F to 150°F, intersects the 97 percent compaction line at 39.22 blows.

By extrapolation and visual inspection of the upper dashed line in Figure 31, the pavement density for 1 blow Marshall is 86.45 percent of laboratory compacted specific gravity. Therefore, the slope m of this upper broken compaction line can be calculated from Equation (1) as follows:

$$97.00 = m \log 30.25 + 86.45$$

$$m = \frac{97.00 - 86.45}{\log 30.25} = \frac{10.55}{1.48073} = 7.12$$

It has already been shown that to increase the density of the paving mixture of Figure 29 by 3.00 percent (from 89.00 to 92.00 percent of laboratory compacted specific gravity) by the first pass of a roller, required an expenditure of **total** compactive effort equal to 3.05 blows Marshall. However, the paving mixture had received the equivalent of 1 blow Marshall before the first roller pass was applied. Therefore, the first roller pass was equivalent to 3.05 – 1.00 = 2.05 blows Marshall.

To obtain compaction data in part (d) that can be compared directly with the compaction data that have already been obtained for part (c), the same compactive effort per roller pass, 2.05 blows Marshall, will be employed for part (d) as was used for part (c).

For the upper dashed line in Figure 31, indicating compaction at a uniform rate over a cooling temperature range from 275°F to 200°F, Equation (1) can be employed to determine the pavement density provided by a total compactive effort of 3.05 blows Marshall, or the first roller pass:

$$D = 7.12 \log 3.05 + 86.45 = (7.12)(0.48465) + 86.45$$
$$= 3.45 + 86.45 = 89.90 \text{ percent.}$$

Applying Equation (2), in which X = 3.05, the numbers of roller passes required to increase the density of the paving mixture in successive steps, each of 3.45 percent, from 86.45 to 97.00 percent of laboratory compacted specific gravity as the temperature of the paving mixture cools from 275°F to 200°F, are:

To Increase Paving Mixture Density		Number of Roller Passes Required
from 86.45 to 89.90 percent	1	1.00
from 89.90 to 93.35 percent	X	3.05
from 93.35 to 96.70 percent	X^2	9.30
from 96.70 to 97.00 percent	$\frac{K-1}{X-1} - (1 + X + X^2)$	
	$= \frac{30.32 - 1}{3.05 - 1} - 13.35 = 14.27 - 13.35$	= 0.92
Total no. of roller passes required =		14.27

Therefore, the number of roller passes required to compact the Fuller graded paving mixture of Figure 31 from 86.45 to 97.00 percent of laboratory compacted specific gravity as the mix cools during compaction from 275°F to 200°F, is 14.27 or 15.

Similar calculations for the solid line representing compaction of the paving mixture of Figure 31 at a constant temperature of 275°F, and for the lower dashed line denoting a paving mixture cooling temperature range from 275°F to 150°F, as the Fuller graded paving mixture of Figure 31 is compacted from 86.45 to 97.00 percent of laboratory compacted specific gravity, shows that 12 and 19 roller passes respectively, by this particular roller would be required.

The influence of paving mixture design, as represented by the "normally" graded paving mixture of Figure 30, and by the Fuller graded paving mixture of Figure 31, on the relative compactive efforts needed to attain 97 percent of laboratory compacted specific gravity over the same ranges of paving mixture cooling temperature can be compared as follows:

Range of Compaction Cooling Range Temperatures	No. of Roller Passes Required to Increase Paving Mixture Density to 97.00 Percent	
	Normal Grading	Fuller Grading
Constant at 275°F	10	12
From 275°F to 200°F	11	15
From 275°F to 150°F	14	19

These comparative data indicate that when all other conditions are equal, the compactive effort required to attain a specified percentage of laboratory compacted specific gravity or density, is greatly influenced by paving mixture design.

If hot-mix compaction were carried out over a cooling temperature range from 200°F to 150°F, a substantially larger number of passes of this same roller would be needed to achieve 97 percent of laboratory compacted specific gravity. For the ''normally'' graded paving mixture represented in Figure 30, 17 roller passes would be required, while 24 passes would be needed for the Fuller graded paving mixture of Figure 31. This provides further evidence of the benefit obtained in the form of greatly reduced rolling effort, when paving mixtures are compacted at the highest possible temperature.

(e) More General Application.

So far the discussion of Figures 29, 30, and 31, has been limited to compaction lines that have been extrapolated back from 6 blows to 1 blow Marshall. However, the denisty of a paving mixture is it leaves the spreader normally appears to be between 75 and 85 percent of laboratory compacted specific gravity.

If it is assumed that the paving mixture of Figure 29 for example has a density of 83.00 percent of laboratory compacted specific gravity as it leaves the spreader, and if it is further assumed that the straight compaction line of Figure 29 can be extrapolated back to this paving mixture density, the number of Marshall blows corresponding to this density of 83.00 percent can be calculated as follows employing Equation (1)

$$83.00 = 6.19 \log B + 89.00$$
$$\log B = \frac{6.00}{6.19} = 0.96931 = 1.03069$$
$$B = 0.1073.$$

Consequently for the extrapolated compaction line of Figure 29, a compaction effort of 0.1073 blow Marshall is associated with a density of 83.00 percent of laboratory compacted specific gravity for this paving mixture.

Let us assume that the first pass of a particular roller will increase the density of this paving mixture by 6.5 percent, that is from 83.00 to 89.50 percent of laboratory compacted specific gravity. How many roller passes will be required to increase the paving mixture density by further increments of 6.5 percent up to 97.00 percent of laboratory compacted specific gravity?

Equation (2) cannot be employed here, but the solution can be obtained by applying the more general Equation (1).

The number of Marshall blows required to increase the paving mixture density from 83.00 to 89.50 percent that is provided by the first pass of the roller, can be calculated as follows using Equation (1).

$$Dn - Dm = 89.50 - 83.00 = (6.19 \log Bn + c) - (6.19 \log Bm + c)$$
$$\log \frac{Bn}{Bm} = \frac{6.5}{6.19} = 1.05008$$
$$\frac{Bn}{Bm} = 11.22$$
$$Bn = (11.22)(0.1073) = 1.2039 \text{ blows Marshall}$$

However, since the paving mixture had received the equivalent of 0.1073 blows Marshall before the first roller pass had been made, the compactive effort applied by the first roller pass = 1.2039−0.1073 = 1.0966 blows Marshall.

The number of blows Marshall, and the number of roller passes, required to increase the paving mixture density by a second increment of 6.5 percent from 89.50 to 96.00 percent of laboratory compacted specific gravity, is determined as follows:

$$Dn - Dm = 96.00 - 83.00 = (6.19 \log Bn + c) - (6..19 \log Bm + c)$$

$$\log \frac{Bn}{Bm} = \frac{13.00}{6.19} = 2.10016$$

$$\frac{Bn}{Bm} = 125.9 = (11.22)^2$$

$$Bn = (125.9)(0.1073) = 13.51 \text{ blows Marshall}$$

Corresponding total number of roller passes required =

$$\frac{13.51 \quad -0.1073}{1.2039-0.1073} = \frac{13.4027}{1.0966} = 12.22$$

For the third increment of paving mixture density from 96.00 to 97.00 percent, the corresponding number of Marshall blows and roller passes are calculated by means of Equation (1) as follows:

$$Dn - Dm = 97.00 - 83.00 = (6.19 \log Bn + c) - (6.19 \log Bm + c)$$

$$\log \frac{Bn}{Bm} = \frac{14.00}{6.19} = 2.26171$$

$$\frac{Bn}{Bm} = 182.7$$

$$Bn = (182.7)(0.1073) = 19.61 \text{ blows Marshall}$$

Corresponding total number of roller passes required =

$$\frac{19.61-0.1073}{1.2039-0.1073} = \frac{19.5027}{1.0966} = 17.78.$$

The step by step solution in terms of total numbers of roller passes that has just been worked out, is summarized in the following table to indicate the number of roller passes needed for each increment in paving mixture specific gravity:

Successive Equal Increments in Paving Mixture Specific Gravity	Corres-ponding Total Number of Marshall Blows	No. of Marshall blows Actually Applied	Corres-ponding Number of Roller Passes	No. of Roller Passes for each successive Increment in Paving Mixture Specific Gravity
(1)	(2)	(3)	(4)	(5)
		(2)−0.1073	(3) ÷ 1.0966	
83.00 to 89.50 percent	1.2039	1.0966	1.00	1.00
89.50 to 96.00 percent	13.51	13.4027	12.22	11.22
96.00 to 97.00 percent	19.61	19.5027	17.78	5.56
Total number of roller passes required				17.78

Consequently, assuming that extrapolation of the straight compaction lines of Figures 29, 30, and 31 toward the left is justified, a procedure similar to that just demonstrated can be followed to determine the number of roller passes required for any stage of compaction, regardless of the corresponding compactive effort, compaction temperature, and resulting density to which the paving mixture may have been subjected before the first roller pass was made.

(f) *Decreasing effectiveness of successive roller passes.*

Figure 29 demonstrates the rapid increase in number of roller passes required to achieve each successive equal increment in paving mixture density. Figure 32, on the other hand illustrates the rapid decrease in the ability of successive passes of a roller to increase the density of a paving mixture.

Figure 32 demonstrates the rapidly decreasing effectiveness of successive passes of two different rollers to increase the density of a paving mixture. The first pass of one roller is equivalent in compactive effort to 3-blows Marshall, while the first pass of the other roller is equivalent to 5-blows Marshall.

Figure 32 and the data in the right hand column of Table 8 indicate that each successive roller pass is much less effective for increasing the percent of laboratory compacted specific gravity than was any preceding roller pas. Furthermore, this roller effectiveness decreases very rapidly with successive roller pass applications. For example, the right hand column of Table 8 indicates the increase in paving mixture density provided by the tenth roller pass is only $\frac{0.27}{150} \times 100 = 18$ percent of the increase in paving mixture density provided by the second roller pass, regardless of the effectiveness of the roller being employed. This also appears to apply regardless of the slope of the compaction line. However, as the slope of the compaction line illustrated in Figure 32 changes due to variations in paving mixture design and range of compaction temperature, the numbers in the right hand column of Table 8 also change. A straight line relationship of negative slope results from the second roller pass onward when the logarithm of percent increase in paving mixture density per roller pass taken from the right hand column of Table 8 is plotted versus the logarithm of successive numbers of roller passes.

Because of the geometry of Figure 32, Table 8 and Figure 32 indicate that very nearly the same decrease in paving mixture specific gravity occurs after each roller pass beginning with the second regardless of the effectiveness of the compaction equipment. For example, whether each pass of the rollers employed is equivalent to 3-blow or 5-blow Marshall compactive effort, for the fifth pass of either roller, the increase in percent of laboratory compacted specific gravity over that provided by the fourth roller pass is approximately 0.58 percent. Nevertheless, for the particular conditions represented by Figure 32, both Table 8 and Figure 32 demonstrate that for the roller for which the compactive effort per pass is equivalent to 3-blows Marshall, seven passes are required to attain 97 percent of laboratory compacted specific gravity, while for the roller with each pass equivalent to 5-blows Marshall, only four passes are needed to achieve the same paving mixture density.

13. Time Available For Effective Compaction.

Figure 33 illustrates the rate at which a hot mix surface course layer 1.5 inches thick cools off on a hot summer afternoon (ambient temperature 86°F) in Ontario. It indicates that the hot layer, which left the spreader at 275°F, cools to 200°F in about 15 minutes, to 175°F in about 30 minutes and to 150°F in approximately 50 minutes. Consequently, if the temperature range for rolling to the minimum specified pavement density is to be from 275°F to 200°F, the time avaialble for rolling on this hot summer afternoon is 15 minutes.

On the other hand, when rolling a 1.25 inch surface course during the cool weather in which so much paving is done in Canada (ambient temperature 40 to 50°F), Figure 34 demonstrates that a paving mixture cooled from 280°F to 200°F in 8 minutes, to 175°F in 12 minutes, and to 150°F in 18 minutes.

The broken line curve in Figure 34 indicates a cooling curve for a thick layer (4 to 5 inches) of asphalt base course. Even during cool weather, this thick layer loses its heat relatively slowly, and requires 20 minutes to cool from 280°F to 200°F, 30 minutes to cool to 175°F, and 50 minutes to cool to 150°F.

Consequently, Figures 33 and 34 emphasize that compaction of surface courses particularly, to the specified minimum density, over the temperature range from 275°F to 200°F where rolling effort can be utilized most efficiently and effectively, requires a concentration of rolling equipment close to the spreader that is seldom seen in actual practice.

14. Compaction Characteristics of Other Road Building Materials.

Most road building materials, soils, aggregates, stabilized soil mixtures, cold asphalt paving mixtures, as well as hot asphalt paving mixtures, perform more effectively if they are adequately compacted.

Figure 35 demonstrates that for each of a very wide variety of these road building materials, a straight line relationship exists when the specific gravity of the material being compacted is plotted versus the logarithm of the number of Marshall blows and probably of other untis of compactive effort.

The specific gravity values illustrated in Figure 35, are for each material *in the condition in which it is being compacted.* That is, for moist soil at a constant moisture content; for moist aggregate at a single moisture content; for a constant composition in terms of water, asphalt for soil asphalt stabilization; for a constant composition in terms of water, portland cement, and soil, for soil cement stabilization; for a single mixture of aggregate and asphalt binder for cold mix compaction; and a single mixture of aggregate and asphalt cement, and a range of cooling temperature, for hot mix asphalt compaction.

The sieve analysis and other characteristics of the materials referred to in Figure 35, are given in Table 9.

The straight line relationships illustrated in Figure 35 indicate that the increase in density or specific gravity becomes less and less with each successive pass of the compaction equipment. It also indicates that the mathematics of compaction presented in Section 12 above for hot mix asphalt compaction, can also be applied to the compaction of other road building materials. However, since for many of these, compaction is carried on at ambient temperature, and the viscosity of water is relatively constant over a substantial temperature range, the temperature of compaction is not an important a variable as it is when compacting hot asphalt paving mixtures.

SUMMARY

1. Some of the results of a factorially designed and randomized laboratory investigation of pavement compaction are presented.
2. The investigation reviews the influence of three factors affecting pavement compaction that can be controlled in the field, the range of compaction temperature, the amount and intensity of the compactive effort, and paving mixture design.
3. Compaction temperatures of 275°F, 200°F and 150°F were employed to study the influence of temperature on compaction, while 100, 60, 20 and 6 blows by a Marshall double compactor provided variable compactive effect.
4. Paving mixture design for Phase 1 of the investigation included the variables: Normal, gap and Fuller grading; three levels of VMA, 13.5, 15.0 and 16.5 percent; three levels of air voids, 2.5, 4.0 and 5.5 percent; a constant aggregate particle index of 11.5; and a constant filler/bitumen ratio of 0.9. The asphalt cement employed was 150/200 penetration from a single source.
5. In Phase 2, the filler/bitumen ratio, the grade and source of asphalt cement, the particle index of the aggregate, and other aggregate gradings resulting in the same VMA value, are being investigated.
6. As expected, degree of compaction in the form of percent of laboratory compacted specific gravity is greatly influenced by temperature of compaction, degree of compactive effort and paving mixture design. The least compactive effort for any given paving mixture design and rolling equipment, is required when compaction is carried on at the highest possible paving mixture temperature.
7. It is clearly demonstrated that there is no single temperature at which pavement compaction by rolling *suddenly* becomes ineffective. Pavement compaction merely becomes less and less efficient as the temperature of the paving mixture being compacted becomes lower and lower.
8. Fuller graded paving mixtures are substantially more difficult to compact than normally graded or gap graded paving mixtures.
9. Paving mixtures made with aggregates having a high particle index have a very much higher Marshall stability than those made with aggregates having a low particle index, but are also more difficult to compact to a specified density.
10. Paving mixtures in which the particle index of the fine aggregate is substantially higher than that of the coarse aggregate, have much higher Marshall stabilities than when the reverse occurs.
11. A common Marshall stability curve versus percent of laboratory compacted specific gravity results from density changes due to differences in either compaction temperature or compactive effort.
12. The VMA of a paving mixture can be most easily increased by deviating the aggregate grading curve farther from the corresponding Fuller Curve.
13. Varying the percent of coarse aggregate over a range of 20 percent when the VMA, air voids, particle index and filler/bitumen ratio were held constant had negligible effect on Marshall stability.
14. When the VMA of a paving mixture was held constant, varying the air voids over the range from 2.5 to 5.5 percent had very little effect on Marshall

stability, although the paving mixture with 2.5 percent air voids was most easily compacted.

15. Marshall stability decreased very noticibly with increasing VMA when the air voids value was constant.

16. For paving mixtures made with several grades of asphalt cement from different sources, the Marshall stability was highest for the paving mixture containing 85/100 penetration asphalt cement, but was nearly the same for paving mixtures made with 150/200 penetration asphalt cement from two different sources, and with 300/400 penetration asphalt.

17. Generally speaking, the paving mixture with the highest asphalt content tended to be the most easily compacted.

18. For paving mixtures with constant VMA and air voids values, the increased Marshall stability normally expected from an increase in percent passing No. 200, can be partially or wholly nullified by the larger bulge in the fine aggregate portion of the grading curve that is needed to maintain a constant VMA value when the percent passing No. 200 is increased.

19. The mathematics for attaining more effective and efficient compaction of hot asphalt paving mixtures is reviewed. This indicates *quantitatively*, differences in the compactive effort, in the form of number of roller passes, required to achieve 97 or any other specified percent of laboratory compacted density, as influenced by the characteristics of the rolling equipment, by the range of compaction temperature, and by paving mixture design.

20. Cooling curves, based on simultaneous measurements of temperature and time started as soon as the paving mixture leaves the spreader, emphasize that the time available for effective compaction after hot mix leaves the spreader is relatively short.

21. In addition to hot asphalt paving mixtures, it is demonstrated that a straight line relationship between compacted specific gravity or density and logarithm of compactive effort in the form of number of applied Marshall blows, exists for other road building materials such as soil, sand, screenings, soil asphalt, soil cement and cold asphalt mixes.

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TABLE I

FACTORIAL DESIGN FOR ASPHALT PAVEMENT

LABORATORY COMPACTION

STUDY

Particle Index 11.5 Filler/Bitumen 0.9

		NORMAL GRADING									GAP GRADING									FULLER		
MIX NO.		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
VMA %		13.5			15.0			16.5			13.5			15.0			16.5			-----		
AIR VOIDS %		2½	4	5½	2½	4	5½	2½	4	5½	2½	4	5½	2½	4	5½	2½	4	5½	2½	4	5½
TEMPERATURE 275 F	Number of Blows 6	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	20	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	60	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	100	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
200 F	60	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	20	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	60	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	100	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
150 F	6	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	20	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	60	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	100	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x

TABLE 2

SIEVE ANALYSES AND ASPHALT CONTENTS FOR MIXES 1 TO 21

Mix No	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
SIEVE SIZE	PER CENT PASSING																				
1/2 inch	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
3/8 inch	87	87	87	87	87	87	87	87	87	65	65	65	65	65	65	65	65	65	87	87	87
No. 4	60	60	60	65	65	65	70	70	70	50	45	46	55	55	55	62	62	62	61	61	61
8	53	54	51	56	59	56	60	63	64	45	43	43	50	50	50	56	57	56	44	44	44
16	49	46	44	51	55	51	55	58	58	40	41	39	44	44	45	51	52	52	30	30	30
30	41	37	34	42	46	41	48	50	54	36	39	37	40	40	41	45	47	49	21	21	21
50	22	19	15	27	25	23	31	30	34	29	30	29	35	35	37	37	41	42	15	15	15
100	16	11	10	14	13	11	15	15	18	19	16	16	20	20	21	22	25	26	10	10	10
200	5.24	4.54	3.75	5.64	5.14	4.64	6.46	5.95	5.34	5.24	4.64	4.04	5.95	5.24	4.74	6.57	5.95	5.44	4.14	3.65	3.17
ASPHALT CONTENT	5.5	4.8	4.0	6.1	5.4	4.9	6.7	6.2	5.6	5.5	4.9	4.3	6.1	5.5	5.0	6.8	6.2	5.7	4.4	3.9	3.4

