Influence of Tolerances from the Job-mix Formula on the Properties of Paving Mixtures

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ABSTRACT

Substantial ranges of values for air voids, VMA, Marshall stability, and flow index, due to differences in paving mixture composition because of AASHTO and ASTM tolerances, have been demonstrated by this investigation. The portion of each of these ranges of values below and above similar values for the corresponding job-mix formula has been determined. It is shown that the single curves presently employed to illustrate design data for various paving mixture properties, such as air voids, VMA, etc., versus asphalt content, should be replaced by bands whose width depends primarily upon the tolerances being applied. ASTM and AASHTO tolerances have a drastic effect on filler/bitumen ratios, and on paving mixture properties that are influenced by filler/bitumen ratios. The test data obtained demonstrate that the density of a paving mixture provided by its job-mix formula can fail by a substantial margin to represent the densities of other paving mixtures within the AASHTO and ASTM tolerance range. Consequently, the target density employed for controlling compaction by rolling in the field should ordinarily be provided by the laboratory compacted density determined on a sample of pavement taken at the precise location where the in-place density measurement was made. The test data tend to support end result specifications with realistic tolerances, and statistical quality control, wherein the contractor would assume full responsibility for the quality of paving operations, and would be subject to a graduated penalty scale for any section (lot) of pavement found to be off-specification.

Key Words: tolerances, job-mix formula, gradation, asphalt content, air voids, VMA, Marshall stability, flow index, particle index, filler/bitumen ratio, compaction control.

I: INTRODUCTION

The job-mix formula for a hot-mix asphalt paving mixture must satisfy specification requirements, and provides or should provide, the following items of information:

1. a single grading curve
2. a single asphalt content in per cent by weight
3. a single VMA value
4. a single air voids value
5. a single Marshall stability rating in pounds at 140°F
6. a single flow index measurement in units of 0.01 inch
7. a single value for 100 per cent laboratory compacted density.

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It is a physical impossibility for even the best operated and most closely controlled hot-mix plants to turn out batch after batch that will conform exactly to the value for each of the above seven basic items that are associated with the job-mix formula. Even if it were, the lack of sufficient precision in current sampling and testing procedures would result in some reported deviation from the job-mix formula. This is recognized in properly written specifications for asphalt concrete, and they therefore contain what are referred to as tolerances. Tolerances are the amounts or degrees by which a paving mixture is permitted to deviate from the job-mix formula and still be considered to be on-specification.

At the present time, even carefully written specifications ordinarily contain tolerances for only each of the first two of the above seven items, that is tolerances for permissible deviation away from the grading curve, and from the per cent asphalt content by weight stipulated by the job-mix formula. Tolerances are not normally specified for four other items, VMA, air voids, Marshall stability, and flow index, probably because the necessary information required does not appear to exist, although the specification limits for each of these four items are expected to be met.

The most generous tolerances from the job-mix formula permitted in North America of which the writer is aware, are those of the American Association of State Highway and Transportation Officials (AASHTO), and of the American Society for Testing and Materials (ASTM), which are identical. The tolerances specified by The Asphalt Institute and by a number of U.S. State Highway Departments are somewhat narrower than those stipulated by ASTM or AASHTO.

The tolerances permitted by AASHTO and ASTM are as follows (1).

Sieve Size	Tolerances Weight Per Cent of Total Aggregate
½ inch and larger	± 8.0
3/8 inch and No. 4 sieve	± 7.0
No. 8 and No. 16 sieves	± 6.0
No. 30 and No. 50 sieves	± 5.0
No. 200 sieve	± 3.0

Asphalt content, weight per cent of total paving mixture ± 0.5

If the gradation tolerances should fall outside the specified grading band for a paving mixture, ASTM considers this to be on-specification provided the full grading curve for the job-mix formula itself is within this grading band.

A question that might very naturally be asked about these tolerances is whether or not they are too generous. Since it is usually an internal matter with most government and other organizations, published inspection data obtained on paving mixtures during their construction are rather scarce. However, some information was published on North Dakota experience by Reich (2) at the 1974 CTAA meeting. Considerable inspection data suitable

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for this purpose appear in the paper by Farr, Millions, and Anderson (3) for presentation at this meeting, and inspection data on paving mixtures laid in Saskatchewan in 1975 are available (4). The main value $\bar{x}$ and the standard deviation σ have been provided for all of these inspection data.

