

# Designing Standard Asphalt Paving Mixtures for Greater Durability

By NORMAN W. McLEOD\*

## ABSTRACT

The asphalt contents of current asphalt paving mixtures are limited by two principal factors, one economic, the other technical. Asphalt cement in North America costs from ten to twenty times as much per ton as aggregates, leading to a tendency to restrict the quantity of asphalt employed for paving mixtures. This is the economic factor. The technical factor pertains to the shape and narrowness of the grading bands that it has become traditional to employ. These grading bands limit the VMA values of paving mixtures and this in turn limits the amount of asphalt cement that can be incorporated into asphalt paving mixtures. These restricted asphalt contents result in less durable asphalt pavements with shortened service lives, higher than necessary maintenance costs, and the development of numerous potholes, particularly during the thaw period in late winter and early spring in colder climates.

This less than perfect pavement service performance has opened the door to the promotion of expensive special paving mixtures containing rubber, asbestos, etc., that are claimed to avoid these pavement service faults. For example, promotion of the use of fine asbestos fibre is based on the principle that this will enable pavements with from one to two per cent more asphalt to be employed. This in turn provides more durable pavements. Because our more affluent society is less tolerant of pavement imperfections, many public agencies have been willing to use these expensive special types of paving mixtures to satisfy the demand for improved pavement performance.

This paper demonstrates that it is not necessary to employ these special expensive paving mixtures to obtain greater pavement durability, lower pavement maintenance, and longer service lives. By simply increasing the current minimum VMA requirements through adjustment of the permissible aggregate grading bands, standard asphalt paving mixtures can be designed with much higher asphalt contents which will provide greater durability and substantially lengthened service lives.

The paper indicates that the VMA value of a paving mixture can be greatly increased by blending the coarse and fine aggregates in proportions that provide a grading curve that has been made to deliberately deviate away from the corresponding Fuller curve.

At constant air voids values, the influence of VMA value on the average thickness of the asphalt film coating the aggregate particles, measured in microns (0.001 mm), is demonstrated for eight surface course and four base courses since pavement durability is related to average asphalt film thickness.

The ratios of these actual asphalt film thicknesses versus the standard asphalt film thicknesses associated with normal paving mixtures containing aggregates of the same surface areas in square feet per pound, for example curve 5 in Figure 17, increase with an increase in VMA. This demonstrates that at least for properly designed paving mixtures, pavement durability can

\*Norman W. McLeod, Vice President and Asphalt Consultant, McAsphalt Engineering Services, Toronto, Ontario, Canada.

be expected to increase with increasing VMA values and the associated higher asphalt contents (at constant air voids). This greater pavement durability will result in longer pavement life and greatly reduced pavement maintenance costs.

Marshall design criteria for these standard paving mixtures with high VMA values and high asphalt contents are included.

**Key words:** more durable standard paving mixtures, higher VMA values, higher asphalt contents, air voids, Marshall stability, flow index, actual asphalt film thickness, standard asphalt film thickness, design criteria.

## INTRODUCTION

In North America asphalt cement usually costs from fifteen to twenty times as much per ton as the aggregates that are also incorporated into asphalt paving mixtures. In the past, because of the great need for large mileages of paved road surfaces, even when the asphalt binders have been provided by public agencies, there has been a tendency to use paving mixtures with relatively low asphalt contents in order to reduce the cost of paving mixtures per ton, and thereby obtain the maximum paved mileage of road surface with the limited funds available. Even when contractors have furnished the asphalt, there has been an understandable tendency to keep the asphalt content at a relatively low value in order to reduce the cost per ton and to improve their position in our system of competitive building, which usually awards a contract to the lowest bidder.

In addition to these economic factors, the shape and the narrowness of the grading bands that are traditionally specified for the aggregates for asphalt paving mixtures, result in very limited VMA values (voids in the mineral aggregate). Consequently, there is not enough void space between the aggregate particles in most compacted paving mixtures for higher asphalt contents than those in current common use.

These restrictions on the asphalt contents of paving mixtures have resulted in shortened service lives, increased pavement maintenance, and much too frequently, the development of numerous potholes, particularly during the thaw period each spring, when the more seriously inadequate portions of a pavement break up completely, Krchma (1, 2),\* an outstanding authority on asphalt paving technology in the United States, has shown that one-half the expected life of a pavement can be lost when the asphalt content is only one-half of one per cent less than the optimum normally employed for paving mixture design.

These obvious faults in many of our existing asphalt pavements have provided an opportunity for the promotion of special and much more expensive paving mixtures such as those containing rubber, asbestos, etc. In addition, the past urgent need for long mileages of paved road surfaces has been substantially satisfied, and our present more affluent society is less tolerant of imperfections in asphalt pavements. Consequently, a number of public organizations have been willing to employ these more expensive special types of paving mixtures to satisfy the public demand for better pavement performance.

The use of fine asbestos fibre in paving mixtures is being promoted on the basis that this practice enables an asphalt content from one to two percent higher than normal to be employed, which results in greatly

\*Numbers in parenthesis denote references listed at end of paper.

improved pavement durability. Therefore, those who are encouraging the use of asbestos in paving mixtures, are making a worthwhile contribution to asphalt paving technology, by stressing to paving engineers that increasing the asphalt content of paving mixtures increases pavement durability, and thereby lengthens pavement service life. This also decreases pavement maintenance, and substantially reduces the development of potholes particularly during the spring break-up period. However, **it cannot be overemphasized that the improved pavement durability in this case, is due to the substantially higher asphalt contents** that paving engineers are encouraged to use in paving mixtures containing fine asbestos.

It is the principal purpose of this paper to demonstrate that there is a normally much less costly method for increasing the asphalt content of paving mixtures for the purpose of increasing pavement durability. By simply increasing the minimum VMA requirements, with due consideration for pavement stability, standard asphalt paving mixtures can be designed with much higher asphalt contents, which will provide greater durability and substantially lengthened service life. This method therefore, provides an engineer with two choices in his search for better asphalt pavement performance:

- (a) the use of special paving mixtures such as those containing asbestos, rubber, etc., and
- (b) the use of standard paving mixtures with higher minimum VMA values which enable higher asphalt contents to be employed.

Ordinarily, an engineer's choice between these two alternatives will be based on the method that can provide him with the improved pavement serviceability he is seeking, at lower cost.

First however, since it is essential to a better understanding of the method for obtaining correctly designed standard paving mixtures with the higher VMA values required for greater durability, some basic information on asphalt paving mixture design will be presented.

## 1. OBVIOUS FAULTS IN ASPHALT PAVEMENT SERVICE PERFORMANCE

There are two glaring faults in asphalt pavement performance that are so obvious they can be seen by the naked eye.

One of these faults is illustrated in Figure 1. This pavement has been so **seriously underasphalted** that it is **ravelling** badly in service. While the rapid wearing away of the paved surface may be difficult to detect in Figure 1, the evidence that it is happening is provided by the long spray patches that have been applied to the worst ravelled areas in the wheel paths to keep this pavement in service until it can be resurfaced. Bad ravelling in the surface of a pavement due to under-asphalting can be easily detected by the naked eye.

The other major fault develops when an asphalt pavement has been so **seriously overasphalted** that it **flushes or bleeds** badly. The pavement illustrated in Figure 2 is less than one year old, but it is already flushing profusely in all four wheel paths, which makes it a serious traffic hazard in wet weather. This flushing or bleeding can be also readily observed by the naked eye.

A street not far away was surfaced with the same paving mixture at the same time that the pavement shown in Figure 2 was constructed. Figure 3 is

a picture of the pavement on this nearby street that was taken on the same date as Figure 2. Figure 3 shows no flushing of the pavement because this street is carrying a very much smaller traffic volume. Consequently, Figures 2 and 3 demonstrate that the anticipated traffic volume should be carefully considered when selecting the asphalt content for a paving mixture, since an asphalt content that results in flushing or bleeding under heavy traffic, may be the correct asphalt content to use for the same paving mixture for lighter traffic.

Figures 1 and 2 illustrate two major faults in asphalt pavements that are so obvious that they can be seen by the naked eye. Nevertheless, it must be emphasized that many asphalt pavements are poorly designed even though they do not flush on one hand or ravel on the other. Their inadequate design shows up only in the form of shortened service life, increased pavement maintenance, and pothole development. It will be shown later that this unsatisfactory pavement performance occurs because many of these pavements are too low in voids in the mineral aggregate (VMA). They do not have sufficient intergranular void space, or room between the aggregate particles, (VMA), to hold the volume of asphalt binder that is required by a pavement if it is to provide a satisfactory service life of from 20 to 25 years.

## 2. THE MARSHALL TEST

Throughout Canada, paving mixtures are designed in accordance with the following Marshall test criteria:

- Marshall stability (lbs. at 140° F)
- Flow index (units of 0.01 inch)
- % VMA (voids in the mineral aggregate)
- % Air Voids

Of the several paving mixture design procedures in current use around the world, the author's preference is for the Marshall test, Figure 4, because when paving mixture stability is determined by this test, both a stress factor, the Marshall stability, and a strain factor, the flow index, are measured.

It is the objective of the compaction procedure employed for the Marshall test to provide test briquettes 4 inches in diameter and 2.5 inches in thickness, that have the same density that the paving mixture being tested will ultimately achieve under the traffic to which it will be subjected in service. Consequently, for heaviest traffic 75 blows of the hand operated compactor are applied to each face of the briquette; for medium traffic, 50 blows of the hand compactor are used; while 35 blows are employed when designing for light traffic.

Because of the physical effort required for hand compaction, mechanical compactors have been developed. Mr. Lefebvre of Imperial Oil's Research Department has developed the following correlation between hand compaction and the mechanical double compactor sold by Marshall Consulting and Testing Laboratory, Jackson, Mississippi:

Traffic Volume	Hand Compaction No. of Blows	Marshall Double Compactor Equivalent No. of Blows
Heavy	75	60
Medium	50	40
Light	35	27

For any given paving mixture, its VMA and air voids values vary with the number of blows employed for its compaction. The air voids and VMA values become correspondingly less and less as the number of blows employed for compaction is increased.

### 3. FLOW INDEX AN IMPORTANT CRITERION OF PAVING MIXTURE STRENGTH

It cannot be too strongly emphasized that the Marshall stability value is only a partial measure of paving mixture strength. As demonstrated by Figure 5, the flow index also provides a measure of the strength of a paving mixture.

Figure 5 results from an investigation conducted by Goetz and co-workers (3) at Purdue University some years ago, in which triaxial test data and corresponding Marshall test data were obtained on three paving mixtures that differed quite widely in gradation. When studying Goetz' data, it appeared to the author (4) that there might be a relationship between values for the angle of internal friction from the triaxial test, and values for the flow index from the Marshall test. Figure 5 illustrates the plotted data.

From soil mechanics, we know that when other factors are equal, the higher the angle of internal friction of a soil or aggregate material, the higher is its stability or load carrying capacity. Figure 5 indicates that a flow index of 35 corresponds to an angle of internal friction of 25°, while a flow index of 10 corresponds to an angle of internal friction of 50°. As those familiar with soil mechanics are aware, with other factors being equal, a material with an angle of internal friction of 50° is very much stronger than one with an angle of internal friction of only 25°. Therefore, with respect to the contribution of flow index to pavement stability, as indicated by Figure 5 a paving mixture with a high flow index tends to be substantially weaker than one with a low flow index.

### 4. THE STRENGTHS OF ASPHALT PAVING MIXTURES

As indicated in the previous section, neither the flow index nor the Marshall stability by itself provides a satisfactory measure of the actual strength of an asphalt paving mixture. A method that combines both flow index and Marshall stability is required. The modulus of stiffness of an asphalt paving mixture (equivalent to its modulus of elasticity) provides a reasonably satisfactory method for this purpose.