TABLE 3

SPECIFIC GRAVITY AND MARSHALL STABILITY DATA

PARTICLE INDEX - 11.5 — FILLER/BITUMEN RATIO-0.9

MIX NO.	AC %	AIR VOIDS %	VMA %	NO. OF BLOWS	SPECIFIC GRAVITY 275°F	200°F	150°F	MARSHALL STABILITY 275 °F	200°F	150°F
1	5.5	2.5 (2.6)	13.5 (13.7)	100	2.435	2.416	2.398	1737 (12.7)	1665 (11.6)	1568 (9.3)
				60	2.407	2.395	2.368	1800 (11.0)	1567 (9.1)	1296 (8.0)
				20	2.355	2.315	2.276	941 (8.5)	617 (10.0)	312 (9.5)
				6	2.253	2.211	2.158	245 (11.6)	123 (13.1)	104 (17.6)
2	4.8	4.0 (3.9)	13.5 (13.3)	100	2.410	2.403	2.378	2275 (7.3)	2205 (7.7)	1672 (7.0)
				60	2.400	2.356	2.326	1945 (10.0)	1410 (7.5)	881 (7.8)
				20	2.321	2.290	2.257	729 (7.4)	504 (7.8)	310 (7.7)
				6	2.227	2.194	2.141	206 (10.9)	96 (10.5)	43 (11.3)
3	4.0	5.5 (5.7)	13.5 (13.5)	100	2.406	2.392	2.333	2873 (7.3)	2287 (7.3)	951 (7.2)
				60	2.373	2.342	2.303	1855 (10.0)	1413 (6.8)	684 (6.3)
				20	2.292	2.283	2.221	516 (7.8)	500 (7.5)	180 (8.6)
				6	2.196	2.179	2.100	169 (8.2)	108 (10.1)	19 (14.8)
4	6.1	2.5 (2.6)	15.0 (15.1)	100	2.397	2.390	2.379	1408 (13.5)	1411 (11.3)	1194 (10.8)
				60	2.382	2.372	2.345	1203 (11.0)	1168 (10.2)	686 (10.3)
				20	2.341	2.292	2.274	782 (9.0)	465 (7.7)	289 (8.9)
				6	2.246	2.210	2.157	199 (4.8)	116 (12.5)	41 (00)
5	5.4	4.0 (4.2)	15.0 (14.9)	100	2.381	2.376	2.339	2006 (7.9)	1558 (8.0)	1193 (6.9)
				60	2.369	2.355	2.324	2046 (8.5)	1401 (8.0)	916 (8.0)
				20	2.286	2.262	2.217	688 (8.9)	476 (8.8)	195 (8.9)
				6	2.201	2.172	2.097	331 (11.3)	162 (11.6)	19 (16.8)
6	4.5	5.5 (5.5)	15.0 (15.2)	100	2.388	2.379	2.346	2320 (6.3)	1840 (6.0)	1170 (6.4)
				60	2.362	2.345	2.311	1312 (6.0)	1302 (6.8)	673 (7.3)
				20	2.283	2.258	2.210	439 (8.4)	297 (9.9)	100 (10.0)
				6	2.195	2.156	2.108	85 (0.0)	125 (0.0)	0 (0.0)
7	6.7	2.5 (2.6)	16.5 (16.4)	100	2.387	2.372	2.362	1312 (11.5)	1180 (11.9)	1150 (11.0)
				60	2.361	2.355	2.345	1190 (13.5)	1116 (12.0)	1057 (9.5)
				20	2.314	2.308	2.266	717 (8.5)	564 (9.0)	274 (9.7)
				6	2.238	2.213	2.168	248 (10.3)	154 (10.4)	53 (1.8)
8	6.2	4.0 (3.8)	16.5 (16.5)	100	2.362	2.369	2.357	1610 (11.2)	1584 (10.0)	1270 (9.0)
				60	2.345	2.345	2.312	1571 (10.2)	1231 (8.0)	773 (7.3)
				20	2.297	2.275	2.236	673 (7.5)	478 (8.0)	248 (8.8)
				6	2.191	2.167	2.096	149 (10.0)	124 (12.6)	13 (16.5)
9	5.6	5.5 (5.5)	16.5 (16.4)	100	2.355	2.357	2.306	1587 (7.6)	1491 (7.6)	1107 (9.0)
				60	2.333	2.301	2.269	1443 (8.5)	825 (6.0)	740 (8.8)
				20	2.236	2.234	2.199	398 (7.3)	435 (8.3)	171 (8.0)
				6	2.170	2.140	2.089	133 (9.0)	158 (13.0)	37 (12.6)
10	5.5	2.5 (2.5)	13.5 (13.5)	100	2.429	2.408	2.397	1940 (13.0)	1700 (9.0)	1504 (9.8)
				60	2.414	2.400	2.361	1741 (10.3)	1594 (10.0)	1155 (8.8)
				20	2.356	2.338	2.283	1009 (8.3)	698 (9.0)	289 (9.8)
				6	2.270	2.238	2.156	286 (11)	192 (12.7)	52 (16.5)
11	4.9	4.0 (4.0)	13.5 (13.5)	100	2.417	2.400	2.358	2583 (8.5)	2197 (7.6)	1578 (8.8)
				60	2.401	2.373	2.320	1873 (9.5)	1526 (7.3)	792 (7.1)
				20	2.325	2.281	2.257	697 (8.8)	369 (8.2)	288 (8.7)
				6	2.251	2.195	2.155	183 (11.4)	173 (18.2)	35 (14.0)
12	4.3	5.5 (5.3)	13.5 (13.5)	100	2.417	2.388	2.358	2560 (8.5)	1978 (7.0)	1234 (7.0)
				60	2.385	2.371	2.334	1660 (8.0)	1434 (6.9)	940 (7.3)
				20	2.320	2.283	2.236	742 (7.5)	527 (7.9)	217 (7.7)
				6	2.227	2.186	2.116	133 (11.5)	76 (8.3)	50 (10.2)
13	6.2	2.5 (2.7)	15.0 (15.2)	100	2.399	2.391	2.382	1533 (12.0)	1286 (11.2)	1161 (12.0)
				60	2.385	2.380	2.355	1372 (13.3)	1206 (11.0)	1121 (12.3)
				20	2.350	2.310	2.289	792 (11.3)	659 (8.6)	446 (10.7)
				6	2.277	2.202	2.154	281 (9.0)	112 (17.7)	41 (00)
14	5.5	4.0 (4.0)	15.0 (14.8)	100	2.399	2.396	2.370	1640 (9.0)	1734 (9.2)	1451 (8.0)
				60	2.379	2.373	2.348	1389 (9.5)	1462 (7.3)	1283 (8.3)
				20	2.313	2.313	2.254	705 (7.7)	617 (7.9)	177 (8.3)
				6	2.233	2.194	2.152	132 (13.4)	76 (00)	34 (00)
15	5.0	5.5 (5.6)	15.0 (15.1)	100	2.380	2.362	2.333	2096 (6.9)	1805 (6.8)	869 (9.2)
				60	2.363	2.338	2.299	1401 (8.8)	1318 (7.5)	613 (8.3)
				20	2.298	2.273	2.229	579 (8.0)	363 (8.5)	206 (7.1)
				6	2.208	2.178	2.122	114 (12.0)	54 (14.0)	41 (00)
16	6.8	2.5 (2.6)	16.5 (16.5)	100	2.377	2.369	2.365	1088 (12.8)	1021 (13.5)	969 (11.2)
				60	2.362	2.355	2.336	1014 (13.0)	1075 (11.9)	849 (10.8)
				20	2.322	2.315	2.265	688 (10.2)	679 (9.9)	294 (8.5)
				6	2.277	2.213	2.170	293 (10.0)	174 (15.2)	67 (16.0)
17	6.2	4.0 (4.2)	16.5 (16.6)	100	2.360	2.355	2.345	1607 (9.3)	1408 (8.3)	1497 (9.0)
				60	2.346	2.339	2.297	1409 (11.0)	1088 (8.7)	736 (7.8)
				20	2.281	2.256	2.199	589 (8.5)	487 (11.5)	158 (9.5)
				6	2.207	2.174	2.109	120 (11.3)	184 (13.9)	31 (31.0)
18	5.7	5.5 (5.4)	16.5 (16.5)	100	2.388	2.344	2.319	1820 (8.9)	1587 (7.5)	1119 (7.5)
				60	2.334	2.295	2.267	1221 (10.0)	923 (7.3)	499 (6.0)
				20	2.252	2.224	2.185	504 (8.0)	304 (7.9)	187 (9.5)
				6	2.181	2.142	2.107	166 (10.3)	107 (17)	41 (8.0)
19	4.4	2.5 (2.4)	—— (11.4)	100	2.471	2.456	2.417	3016 (9.3)	2589 (9.6)	1650 (8.2)
				60	2.443	2.429	2.372	2141 (10.8)	1808 (8.1)	461 (8.0)
				20	2.363	2.326	2.256	973 (9.6)	554 (9.2)	280 (10.6)
				6	2.239	2.208	2.161	260 (13.2)	145 (10.8)	50 (16.7)
20	3.9	4.0 (4.1)	—— (11.5)	100	2.453	2.432	2.403	3224 (11.0)	2300 (8.5)	1783 (6.8)
				60	2.426	2.368	2.306	2399 (8.3)	1227 (8.2)	492 (7.3)
				20	2.332	2.307	2.238	704 (10.5)	442 (8.0)	233 (10.5)
				6	2.240	2.182	2.129	251 (10.0)	108 (18)	22 (15.7)
21	3.4	5.5 (5.6)	—— (11.8)	100	2.426	2.396	2.365	2903 (7.8)	2167 (7.5)	1500 (7.0)
				60	2.405	2.349	2.330	1913 (12.2)	1175 (7.2)	1016 (8.7)
				20	2.315	2.274	2.207	688 (8.0)	415 (8.9)	163 (8.9)
				6	2.205	2.181	2.140	208 (10.3)	67 (6.8)	21 (21.0)

TABLE 4

SPECIFIC GRAVITY AND MARSHALL STABILITY DATA AS PERCENTAGES OF 60-BLOW AT 275°F

PARTICLE INDEX - 11.5 FILLER/BITUMEN RATIO -0.9

MIX NO.	AC %	AIR VOIDS %	VMA %	NO. OF BLOWS	SPECIFIC GRAVITY 275°F	200°F	150°F	MARSHALL STABILITY 275°F	200°F	150°F
1	5.5	2.5 (2.6)	13.5 (13.7)	100	101.16	100.37	99.63	96.50	92.50	87.11
				60	100.00	99.50	58.33	100.00	87.06	72.00
				20	97.84	96.18	94.55	52.28	34.28	17.33
				6	93.60	91.86	89.65	13.61	6.83	5.78
2	4.8	4.0 (3.9)	13.5 (13.3)	100	100.42	100.13	99.08	116.97	113.37	85.96
				60	100.00	98.17	96.52	100.00	72.49	45.30
				20	96.71	95.42	94.04	37.48	25.91	15.94
				6	92.79	91.42	89.21	10.59	4.94	2.21
3	4.0	5.5 (5.7)	13.5 (13.5)	100	101.39	100.80	98.31	154.88	123.29	51.27
				60	100.00	98.69	97.05	100.00	76.17	36.87
				20	96.59	96.21	93.55	28.36	26.95	9.70
				6	92.54	91.82	88.55	9.11	5.82	1.02
4	6.1	2.5 (2.6)	15.0 (15.1)	100	100.42	100.34	99.87	117.04	117.29	99.25
				60	100.00	99.58	98.45	100.00	97.09	57.02
				20	98.28	96.22	95.47	65.00	36.99	24.02
				6	94.29	90.55	90.55	16.54	9.64	3.41
5	5.4	4.0 (4.2)	15.0 (14.9)	100	100.51	100.30	98.73	98.04	76.15	58.31
				60	100.00	99.41	98.10	100.00	68.48	44.77
				20	96.50	95.48	93.55	33.63	23.26	9.53
				6	92.91	91.68	88.52	16.18	7.92	1.00
6	4.5	5.5 (5.5)	15.0 (15.2)	100	101.10	100.72	99.32	175.83	140.24	89.18
				60	100.00	99.28	57.84	100.00	99.24	51.30
				20	96.66	95.60	93.55	33.45	22.64	7.62
				6	92.93	91.20	89.25	6.45	1.00	1.00
7	6.7	2.5 (2.6)	16.5 (16.4)	100	101.10	100.47	100.04	110.25	99.16	96.64
				60	100.00	99.75	99.32	100.00	93.78	88.82
				20	98.01	97.76	95.58	60.25	47.39	23.02
				6	94.79	93.73	91.83	20.84	12.94	4.45
8	6.2	4.0 (3.8)	16.5 (16.5)	100	100.72	101.02	100.51	102.49	100.83	80.84
				60	100.00	100.00	98.59	100.00	78.36	49.20
				20	97.95	97.01	95.35	42.84	30.43	15.79
				6	93.43	92.41	89.38	9.48	7.89	1.00
9	5.6	5.5 (5.5)	16.5 (16.4)	100	100.94	101.03	98.84	109.53	103.33	76.72
				60	100.00	98.63	97.26	100.00	57.17	51.28
				20	95.84	55.76	94.26	27.44	30.15	11.85
				6	93.01	91.73	89.54	9.22	10.95	2.56
10	5.5	2.5 (2.5)	13.5 (13.5)	100	100.62	99.75	99.30	111.43	97.65	86.39
				60	100.00	99.42	97.80	100.00	91.56	66.34
				20	97.60	96.85	94.57	57.56	40.09	16.26
				6	94.03	92.71	89.31	16.43	11.03	2.99
11	4.9	4.0 (4.0)	13.5 (13.5)	100	100.67	99.96	98.21	137.91	117.30	84.25
				60	100.00	98.83	96.63	100.00	81.47	42.29
				20	96.83	95.00	94.00	37.21	19.70	15.38
				6	93.75	91.42	89.75	9.77	9.24	1.87
12	4.3	5.5 (5.3)	13.5 (13.5)	100	101.34	100.13	98.87	154.22	119.16	74.34
				60	100.00	99.41	97.86	100.00	86.39	56.63
				20	97.27	95.72	93.75	45.70	31.75	13.07
				6	93.38	91.66	88.72	8.01	4.58	3.01
13	6.2	2.5 (2.7)	15.0 (15.2)	100	100.59	100.25	99.87	111.73	93.73	84.62
				60	100.00	99.79	98.74	100.00	87.90	81.71
				20	98.53	96.86	95.97	57.73	48.03	32.51
				6	95.47	92.33	90.31	20.48	8.16	2.99
14	5.5	4.0 (4.0)	15.0 (14.8)	100	100.84	100.71	99.62	118.07	124.84	104.46
				60	100.00	99.75	98.70	100.00	105.26	92.37
				20	97.23	97.23	94.75	50.76	44.42	12.74
				6	93.86	92.22	90.46	9.50	5.47	2.45
15	5.0	5.5 (5.6)	15.0 (15.1)	100	100.72	99.96	98.73	149.61	128.84	62.03
				60	100.00	98.94	97.29	100.00	94.08	43.75
				20	97.25	96.19	94.33	41.33	25.91	14.70
				6	93.44	92.17	89.80	8.14	3.85	2.93
16	6.8	2.5 (2.6)	16.5 (16.5)	100	100.64	100.30	100.13	107.30	100.69	95.56
				60	100.00	99.70	98.90	100.00	101.08	03.73
				20	98.31	98.01	95.89	67.85	66.96	28.99
				6	96.40	93.69	91.87	28.50	17.16	6.61
17	6.2	4.0 (4.2)	16.5 (16.6)	100	100.60	100.38	99.96	114.05	99.93	106.25
				60	100.00	99.70	97.91	100.00	77.22	52.24
				20	97.23	96.16	93.73	41.80	34.56	11.21
				6	94.08	92.67	89.90	8.52	13.06	2.20
18	5.7	5.5 (5.4)	16.5 (16.5)	100	102.31	100.43	99.36	143.05	129.98	91.65
				60	100.00	98.33	97.13	100.00	75.59	40.87
				20	96.49	95.29	93.62	41.28	24.90	15.32
				6	93.44	91.77	90.27	13.60	8.76	3.36
19	4.4	2.5 (2.4)	—* (11.4)	100	101.15	100.53	98.94	140.87	120.92	77.07
				60	100.00	99.43	97.09	100.00	84.45	21.53
				20	96.73	95.21	92.35	45.45	25.88	13.08
				6	91.65	90.38	88.46	12.14	6.77	2.34
20	3.9	4.0 (4.1)	— (11.5)	100	101.11	100.25	99.05	134.39	95.87	74.32
				60	100.00	97.61	95.05	100.00	51.15	20.51
				20	96.13	95.09	92.25	23.35	18.42	9.71
				6	92.33	89.94	87.76	10.46	4.50	1.00
21	3.4	5.5 (5.6)	— (11.8)	100	100.87	99.63	98.34	151.75	113.28	78.41
				60	100.00	97.67	96.88	100.00	61.42	53.11
				20	96.26	94.55	91.77	35.96	21.69	8.52
				6	91.68	90.69	88.98	10.87	3.50	1.10

TABLE 5

SIEVE ANALYSES AND OTHER DATA FOR PAVING MIXTURES WITH NORMAL AND ODD GRADINGS

All Mixes - Air Voids = 4% and Particle Index = 11.5

	NORMAL GRADING				ODD GRADING			
	Filler/Bitumen = 0.9				Filler/Bitumen = 0.4			
MIX NO.	2a	5a	8a	20	30	31	32	33
SIEVE SIZE	PER CENT PASSING							
1/2	100	100	100	100	100	100	100	100
3/8	87	87	87	87	87	87	87	87
4	60	65	70	61	60	65	70	61
8	52	57	60	44	43	50	58	44
16	42	49	55	30	33	36	45	30
30	32	39	48	21	21	22	25	21
50	19	23	29	15	14	13	11	15
100	11	13	15	10	8	5	5	10
200	4.54	5.24	5.85	3.65	2.06	2.33	2.55	1.93
Asphalt Content %	4.8	5.5	6.1	3.9	4.9	5.5	6.0	4.6
Actual Air Voids %	4.1	4.1	4.0	3.9	3.9	3.9	4.2	4.2
Actual VMA %	13.6	15.1	16.4	11.3	13.6	15.2	16.5	13.2

TABLE 6

COMPARISON OF SPECIFIC GRAVITY AND MARSHALL STABILITY DATA
FOR PAVING MIXTURES WITH NORMAL AND ODD GRADINGS
ALL MIXES - AIR VOIDS = 4% AND PARTICLE INDEX = 11.5
COMPACTION TEMPERATURE 275°F

MIX NO.	AC %	ACTUAL VMA %	ACTUAL AIR VOIDS %	F/B %	SPECIFIC GRAVITY				MARSHALL STABILITY			
					100 BLOW	60 BLOW	20 BLOW	6 BLOW	100 BLOW	60 BLOW	20 BLOW	6 BLOW
PAVING MIXTURES WITH NORMAL GRADING												
2a	4.8	13.6	4.1	0.9	2.420	2.396	2.314	2.224	2640	2057	721	222
5a	5.5	15.1	4.1	0.9	2.394	2.372	2.303	2.213	1936	1492	575	183
8a	6.1	16.4	4.0	0.9	2.366	2.350	2.288	2.191	1577	1615	771	192
20	3.9	11.3	3.9	0.9	2.450	2.418	2.326	2.225	2696	2343	926	171
PAVING MIXTURES WITH ODD GRADING												
30	4.9	13.6	3.9	0.4	2.424	2.399	2.304	2.208	2225	1760	422	75
31	5.5	15.2	3.9	0.4	2.401	2.368	2.281	2.190	2111	1476	404	61
32	6.0	16.5	4.2	0.4	2.358	2.343	2.244	2.152	1865	1698	398	65
33	4.6	13.2	4.2	0.4	2.431	2.400	2.306	2.207	2577	1690	558	172

TABLE 7

ASPHALT CEMENT INSPECTION DATA

GRADE	150/200	85/100	150/200	150/200	300/400
SOURCE	LLOYDMINSTER	MONTREAL	MONTREAL	WINNIPEG	MONTREAL
SUPPLIED BY	HUSKY	IMPERIAL	IMPERIAL	IMPERIAL	IMPERIAL
Specific Gravity 60°F	1.029	1.012	1.008	1.004	0.993
Flash Point COC°F	475	645	620	600+	595
Penetration at 77°F	156	91	167	160	375
Viscosity at 275°F cs	284	360	257	124	136
Ductility at 77°F cm	150+	150+	150+	150+	---
Ductility at 60°F cm	---	---	---	---	150+
Solubility CCL_4 %	99.9	99.9	99.8	99.8	99.9
Thin Film Oven Test					
% Loss	0.55	NIL	NIL	NIL	NIL
% Retained Pen. at 77°F	58	70	57	56	64
Ductility of Resid. at 77°F	---	150+	150+	103	150+

TABLE 8

ILLUSTRATING DECREASING EFFECTIVENESS OF SUCCESSIVE ROLLER PASSES

Equation for any compaction line ----------D+mlog B+c

where

D = percent of laboratory compacted specific gravity

B = number of Marshall blows

m = slope of compaction line = 6.19 in Figures 29 and 32

c = intercept of compaction line with 1-blow Marshall = 89.00 in Figures 29 and 32.

Initial paving mixture density = 89.00 percent of laboratory compacted specific gravity.

Compaction temperature = 275°F

No. of Roller Passes	Corresponding Number of Blows Marshall	D=6.19log B+89.00	% Lab.Comp.Spec.Grav. Achieved by Roller Passes	Increase in Percent Paving Mixture Density Per Roller Pass
(a) Each roller pass equivalent in compactive effort to 3-blows Marshall				
0	1.00	-----	89.00	----
1	4.00	6.19log 4.00 + 89.00	72.73	3.73
2	7.00	6.19log 7.00 + 89.00	94.23	1.50
3	10.00	6.19log10.00 + 89.00	95.19	0.96
4	13.00	6.19log13.00 + 89.00	95.90	0.71
5	16.00	6.19log16.00 + 89.00	96.45	0.55
6	19.00	6.19log19.00 + 89.00	96.92	0.47
7	22.00	6.19log22.00 + 89.00	97.31	0.39
8	25.00	6.19log25.00 + 89.00	97.65	0.34
9	28.00	6.19log28.00 + 89.00	97.96	0.31
10	31.00	6.19log31.00 + 89.00	98.23	0.27
(b) Each roller pass equivalent in compactive effort to 5-blows Marshall				
0	1.00	-----	89.00	----
1	6.00	6.19log 6.00 + 89.00	93.82	4.82
2	11.00	6.19log11.00 + 89.00	95.45	1.63
3	16.00	6.19log16.00 + 89.00	96.45	1.00
4	21.00	6.19log21.00 + 89.00	97.18	0.73
5	26.00	6.19log26.00 + 89.00	97.76	0.58
6	31.00	6.19log31.00 + 89.00	98.23	0.47
7	36.00	6.19log36.00 + 89.00	98.63	0.40
8	41.00	6.19log41.00 + 89.00	98.98	0.35
9	46.00	6.19log46.00 + 89.00	99.29	0.31
10	51.00	6.19log51.00 + 89.00	99.57	0.28

TABLE 9

SIEVE ANALYSIS AND OTHER CHARACTERISTICS OF SOILS, AGGREGATES, STABILIZED SOILS AND ASPHALT COLD MIX

SIEVE SIZE	SOIL	SAND	SCREENINGS	SOIL CEMENT	SOIL ASPHALT	ASPHALT COLD MIX
	PER CENT PASSING					
1/2 inch		100.0			100.0	100.0
3/8 inch	100.0	99.2	100.0	100.0	99.2	89.5
No. 4 sieve	98.0	97.0	96.6	99.9	97.0	66.7
No. 8 sieve	95.5	95.4	71.8	99.8	95.4	52.5
No. 16 sieve	92.2	92.0	49.2	99.7	92.0	39.1
No. 30 sieve	88.3	85.2	34.3	99.4	85.2	29.4
No. 50 sieve	81.7	49.1	25.6	94.3	49.1	20.1
No.100 sieve	69.7	20.1	20.2	41.2	20.1	13.0
No.200 sieve	58.1	13.0	16.1	4.0	13.0	8.1
Moisture Content %	20.6	10.0	7.0	8.0	6.0	----
Asphalt Content %	----	----	----	----	5.0	4.5
Portland Cement Content %	----	----	----	7.0	----	----
Liquid Limit	36.1	----	----	----	----	----
Plasticity Index	8.1	NP	NP	NP	NP	NP

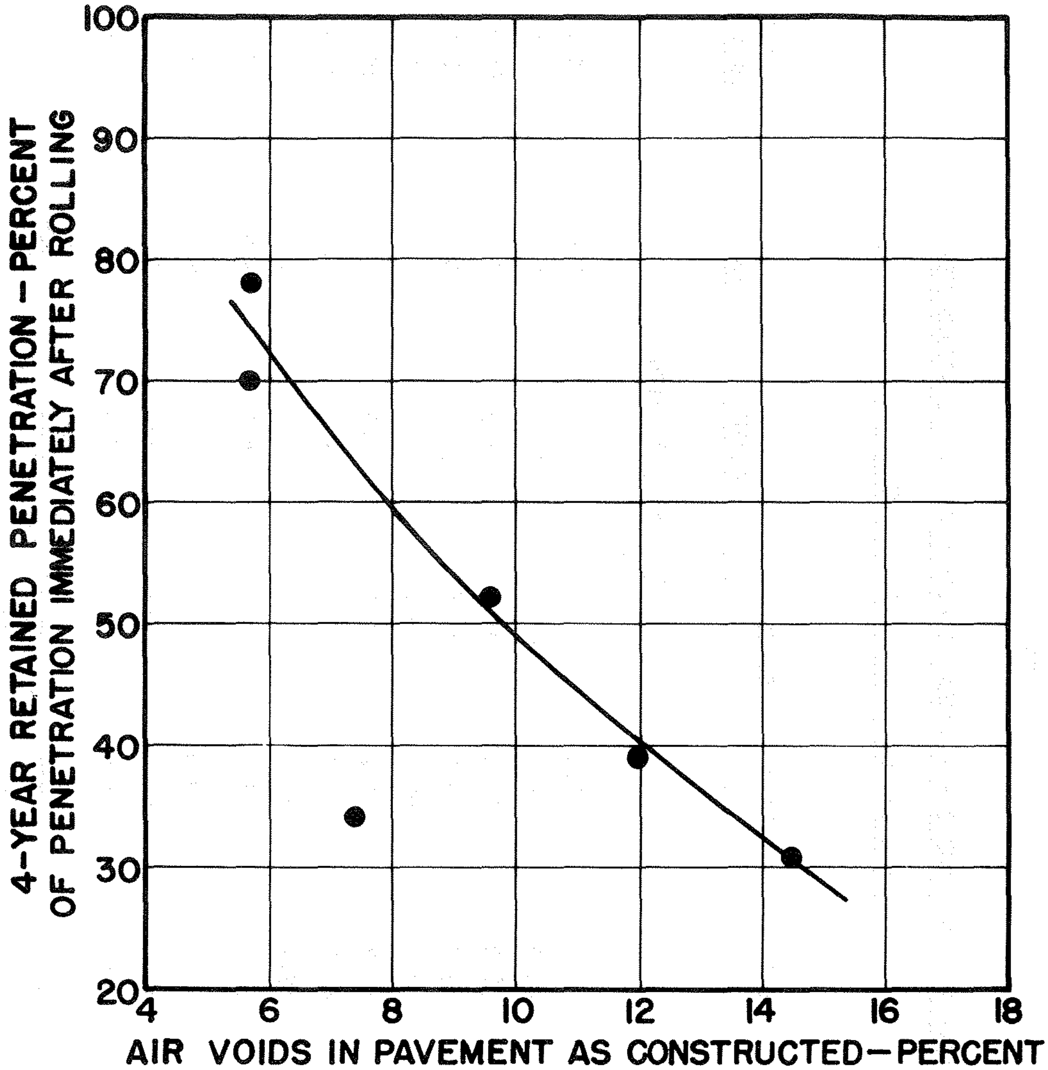

FIG. I EFFECT OF INITIAL AIR VOIDS IN PAVEMENT ON CHANGE IN PENETRATION OF ASPHALT AFTER FOUR YEARS OF SERVICE.