The mean value $\bar{x}$ plus and minus one standard deviation ($\bar{x} \pm \sigma$), include only 67% of the test values. Consequently, in general, if the specified tolerance limits were based on the mean value $\bar{x}$ plus and minus one standard deviation, that is on $\bar{x} \pm \sigma$, 33 per cent of all inspection data would be outside (either above or below) the tolerance limits. Therefore, in applications of statistics on problems of this kind, it is common practice to base acceptable limits of variation on the mean value $\bar{x}$ plus and minus two standard deviations, that is on $\bar{x} \pm 2\sigma$, since these limits cover 95 per cent of all test data.

Using tolerance limits equal to $\bar{x} \pm 2\sigma$, the data for North Dakota published by Reich (1) indicated that the ASTM and AASHTO tolerances are exceeded by a considerable margin at the No. 4, No. 30, and No. 200 sieves, as well as for the paving mixture asphalt contents.

Inspection data listed by Farr, Millions, and Anderson (3) for 73 cold feed analyses for the paving mixture that was laid on Alberta Highway 43, Central Section 22, substantially exceeded the AASHTO and ASTM tolerances at the 3/8 inch and Nos. 4, 10 and 40 sieves. This is also true for the sieve analysis of aggregates recovered from 18 field extraction tests. The asphalt contents by field extraction on 17 paving mixture samples from this project show variations that are nearly twice the tolerance for asphalt content permitted by ASTM or AASHTO. Even the data for the daily asphalt quantities actually consumed relative to the amount of paving mixtures actually produced each day over a 17-day period, show a variation that materially exceeds the AASHTO and ASTM tolerance for asphalt content.

Inspection data on paving mixtures produced and laid in Saskatchewan in 1975 (4), while demonstrating good aggregate gradation control, show a very wide variation in asphalt content. For 15 out of 18 paving projects, these variations ($\pm 2\sigma$) from the mean value $\bar{x}$, exceed the $\pm$0.5 per cent range in asphalt content tolerance permitted by ASTM and AASHTO, and in two cases amounted to a variation ($\pm 2\sigma$) in asphalt content of 2.16 and 2.46 per cent, which is more than four times the asphalt content tolerance specified by AASHTO and ASTM.

These are just three examples illustrating the considerable variations in gradation and asphalt content that can occur in asphalt mixtures being placed on actual paving projects. It is suspected that inspection data obtained on numerous paving mixtures being placed elsewhere would show a similar pattern, which could be very much worse on paving projects for which no inspection is being provided. Consequently, the AASHTO and ASTM tolerances, far from being too generous, could provide the target for more effective paving mixture control on a great many paving projects.

The AASHTO and ASTM tolerances are limited to the sieve analyses and asphalt contents of paving mixtures. It is the principal purpose of this paper to present the results of an investigation into the influence that these

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ASTM and AASHTO tolerances can have on test values for the five major properties, VMA, air voids, Marshall stability, flow index, and 100 per cent laboratory compacted density, that are associated with sensible paving mixture design.

II: SCOPE OF THE INVESTIGATION

For this investigation, two HL3 and HL6 asphalt paving mixtures were employed. HL3 is a hot-laid surface course paving mixture, Figure 1, and HL6 is a hot-laid binder or base course paving mixture, Figure 2, specified by the Ontario Ministry of Transportation and Communications.

The two HL3 paving mixtures, A-HL3 and B-HL3, differed primarily in that for the A-HL3 paving mixtures, the grading curves for lower-upper and upper-lower, Figure 3, were permitted to be variable with respect to per cent passing the No. 4 sieve. For the B-HL3 paving mixtures, these two grading curves (lower-upper and upper-lower) were required to have the same per cent passing the No. 4 sieve as the corresponding grading curve for the job-mix formula, namely 55 per cent, Table 2. This difference in gradation was imposed on the B-HL3 paving mixtures to determine the influence that this restraint on the per cent passing the No. 4 sieve would have on the test values for paving mixture properties, when compared with similar data for the A-HL3 paving mixtures. For the HL6 paving mixtures, the lower-upper and upper-lower grading curves were likewise restricted (like the B-HL3 paving mixtures) to the same per cent passing the No. 4 sieve as the corresponding job-mix formula, which in this case was also 55 per cent.