By definition:

$$\text{Modulus of stiffness} = \frac{\text{stress in psi}}{\text{strain in inches per inch}} \quad (1)$$

Insofar as Marshall criteria are concerned, the Marshall stability is the load applied at failure over the cross section of the test briquette, which is 4 inches in diameter and 2.5 inches thick. Consequently, the stress referred to in Equation (1) is:

$$\frac{\text{stability}}{4 \times 2.5}$$

The strain at failure is the flow index, which measures the decrease in diameter in units of 0.01 inch over the 4-inch diameter of the test specimen. Therefore the strain factor in Equation (1) is:

$$\frac{\text{flow}}{100 \times 4}$$

Substituting these two items in Equation (1) gives:

$$\text{Modulus of stiffness} = \frac{\frac{\text{stability}}{4 \times 2.5}}{\frac{\text{flow}}{100 \times 4}} = \frac{\text{stability}}{10} \times \frac{400}{\text{flow}} = 40 \frac{\text{stability}}{\text{flow}} \quad (2)$$

By substituting in Equation (2), it can be demonstrated that the strengths of paving mixtures with (a) a Marshall stability of 1000 pounds and a flow index of 10; (b) a Marshall stability of 2000 pounds and a flow index of 20; (c) a Marshall stability of 3000 pounds and a flow index of 30; and even (d) a Marshall stability of 500 pounds and a flow index of 5, are all the same, namely 4000 psi, as shown below:

$$\text{Modulus of stiffness} = 40 \frac{1000}{10} = 40 \frac{2000}{20} = 40 \frac{3000}{30} = 40 \frac{500}{5} = 4000 \text{ psi.}$$

Consequently, a high Marshall stability value does not indicate a paving mixture with high strength unless at the same time it has a relatively low flow index.

## 5. INFLUENCE OF COMPACTION BY ROLLING ON PAVING MIXTURE STABILITY

Figure 6 illustrates the influence of degree of compaction on the Marshall stability value of an asphalt paving mixture. The only Marshall stability that is normally reported for a paving mixture is its stability at 100 per cent of laboratory compacted density. In Figure 6, this is 1760 pounds, which would more than satisfy nearly all existing specification requirements for Marshall stability. However, with current rolling equipment, 100 per cent of laboratory compacted density is very rarely achieved in the field, particularly for surface courses. Many road building agencies are satisfied with compaction to 95 per cent of laboratory compacted density, while The Asphalt Institute stipulates compaction to a minimum of 97 per cent of laboratory compacted density.

Figure 6 shows very clearly, that if the paving mixture illustrated is compacted to only 95 per cent of laboratory compacted density, its stability is not 1760 pounds but is only 400 pounds, that is, a little more than 20 per cent of the 1760 pounds stability reported by the laboratory for this paving mixture. Even when compacted to 97 per cent of laboratory compacted density, Figure 6 demonstrates that the Marshall stability is only 750 pounds, or only slightly more than 40 per cent of its stability at 100 per cent of laboratory compacted density.

It ordinarily requires several years of traffic to complete the compaction of a pavement to 100 per cent of laboratory compacted density. Consequently, most surface courses after rolling have relatively low stabilities (as low as 400 pounds for the paving mixture of Figure 6) for a period of several months. In spite of their low stabilities due to inadequate compaction by rolling, these paving mixtures very seldom develop indications of instability in service.

This in turn implies that paving mixtures with substantially lower Marshall stabilities than most current specifications normally permit, would provide satisfactory service performance, if they were compacted by rolling to a higher percentage of laboratory compacted density than is ordinarily presently achieved.

## 6. PAVING MIXTURES ARE DESIGNED ON A VOLUME BASIS

Because the plant-mix formula given to the superintendent of a hot-mix plant is always in the form of weights, for example, 3800 pounds of aggregate and 200 pounds of asphalt cement for a 4000 pound batch that is to contain 5 percent of asphalt cement, there is a tendency to believe that paving mixtures are designed on a weight basis. However, air voids and VMA are volume quantities that cannot be weighed. Therefore, any specification containing air voids and VMA design criteria implies that paving mixtures must be designed or analysed on a volume basis (5).

Figure 7 illustrates the composition of a thoroughly compacted paving mixture in terms of its components by volume. The upper cross-hatched area represents the volume of air voids in the compacted mixture, 3 to 5 per cent of the total volume of the compacted mix for surface courses, or 2 to 4 per cent for base or binder courses. The dotted area illustrates the volume occupied by the aggregate. The difference between the total bulk volume of the compacted mixture, and the volume of the aggregate as given by its ASTM bulk specific gravity, is the volume of voids in the mineral aggregate, which is usually abbreviated to VMA. This is the intergranular void space between the aggregate particles in the compacted mixture. Every aggregate absorbs some of the asphalt binder into the capillary pores within each of the aggregate particles. The volume of this absorbed asphalt is indicated by the single hatching in Figure 7. The blank space in Figure 7 illustrates the volume of the portion of the asphalt cement that remains as a coating on the outside of the aggregate particles, which is referred to as the "effective" asphalt content. The "effective" asphalt content is equal to the total asphalt minus the asphalt absorbed into the aggregate particles.

## 7. PRACTICAL SIGNIFICANCE OF AIR VOIDS DESIGN CRITERIA

One of the Marshall design criteria listed earlier in this paper was an air voids requirement. What is its practical significance?

It was pointed out earlier that flushing or bleeding is a major fault of some asphalt pavements that is so serious that it can be easily seen by the naked eye, Figure 2.

**It is the principal purpose of the air voids criteria of 3 to 5 per cent for surface courses, and from 2 to 4 per cent for base or binder courses, to avoid pavement designs that will result in a flushed or bleeding pavement.**

Figure 8 is an oversimplified illustration of a small portion of a compacted paving mixture. The circles represent aggregate particles, while the black bands around the circles represent the coating of asphalt binder on the particles of aggregate. Figure 8 demonstrates that the air voids in a compacted paving mixture consist of small pockets of air between the coated aggregate particles. An air voids content of from 3 to 5 per cent for dense graded asphalt concrete surface courses, means that the total volume of all the small pockets of air between the coated aggregate particles in a thoroughly compacted surface course mixture amounts to from 3 to 5 per cent of the bulk volume of the compacted mixture.

Tests by Mr. Lefebvre of Imperial Oil's Research Department on scores of pavement samples that have been sent in from all parts of Canada during the past 15 years, have shown that the air voids content has always been within the range of 0 to 1 per cent for samples of pavements that were reported to be flushed or bleeding.

There is very good reason for expecting pavements to flush or bleed when their air voids have been reduced by compaction to the range of 0 to 1 per cent. Let us suppose that through either poor design or no design, a pavement has been placed that has an air voids value of only 0.5 per cent at 100 per cent of laboratory compacted density. That is, this pavement can be expected to be flushing or bleeding after its ultimate compaction by traffic to 0.5 per cent air voids. If this pavement is compacted by rolling to 95 per cent of laboratory compacted density, it will have an air voids value of approximately 5.5 per cent when rollers leave the job. At 5.5 per cent air voids, the small pockets of air scattered throughout the paving mixture are all interconnected. Consequently, as the mix compacts to higher and higher density under traffic, at first only air is squeezed out of the pavement. However, when the mix densifies to an air voids content in the vicinity of 1 per cent, the air voids are no longer interconnected. Therefore, as traffic continues to densify the pavement below about 1 per cent air voids, it can no longer squeeze out air, but squeezes out asphalt binder instead, and the flushed or bleeding condition begins to develop.

Several years ago, a number of highway departments attempted to correct flushed or bleeding asphalt pavements by burning off the asphalt cement that had oozed out onto the pavement surface. As illustrated by the right lane in Figure 9, which is a quite typical example, this treatment was effective for only a few weeks, after which the flushed or bleeding condition gradually reappeared under traffic and soon became as serious as the flushed condition in the left lane that had not been burned off. The pavement in Figure 9 is located in Eastern Canada and was constructed with high viscosity 85/100 penetration asphalt from Venezuelan crude oil. The asphalt cement on the surfaces of several other badly flushed pavements in the same area had been burned off three times in succession, with intervals of a number of months between burnings, but on each occasion, after a few weeks of warm weather traffic they were again flushed and bleeding profusely.

As already explained, this flushed or bleeding condition begins to occur when a poorly designed pavement has been densified by traffic to an air voids value of from 0 to 1 per cent. Once flushing has started, the pavement will continue to flush and bleed as long as traffic continues to compact the pavement to higher and higher density. Consequently, as clearly shown by the right lane in Figure 9, burning off the asphalt cement that has oozed out onto the surface provides only a brief temporary solution. More and more asphalt cement will gradually be forced onto the pavement surface as long as further pavement densification under traffic continues, which can extend over a period of years.

To keep out air and water, which cause pavement deterioration, pavements should be designed to have the lowest practical air voids value. Since an air voids value of 1 per cent is likely to result in pavement flushing or bleeding, why not set the minimum permissible air voids value **for surface courses** at 2 per cent? The reason is that due to the lack of precision of the current laboratory tests on which the air voids value is based, any air voids result reported on the basis of routine laboratory testing could be in error by at least  $\pm 1$  per cent. Consequently, for **surface course paving mixtures**, if the minimum air voids value specified were 2 per cent, because of the inevitable variations from batch to batch at the mixing plant, together with the uncertainty of at least 1 per cent concerning any reported air voids value, some of the paving mixture being laid would almost certainly have only 1 per cent air voids or less, and as a result could be expected to ultimately flush or bleed. Therefore, to provide some small margin of safety **for surface**

**course paving mixtures** against flushing or bleeding, they should be designed for a minimum air voids value of 3 per cent.

Because of the need to keep the air voids content of the paving mixture as low as possible, we would also like to set the maximum air voids at 3 per cent. However, the engineer who must design paving mixtures, and even more important, the producers of paving mixtures at hot-mix plants, both need some elbow room. As a result of paving mixture experience in North America during the past 30 years, this required latitude in air voids has been widely accepted as 2 per cent. Since the minimum air voids for surface courses should be 3 per cent, this establishes the range of air voids as 3 to 5 per cent.

From the analysis of numerous pavement samples by the Research Department of Imperial Oil Limited, it is clearly established that traffic compacts the surface course of an asphalt pavement substantially more than the underlying base or binder course layers. That is, the increase in density of a pavement due to traffic decreases from the pavement surface downwards. Data obtained by Mr. Lefebvre of Imperial Oil's Research Department have consistently shown a lower percentage of laboratory compacted density, corresponding to from 1 to 2 per cent more air voids, in base or binder courses than in the overlying surface courses which usually range from 1¼ to 2 inches in thickness. In practical terms, and with present rolling equipment, this means that if the **surface course** is designed for an air voids content of from 3 to 5 per cent, the **binder or base course** should be designed for an air voids content of from 2 to 4 per cent.

With the present Asphalt Institute compaction requirement of 97 per cent of laboratory compacted density, a base course or binder course paving mixture that is designed to have only 2 percent air voids would contain a minimum of very nearly 5 per cent air voids when compaction by rolling was complete, provided it just satisfied the minimum 97 per cent compaction requirement. Because of the substantially lower temperatures that exist in the deeper layers of a full depth or deep strength asphalt pavement, very little or no increase in density above that provided by the rollers can be expected in service. Consequently, even if base or binder course layers are designed for from 2 to 4 per cent air voids, they are unlikely to densify under traffic to the vicinity of 0 to 1 per cent air voids where flushing or bleeding might be expected.

To recapitulate, the primary reason for including a minimum air voids requirement in the design criteria for asphalt paving mixtures is to avoid pavements that will flush or bleed in service.

## 8. PRACTICAL SIGNIFICANCE OF VOIDS IN THE MINERAL AGGREGATE (VMA)

A minimum requirement for voids in the mineral aggregate, which is usually abbreviated to VMA, was included in the Marshall design criteria referred to earlier in this paper. What is the practical significance of VMA?

The early ravelling (rapid wearing away) of some asphalt pavement surfaces under normal traffic usually occurs because the paving mixtures do not contain sufficient asphalt binder. As illustrated by Figure 1, this fault is quite obvious to the naked eye.

It is the primary function of the minimum requirements for VMA illustrated in Figure 10, to prevent the underasphalting of paving mixtures that results in early raveling, excessive pavement maintenance, and shortened pavement service life. With respect to the objectives of this paper, it will be demonstrated later that it is to higher VMA values that we must look for standard paving mixture designs that contain higher asphalt contents, which in turn will result in greater pavement durability and longer pavement service lives.

Referring to Figure 8, the voids in the mineral aggregate (VMA) consist of the intergranular void space **between** the aggregate particles in a thoroughly compacted paving mixture. Figure 10 demonstrates that a dense graded asphalt concrete surface course made with aggregate of  $\frac{1}{2}$  inch nominal maximum particle size should have a minimum VMA value of 15 per cent. This minimum VMA value of 15 per cent means that the total volume of the intergranular space between the aggregate particles in a paving mixture after 75-blow, 50-blow, etc., or equivalent compaction in a laboratory, amounts to a minimum of 15 per cent of the bulk volume of the compacted mixture. As illustrated by Figure 7, the VMA value is usually obtained by subtracting the volume of the aggregate in a sample of compacted paving mixture, as given by the aggregate's ASTM bulk specific gravity, from the bulk volume of the compacted mixture sample. It must be emphasized that in paving mixture design, the VMA value has significance only when determined for a compacted paving mixture. The VMA value of a paving mixture cannot be determined from tests made on the aggregate by itself.