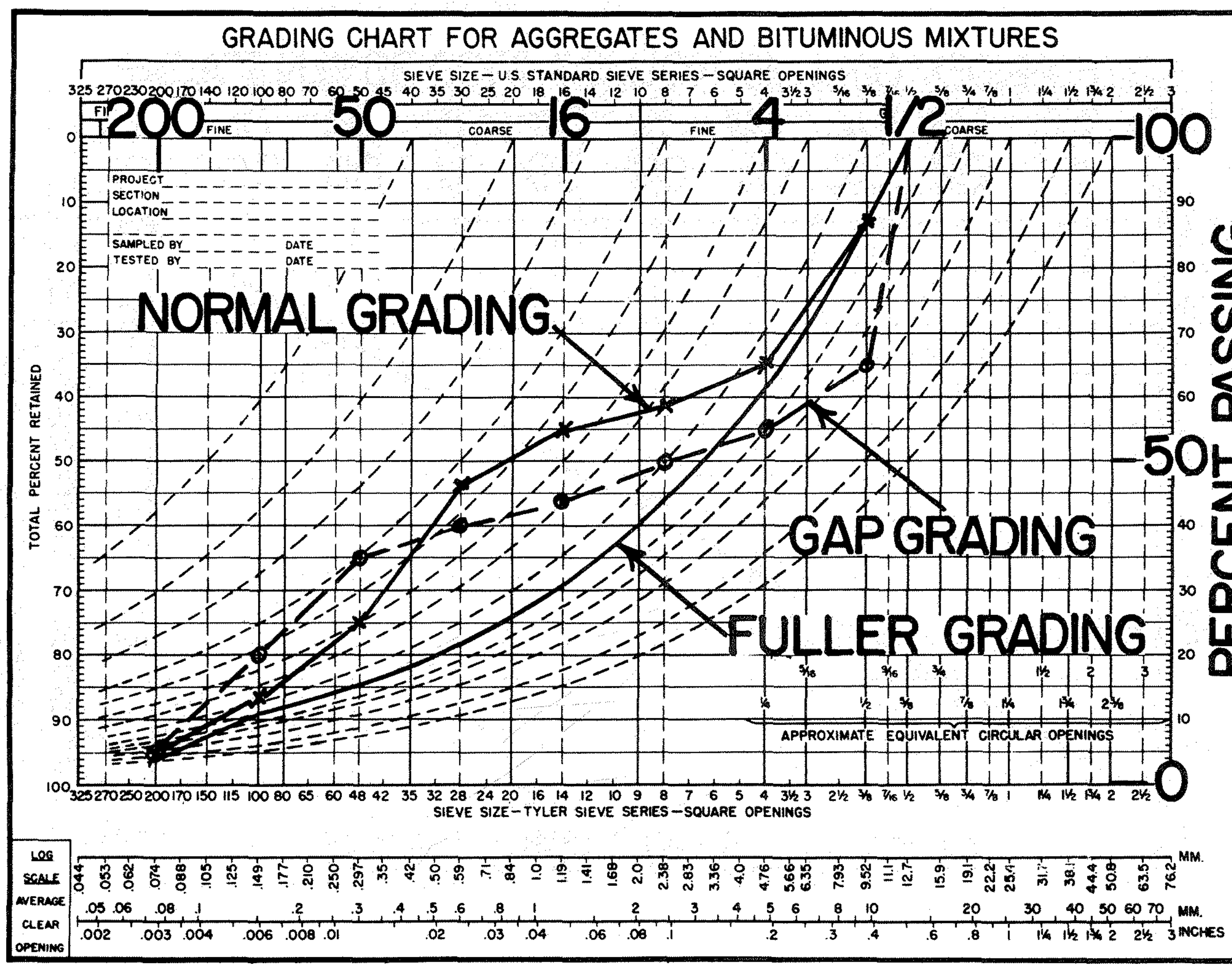

FIGURE 2 ILLUSTRATING NORMAL GRADING, GAP GRADING AND FULLER GRADING.

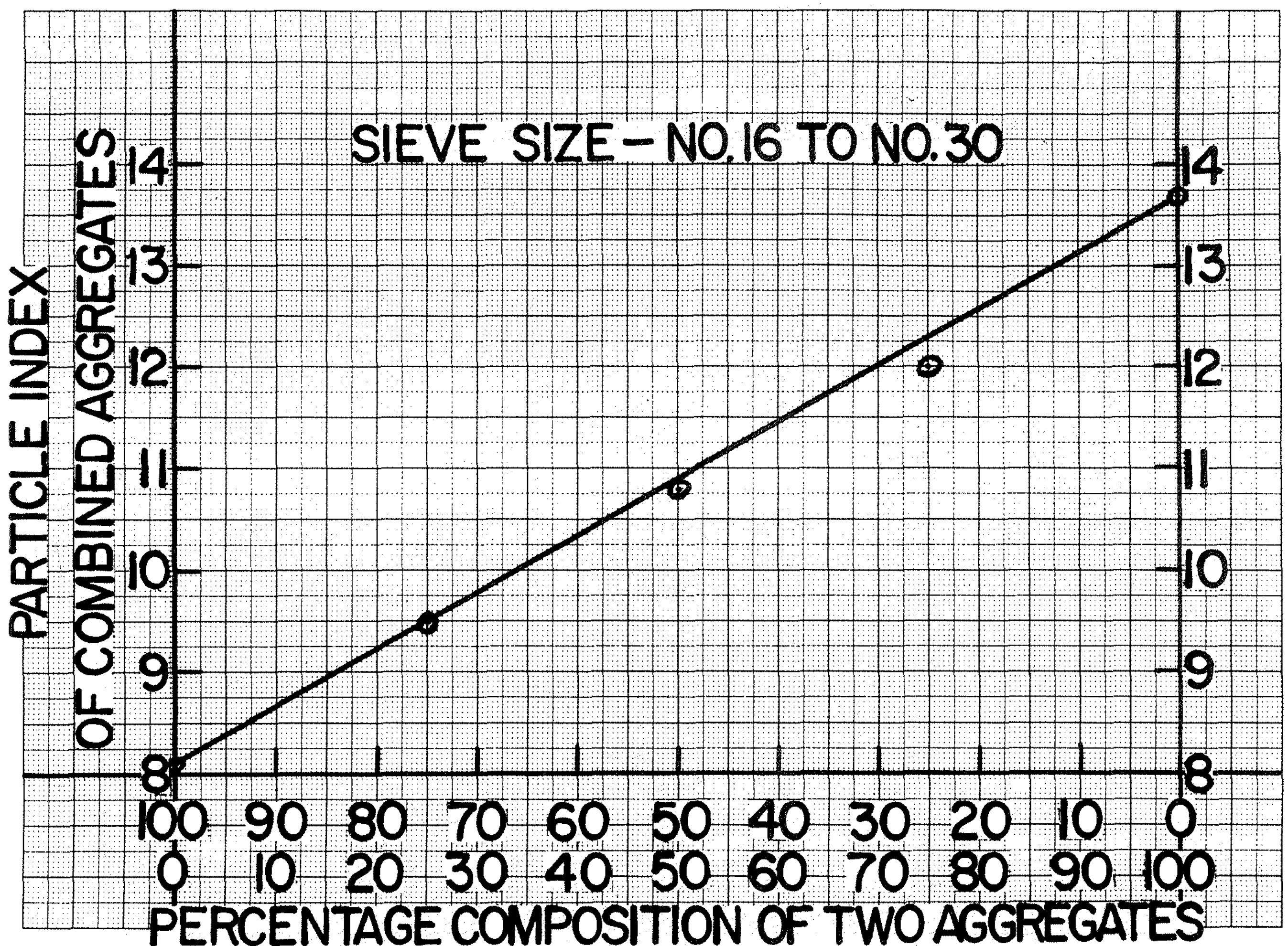

FIGURE 3 DEMONSTRATING THAT PARTICLE INDEX VARIES DIRECTLY WITH THE PERCENTAGE COMPOSITION OF TWO AGGREGATES.

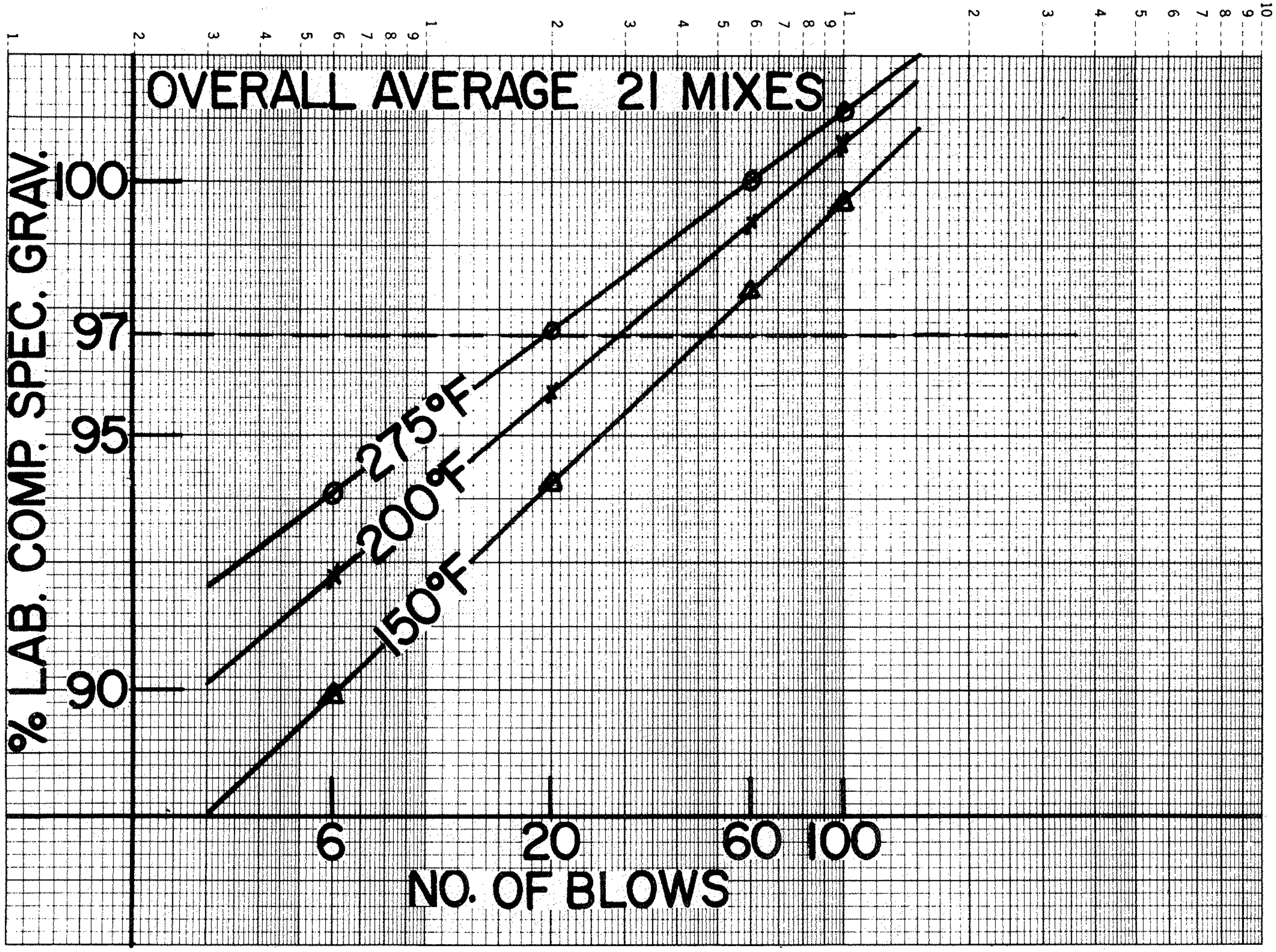

FIGURE 4 ILLUSTRATING INFLUENCE OF COMPACTIVE EFFORT AND COMPACTION TEMPERATURE ON PAVING MIXTURE DENSITY.

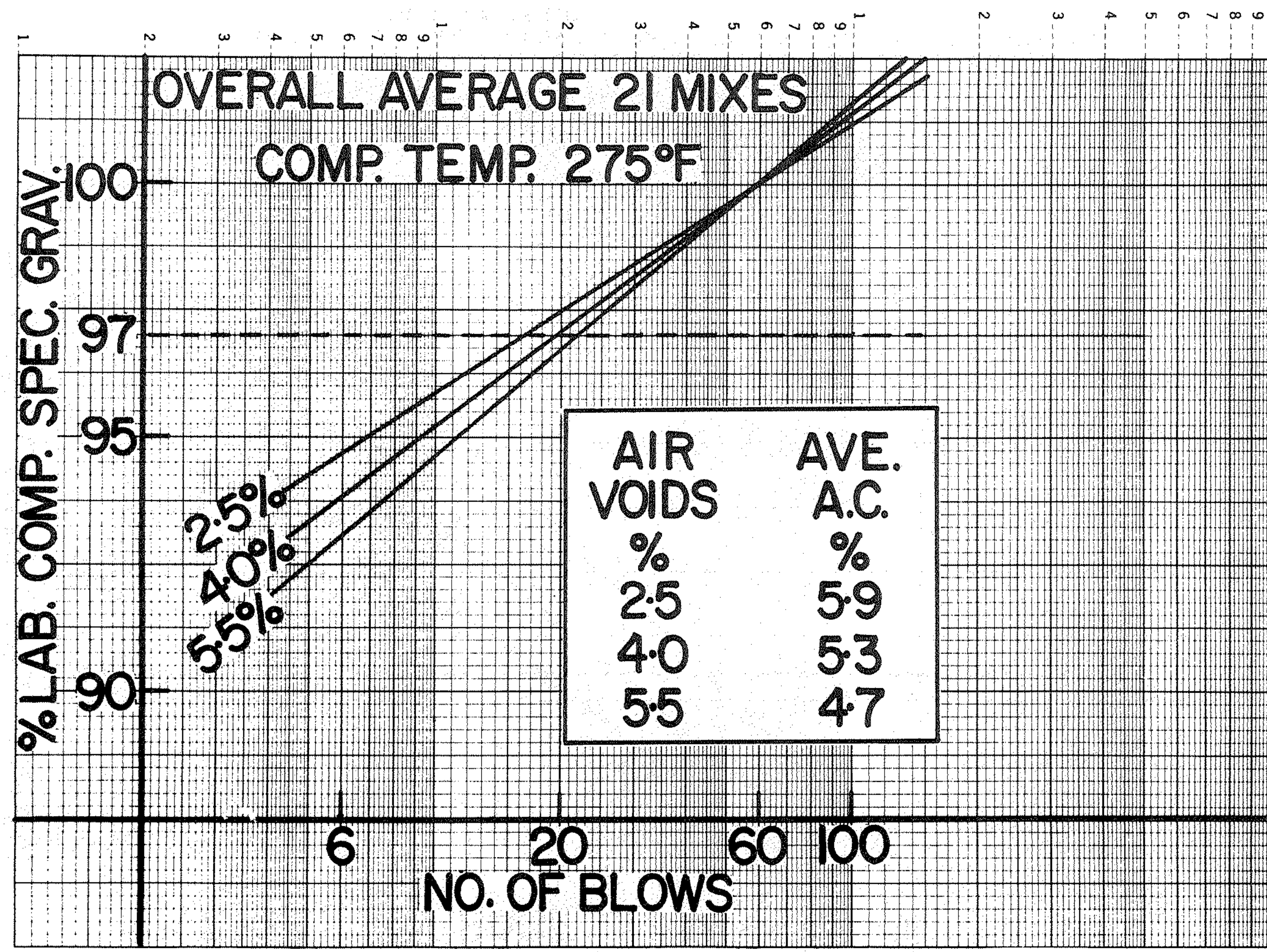

FIGURE 5 FOR A GIVEN COMPACTIVE EFFORT, PAVING MIXTURE DENSITY INCREASES WITH DECREASING AIR VOIDS PROBABLY BECAUSE OF INCREASING ASPHALT CONTENT.

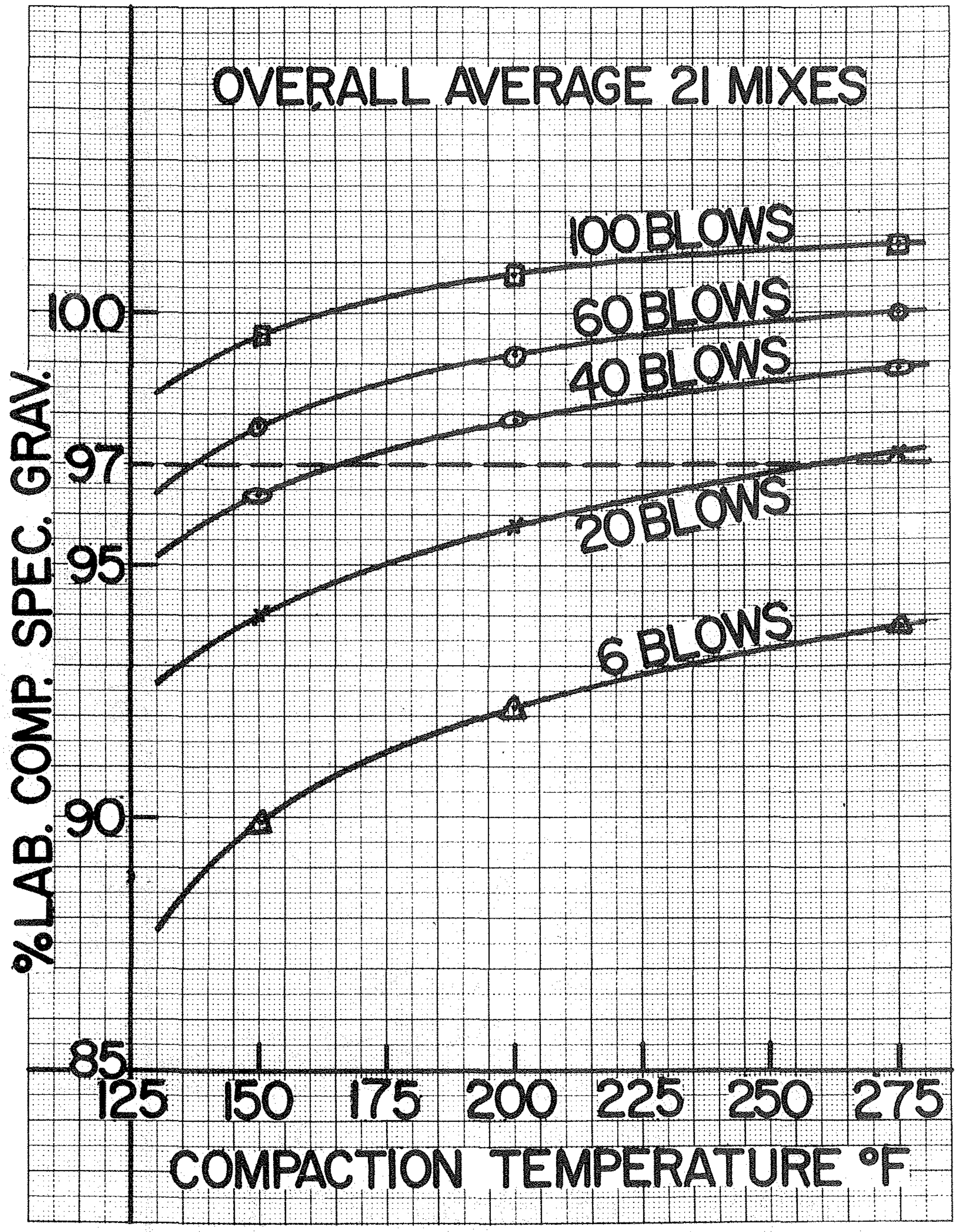

FIGURE 6 FOR ANY GIVEN COMPACTION TEMPERATURE PAVING MIXTURE DENSITY INCREASES WITH AN INCREASE IN COMPACTIVE EFFORT.