Each of the two HL3 surface course and the HL6 base course studies have been conducted on paving mixtures made with three different types of aggregates:

1. all crushed aggregate with a particle index of 14.0
2. rounded aggregate with a particle index of 9.0
3. intermediate aggregate with a particle index of 11.5

The particle index (PI) of an aggregate is determined by the procedure described in ASTM D3398. The particle index measures the combined influence of differences in aggregate particle shape and surface texture. The higher the particle index, the more stable is the aggregate.

Until the job-mix formula has been determined, the grading curve can be anywhere between the upper and lower limits of the grading band, Figures 1 and 2. However, as soon as the grading curve for the job-mix formula has been established, the specified tolerances take over. To be on-specification, every batch of hot-mix must then have a gradation that lies within the hatched area of Figure 1 and 2 representing the range of ASTM or AASHTO tolerances permitted. To satisfy these tolerances, it must also have an asphalt content with $\pm$ 0.5 per cent of the asphalt content indicated by the job-mix formula.

It is clear that within the tolerance areas illustrated in Figures 1 and 2, an infinite number of grading curves could be drawn. However, as illustrated by Figure 3, this study concentrated on five grading curves within the tolerance area that probably provide the most extreme variation in paving

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mixture test values that can be obtained with normally graded paving mixtures:

1. the grading curve representing the job-mix formula, indicated by the line through the middle of the hatched area, Figures 1, 2 and 3, and referred to as "job-mix" in a number of the tables of data
2. the grading curve given by the extreme lower boundary of the hatched area, and referred to as "lower"
3. the grading curve corresponding to the extreme upper boundary of the hatched area, and designated "upper"
4. the grading curve provided by the extreme lower boundary of the hatched area through the coarse aggregate, but crossing over at the No. 4 sieve to the extreme upper boundary of the hatched area through the five aggregate sizes. This grading is labelled "lower-upper"
5. the grading curve provided by the extreme upper boundary of the hatched area through the coarse aggregate, but crossing over at the No. 4 sieve to the extreme lower boundary of the hatched area through the finer sizes. This grading has been designated "upper-lower"

The sieve analysis provided by each of these five grading curves is listed in Table 1 for A-HL3 paving mixtures, in Table 2 for B-HL3 paving mixtures, and in Table 3 for HL6 paving mixtures.

This paper will show the influence that these five well distributed grading curves, all within each tolerance grading band, together with an asphalt content tolerance limit of $\pm$ 0.5 per cent from that of the job-mix formula, can have on the test properties of the corresponding A-HL3, B-HL3, and HL6 paving mixtures.

III: TEST PROCEDURES

For each paving mixture, for example HL6 with a particle index of 14.0, each aggregate particle size in the paving mixture, ¾ to ½ inch, ½ to 3/8 inch, 3/8 to No. 4 sieve, No. 4 to No. 8, No. 8 to No. 16, No. 16 to No. 30, No. 30 to No. 50, No. 50 to No. 100, and No. 100 to No. 200, was required to have a particle index of 14.0. Similarly, for the paving mixtures with particle indices of 11.5 and 9.0, each of these sizes fractions was required to have a particle index of 11.5 and 9.0 respectively. This procedure was followed to ensure that only the influence of a change in gradation (for the five gradations employed, job-mix, lower, upper, lower-upper and upper-lower) was affecting the test results, and not the combined effect of a change in gradation and a change in aggregate properties. By maintaining a constant particle index for all sieve sizes throughout the study of each of the nine groups of paving mixtures (3 A-HL3, 3 B-HL3 and 3 HL6), the unknown influence that a change in aggregate properties would introduce was avoided.