Figure 10 indicates that the minimum VMA value specified by The Asphalt Institute (6) for normal dense graded paving mixtures should vary with the nominal maximum particle size of the aggregate employed (5). For a surface course paving mixture with  $\frac{1}{2}$  inch nominal maximum particle size, the minimum VMA value should be 15 per cent; for a binder or base course paving mixture with 1-inch nominal maximum particle size, the minimum VMA should be 13 per cent; while for a sheet asphalt paving mixture with No. 8 sieve as its nominal maximum particle size, the minimum VMA should be 21 per cent, and so on. As illustrated by Figure 10, for each nominal maximum particle size, the minimum corresponding VMA value to be permitted should be on the diagonal line, and should preferably be somewhat above it. If the VMA value for any paving mixture is below the diagonal line, the paving mixture is deficient either in air voids, or in asphalt content, or in both, as noted on Figure 10. When the intergranular void space in a thoroughly compacted **surface course paving mixture**, represented by its VMA value, lies below the diagonal line in Figure 10, there is not sufficient room or space between the aggregate particles for the 3 to 5 per cent air voids required to prevent flushing or bleeding, plus the volume of asphalt binder needed for a durable pavement. In this case, if a normal asphalt content is used, the air voids may be reduced to from 0 to 1 per cent, and the pavement may flush or bleed. On the other hand, if the paving mixture is designed to contain from 3 to 5 percent air voids, the asphalt content will be so low that the pavement may ravel badly in its early life, and at least its service life will be relatively short.

It was stated earlier in connection with Figures 1 and 2, that pavements which do not flush or bleed on one hand, or ravel on the other, can still be poorly designed, although this will become obvious only from their short service lives or excessive maintenance. Paving

mixtures made with the gravels and sands that are plentiful in Canada and in many other parts of the world, often tend to be much too densely graded. Therefore, when these paving mixtures are compacted to their ultimate densities, their VMA values are well below the diagonal line of Figure 10. This means that there is not enough room between the aggregate particles in the compacted paving mixture for the 3 to 5 per cent air voids needed to prevent flushing or bleeding in surface courses, plus the volume of asphalt binder required for a durable pavement. Consequently, while these pavements may neither ravel nor flush or bleed, they are under-asphalted and their maintenance costs are higher, and their service lives are much shorter than they should be.

Figure 11 illustrates fairly typical VMA values that were measured for 8 binder course and 8 surface course asphalt concrete pavement samples that were taken from actual Canadian pavements that were giving poor performance. Since the nominal maximum particle size of the binder course in each case was  $\frac{3}{4}$  inch, the diagonal line of Figure 10 indicates that the minimum VMA value for these 8 binder course pavement samples should have been about 14 per cent. Instead, as demonstrated by Figure 11, their VMA values ranged from only 8.4 to 10.4 per cent. Similarly, for the nominal maximum particle size of  $\frac{1}{2}$  inch for each of the 8 surface course pavement samples, the diagonal boundary of Figure 10 shows that the minimum VMA value should have been 15 per cent, whereas the VMA values for the 8 samples ranged from 10.7 to 13.9 per cent. Consequently, these binder and surface courses were both seriously underasphalted, and it should not be surprising that the pavements represented by these samples were reported to show early ravelling, cracking, and other indications of serious deterioration.

Briefly summarized, this section of the paper has demonstrated very clearly, that the VMA value of a dense graded paving mixture essentially controls the quantity of asphalt cement that can be incorporated.

## 9. INCREASING VMA BY DEVIATION FROM FULLER CURVE

There is considerable evidence that VMA values that are well below the minimum requirements of Figure 10, are one of the most common causes of inferior pavement performance and shortened pavement service life in many regions. In these areas, the aggregates available for paving mixtures tend to be too densely graded, resulting in low VMA values and correspondingly low asphalt contents. Consequently, even for normal asphalt concrete paving mixtures, the No. 1 design problem in many regions is how to open up the aggregate in a dense graded paving mixture, to obtain increased VMA values that are equal to or exceed the minimum VMA requirements of Figure 10.

Engineers prefer sound rational solutions to their problems. A very simple but very basic solution to this problem is illustrated by Figure 12. The solid curve through the centre of Figure 12 is a theoretical Fuller grading curve which provided the highest density or the lowest VMA value for the aggregate or combination of aggregates it represents.

There is a whole family of Fuller curves, one for each maximum particle size, 2-inch,  $\frac{3}{4}$  inch, No. 4 sieve, etc. The equation for any Fuller curve is:

$$P = 100 \left( \frac{d}{D} \right)^{0.5}$$

where  $D$  = the sieve opening in inches or millimeters corresponding to the maximum particle size of any given aggregate

$d$  = any sieve opening smaller than  $D$

$P$  = the per cent of aggregate passing sieve opening “ $d$ ”.

It should be noted that the grading curves for the aggregates recovered from the 16 binder and surface course asphalt pavement samples referred to in Figure 11 all conformed very closely to the corresponding Fuller curves. This dense grading was the principal reason for the failure of these pavement samples to satisfy the minimum VMA criteria of Figure 10.

Since the Fuller grading curve provides maximum aggregate density and therefore the lowest VMA value for an asphalt concrete paving mixture, it should be obvious that the VMA value can be increased by the very simple procedure of blending the coarse and fine aggregates in such proportions that the resulting grading curve has been made to deliberately deviate away from the corresponding Fuller curve (5). This provides a simple, sound engineering solution to the problem of low VMA values in asphalt paving mixtures. As illustrated by Figure 12, this deviation away from the corresponding Fuller curve can follow any one of four basic patterns:

- (a) the grading curve can lie to the left of the corresponding Fuller curve, curve (1) in Figure 12. This is achieved by reducing the proportion of coarse aggregate and increasing the proportion of fine aggregate.
- (b) the grading curve can lie to the right of the corresponding Fuller curve, curve (2) in Figure 12. This is attained by increasing the proportion of coarse aggregate and reducing the proportion of fine aggregate.
- (c) the grading curve can start out on the right side of the Fuller curve, for the coarse aggregate portion, then cross over the Fuller curve, and finish on the left side of the Fuller curve for the fine aggregate portion, curve (3) in Figure 12. This is usually referred to as “gap” grading because of the relative absence of the intermediate sieve sizes where the grading curve crosses the Fuller curve.
- (d) the grading curve can begin on the left side of the Fuller curve, for the coarse aggregate portion, then cross over the Fuller curve, and finish on the right side of the Fuller curve for the fine aggregate portions, curve (4) in Figure 12. This in part approximates the grading of a one-size aggregate because of the unusually high percentage of the intermediate sieve sizes where the grading curve crosses the Fuller curve.

Which one of these four procedures for increasing the VMA value of a paving mixture is to be adopted, will depend on the grading and relative costs of the coarse and fine aggregates available, upon the surface texture desired for the pavement, and upon the possibility of segregation of the aggregate occurring, which could be greater with curve (2) in Figure 12. In Canada, where fine aggregates are usually less costly than coarse aggregates either curves (1) or (3) are usually favoured.

It should be clearly recognized that the amount of deviation away from the corresponding Fuller curve that is required to achieve the minimum VMA values of Figure 10, depends very greatly on the angularity and surface roughness of the coarse and fine aggregate particles in the paving mixture. If both are prepared in a stone quarry from a stone crushing operation, the coarse and fine aggregate particles may be so angular and rough textured that

when paving mixtures containing them are compacted with 75-blow or 50-blow Marshall, the paving mixtures may satisfy the minimum VMA requirements of Figure 12 even when the grading curves for the aggregates in these paving mixtures conform to the corresponding Fuller curves. (However, such paving mixtures tend to be harsh and less workable in the field.) Consequently, the only certain way to establish the proportions of coarse and fine aggregates that are needed to satisfy the minimum VMA requirements of Figure 10, is to make up trial paving mixtures with different coarse and fine aggregate blends, compact them with 75-blow or 50-blow Marshall or equivalent as required, and determine the VMA value for each paving mixture. If the VMA value is too low, a paving mixture containing a further adjustment in proportions of coarse and fine aggregates should be tried, with the blend selection being guided by the principles illustrated in Figure 12. An experienced laboratory will seldom need to investigate paving mixtures made with more than two trial blends of coarse and fine aggregates to satisfy any required minimum VMA value of Figure 10.

Mineral dust passing the No. 200 sieve is a void filling material which tends to decrease the VMA value of any paving mixture. Consequently, when selecting coarse and fine aggregates for blending to achieve paving mixtures with higher VMA values, care must be taken to avoid percentages passing the No. 200 sieve that are higher than the percentage associated with the corresponding Fuller curve, and the percentage passing the No. 200 sieve should preferably be less than this.

We have used the method illustrated by Figure 12, of deliberately deviating away from the corresponding Fuller curve to increase the VMA values of paving mixtures for the past 15 years. We have found this method to be simple, adequate, reliable, and inexpensive. An increase in VMA of 5 per cent above that provided by Fuller grading can be easily obtained by this method.

## **10. MORE DURABLE PAVEMENTS REQUIRE HIGHER VMA VALUES**

We come now to the principal objective of this paper, which is the design of standard paving mixtures of greater durability.

Assuming that an asphalt pavement is otherwise well designed, it can be made more durable by increasing its asphalt content. However, from the previous section of this paper, it should be evident that the asphalt content of a properly designed asphalt pavement cannot be increased unless more intergranular void space is provided for it within the fully compacted pavement. That is, the asphalt content can be substantially increased only if higher VMA values can be provided. This means that paving mixtures must contain aggregate blends with grading curves that deviate well away from the corresponding Fuller curves.

Figure 13 illustrates the grading curves for the seven aggregates that were employed in our study of this problem. The gradings are also listed in Table 1. The base or binder course paving mixtures were made with aggregates with a maximum particle size of  $\frac{3}{4}$  inch. For the surface course paving mixtures, the maximum aggregate particle size was essentially  $\frac{1}{2}$  inch.

Two series of surface course paving mixtures were included. One series contained crushed gravel, crushed gravel screenings, and natural sand, since these aggregates are the most widely used for asphalt paving mixtures in Canada. The other surface course series of paving mixtures, was made with crushed limestone, crushed limestone screenings, and natural sand, since

crushed limestone aggregates are extensively employed in some portions of Canada. Normally, because of their greater angularity, and rougher surface texture, limestone aggregates provide paving mixtures with higher stabilities than crushed gravel aggregates. For the base or binder course paving mixtures, the aggregates were limited to crushed gravel, crushed gravel screenings, and natural sand.

It is typical of screenings from most sources in southern Ontario to have grading curves of a generally concave upward shape. The grading curves for sands on the other hand tend to be concave downward. Consequently, screenings tend to dominate as fine aggregate if gradings on or in the vicinity of the corresponding Fuller curve are desired, while more sand is employed to obtain grading curves that are made to deviate away from the corresponding Fuller curve.

The surface and base course paving mixture designs investigated, included aggregate blends to provide the following wide range of gradations:

- (a) an aggregate blend of Fuller grading, Mix 1,
- (b) an aggregate blend that would provide a surface course mixture with a VMA value of approximately 15 (Figure 10), and a base course paving mixture with a VMA value of approximately 14 (Figure 10), Mix 2.
- (c) aggregate blends that would provide both base and surface courses with VMA values of approximately 18. One of these was to be coarse textured by including a normal quantity of coarse aggregate, Mix 3, the other was to be sandy textured by substantially reducing the quantity of coarse aggregate, Mix 4.

In addition, surface course paving mixtures were designed to have approximately 3 per cent air voids, and base course mixtures to have air voids of about 2 per cent. This enabled all surface and all base course paving mixtures to be compared on the basis of similar air voids values. Asphalt cement of 85/100 penetration meeting the Ontario specification was used throughout, and all mixtures were compacted with 60 blows of a Marshall mechanical compactor.

Not more than three of the seven aggregates listed in Table 1, with grading illustrated in Figure 13, were blended to obtain any one of the eight surface course gradings illustrated in Figures 14 and 15, or of the four base course gradings shown in Figure 16. The aggregate gradations for the twelve paving mixtures are given in Table 2.