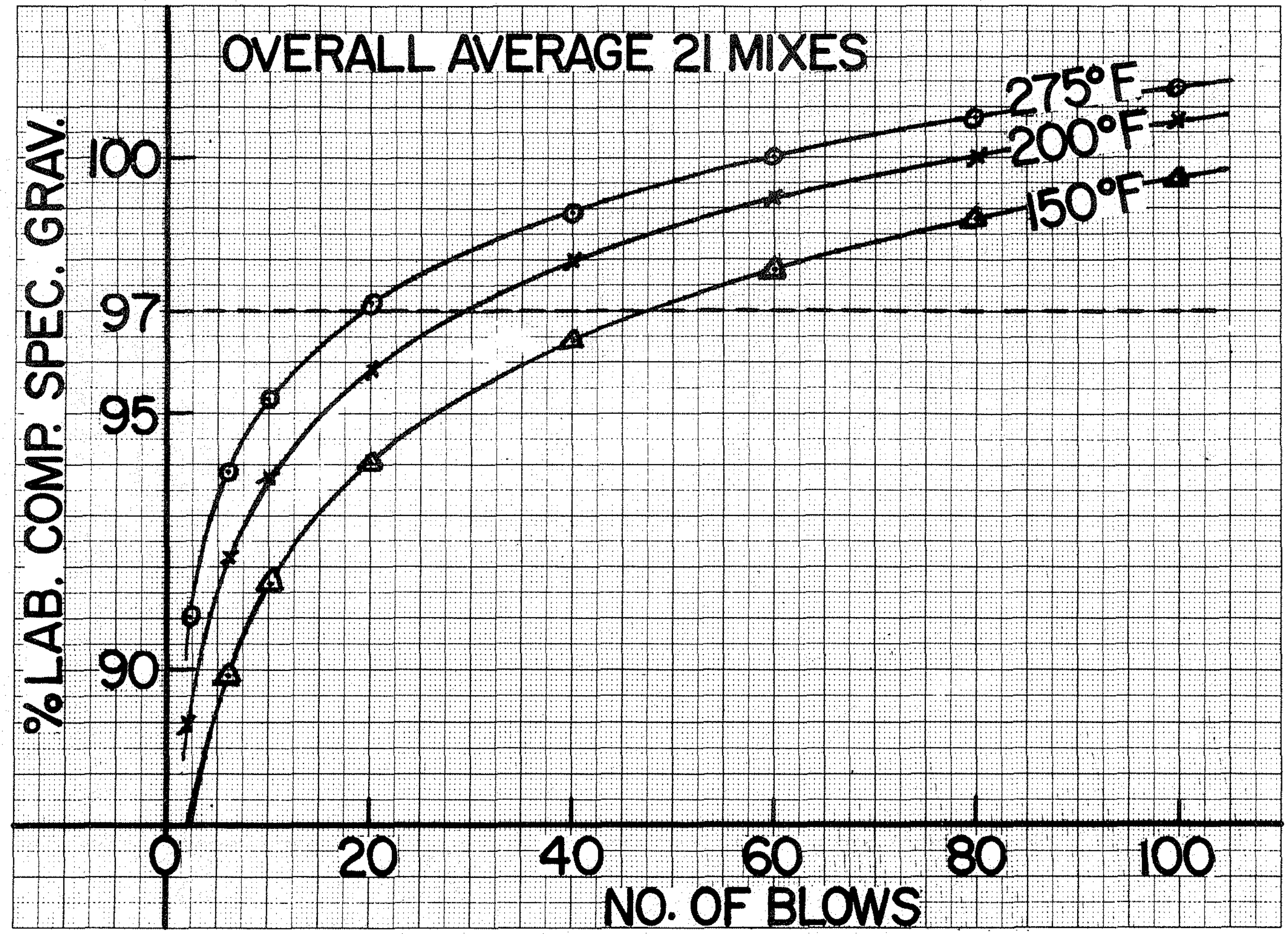

FIGURE 7 FOR ANY GIVEN COMPACTIVE EFFORT, PAVING MIXTURE DENSITY INCREASES WITH COMPACTION TEMPERATURE.

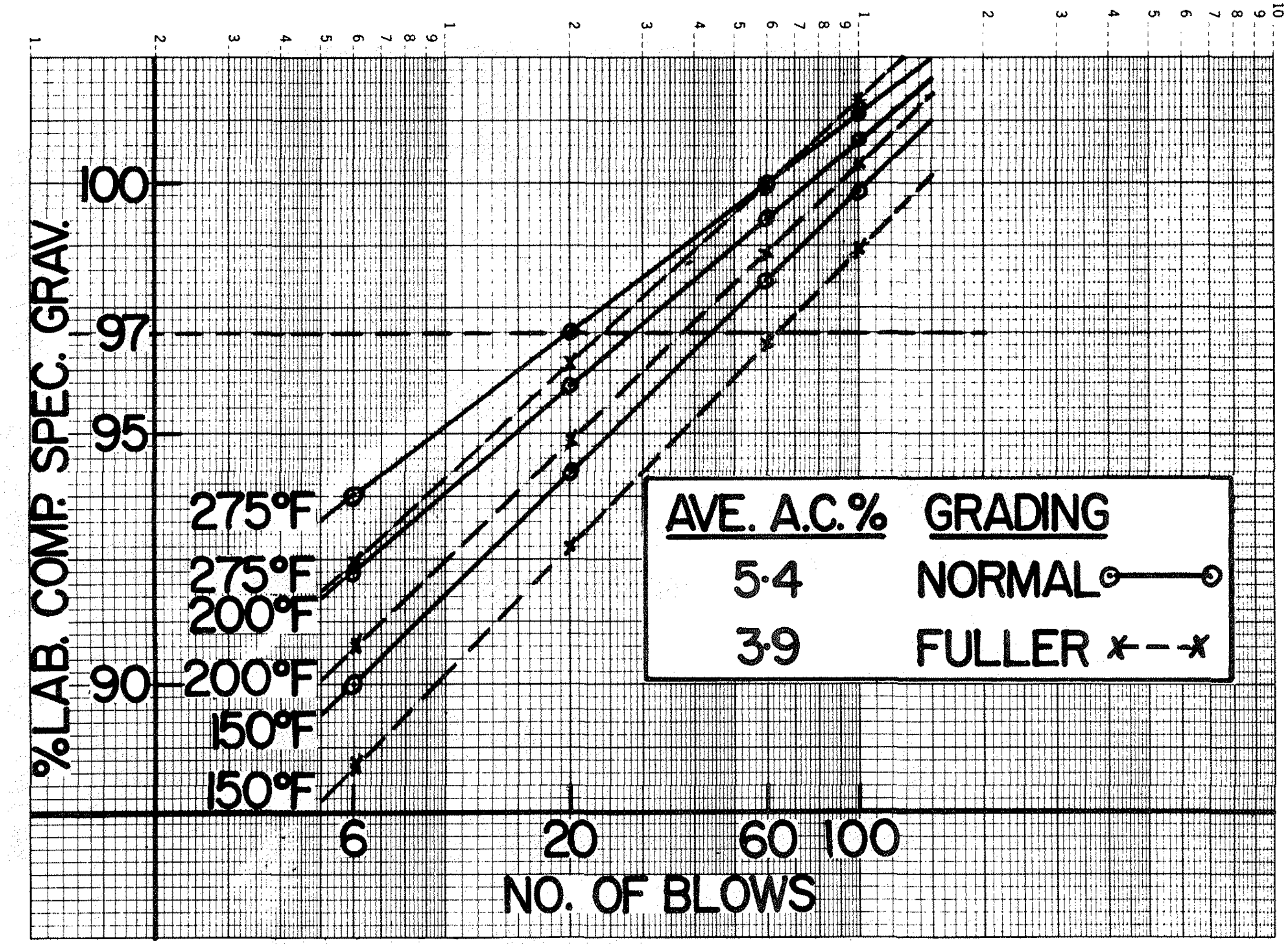

FIGURE 8 PAVING MIXTURES WITH FULLER GRADING CURVES HAVE THE HIGHEST RESISTANCE TO COMPACTION.

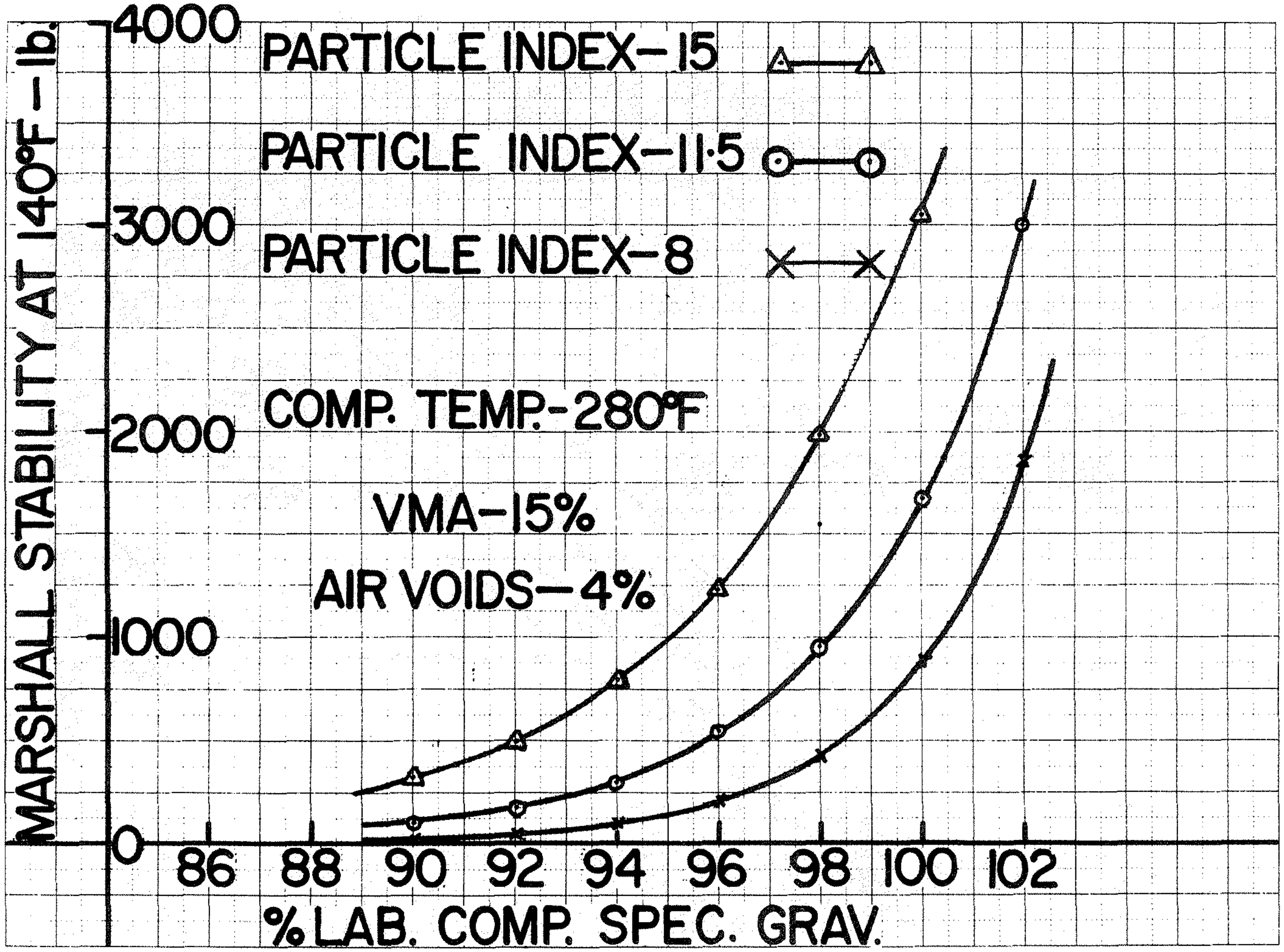

FIGURE 9 MARSHALL STABILITY INCREASES WITH AN INCREASE IN THE PARTICLE INDEX OF THE AGGREGATE.

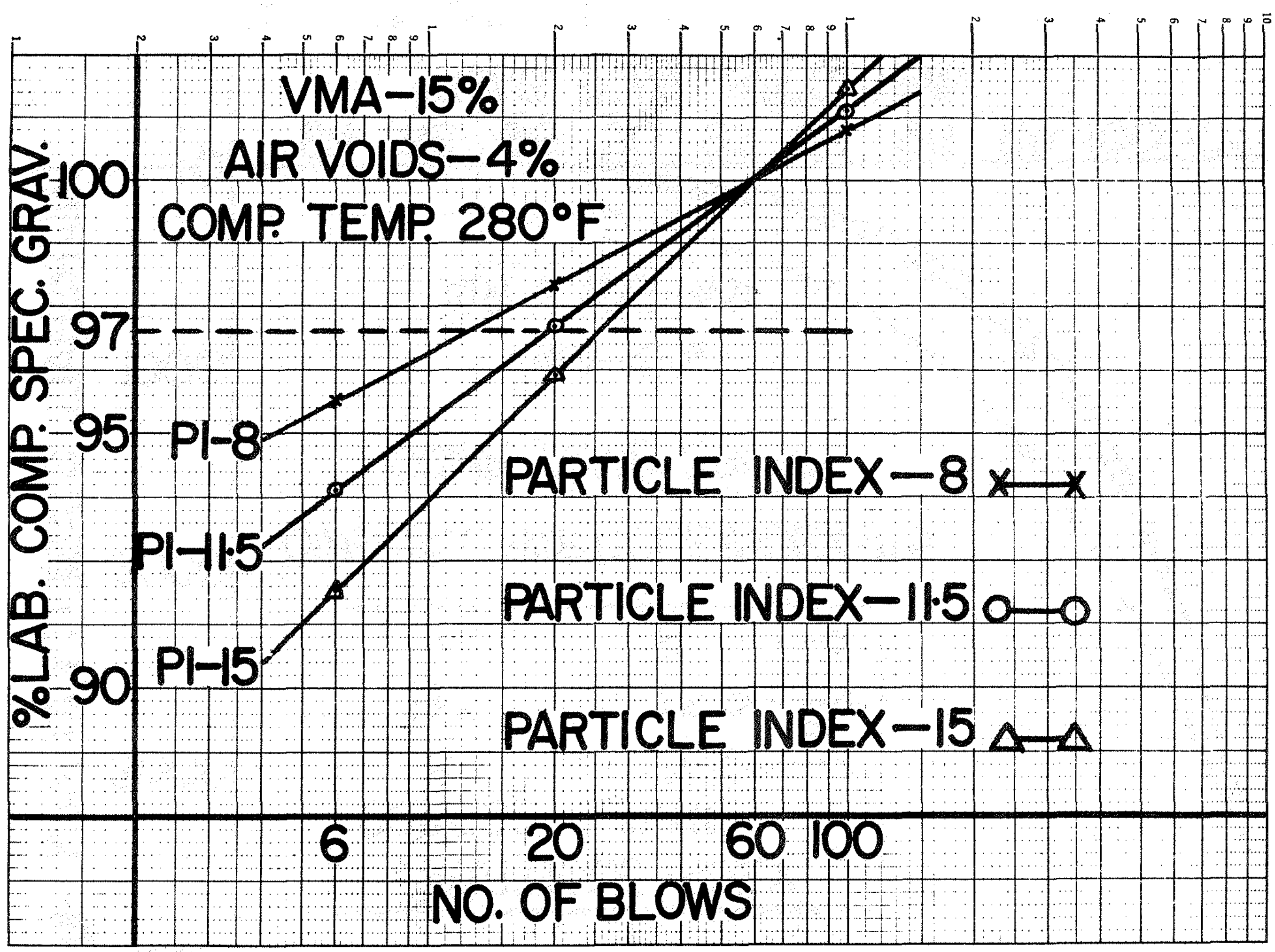

FIGURE 10 RESISTANCE OF A PAVING MIXTURE TO COMPACTION INCREASES WITH AN INCREASE IN THE PARTICLE INDEX OF THE AGGREGATE.

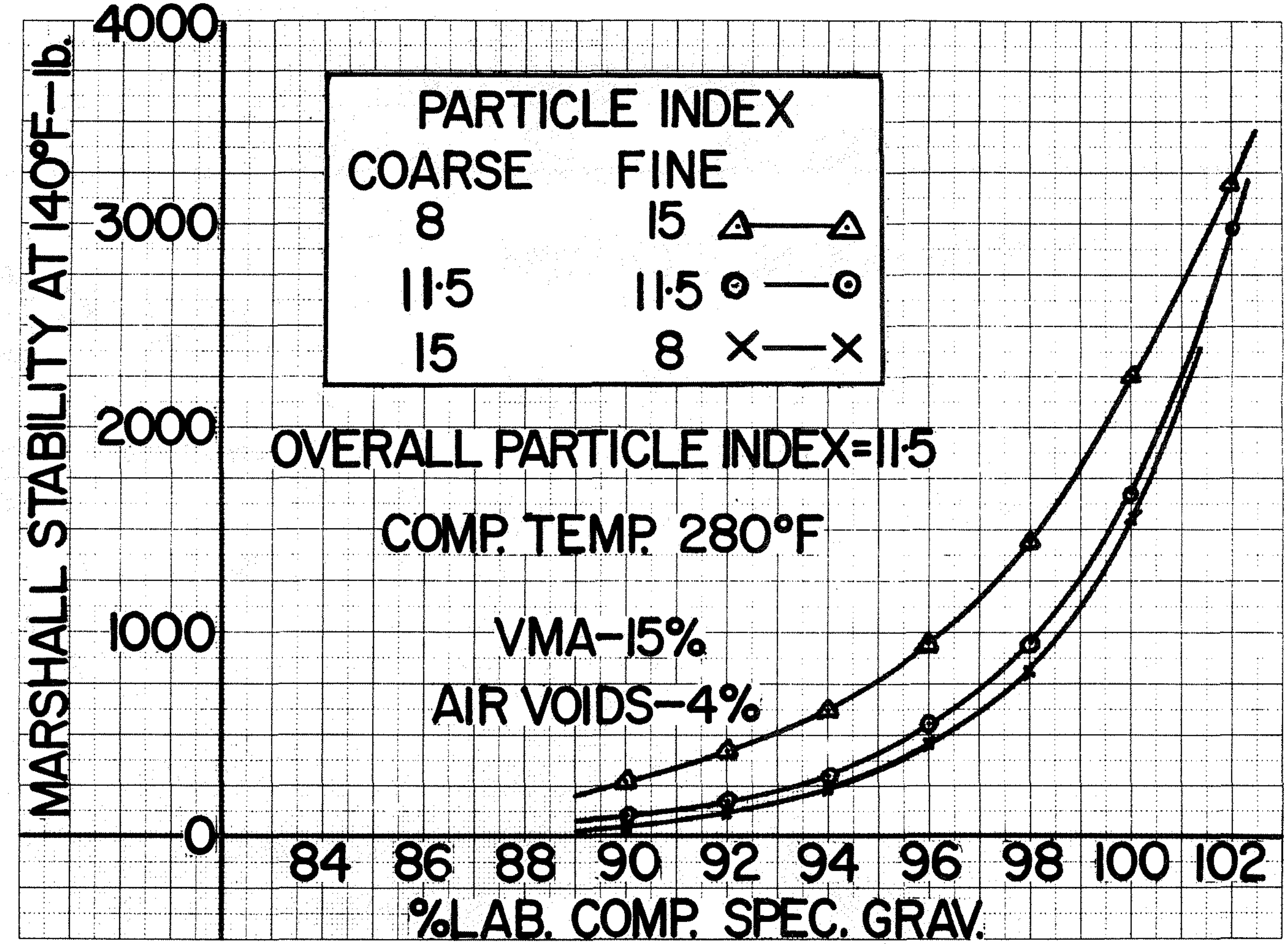

FIGURE 11 FOR A GIVEN OVERALL PARTICLE INDEX, MARSHALL STABILITY INCREASES WITH AN INCREASE IN THE PARTICLE INDEX OF THE FINE AGGREGATE.

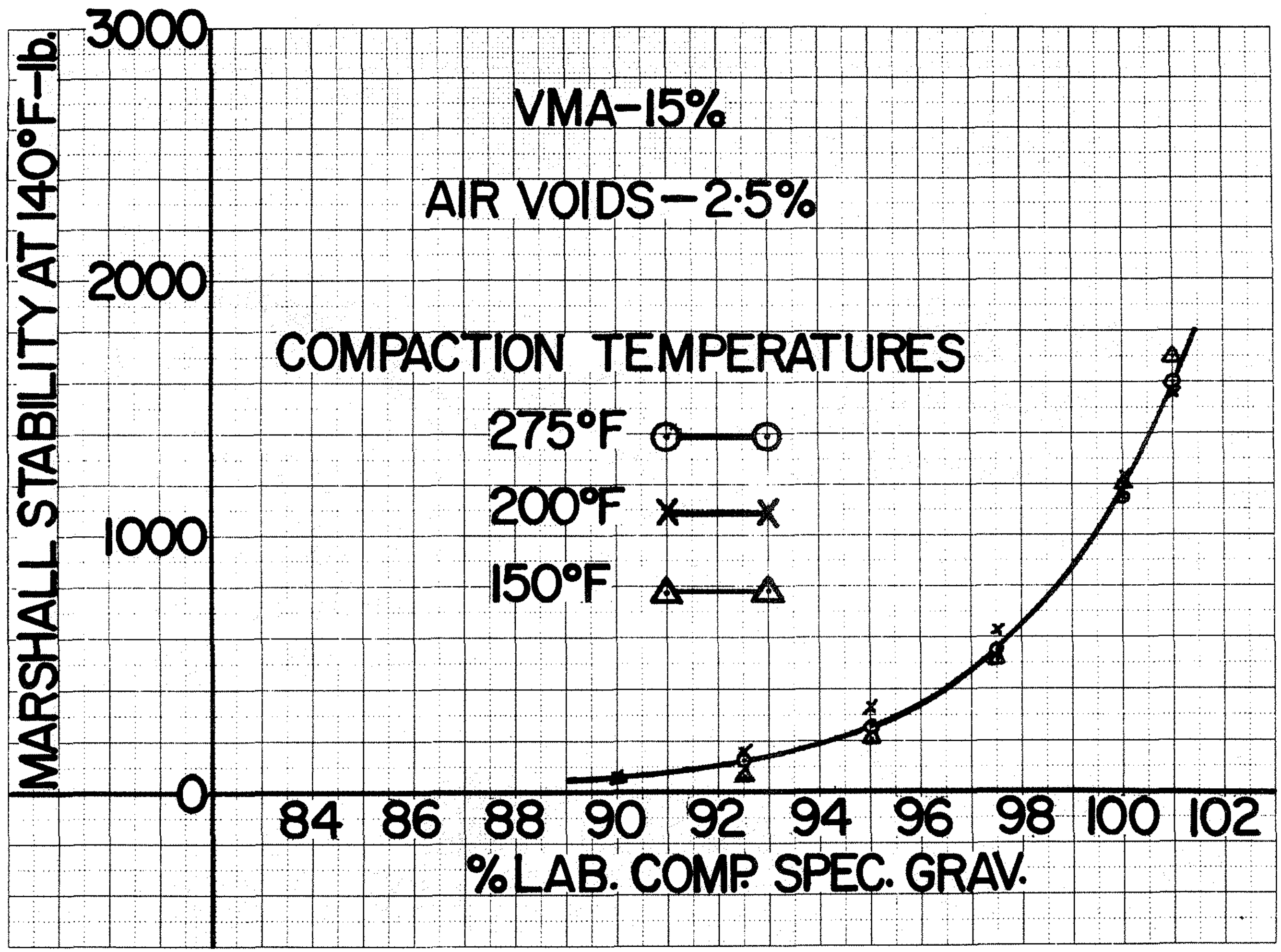

FIGURE 12 A COMMON MARSHALL STABILITY CURVE RESULTS FROM DENSITY CHANGES DUE TO DIFFERENCES EITHER IN COMPACTIVE EFFORT OR IN COMPACTION TEMPERATURE.