Consequently, the first step in the investigation was the preparation of a sufficient quantity of each of the previously named sieve sizes with particle indices of 14.0, 11.5 and 9.0.

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The job-mix formula for each of the nine groups of paving mixtures was next established, which ordinarily required a substantial number of trials to obtain the combination of voids in the mineral aggregate (VMA) and air voids values that were set as the objective. For the HL3 job-mix formula this objective was a VMA requirement of 15.0 $\pm$ 0.1 per cent and an air voids value of 3.0 $\pm$ 0.1 per cent. For the HL6 job-mix formula, the objective was a VMA value of 14.0 $\pm$ 0.1 per cent and an air voids value of 3.0 $\pm$ 0.1 per cent. Ontario specifies a minimum VMA limit of 15.0 per cent for HL3 and a minimum of 14.0 for HL6. Ontario's specified range for air voids is from 2 to 4 per cent. The VMA values for the job-mix formulae for this investigation were set at the minima permitted by Ontario in order to determine by how much the AASHTO and ASTM tolerances would result in failure to conform to Ontario's minimum VMA limits. Similarly for this study, by establishing the job-mix formulae air voids value at Ontario's mid-point requirement of 3.0 per cent, it could be determined by how much these tolerances would result in air voids values that were outside of Ontario's specified range of 2 to 4 per cent.

Each of the individual aggregate sieve sizes, ¾ to ½ inch, ½ to 3/8 inch, 3/8 to No. 4 sieve, No. 4 to No. 8, No. 8 to No. 16, No. 16 to No. 30, No. 30 to No. 50, No. 50 to No. 100, No. 100 to No. 200, and passing No. 200 were weighed out separately in the quantity required for each Marshall briquette. This was duplicated to provide loose paving mixtures needed for the corresponding theoretical maximum specific gravity determination.

The asphalt cement employed throughout was 150/200 penetration meeting the Ontario specification.

For A-HL3 and B-HL3 the per cent passing No. 200 for each job mix formula was established by specifying a filler/bitumen ratio of 0.9 by weight, where all material passing No. 200 was considered to be filler. However, for HL6, the filler/bitumen ratio for each job-mix formula had to be reduced to 0.6 by weight. Otherwise to satisfy the VMA and air voids objectives, the grading curve for the job-mix formula would have been outside of Ontario's specified grading band.

As demonstrated by Table 4 for A-HL3 with a particle index of 14.0 for example, the aggregate representing each of the five gradings, job-mix formula, lower, upper, lower-upper, and upper-lower, was combined with three asphalt contents, the asphalt content provided by the job-mix formula, and this asphalt content $\pm$ 0.5 per cent. Consequently, for each job-mix formula and its four tolerances, 5 x 3 = 15 different paving mixtures had to be made and tested (five aggregate gradings, each with three asphalt contents). As indicated previously, for each paving mixture type, A-HL3 and HL6 there were three job-mix formulae, one for crushed aggregate with a particle index of 14.0, one for rounded aggregate with a particle index of 9.0, and one for intermediate aggregate with a particle index of 11.5. Therefore, for A-HL3, and total of 3 x 15 = 45 different paving mixtures had to be investigated. When the B-HL3 and HL6 paving mxiture types are included, the number of different paving mixtures made and tested became 3 x 45 = 135.

For each paving mixture, three Marshall briquettes compacted by 75 blows on each face with a Marshall double compactor (corresponding to

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75-blow hand compaction), and two loose paving mixtures, each of the same size as a Marshall briquette, were prepared. Each of the three Marshall briquettes for each paving mixture was tested for bulk specific gravity, air voids, VMA, Marshall stability and flow index, and the results were averaged for listing in Tables 4 and 12. The average of test values on each of the two loose mixes was used for theoretical maximum specific gravity and for asphalt absorption determinations, which are also reported in Tables 4 to 12.

Marshall stability and flow index values were read directly from charts operated by a stress/strain recorder attached to a Rainhart Automatic Tester and Recorder.

For each job-mix formula and its four corresponding tolerance gradations, the order of testing for the 15 paving mixtures was randomized.