The principal data obtained on the surface course and base course paving mixtures are summarized in Table 3. The asphalt contents for both base and surface course mixtures range from approximately 4.0 to 8.0 per cent. The air voids for the surface course mixtures are very nearly 3.0 per cent in each case, and 2.0 per cent for the base course mixtures. The VMA values range from less than 11 per cent for Fuller grading, Mix 1, to about 15 and 14 per cent respectively, to satisfy the VMA requirements of Figure 10 for surface and base mixtures, Mix 2, to more than 18 per cent, Mixes 3 and 4. The Marshall stability values are all well above 1200 pounds, and with one minor exception, the flow indices do not exceed 15. As anticipated, the Marshall stabilities for surface course paving mixtures containing crushed limestone aggregates are substantially higher than those made with crushed gravel and sand.

The surface area value for each paving mixture in square feet per pound, shown in the second column from the right in Table 3, was calculated for the

various paving mixture aggregate blends by means of the method given in The Asphalt Institute's publication "Mix Design Methods for Asphalt Concrete", Third Edition, October 1969, page 61, (6). As expected, the surface area in square feet per pound tends to increase with increasing distance of the grading curve to the left of the Fuller curve, because of the increasing proportion of finer aggregate.

After making allowance for the amount of asphalt lost by absorption into the aggregate particles, the average thickness of the asphalt coating on the aggregate particles in each paving mixture was calculated. The film thickness values are given in the right hand column of Table 3 in microns (1 micron = 0.001 mm).

The data of Table 3 tend to show that on the basis of asphalt coating film thickness by itself, increasing the VMA value of a paving mixture (at constant air voids) does not always increase the thickness of the asphalt film coating. Compare for example, the film thicknesses for Mix 2 and Mix 3 for both surface and base course paving mixtures. As a first impression, this might seem to indicate that increasing the VMA value of a paving mixture (at constant air voids) does not necessarily assure a more durable pavement, since greater pavement durability might be assumed to be associated with greater film thickness. Nevertheless, even with this reasoning, Mix 4 with its high VMA value would be more durable than any of the other mixes because it has the greatest asphalt film thickness.

In this evaluation however, it is not the thickness of the asphalt film itself that should be accepted as the criterion of pavement durability. Instead, it is the ratio of this asphalt film thickness in any paving mixture, to the film thickness of asphalt in a paving mixture of normal design in which the aggregate has the same surface area in square feet per pound, that is important. Figure 17, which was developed by the California Department of Highways (7), shows very clearly that in normal asphalt paving mixture design, the required thickness of asphalt film coating on the aggregate particles decreases substantially with an increase in area surface in square feet per pound of aggregate, since bitumen index, or pounds of asphalt per square foot of surface area, provides an indirect measure of asphalt film thickness. That is, for normal paving mixture design practice, thicker asphalt films are required on the aggregate particles in coarser textured than in finer textured paving mixtures. For example, because of its very much greater surface area in square feet per pound of aggregate, the asphalt film thickness on the aggregate particles is very much thinner in a sheet asphalt paving mixture containing 10 per cent of asphalt cement, than in an asphalt concrete paving mixture containing 5 per cent of asphalt cement. Curve 5 in the middle of the family of curves in Figure 17 was selected as an average curve to provide a standard of asphalt film thicknesses for a comparison with the asphalt coating thicknesses given in the right hand column of Table 3. The results of this comparison are given in Table 4.

The right hand column of Table 4 lists the ratio of the actual asphalt film thicknesses for each of the surface course and base course mixtures of Figures 14, 15 and 16 versus the corresponding asphalt film thickness for the same surface area in square feet per pound of aggregate taken from curve 5 of Figure 17. The data in this column indicate that at least for the VMA values of the paving mixtures investigated, as the VMA value is increased, the ratio of actual asphalt film thickness versus the film thickness required for the corresponding normal paving mixture design also increases.

Based on curve 5 of Figure 17 as an average standard asphalt film thickness requirement, the right hand column of Table 4 indicates that for

either surface course (3 per cent air voids) or base course (2 per cent air voids) paving mixtures with Fuller grading curves, Mix 1, the actual asphalt film thickness is substantially less than this standard film thickness. For paving mixtures that just satisfy the minimum VMA requirements of Figure 10, Mix 2, the thickness of the asphalt coating is about 30 per cent higher than the standard asphalt film thickness for the surface course paving mixtures, and about 20 per cent higher for the base course mixture.

As illustrated by Mixes 3 and 4, for both base and surface course mixtures, the principal conclusion provided by the data of Tables 3 and 4 is that the higher asphalt contents associated with higher VMA values provide paving mixtures in which the ratio of actual film thickness to standard film thickness is greatly increased. For both the surface and base or binder course mixtures, Table 4 indicates that for Mixes 3 and 4 with their high VMA values, the actual asphalt film thicknesses are from 50 to 80 per cent thicker than the corresponding standard asphalt film thicknesses represented by curve 5 in Figure 17. This will result in asphalt pavements of much greater durability, and with substantially lengthened service lives.

It will be recalled that the principal difference between both surface and base course Mixes 3 and 4, is in the quantities of coarse aggregate they contain. Mix 3 contains a substantial percentage of coarse aggregate, and obtains its higher VMA value from the excess of fine dune sand that was incorporated. As indicated by Tables 3 and 4, the use of this excess of fine material to provide the necessary deviation away from the corresponding Fuller curve, results in a much higher surface area in square feet per pound, and therefore in a somewhat thinner asphalt film thickness than Mix 4. On the other hand, Mix 4 contains less coarse aggregate, but more coarse sand. This results in a lower surface area in square feet per pound, and therefore in a very high asphalt film thickness. Consequently, depending on the surface texture desired, either Mix 3 or Mix 4, or some high VMA modification of these, can serve as a model for high VMA surface or base course mixtures.

Each of the 12 surface and base course paving mixtures included in this study has a Marshall stability value that is higher than those normally specified.

Incidentally, the data for Mix 1 base and surface courses in Tables 3 and 4 indicate the low VMA values and the thin asphalt film thicknesses that are associated with paving mixtures with Fuller grading curves. In every case, the actual film thickness is less than the standard film thickness represented by curve 5 in Figure 17. It should not be surprising therefore, that paving mixtures containing aggregates that approximate Fuller grading curves (as many paving mixtures do) are not particularly durable, as illustrated by the data and the note on Figure 11.

## 11. MARSHALL DESIGN CRITERIA FOR MORE DURABLE ASPHALT PAVEMENTS

For general use, the following Marshall design criteria are suggested for more durable asphalt pavements of standard design:

	<i>Min.</i>	<i>Max.</i>
Marshall Stability (lb. at 140°F) .....	1000	
Flow Index (Units of 0.01 inch) .....		15
% Voids in the Material Aggregate (VMA) .....	See Fig. 18	—
(Based on the aggregate's ASTM bulk specific gravity)		

% Air Voids		
Surface Course .....	3	5
Base Course .....	2	4

(Allowance for asphalt absorption by the aggregate must be made when calculating the air voids value.)

The minimum VMA values referred to in the above design criteria are those illustrated by the upper diagonal line in Figure 18. Consequently, Figure 18 should be included with the design requirements in any specification. This upper diagonal has been drawn to require a VMA value two per cent higher than those indicated for normal paving mixture designs in The Asphalt Institute chart. This in turn will increase the asphalt content of any paving mixture by approximately one per cent above that needed to satisfy The Asphalt Institute's minimum VMA requirements.

For special situations, or where still higher asphalt contents are desired for paving mixtures, the minimum VMA value can be increased by one per cent or more above the upper diagonal line in Figure 18.

It is the policy of some organizations to require a contractor to submit paving mixture designs either at or shortly after the time of his successful bid. Because the samples of aggregate on which these designs are based may not be representative of the aggregates actually put through the mixing plants, these designs may not represent actual production. However, in some cases, no follow-up is required to determine whether or not the paving mixture being produced more than approximates the design submitted. If these more durable high VMA paving mixtures are specified, they must not only be carefully designed, but there should be sufficient testing of actual paving mixture production to ensure that the paving mixture designed, or its equivalent, is also the paving mixture that is placed in the pavement.

### CONCLUSIONS

This paper has demonstrated quite conclusively, that more durable asphalt pavements can be obtained by employing properly designed standard paving mixtures with much higher than normal VMA values. Therefore, there are now available two alternative methods for increasing the asphalt content of correctly designed paving mixtures for the purpose of achieving greater pavement durability:

- (a) by the use of special paving mixtures such as those containing rubber, asbestos, etc., and
- (b) by the use of standard paving mixtures with much higher than normal VMA values.

Since engineers are normally economy minded, of these two methods they will ordinarily select the alternative that results in lower cost based on the aggregate and other conditions that exist in the locality where the pavement is to be laid. In a great many areas, and particularly in regions where a wide variety of aggregates is available, the standard paving mixture with a high VMA value will almost always be by far the least expensive.

Incidentally, the use of standard asphalt paving mixtures with higher VMA values and therefore higher asphalt contents, which in turn, as demonstrated by Table 4, result in substantially greater effective asphalt

film thicknesses on the aggregate particles, will greatly reduce the rate at which asphalt cements harden in pavements in service. This means that a much longer period of time will be required for the asphalt cement to harden to the point where the tensile stress generated by the tendency of a pavement to contract during chilling to low temperature, exceeds the tensile strength of the pavement, and transverse pavement cracking begins to occur. Consequently, these high VMA, high asphalt content pavements could be constructed with somewhat harder asphalt cements (lower penetration at 77° F), than applies to pavements as they are normally designed and constructed at the present time (8, 9).

It could be emphasized again, that the approach that has been described in this paper to provide standard asphalt paving mixtures with high VMA values and correspondingly higher than normal asphalt contents, in order to obtain greater durability and substantially longer pavement service lives, is not an untried academic or purely theoretical method. As indicated earlier, the method described in this paper to obtain higher VMA values by deliberately deviating away from the corresponding Fuller curve, has been used by the author for the past 15 years to obtain paving mixture designs that satisfy The Asphalt Institute minimum VMA requirements of Figure 10.

#### SUMMARY

1. It is the principal purpose of this paper to demonstrate that standard paving mixtures with high VMA values provide an alternative to special paving mixtures such as those containing asbestos, rubber, etc. for achieving pavements of greater durability.
2. The principal faults of current pavements are reviewed.
3. The Marshall test and the significance of the compactive effort employed are briefly described.
4. The influence of the flow index as a criterion of paving mixture strength is emphasized.
5. The practical significance of air voids and VMA design criteria is discussed.
6. The dependence of the VMA value on the relationship between the grading curve of the aggregate in a paving mixture and the corresponding Fuller grading curve is pointed out.
7. The asphalt film thicknesses measured in microns (0.001 mm) are listed for surface course and base course paving mixtures with widely different VMA values but constant air voids values.
8. The ratios of these actual asphalt film thicknesses versus the standard asphalt film thicknesses associated with normal paving mixtures containing aggregates of the same surface areas in square feet per pound, for example, curve 5 in Figure 17, increase with an increase in VMA. This demonstrates that at least for properly designed paving mixtures, pavement durability can be expected to increase with increasing VMA values and the associated higher asphalt contents (at constant air voids). This greater pavement durability will result in longer pavement life and greatly reduced pavement maintenance costs.

9. Marshall design criteria for these standard paving mixtures with high VMA values and high asphalt contents are included.
10. It is emphasized that these high VMA high asphalt content paving mixtures require not only proper design but adequate inspection during their construction to ensure that the paving mixture designed, or its equivalent, is the paving mixture that is actually placed in the pavement.

### ACKNOWLEDGMENTS

Grateful acknowledgment is made to Leslie Pamplin, William Merritt, Kar Yew Cheng, and Allen Morrow for their capable assistance in obtaining the laboratory data required for this paper.