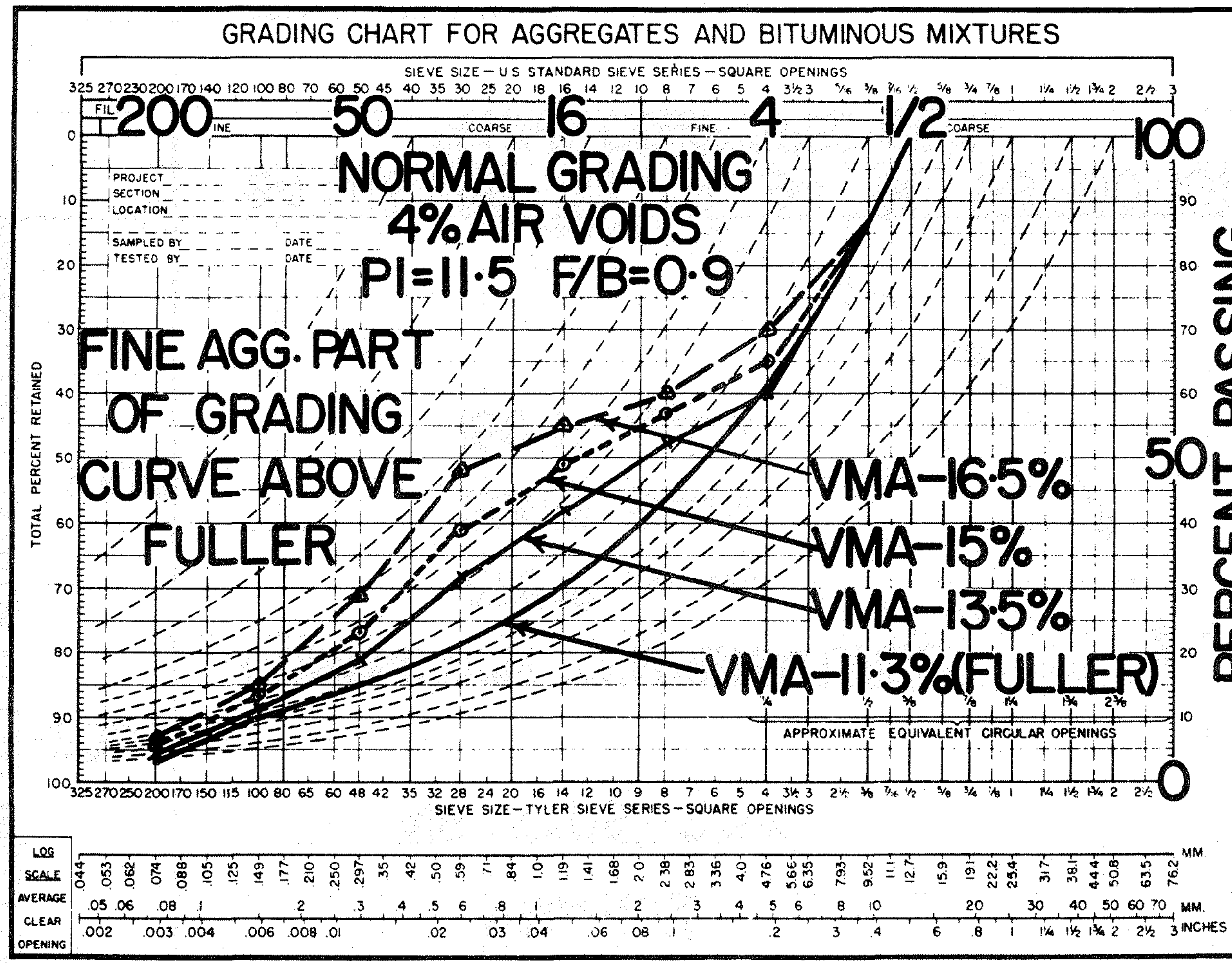

FIGURE 13 FOR CONSTANT AIR VOIDS, INCREASINGLY HIGHER VMA VALUES ARE OBTAINED BY DEVIATING THE FINE AGGREGATE PORTION OF THE GRADING CURVE INCREASINGLY FARTHER FROM THE CORRESPONDING FULLER CURVE.

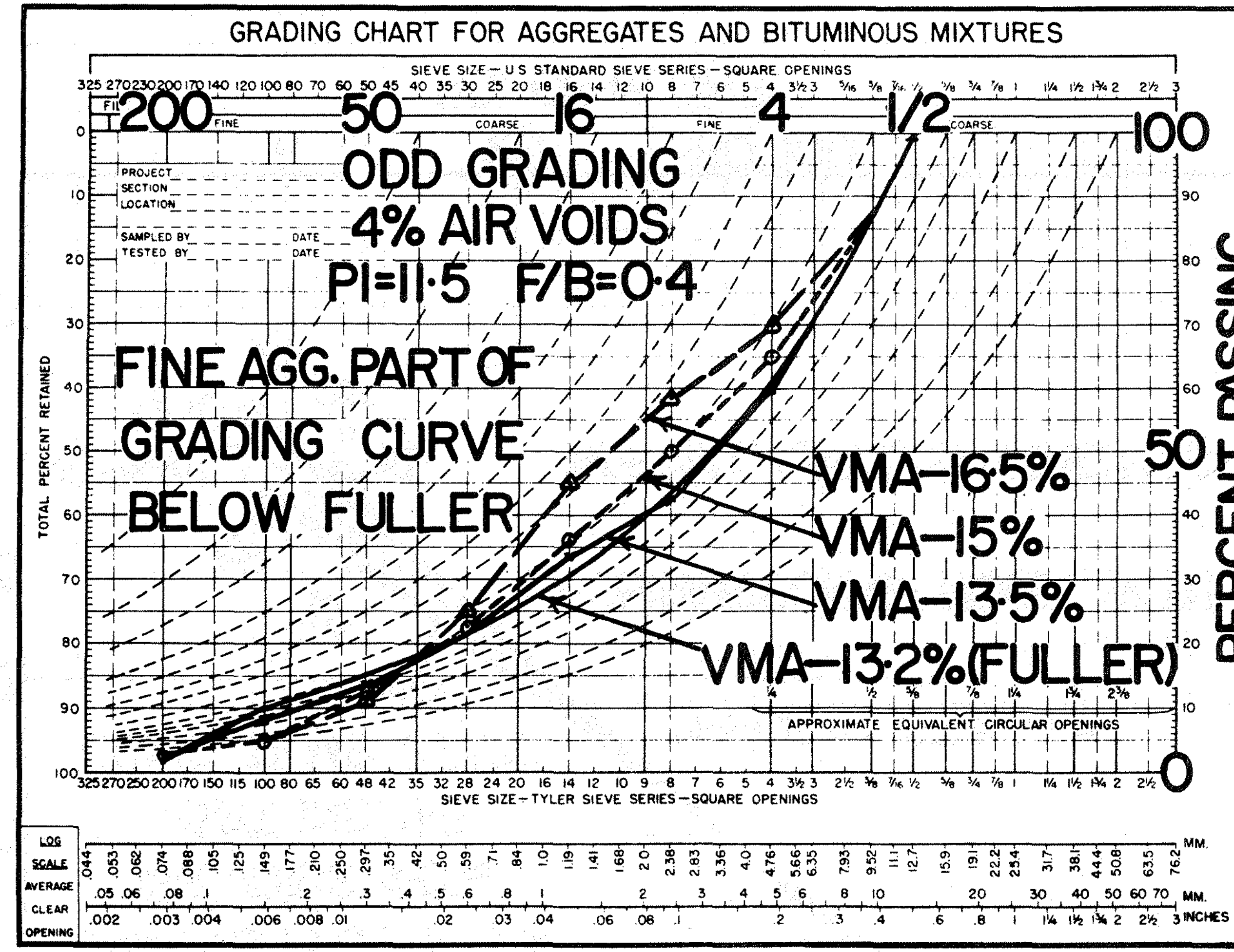

FIGURE 14 FOR CONSTANT AIR VOIDS, INCREASINGLY HIGHER VMA VALUES ARE OBTAINED BY DEVIATING THE GRADING CURVE INCREASINGLY FARTHER BOTH ABOVE AND BELOW THE CORRESPONDING FULLER CURVE.

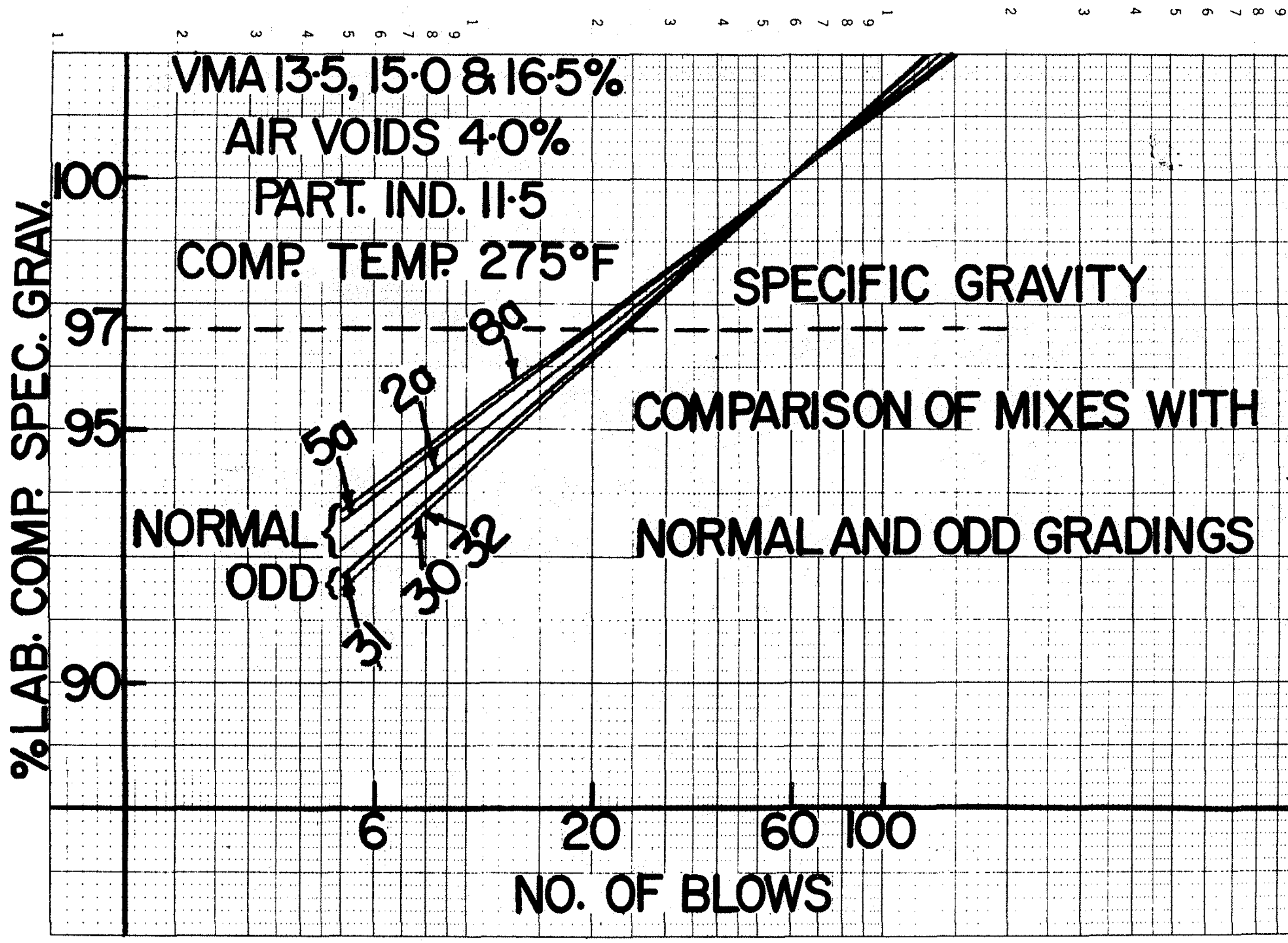

FIGURE 15 A COMPARISON OF THE SPECIFIC GRAVITIES OF PAVING MIXTURES WITH NORMAL AND ODD GRADINGS.

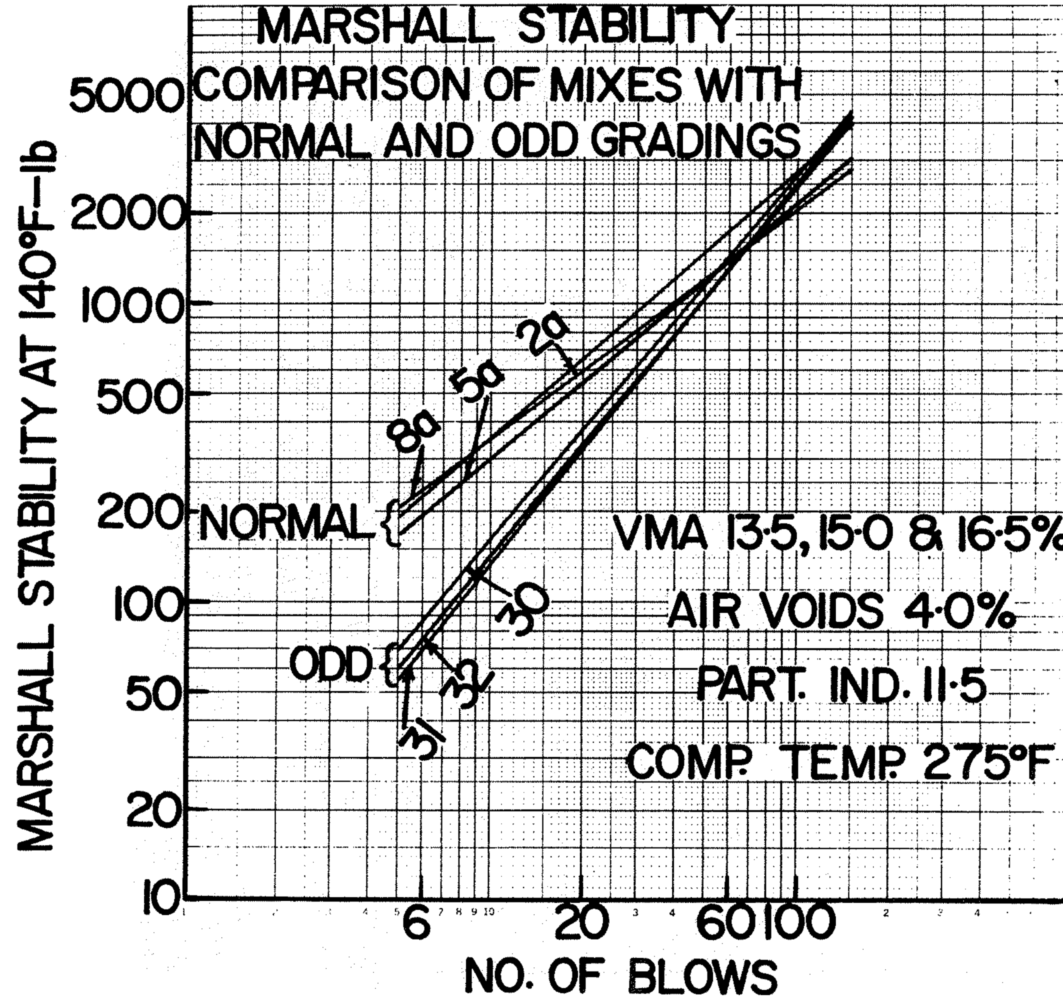

FIGURE 16A COMPARISON OF THE MARSHALL STABILITES OF PAVING MIXTURES WITH NORMAL AND ODD GRADINGS.

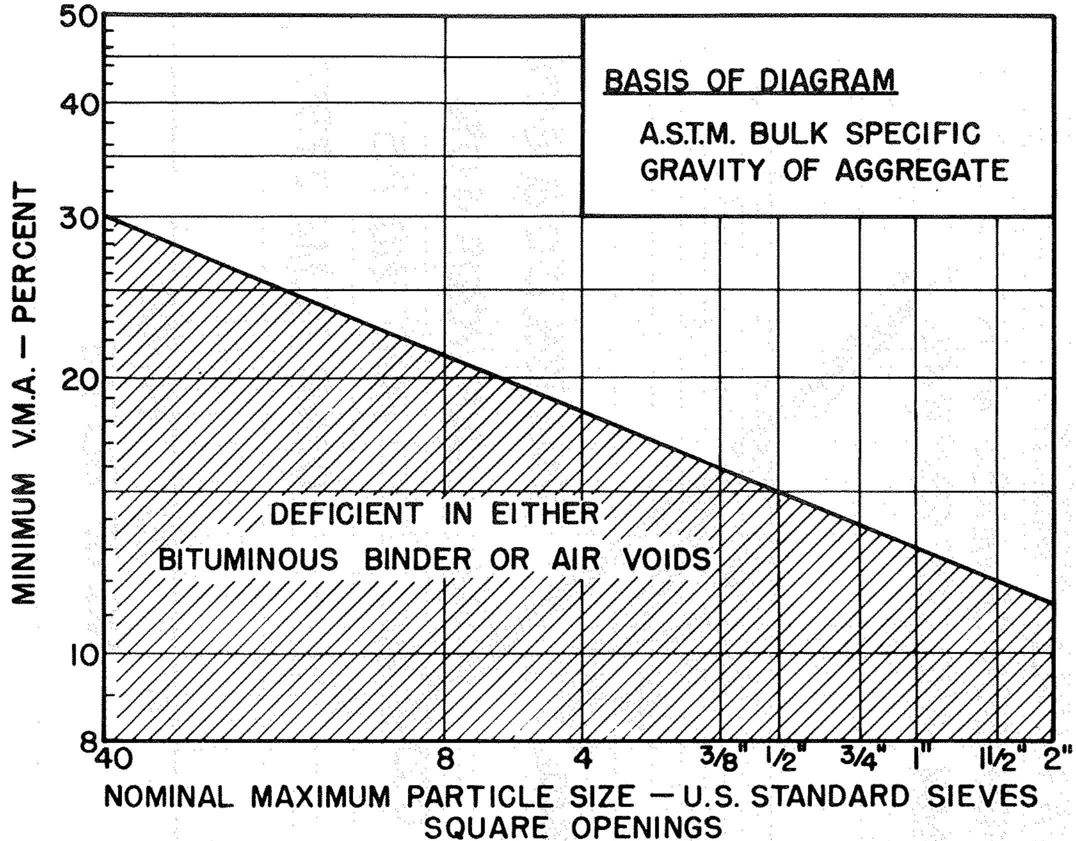

FIGURE 17 RELATIONSHIP BETWEEN MINIMUM V.M.A. AND NOMINAL MAXIMUM PARTICLE SIZE OF THE AGGREGATE FOR COMPACTED DENSE GRADED PAVING MIXTURES.

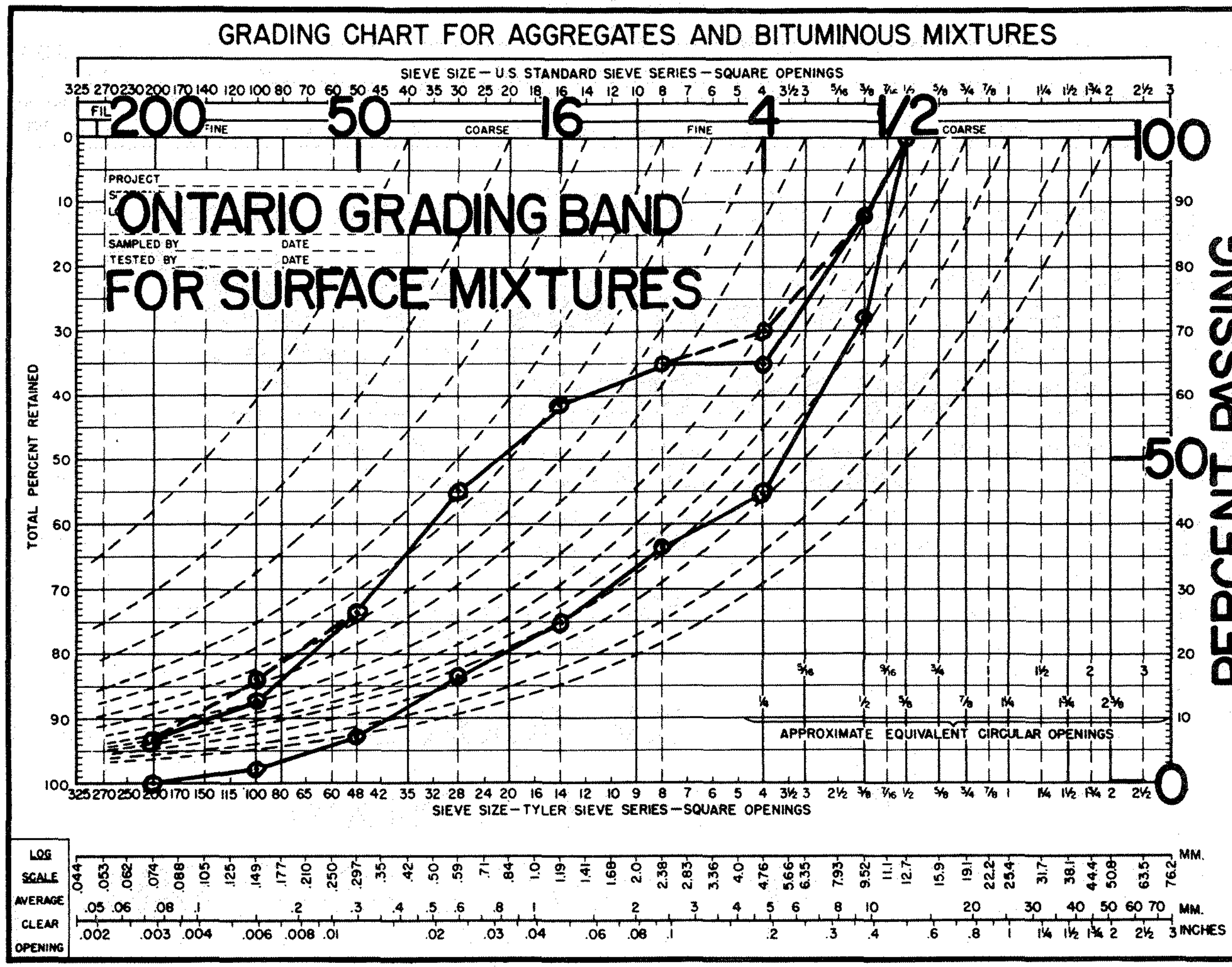

FIGURE 18 BULGE IN ONTARIO'S GRADING BANDS MAKES IT POSSIBLE TO SATISFY NORMAL VMA REQUIREMENTS.