### REFERENCES

1. L. C. Krchma, "Relationship of Mix Design to Hardening," Proceedings, Association of Asphalt Paving Technologists, Volume 27, 1959.
2. L. C. Krchma and T. Groening, "Influence of Pavement Voids, Asphalt Content and Asphalt Grade on Asphalt Performance," Proceedings, Association of Asphalt Paving Technologists, Volume 28, 1959.
3. W. H. Goetz, "Marshall Test and Triaxial Data Compared," Proceedings, Association of Asphalt Paving Technologists, Volume 21, 1952.
4. N. W. McLeod, Prepared Discussion on Above Paper, Proceedings, Association of Asphalt Paving Technologists, Volume 21, 1952.
5. N. W. McLeod, "Void Requirements for Dense Graded Bituminous Paving Mixtures," American Society for Testing and Materials, Special Technical Publication No. 252, 1959.
6. The Asphalt Institute, "Mix Design Methods for Asphalt Concrete and Other Hot-Mix Types", Manual Series No. 2, Third Edition, October 1969.
7. F. N. Hveem, "Use of the Centrifuge Kerosene Equivalent as Applied to Determining the Required Oil Content for Dense Graded Bituminous Mixtures", Proceedings, Association of Asphalt Paving Technologists, Volume 13, 1942.
8. N. W. McLeod, "Influence of Hardness of Asphalt Cement on Low Temperature Transverse Pavement Cracking", Presented, Sixth World Highway Conference, Montreal, P.Q., October 4 to 10, 1970, Proceedings, Canadian Good Roads Association, 1970.
9. N. W. McLeod, "A 4-Year Survey of Low Temperature Transverse Pavement Cracking on Three Ontario Test Roads", to be Presented, Annual Meeting, Association of Asphalt Paving Technologists, Cleveland, Ohio, February 14 to 16, 1972.

TABLE I

AGGREGATE SIEVE ANALYSES

Aggregate No.	1	2	3	4	5	6	7
Sieve Size	3/4 inch Crushed Gravel	1/2 inch Crushed Gravel	1/2 inch Crushed Limestone	Crushed Gravel Screenings*	Crushed Limestone Screenings*	Sand	Dune Sand*
			Per Cent Passing				
3/4 inch	100.0						
5/8 inch	86.7	100.0	100.0				
1/2 inch	57.7	97.7	98.5				
3/8 inch	29.1	65.3	66.7	100.0	100.0	100.0	
No. 4 sieve	5.7	17.4	9.6	99.4	89.1	95.8	
" 8 "	3.8	5.1	5.4	81.2	46.8	89.0	
" 16 "	3.4	4.0	4.6	60.0	28.2	79.5	
" 30 "	3.1	3.6	3.7	45.4	19.9	62.6	100.0
" 50 "	2.8	3.2	3.5	32.5	15.0	29.9	97.6
" 100 "	2.3	2.8	3.2	22.4	12.6	7.1	40.1
" 200 "	1.8	2.3	2.7	16.2	10.0	2.3	5.4

\* Wet sieve analysis

TABLE 2

AGGREGATE GRADATIONS FOR SURFACE AND BASE COURSE PAVING MIXTURES

Paving Mixture Type	Surface Course				Surface Course				Base Course			
Paving Mixture Composition	Crushed Gravel, Crushed Gravel Screenings and Sand				Crushed Limestone, Crushed Limestone Screenings & Sand				Crushed Gravel, Crushed Gravel Screenings and Sand			
Paving Mixture No.	1	2	3	4	1	2	3	4	1	2	3	4
Sieve Size	Per				Cent				Passing			
3/4 inch									100.0	100.0	100.0	100.0
5/8 "		100.0	100.0	100.0					91.0	94.0	94.7	97.3
1/2 "	100.0	99.0	99.1	99.5	100.0	100.0	100.0	100.0	81.0	81.0	83.1	91.5
3/8 "	87.0	94.4	86.1	93.2	87.0	84.4	87.1	94.5	70.7	68.1	71.6	85.8
No. 4 Sieve	61.0	60.9	66.9	80.7	61.0	60.5	62.3	80.0	50.0	56.0	62.1	78.4
" 8 "	44.0	50.5	57.3	70.6	44.0	50.5	51.5	67.2	35.4	49.0	55.9	70.4
" 16 "	30.5	43.4	51.6	60.4	30.5	43.6	47.0	57.1	25.0	41.3	49.4	60.3
" 30 "	21.5	34.3	47.8	47.4	21.5	34.2	45.0	44.6	17.7	32.4	44.8	47.3
" 50 "	15.0	18.2	43.6	25.0	15.0	18.2	42.8	22.4	12.5	18.3	40.3	25.0
" 100 "	10.5	6.7	20.1	9.4	10.5	6.7	19.2	7.1	8.8	8.0	19.1	9.3
" 200 "	7.5	3.6	6.8	5.1	7.5	3.7	4.7	3.5	6.3	4.8	7.1	5.0

73

**TABLE 3**

**PAVING MIXTURE CHARACTERISTICS**

Paving Mixture Type	AC %	Air Voids %	VMA %	Stability lbs.	Flow	Surface Area ft. <sup>2</sup> /lb.	Film* Thickness Microns
<b>Surface Course A</b> (Crushed Gravel, Crushed Gravel Screenings, Sand)							
1	4.2	3.2	12.0	3500	15	31.3	5.89
2	5.6	2.9	15.1	2500	11	28.6	8.65
3	7.5	2.7	18.6	1350	14	48.5	7.46
4	7.2	3.1	18.7	1450	16.5	37.6	9.4
<b>Surface Course B</b> (Crushed Limestone, Crushed Limestone Screenings, Sand)							
1	4.65	3.1	11.6	4420	15	31.3	5.61
2	6.0	3.0	15.2	2790	12	28.9	9.13
3	7.5	3.1	18.3	1530	12.5	47.3	7.34
4	8.0	2.9	19.7	1720	14.0	33.7	11.45
<b>Base Course</b> (Crushed Gravel, Crushed Gravel Screenings, Sand)							
1	4.0	1.7	10.5	3000	13.5	28.0	6.52
2	5.2	2.1	13.7	2540	12	30.9	7.85
3	7.0	2.3	17.7	2050	14	50.6	6.80
4	7.5	2.3	18.5	1470	12.5	38.1	9.64

\* After allowing for asphalt absorption by aggregate.

**TABLE 4**

**COMPARISON OF ACTUAL FILM THICKNESS WITH STANDARD FILM THICKNESS**

Paving Mixture Type	VMA %	Surface Area ft. <sup>2</sup> /lb.	Actual Film Thickness Microns	Standard Film Thickness Microns	Ratio Actual Thickness Std. Thickness
<b>Surface Course A</b> (Crushed Gravel, Crushed Gravel Screenings, Sand)					
1	12.0	31.3	5.89	6.34	0.93
2	15.1	28.6	8.65	6.73	1.29
3	18.6	48.5	7.46	4.57	1.63
4	18.7	37.5	9.40	5.45	1.72
<b>Surface Course B</b> (Crushed Limestone, Crushed Limestone Screenings, Sand)					
1	11.6	31.3	5.61	6.34	0.88
2	15.2	28.9	9.13	6.73	1.36
3	18.3	47.3	7.34	4.88	1.50
4	19.7	33.7	11.45	6.05	1.89
<b>Base Course</b> (Crushed Gravel, Crushed Gravel Screenings, Sand)					
1	10.5	28.0	6.52	6.85	0.95
2	13.7	30.9	7.85	6.41	1.22
3	17.7	50.6	6.80	4.65	1.46
4	18.5	38.1	9.64	5.54	1.74

\* After allowing for asphalt absorption by aggregate.



Fig. 1 Badly Ravelled Pavement Due To Serious Underasphalting



Fig. 2 Serious Flushing Or Bleeding Due To Excessive Asphalt



Fig. 3 Same Paving Mixture As For Fig. 2 But On A Nearby Street With Lower Traffic Volume

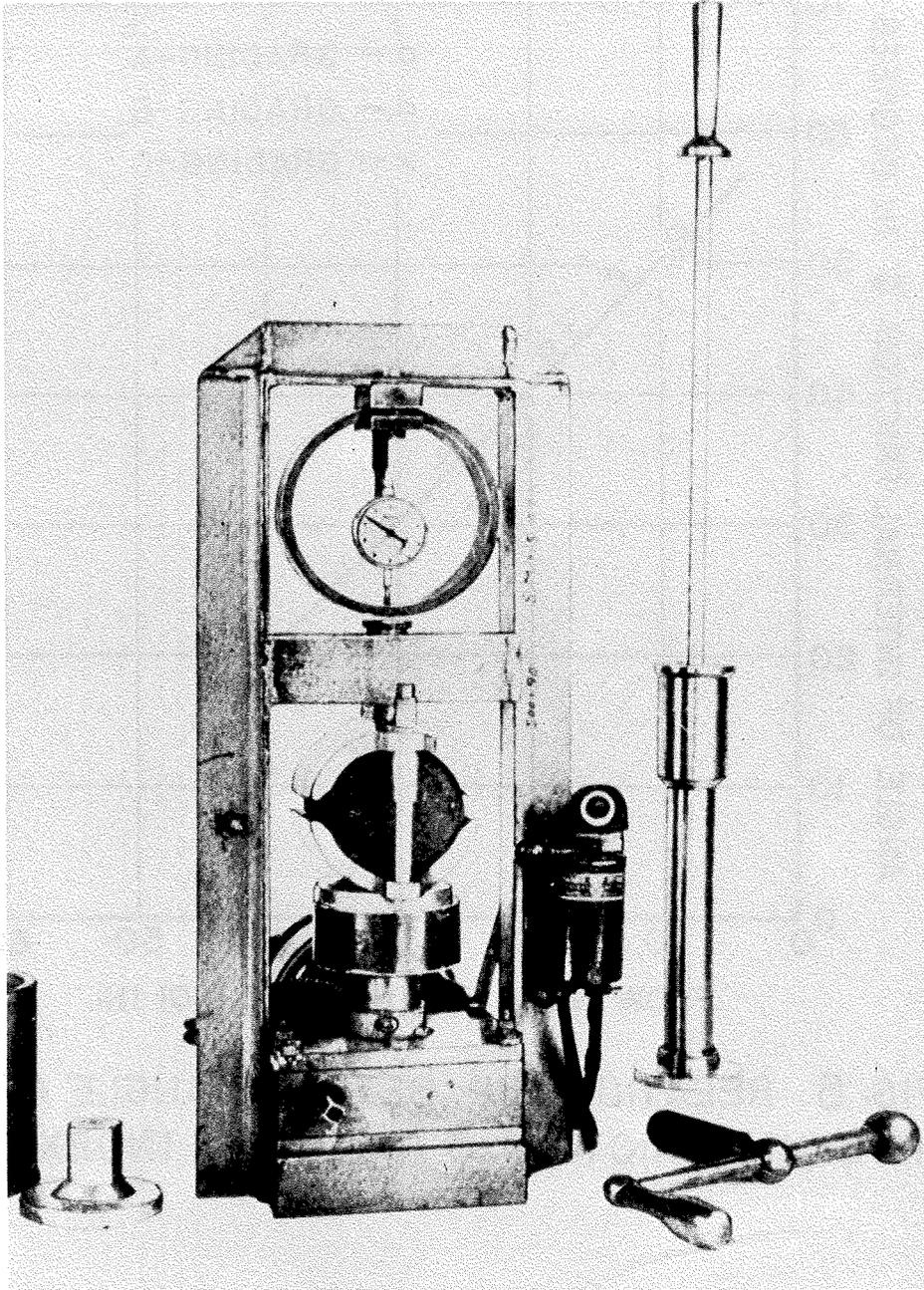


Fig. 4 Marshall Stability Apparatus For Field Or Laboratory Use

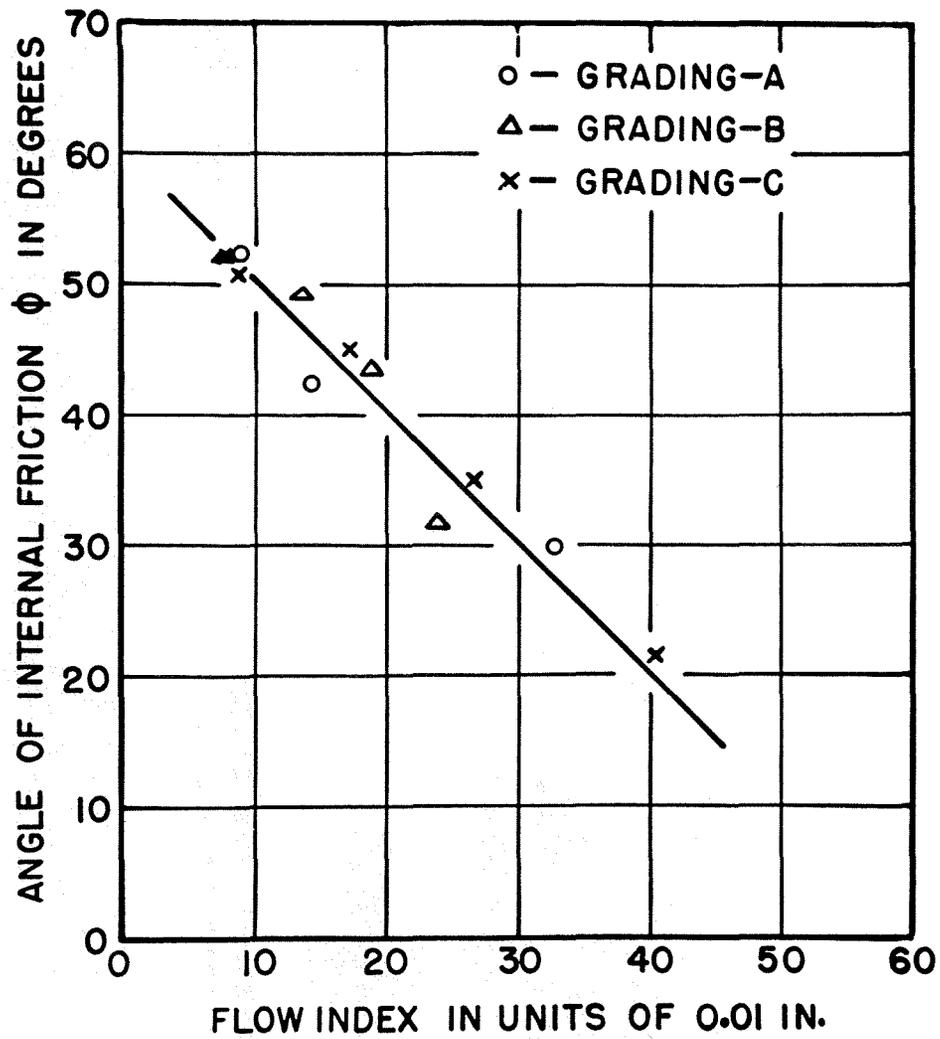


FIG. 5 RELATIONSHIP BETWEEN ANGLE OF INTERNAL FRICTION  $\phi$  AND FLOW INDEX

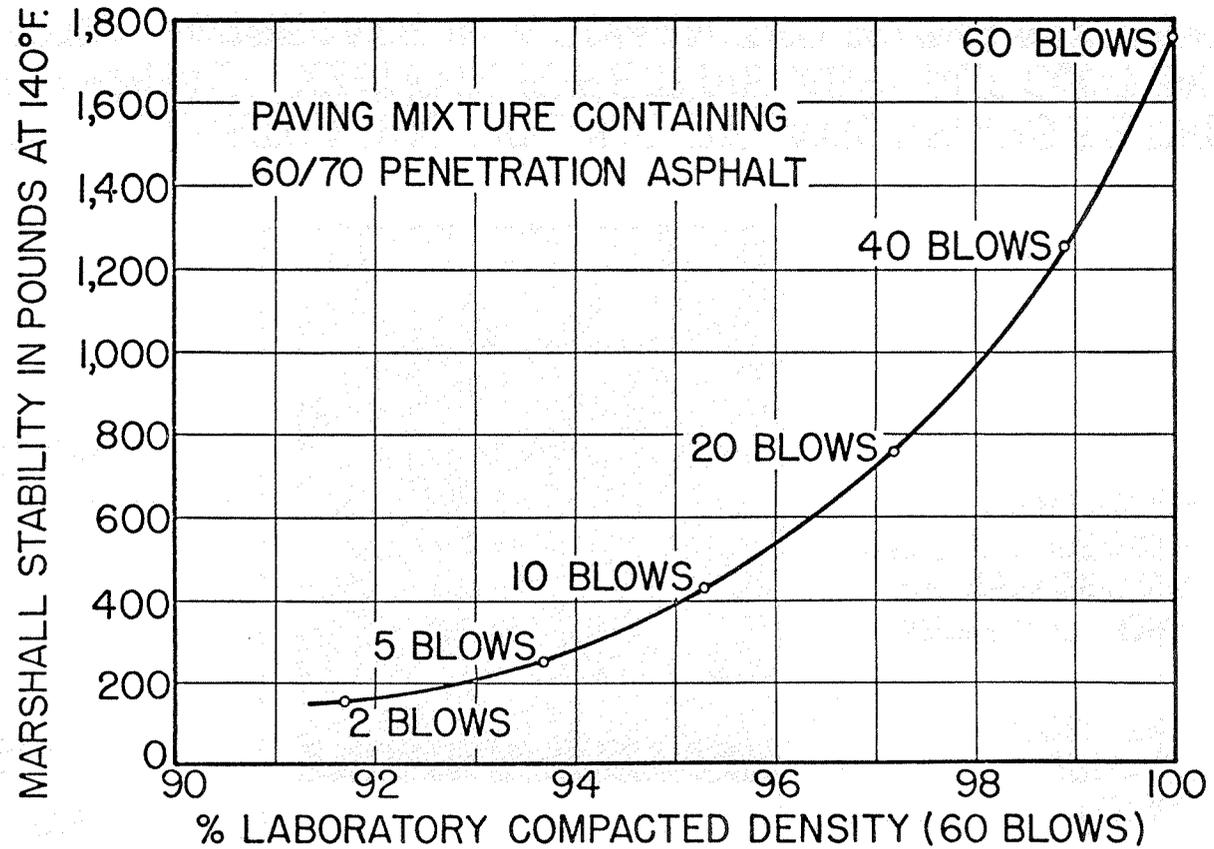


FIG. 6 ILLUSTRATING MARSHALL STABILITY VERSUS PERCENT LABORATORY COMPACTED DENSITY.

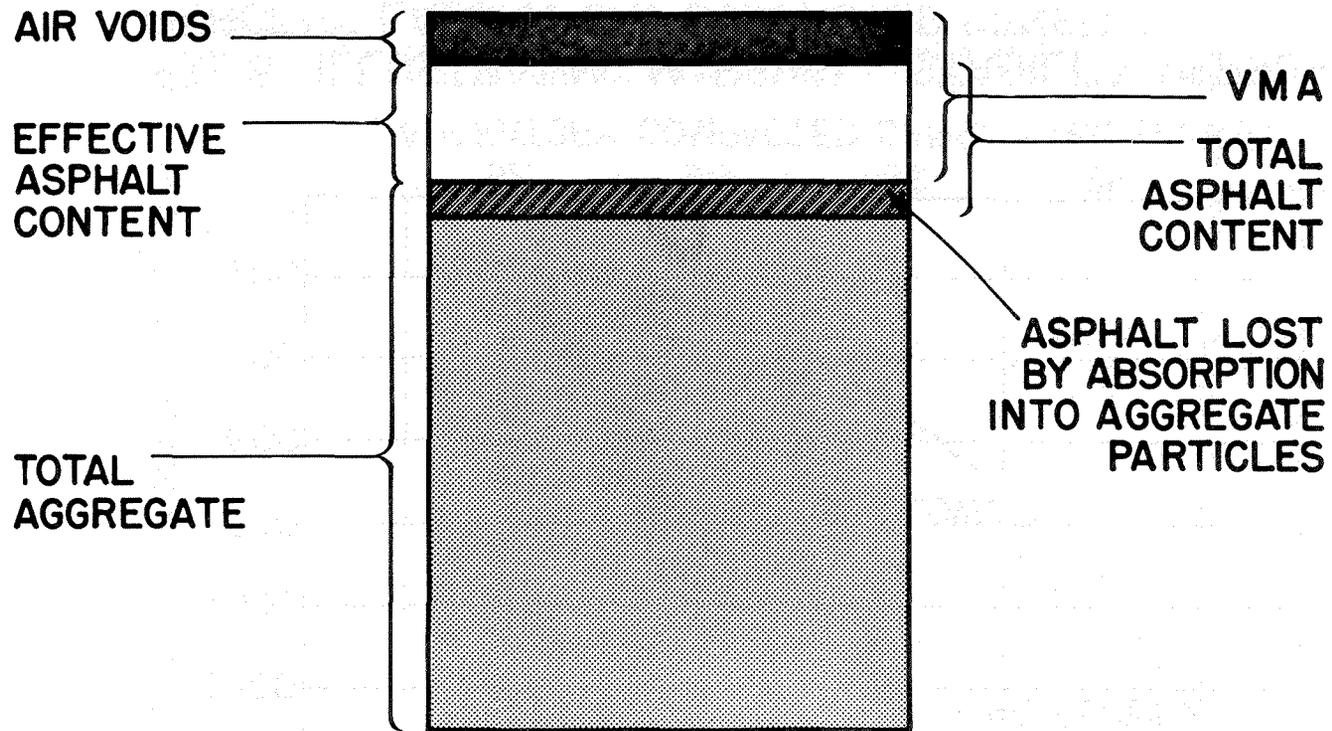
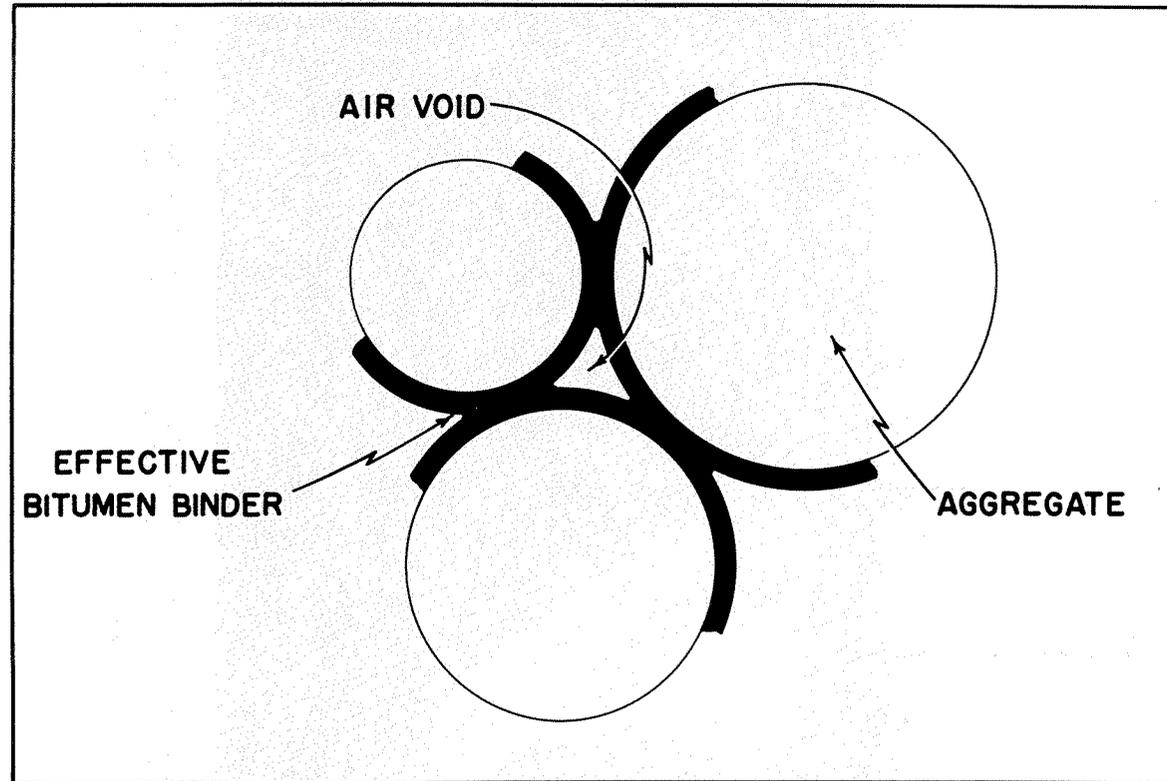


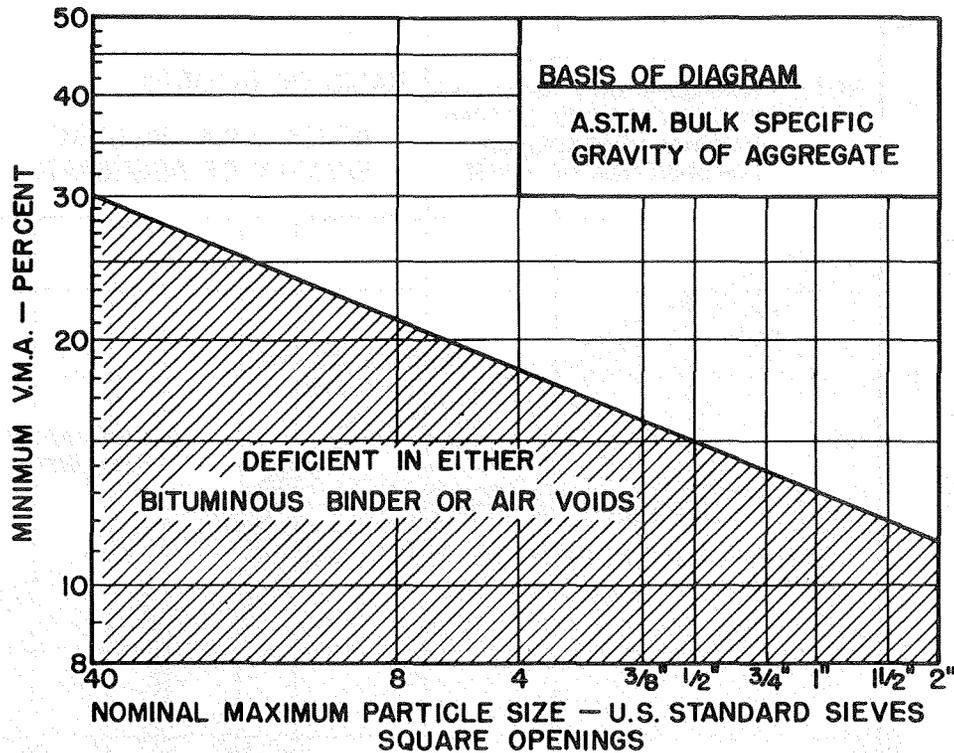
FIG. 7 ILLUSTRATING VOLUME RELATIONSHIPS BETWEEN TOTAL ASPHALT CONTENT, EFFECTIVE ASPHALT CONTENT AND TOTAL AGGREGATE IN A COMPACTED PAVING MIXTURE.