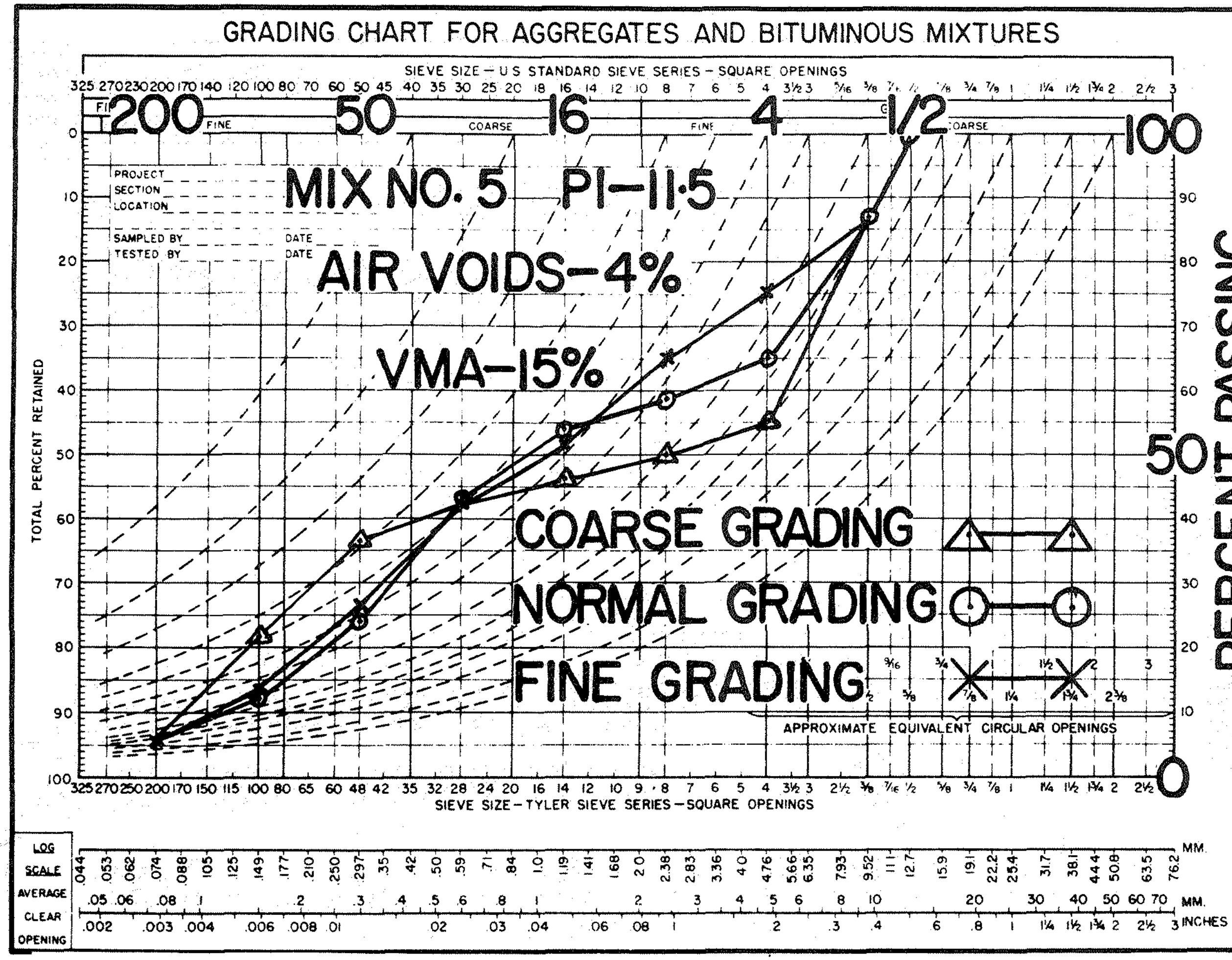

FIGURE 19 ILLUSTRATING THE INFLUENCE OF A CHANGE IN PER CENT OF COARSE AGGREGATE ON THE GRADING CURVE WHEN PI, AIR VOIDS, AND VMA ARE HELD CONSTANT.

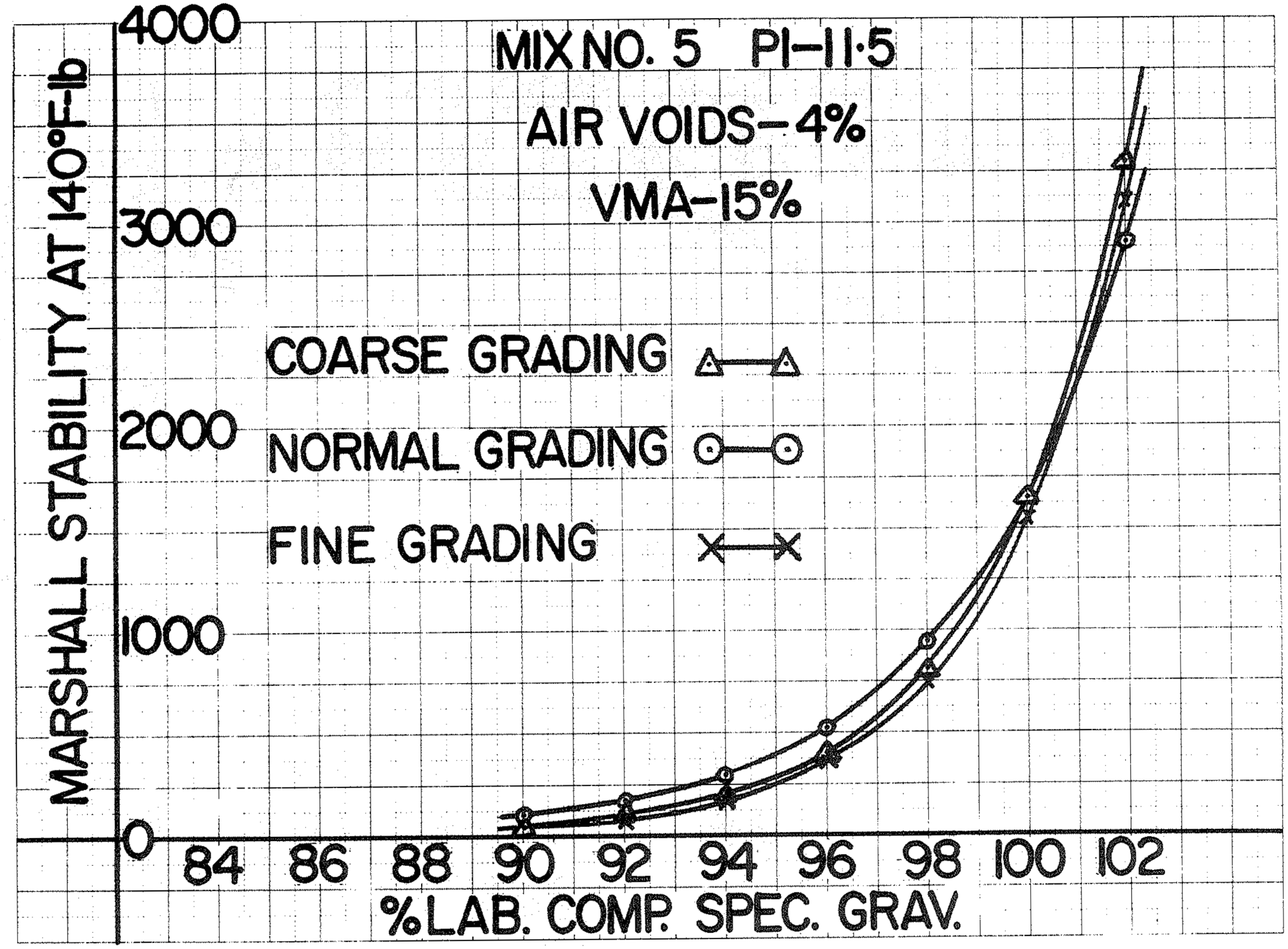

FIGURE 20 ILLUSTRATING NEGLIGIBLE INFLUENCE ON MARSHALL STABILITY DUE TO A CHANGE IN PER CENT COARSE AGGREGATE, WHEN PI, AIR VOIDS, AND VMA ARE HELD CONSTANT.

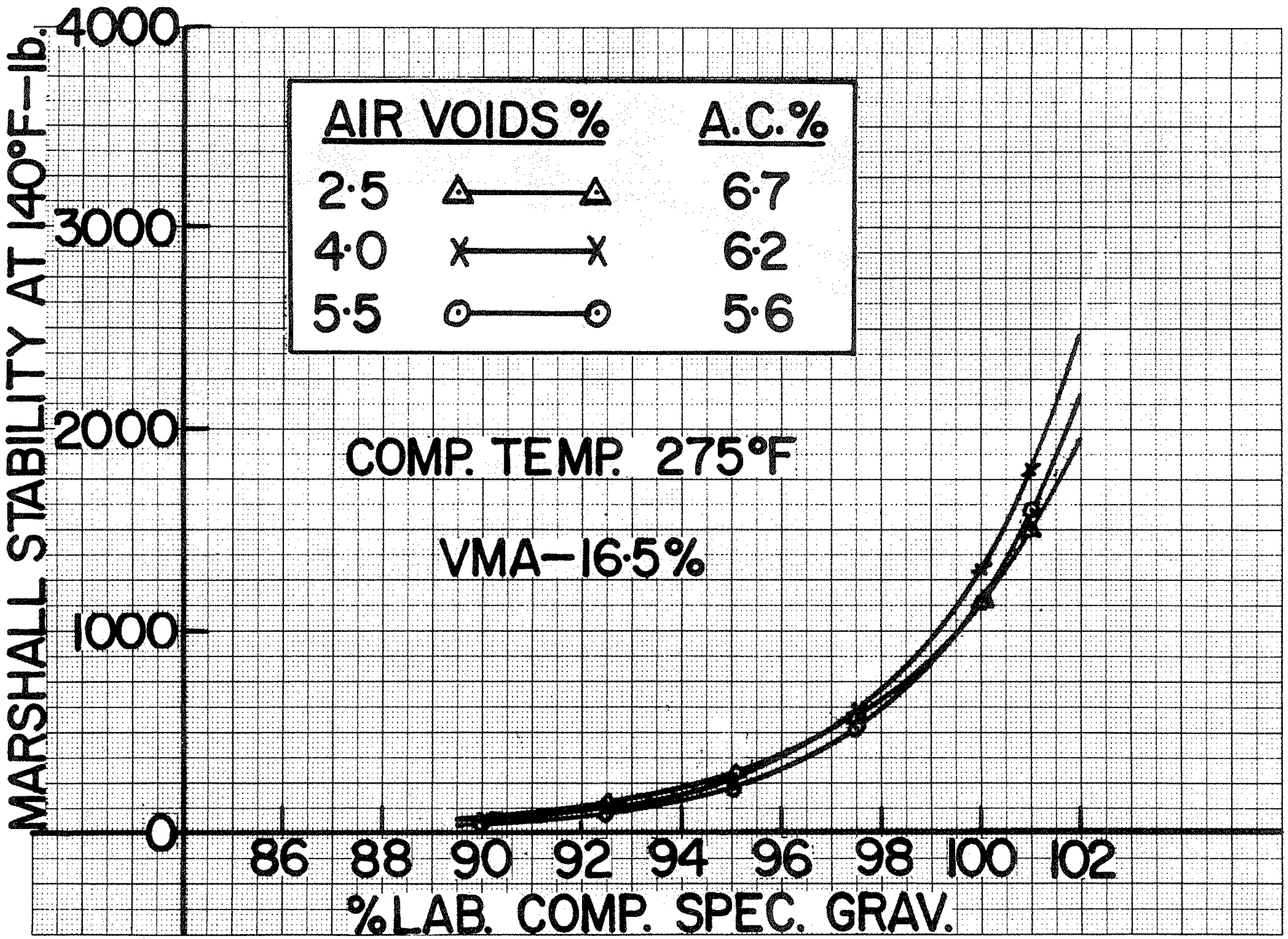

FIGURE 21 AT A CONSTANT VMA VALUE MARSHALL STABILITY IS NOT INFLUENCED BY CHANGING AIR VOIDS VALUES.

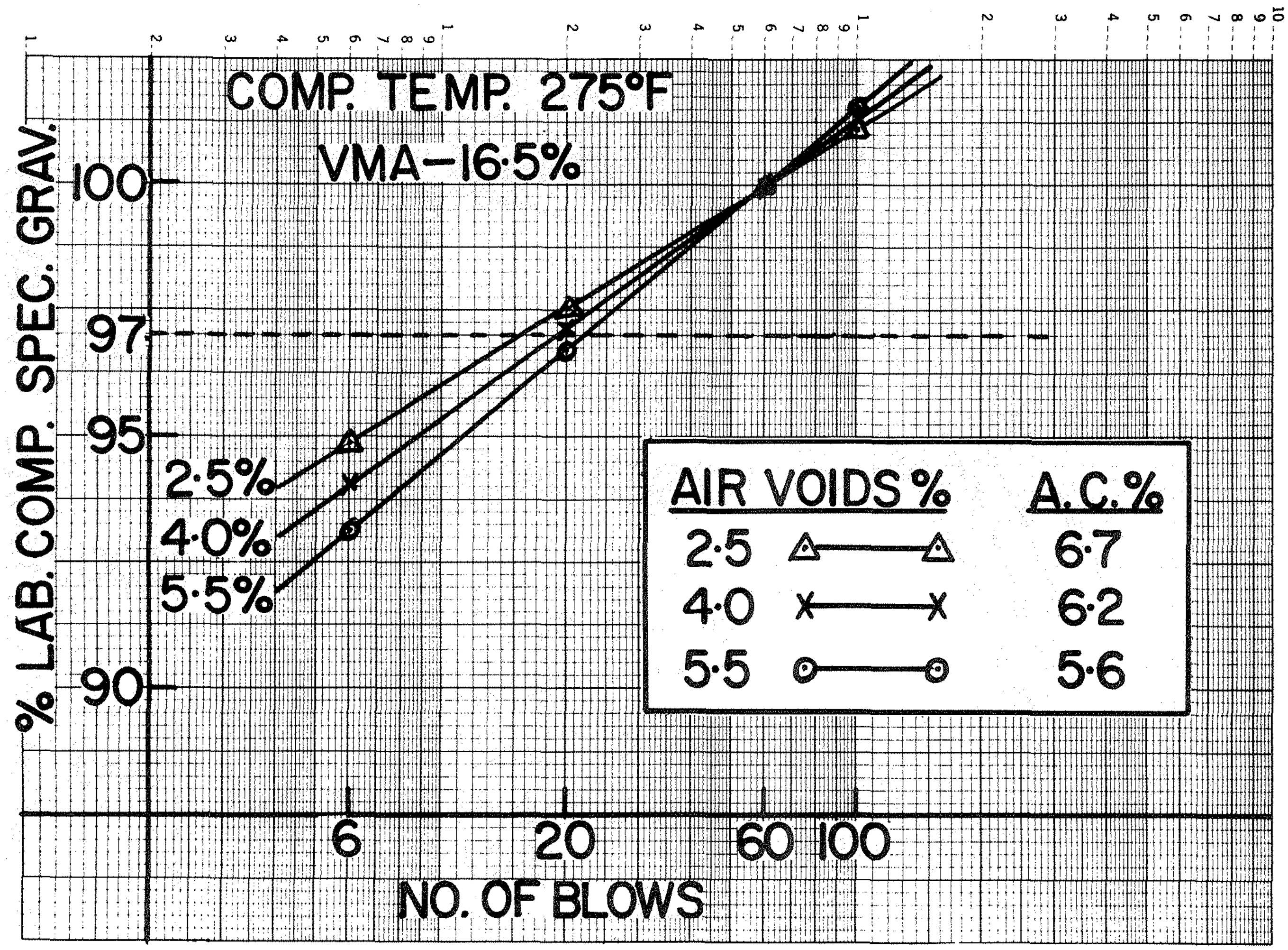

FIGURE 22 AT CONSTANT VMA VALUE EASE OF COMPACTION AT ANY GIVEN COMPACTION TEMPERATURE INCREASES WITH A DECREASE IN AIR VOIDS.

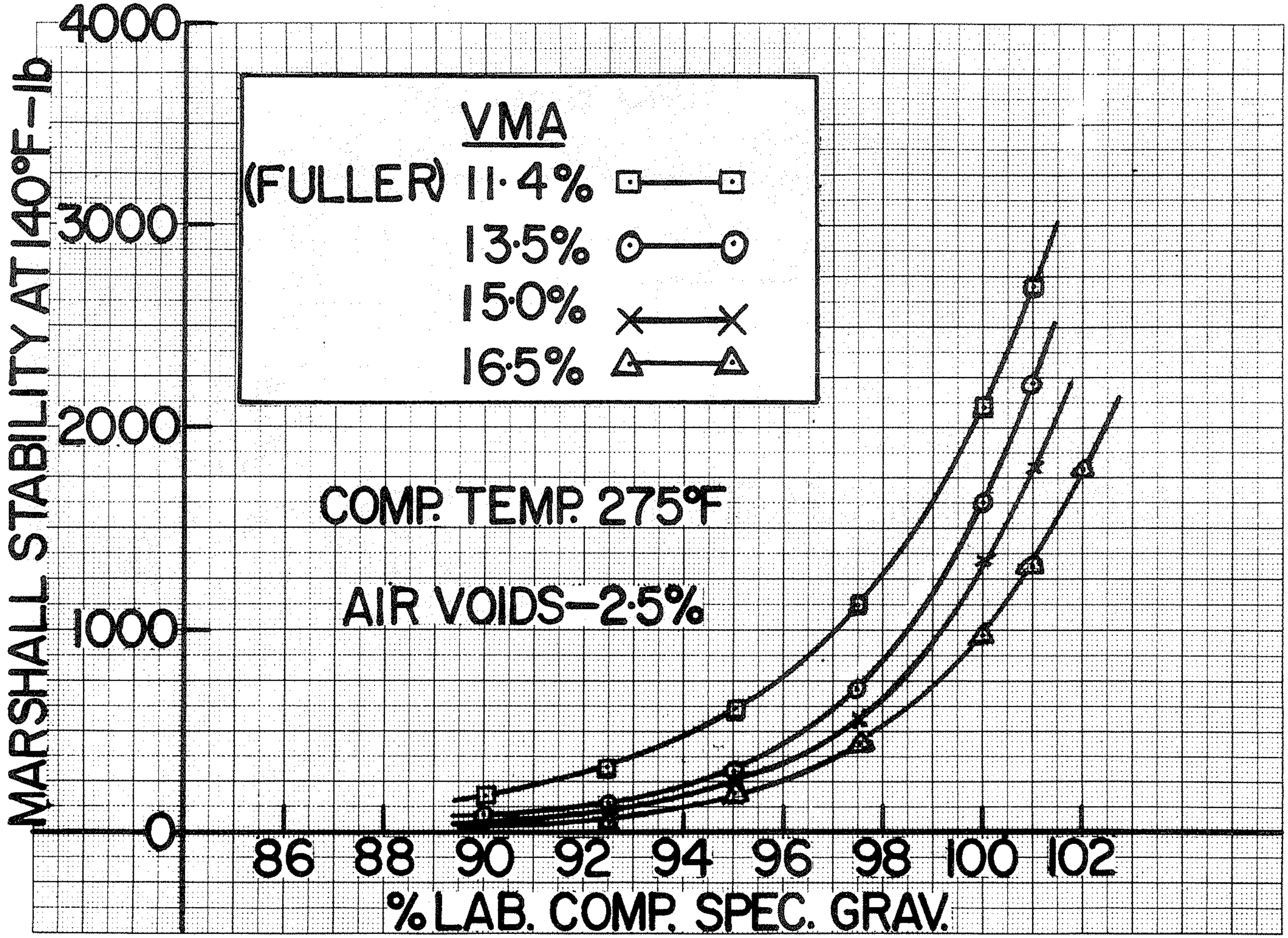

FIGURE 23 AT A CONSTANT AIR VOIDS VALUE MARSHALL STABILITY INCREASES AS VMA DECREASES.