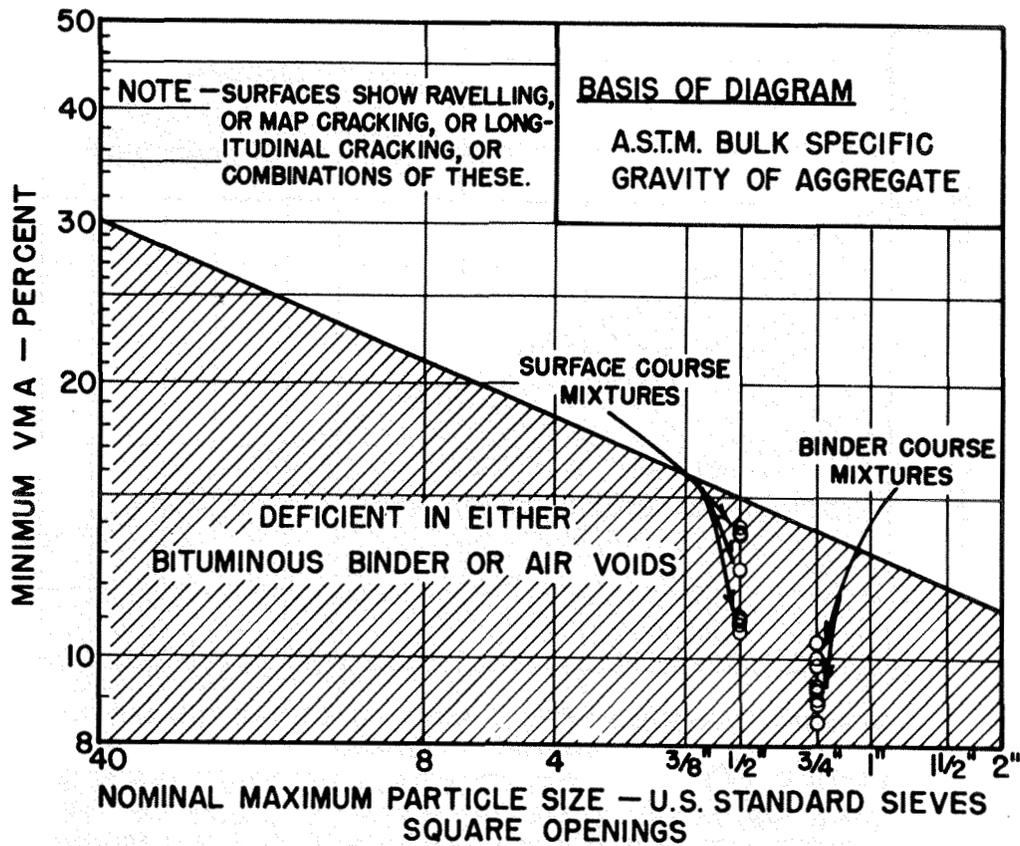
**FIG. 8 ILLUSTRATING VMA, AIR VOIDS AND EFFECTIVE BITUMEN CONTENT IN A COMPACTED BITUMINOUS PAVING MIXTURE WHEN THE AGGREGATE ABSORBS NO BITUMEN AND NO WATER.**



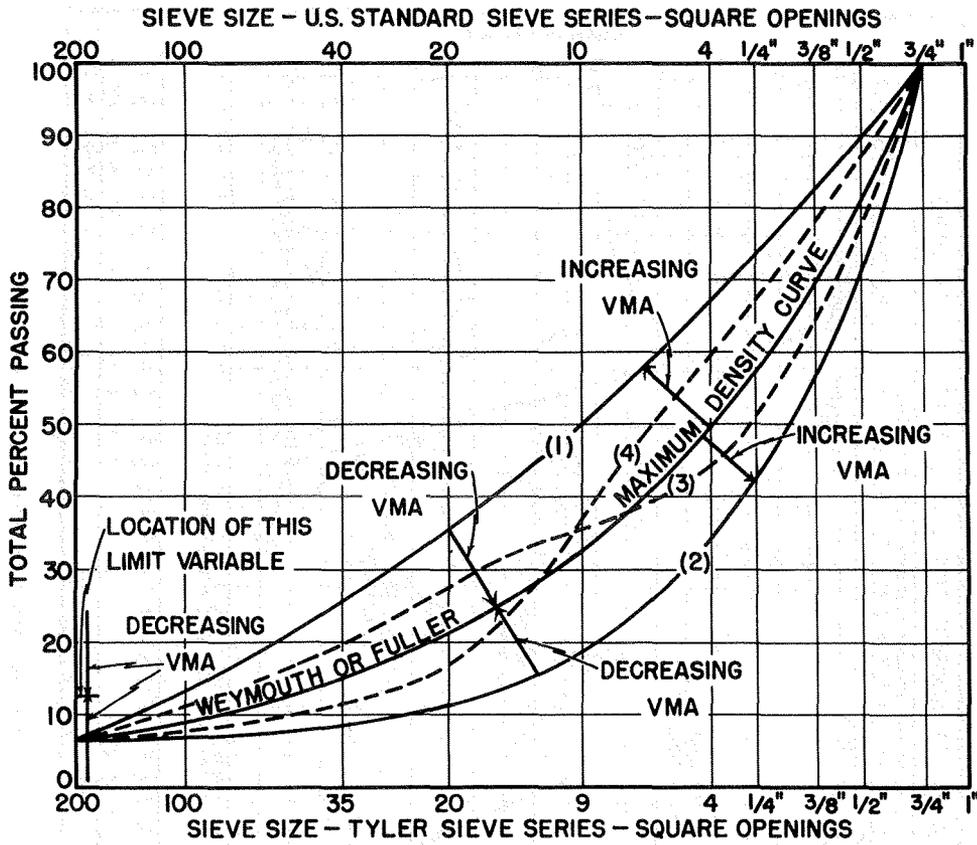
Fig. 9 Illustrating The Futility Of Trying To Cure A Flushed Or Bleeding Asphalt Pavement Condition By Burning Off The Asphalt That Has Oozed Out Onto The Pavement Surface.



**FIGURE 10** RELATIONSHIP BETWEEN MINIMUM V.M.A. AND NOMINAL MAXIMUM PARTICLE SIZE OF THE AGGREGATE FOR COMPACTED DENSE GRADED PAVING MIXTURES.



**FIG. II ILLUSTRATING LOW VMA VALUES OF MANY COMPACTED PAVING MIXTURES.**



**FIG. 12 INFLUENCE OF AGGREGATE GRADATION ON VOLUME OF VOIDS IN THE MINERAL AGGREGATE (VMA) FOR DENSE GRADED PAVING MIXTURES.**



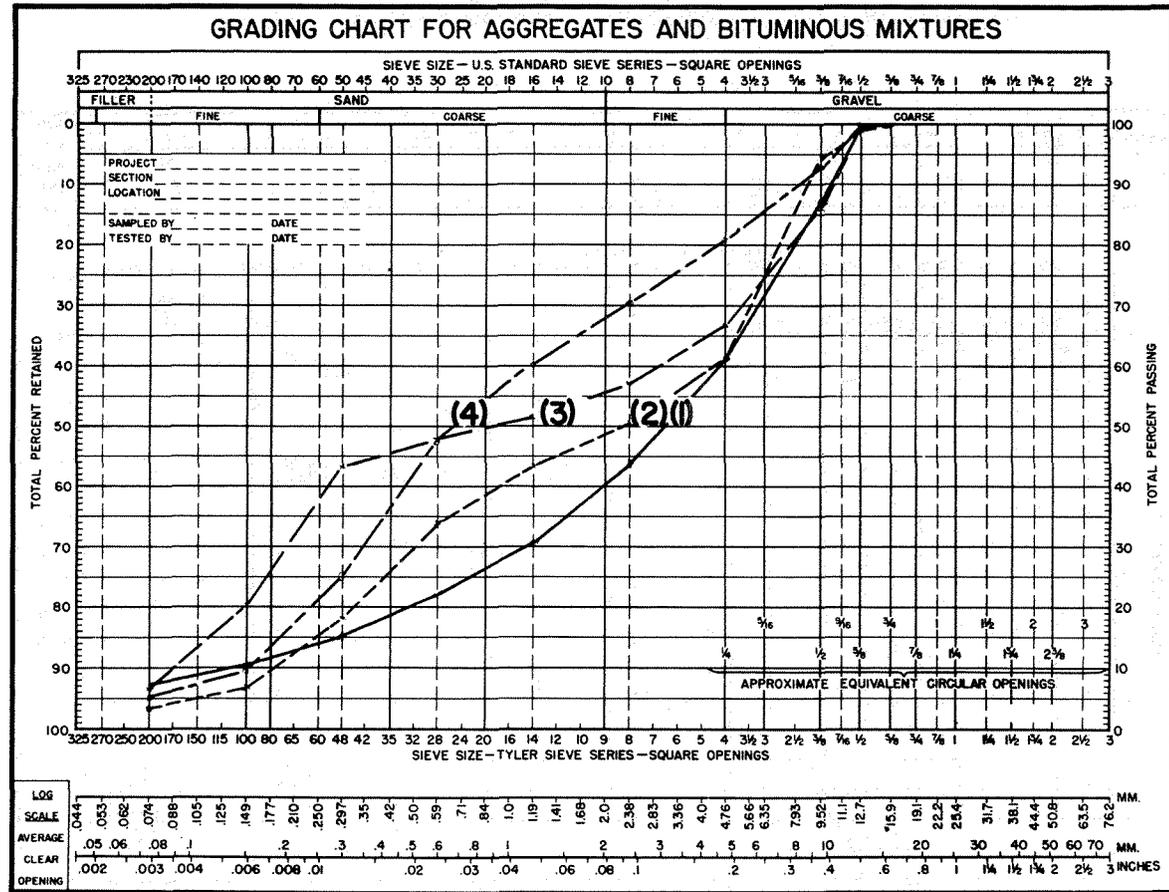


FIGURE 14 GRADING CURVES FOR SURFACE COURSE PAVING MIXTURES MADE WITH CRUSHED GRAVEL AND SAND.