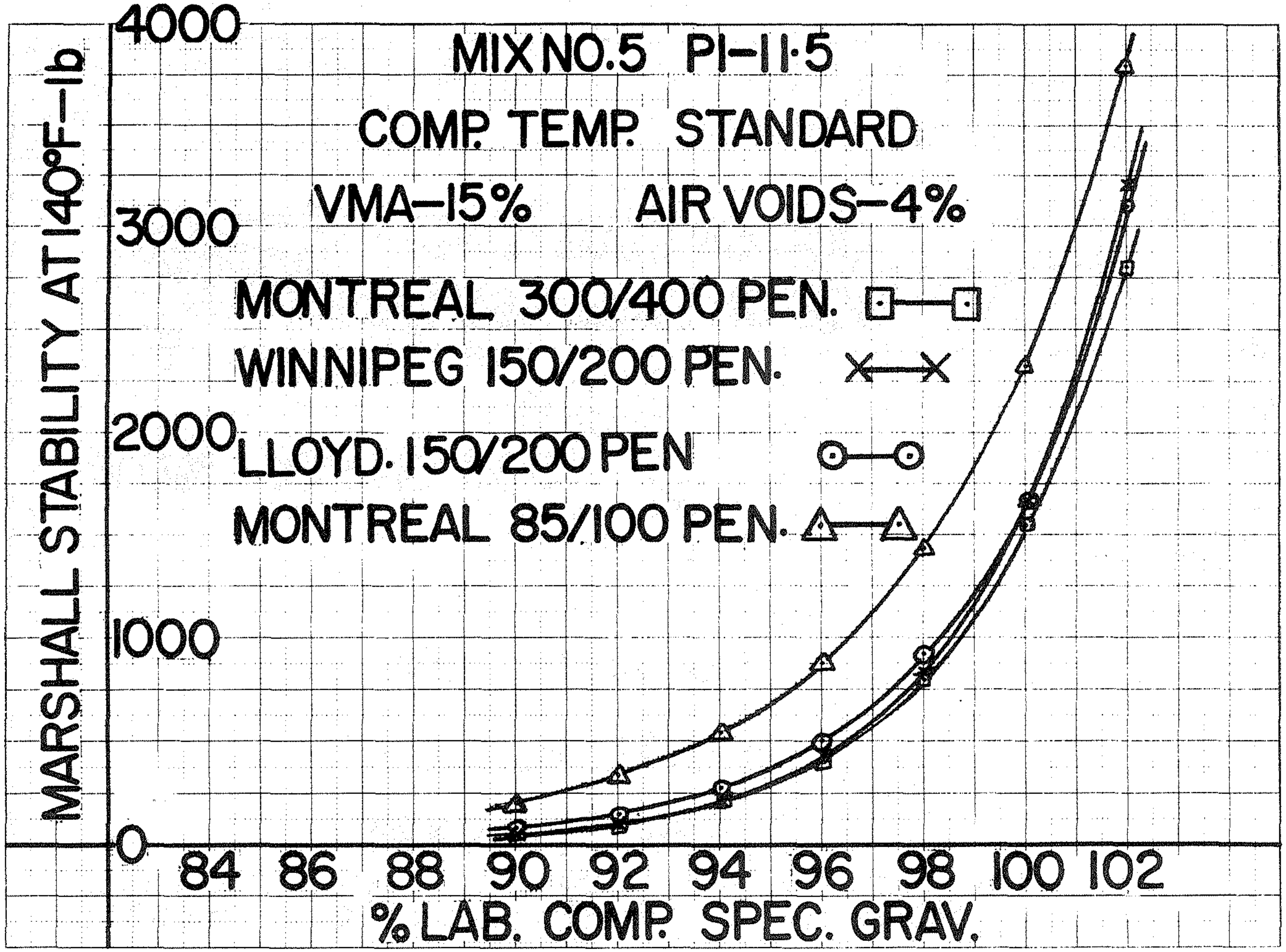

FIGURE 24 ILLUSTRATING THE INFLUENCE OF GRADE AND SOURCE OF ASPHALT CEMENT ON THE MARSHALL STABILITY OF A GIVEN PAVING MIXTURE.

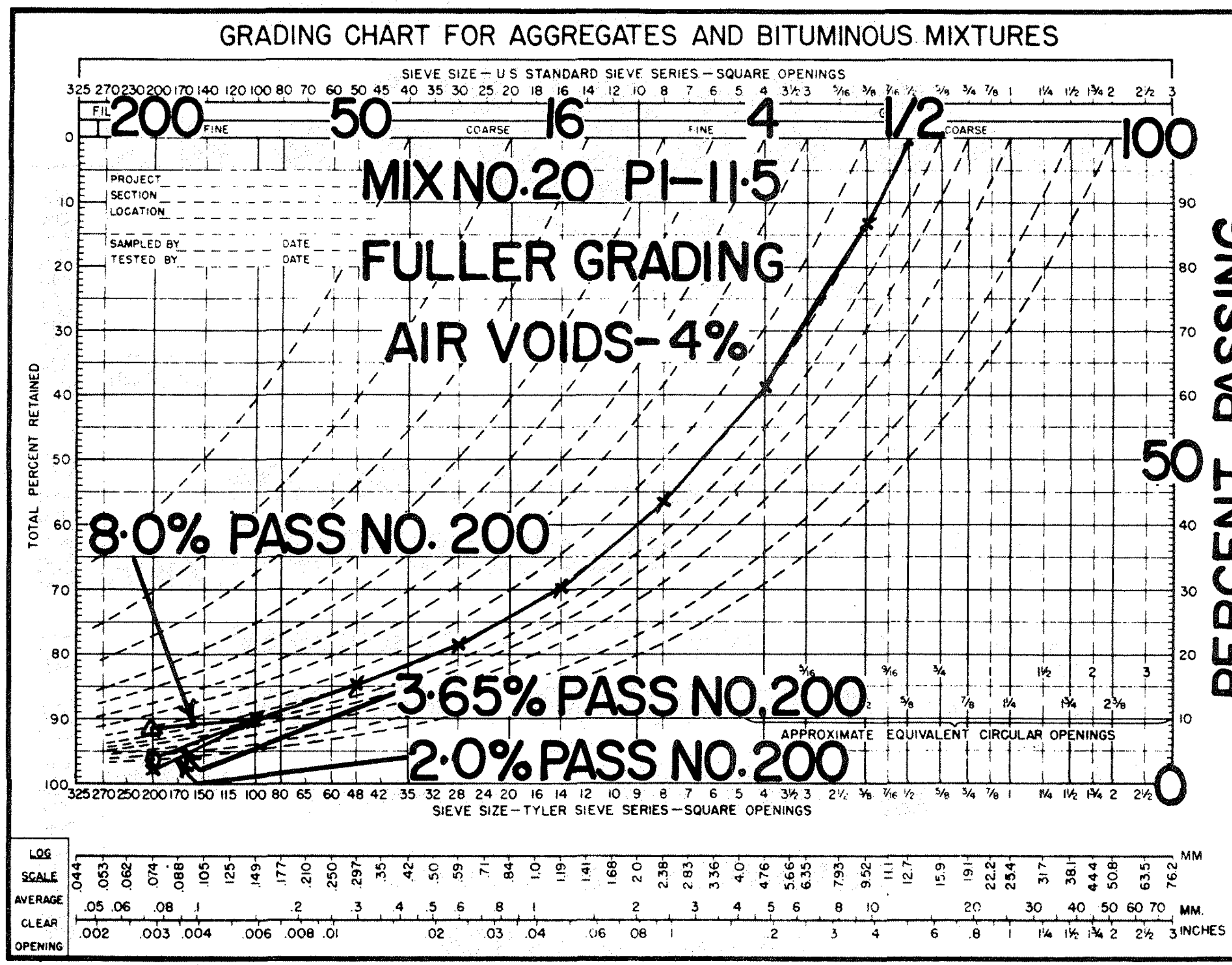

FIGURE 25 FULLER GRADING CURVES FOR VARIOUS PERCENTAGES PASSING NO. 200.

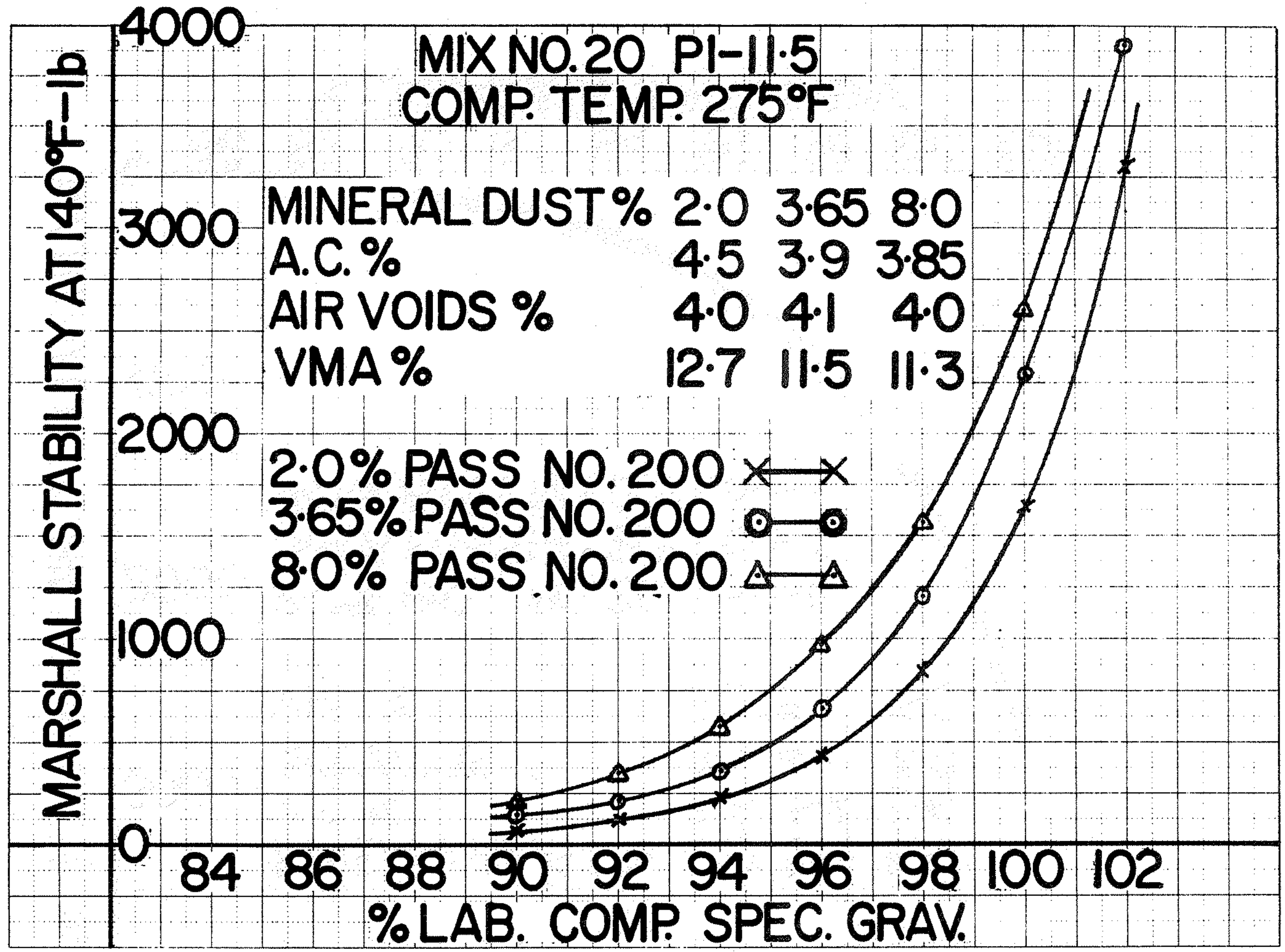

FIGURE 26 ILLUSTRATING INCREASE IN MARSHALL STABILITY WITH AN INCREASE IN PERCENT PASSING NO. 200.

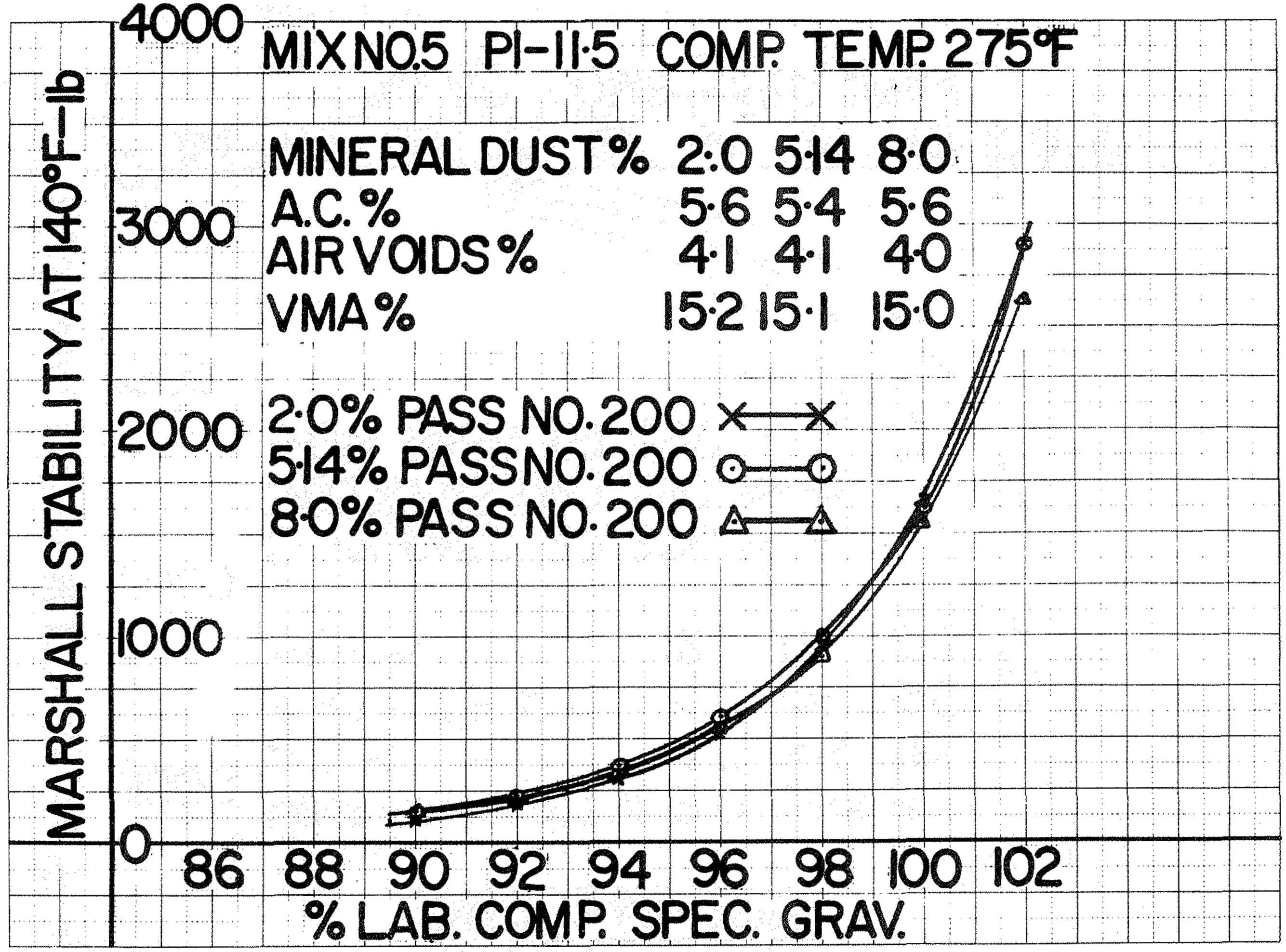

FIGURE 27 ILLUSTRATING NO INCREASE IN MARSHALL STABILITY FOR AN INCREASE IN PERCENT PASSING NO. 200.

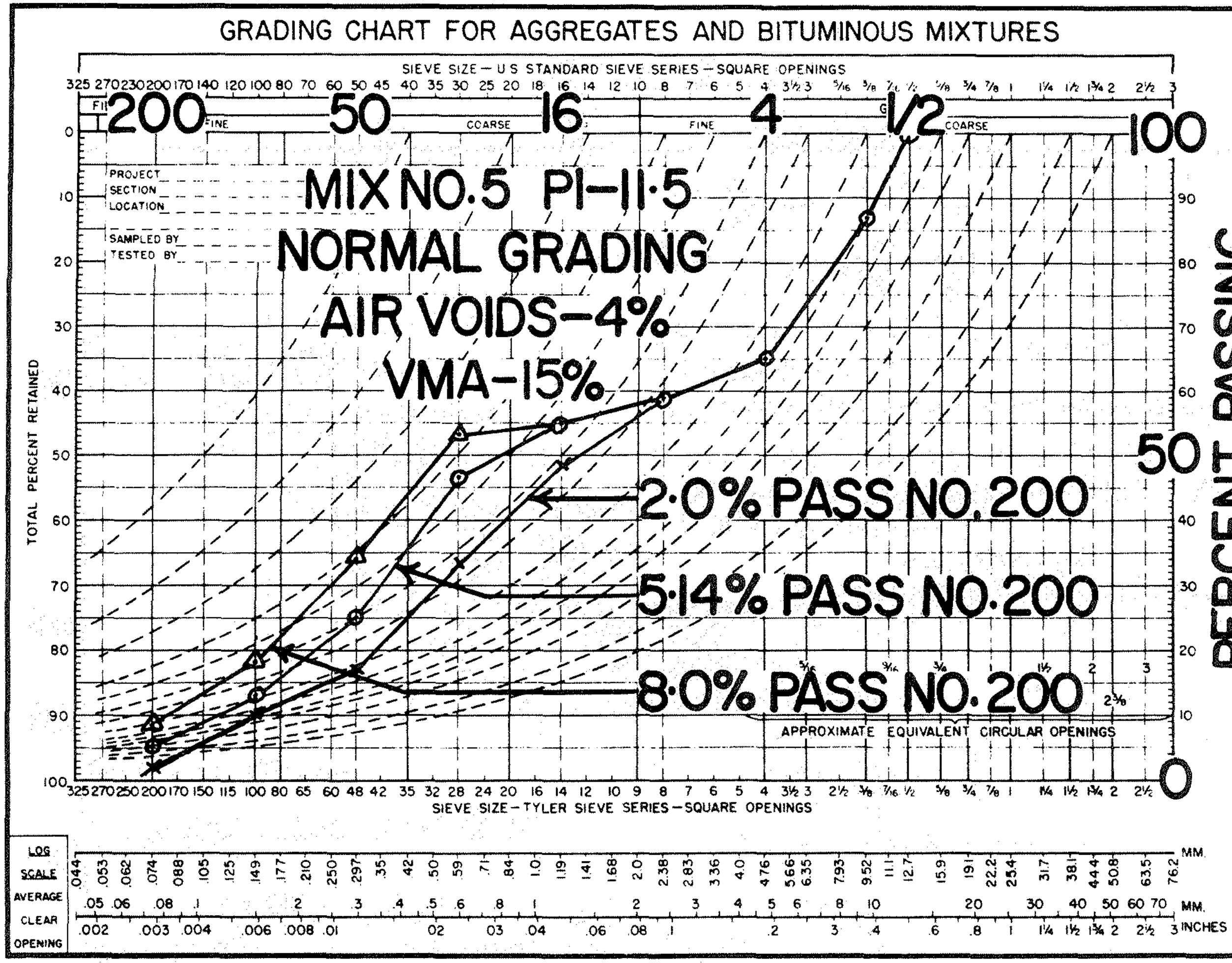

FIGURE 28 GRADING CURVES ILLUSTRATE REASON FOR NO INCREASE IN MARSHALL STABILITY FOR AN INCREASE IN PER CENT PASSING NO. 200.

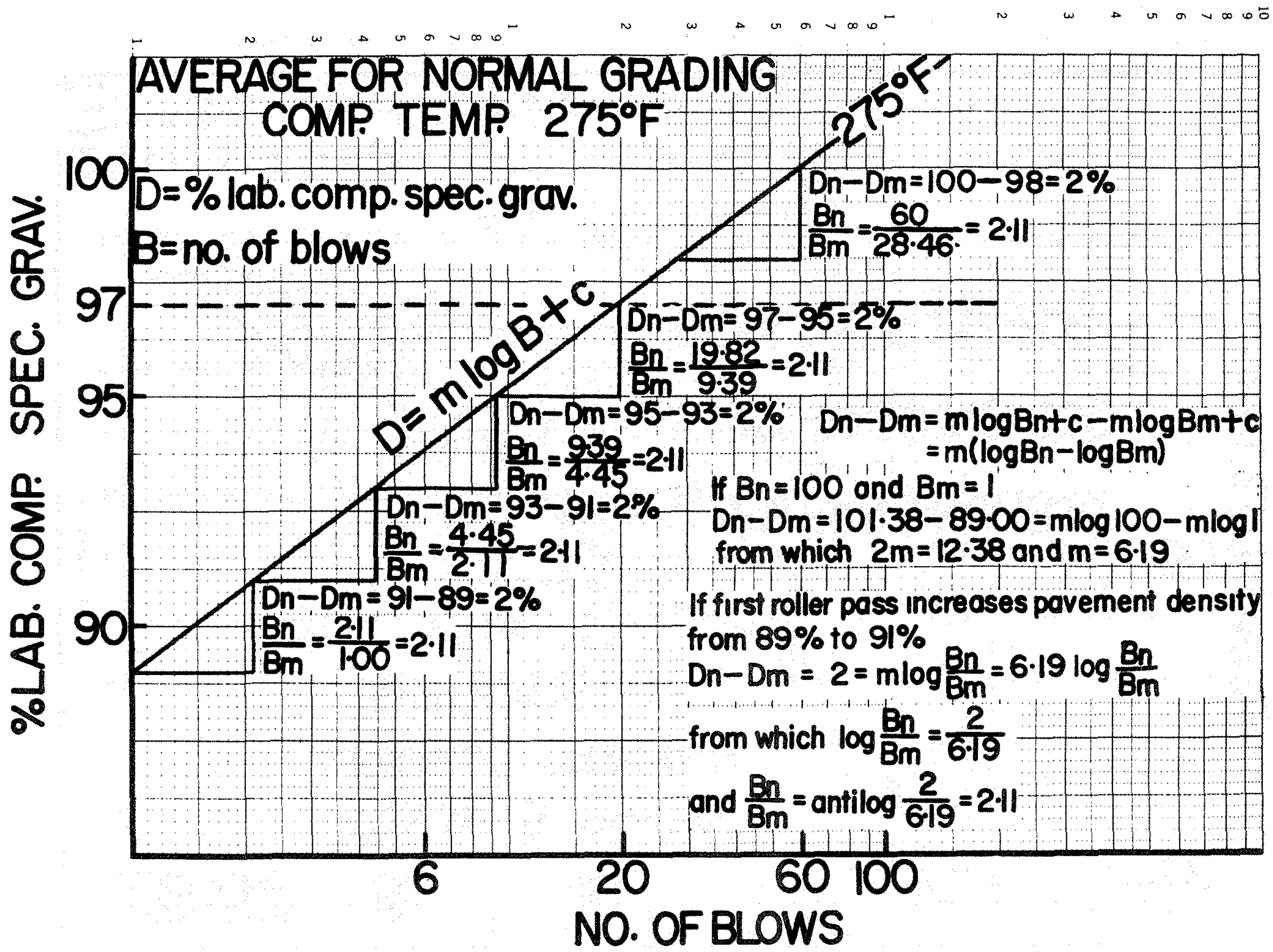

FIGURE 29 ILLUSTRATING THE MATHEMATICS OF ASPHALT CONCRETE PAVING MIXTURE COMPACTION.

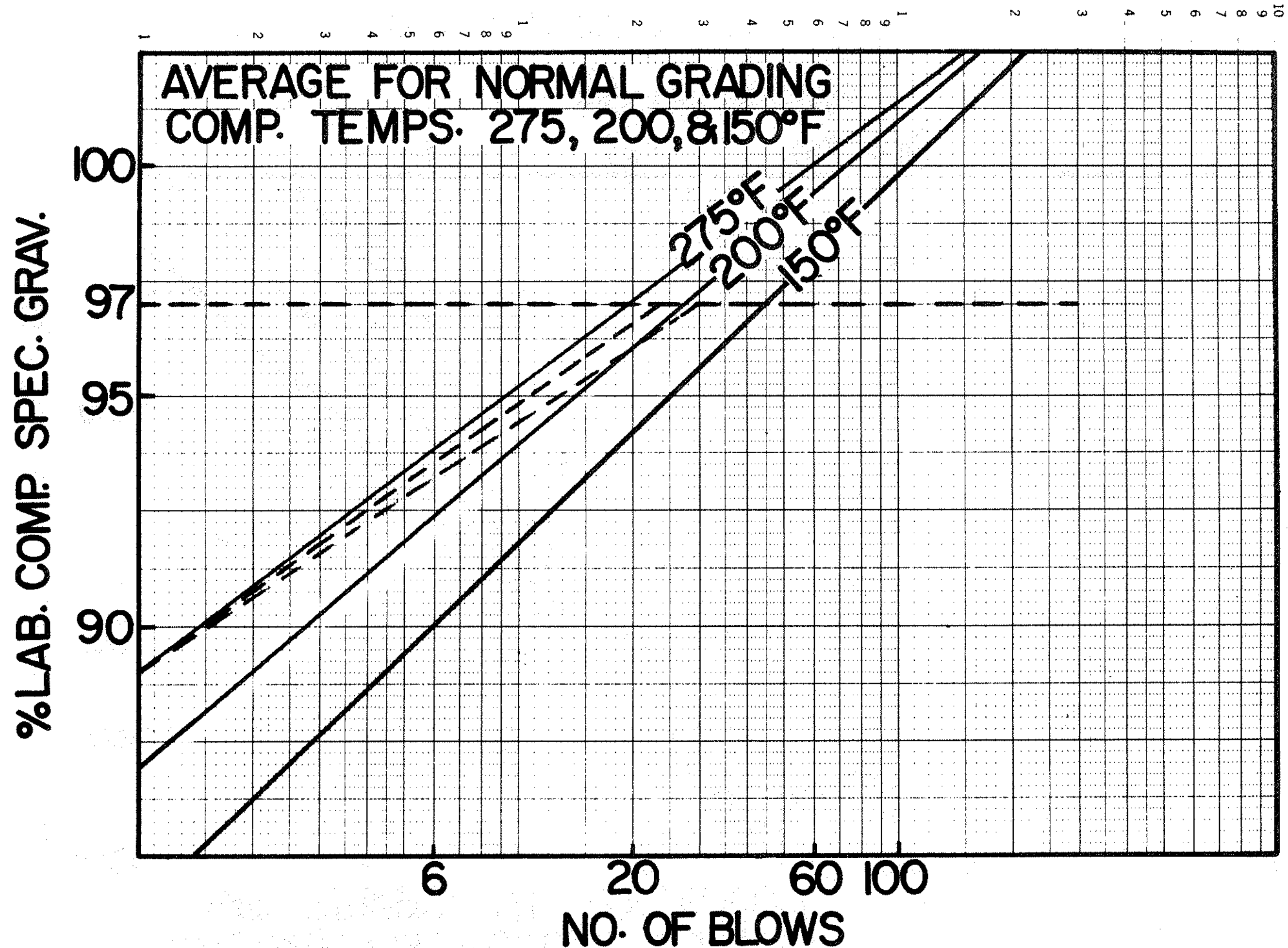

FIGURE 30 ILLUSTRATING INFLUENCE OF TEMPERATURE RANGE EMPLOYED FOR COMPACTION OF A PAVING MIXTURE ON THE COMPACTIVE EFFORT REQUIRED FOR AVERAGE NORMAL GRADING.

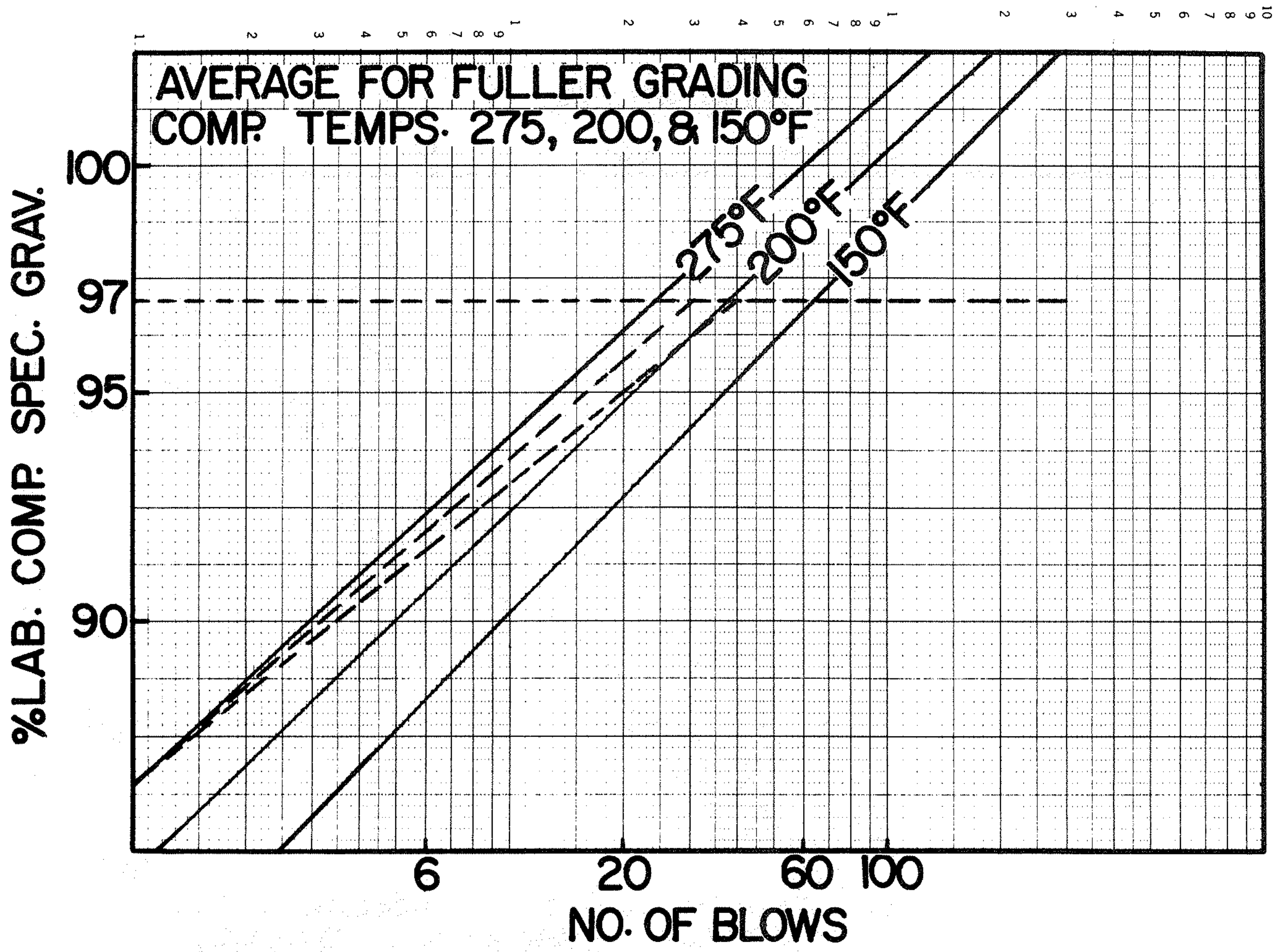

FIGURE 31 ILLUSTRATING INFLUENCE OF TEMPERATURE RANGE EMPLOYED FOR COMPACTION OF A PAVING MIXTURE ON THE COMPACTIVE EFFORT REQUIRED FOR FULLER GRADING.

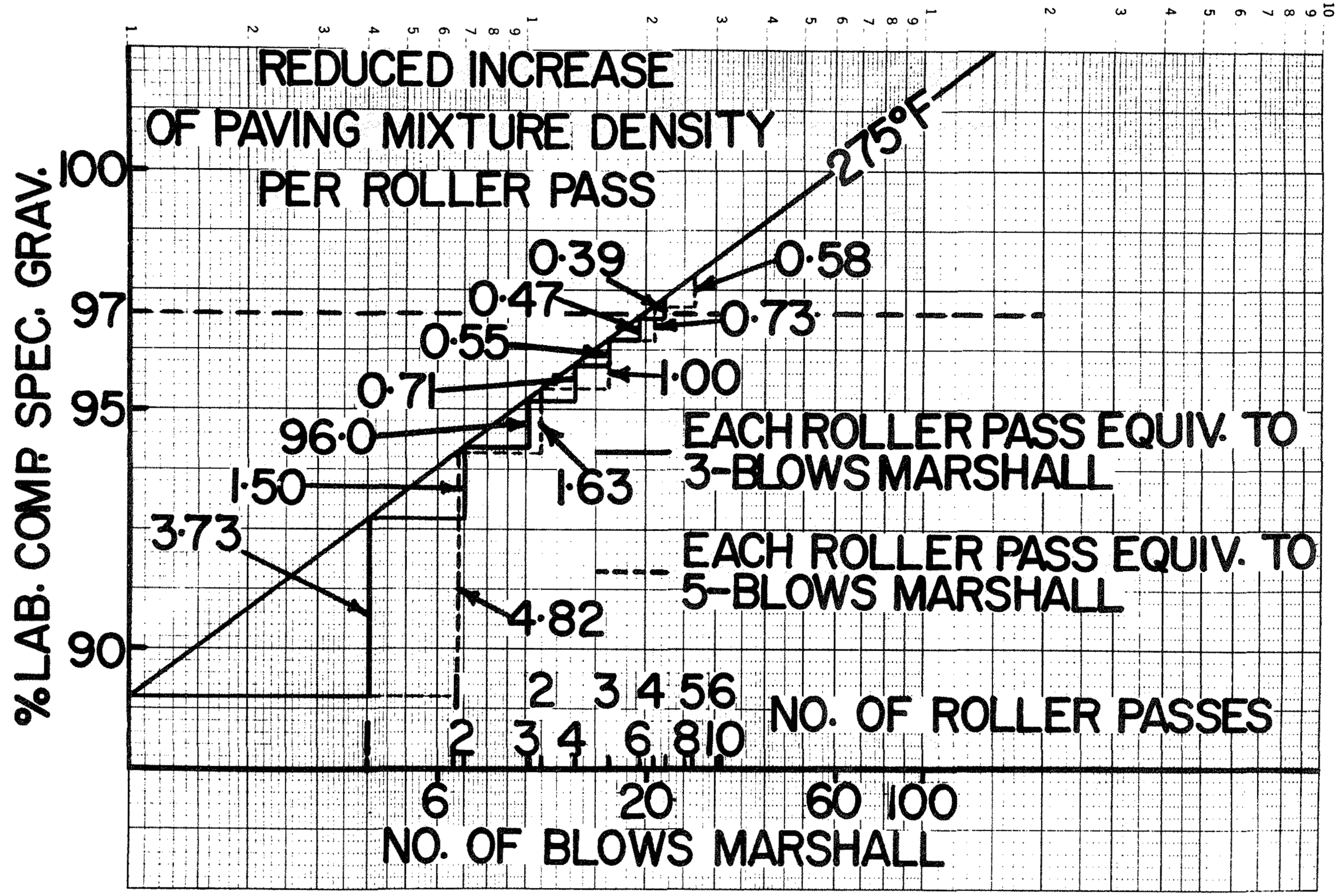

FIGURE 32 RAPID REDUCTION OF PERCENT INCREASE IN PAVING MIXTURE DENSITY FOR SUCCESSIVE ROLLER PASSES.

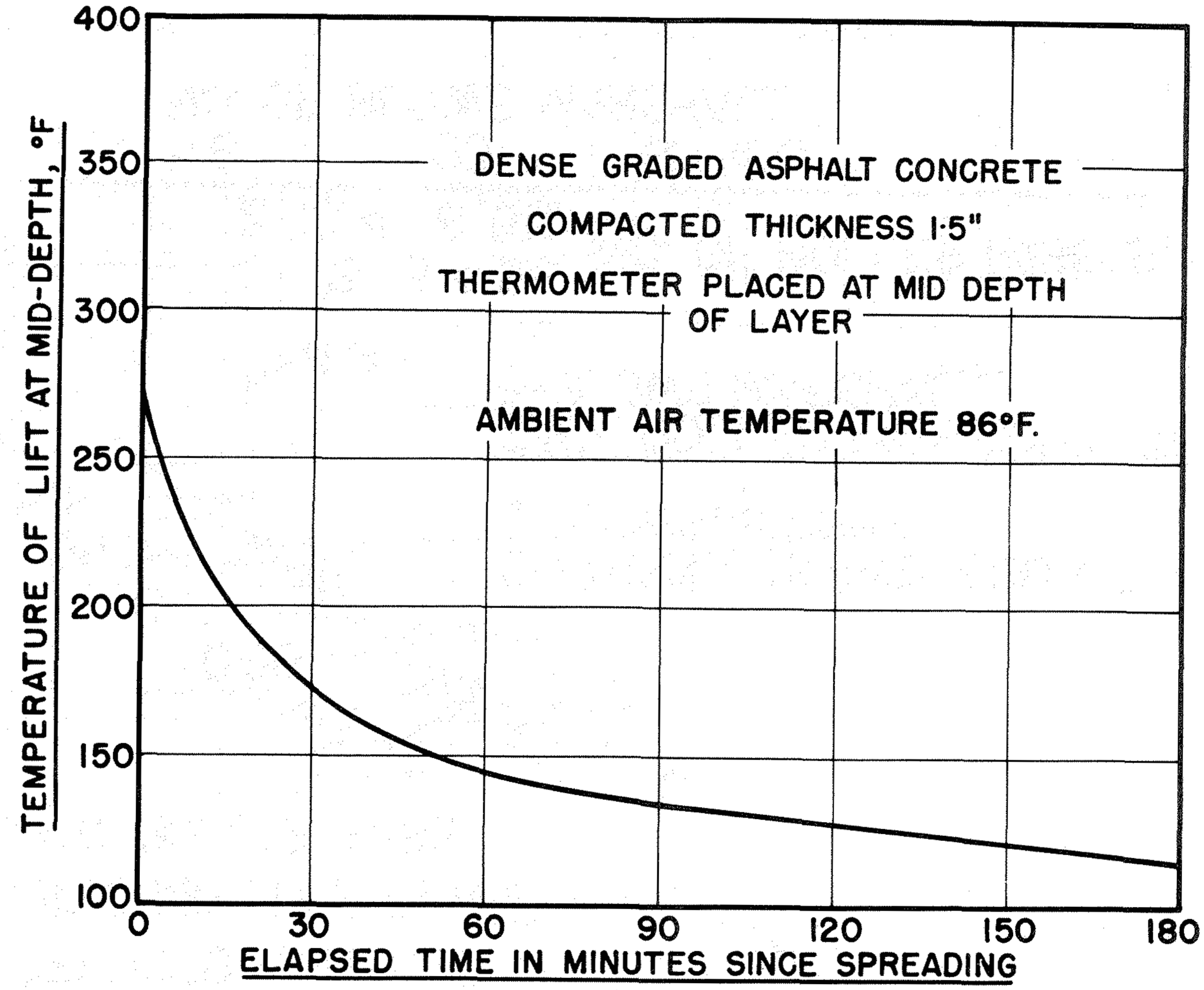

FIGURE 33 COOLING RATE OF HOT MIX BEHIND SPREADER ON A WARM DAY.

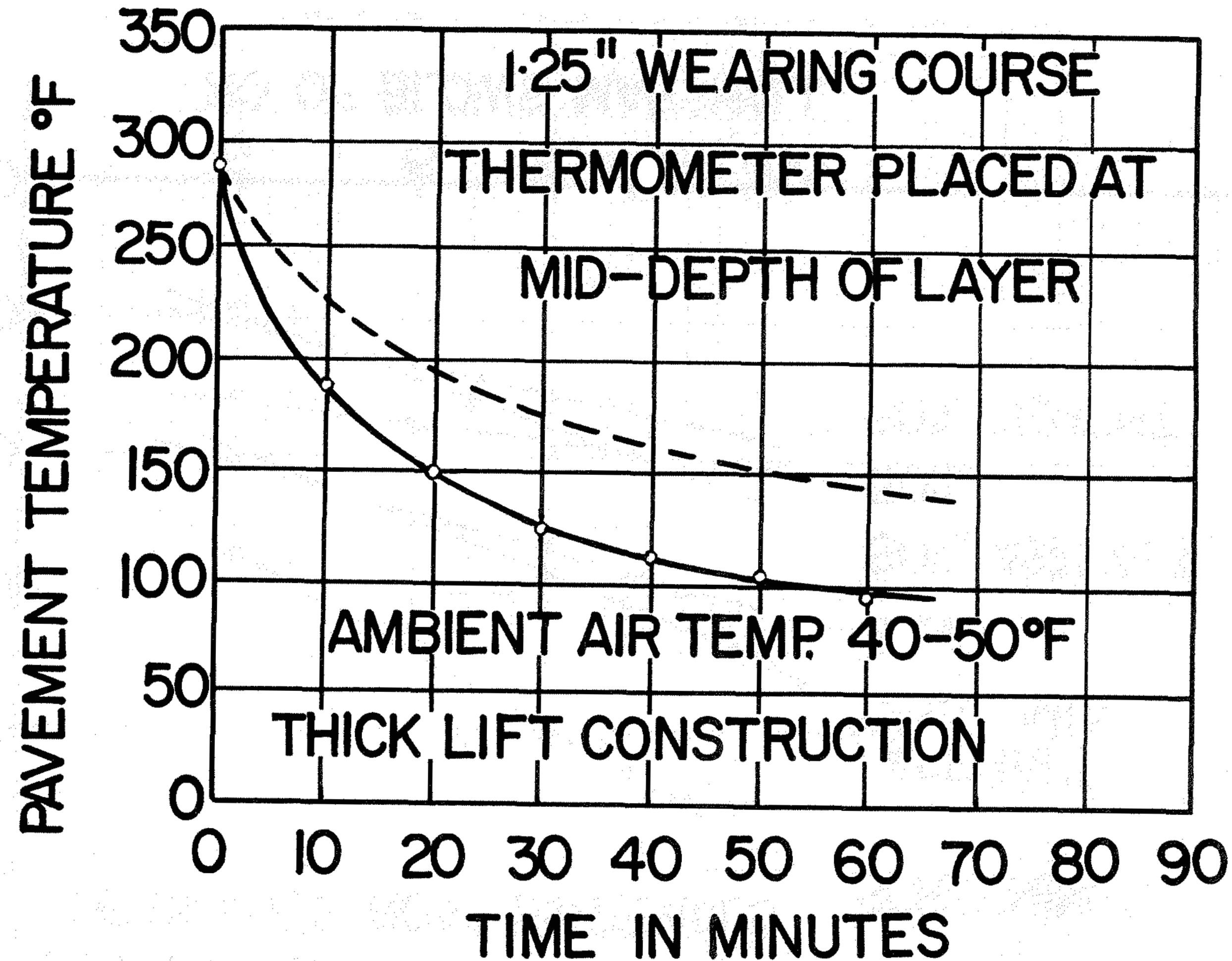

FIGURE 34 COOLING RATE OF HOT MIX BEHIND SPREADER ON A COOL DAY.

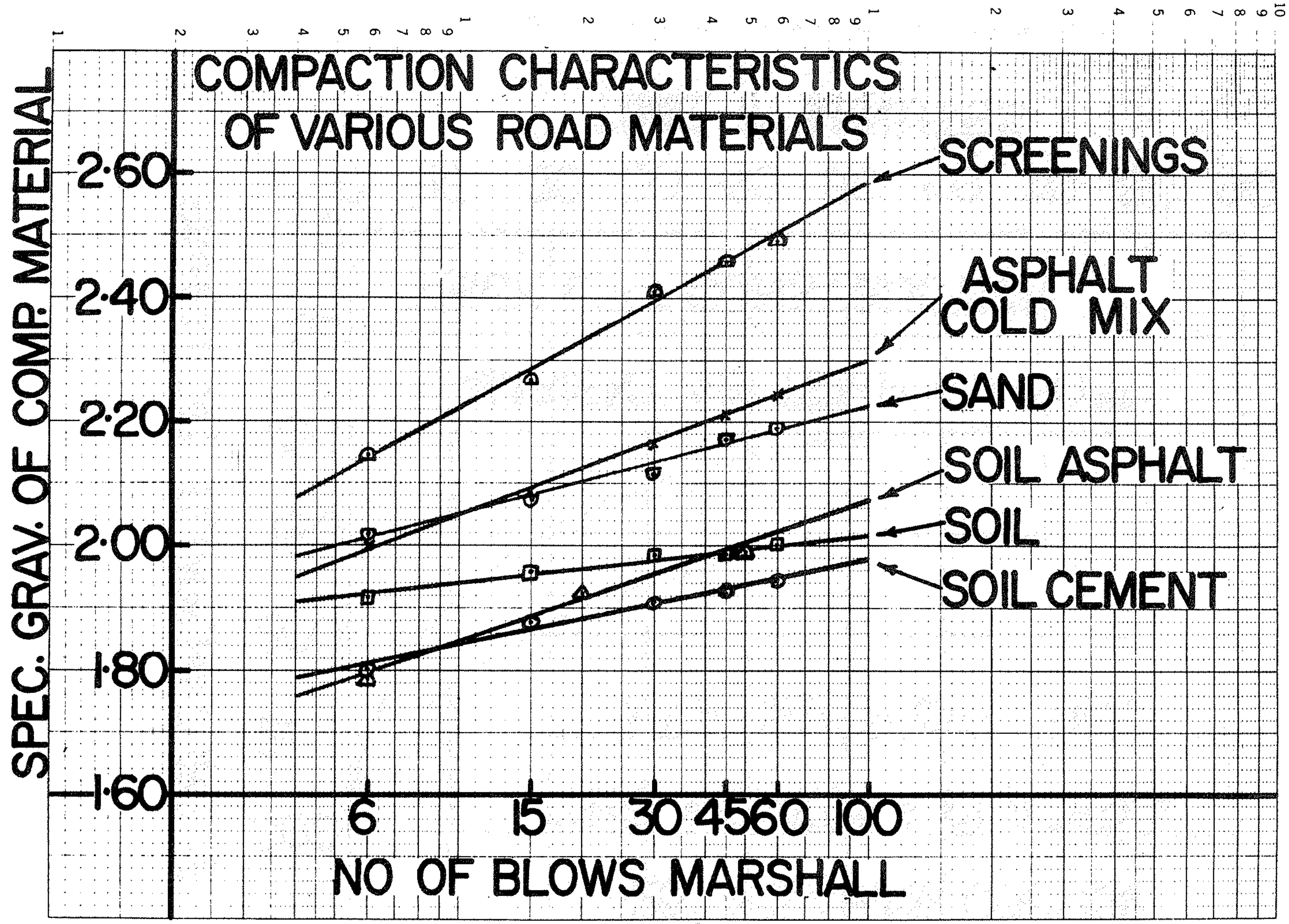

FIGURE 35 ILLUSTRATING COMPACTION CHARACTERISTICS OF VARIOUS ROAD BUILDING MATERIALS.