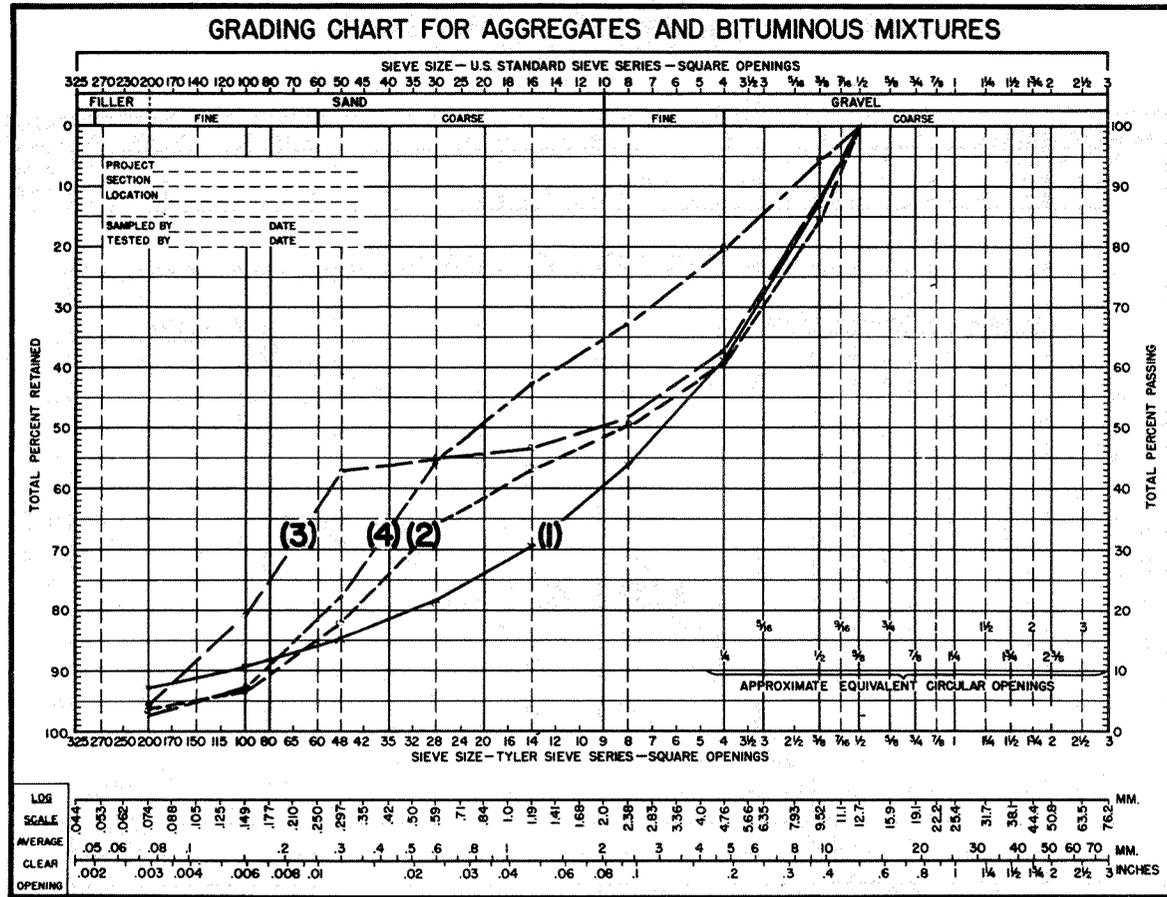


FIGURE 15 GRADING CURVES FOR SURFACE COURSE PAVING MIXTURES MADE WITH CRUSHED LIMESTONE AND SAND.

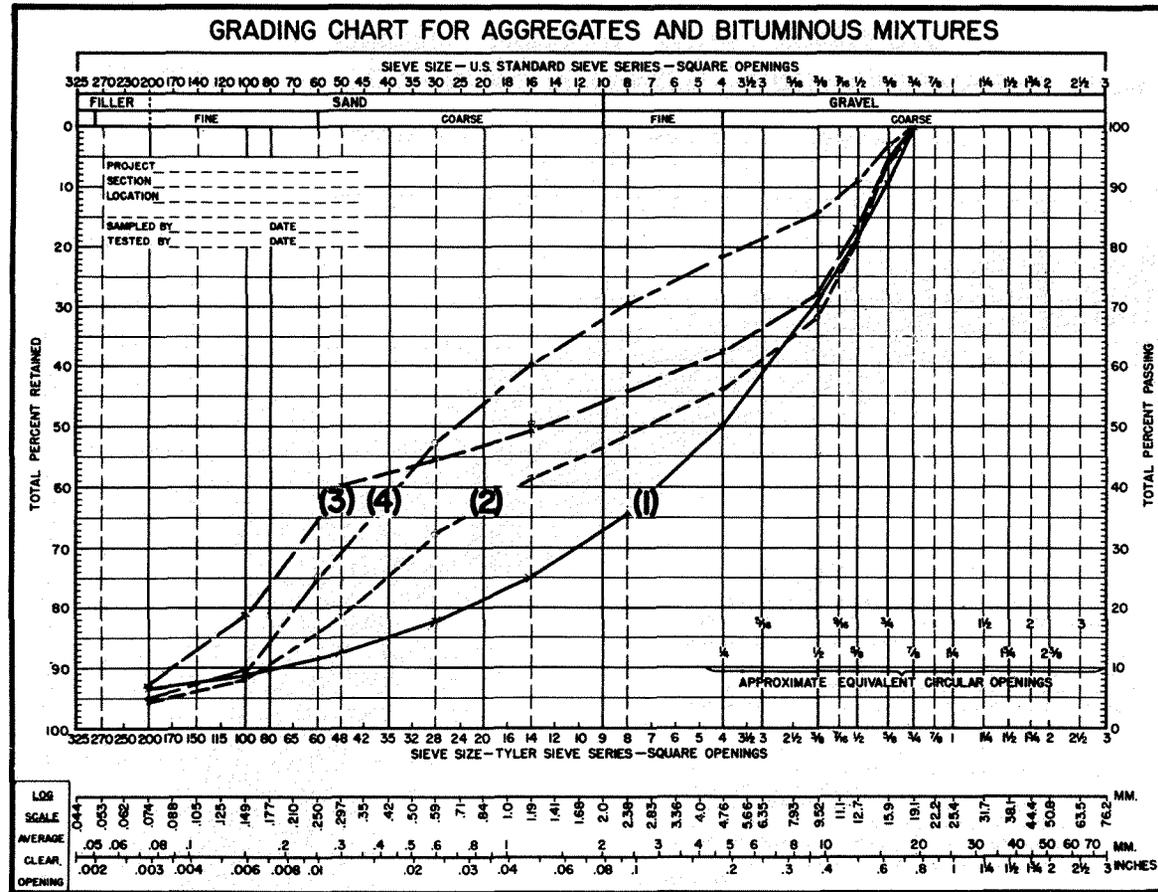
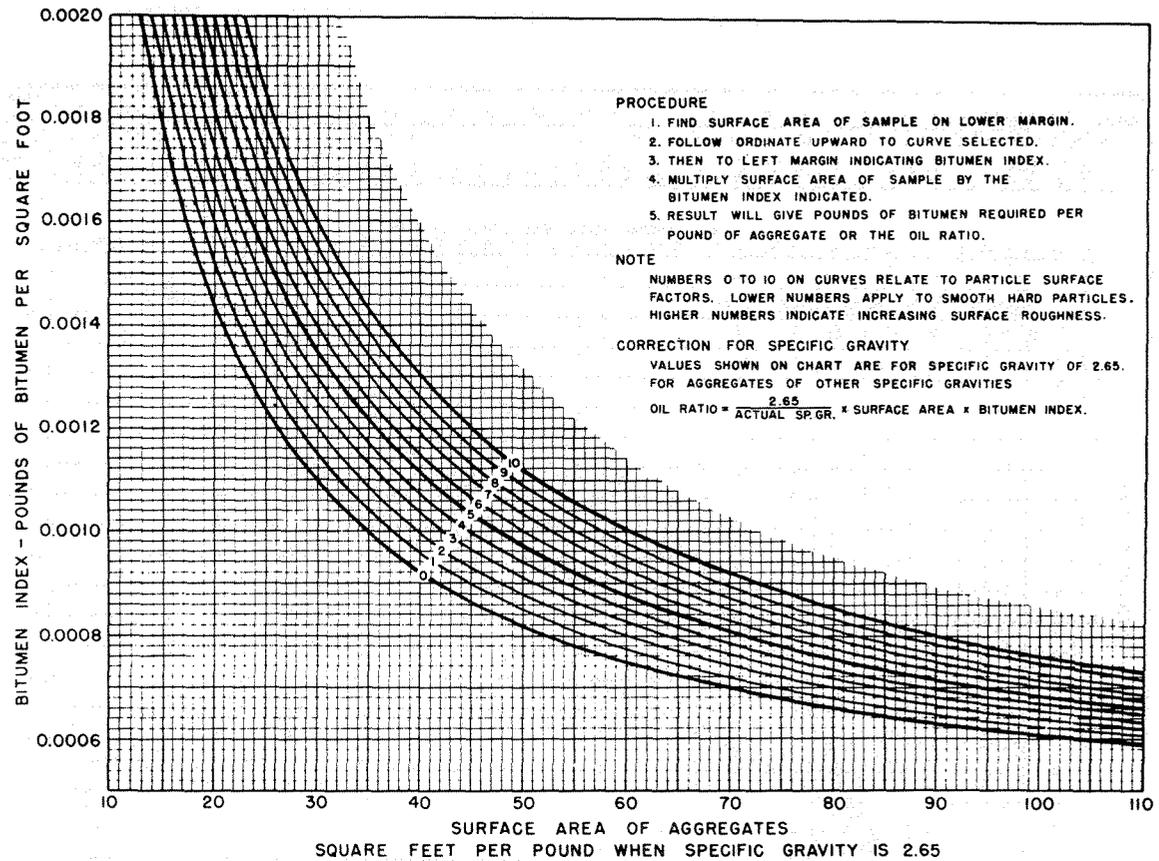


FIGURE 16 GRADING CURVES FOR BASE COURSE PAVING MIXTURES MADE WITH CRUSHED GRAVEL AND SAND.



**FIG. 17** CHART FOR DETERMINING BITUMINOUS BINDER REQUIREMENT FROM SURFACE AREA OF TOTAL AGGREGATE

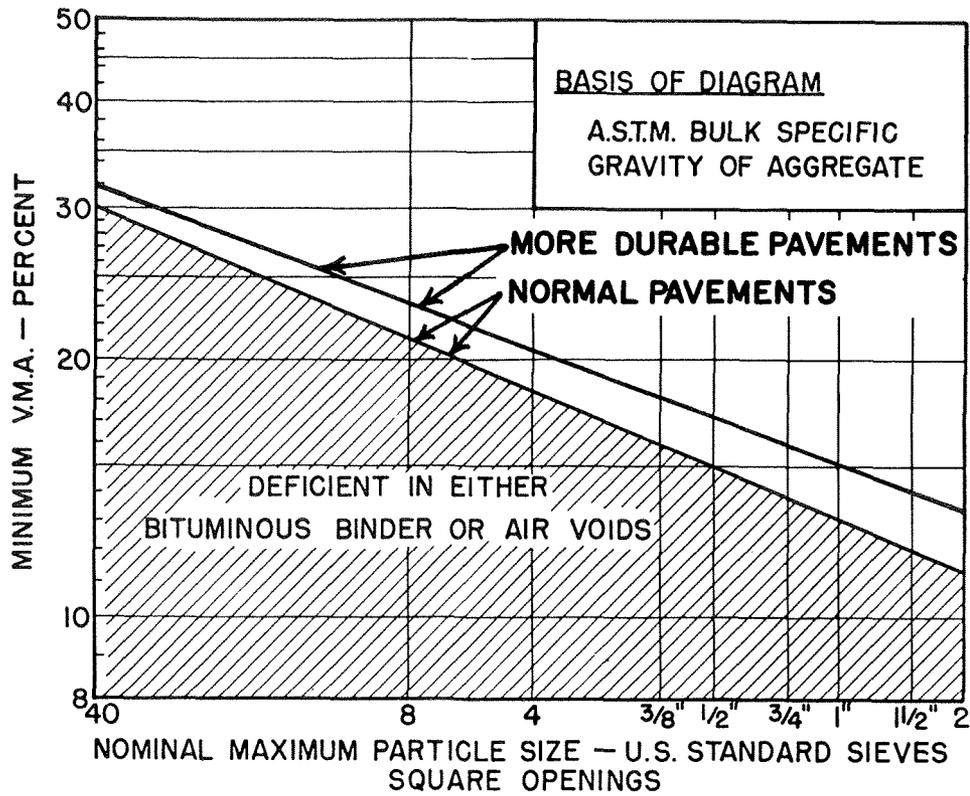


FIGURE 18 RELATIONSHIP BETWEEN MINIMUM REQUIRED VMA AND NOMINAL MAXIMUM PARTICLE SIZE FOR NORMAL AND FOR MORE DURABLE DENSE GRADED ASPHALT PAVING MIXTURES.