Per cent VMA was determined from the bulk compacted specific gravity (ASTM D 2726) of the paving mixture, its asphalt content, and the ASTM bulk specific gravity of the aggregate (ASTM C 127 and C 128).

Per cent air voids was calculated from the ratio of the bulk compacted specific gravity determined by ASTM D 2726, and the theoretical maximum specific gravity determined by ASTM D 2041 (using 29 inches of vacuum).

IV: DISCUSSION OF TEST RESULTS

1. Tolerances Introduce Uncertainties Into Job-Mix Formulae

All of the test data obtained on the 135 paving mixtures are presented in Tables 4 to 6 for A-HL3, in Tables 7 to 9 for B-HL3, and in Tables 10 to 12 for HL6.

The influence of the AASHTO or ASTM tolerances on the range of values below and above those for the corresponding job-mix formula for bulk density in lb/ft^3, per cent VMA, per cent air voids, Marshall stability in lb at 140°F, flow index in units of 0.01 inch, and modulus of stiffness at 140°F in psi, is illustrated in Figures 4, 5 and 6 for A-HL3 with particle indices of 14.0, 11.5 and 9.0 respectively, in Figures 7, 8, and 9 for B-HL3 and in Figures 10, 11 and 12 for HL6 for the same respective values of particle index.

The modulus of stiffness in psi at 140°F is calculated from the Marshall stability and flow index values as follows:

$$\text{Modulus of stiffness} = \frac{\text{stress in psi}}{\text{strain in in/in}}$$

$$= \frac{\dfrac{\text{Marshall stability}}{4.0 \times 2.5}}{\dfrac{\text{Flow index}}{100} \times \frac{1}{4}}$$

$$= \frac{40 \text{ Marshall stability}}{\text{Flow index}}$$

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Because it takes both Marshall stability and flow index into account, the stiffness modulus tends to provide a more accurate value for the stability of a paving mixture than the Marshall stability by itself for paving mixtures with flow indices less than 16.0.

Figure 13 demonstrates the way in which Marshall design is ordinarily illustrated. Since only the job-mix formula grading is considered for this purpose, a single curve results when each test property is plotted versus a range of asphalt contents as shown in Figure 13. This approach totally disregards the influence that the specified tolerances can have on paving mixture design, which is illustrated in Figures 4 to 12.

In Figure 4, for example, which illustrates test data taken from Table 4 for A-HL3 with a particle index of 14.0, the broken lines present the job-mix formula gradation and the influence that the job-mix formula asphalt content $\pm$ 0.5 per cent has on the value of each paving mixture property referred to. However, as demonstrated by the solid lines, the tolerances introduce a very wide variation into the value of each paving mixture property. For instance, at the job-mix formula asphalt content of 6.0 per cent, the corresponding air voids value is 2.9 per cent. At the job-mix formula asphalt content minus 0.5 per cent, or at 5.5 per cent, based on the single curve approach (broken line) currently used (Figure 13), the air voids value would be expected to be 4.0 per cent. However, because of AASHTO or ASTM tolerances, Figure 4 shows that at an asphalt content of 5.5 per cent the air voids value could be anywhere between 2.2 and 5.0 per cent. Those familiar with single line design charts like Figure 13 might argue that at the lower asphalt content of 5.5 per cent, the air voids value could not be less than the 2.9 per cent obtained for the job-mix formula at an asphalt content of 6.0 per cent.

This overlooks the fact that as shown in the middle chart on the left side of Figure 4, the VMA at 5.5 per cent asphalt is not necessarily the 14.9 per cent associated with the job-mix formula, but because of the tolerances can be as low as 13.2 per cent. Therefore, because at any given asphalt content, the air voids value moves up and down with the VMA value, at the asphalt content of 5.5 per cent in Figure 4 the air voids can have the low value of 2.2 per cent because the corresponding VMA value is only 13.2 per cent, instead of the 14.9 per cent associated with the job-mix formula grading.

Figures 4 to 12 illustrate the effect that the AASHTO or ASTM tolerances can have on other paving mixture properties for both surface course (A-HL3 and B-HL3) and base course mixes (HL6). Therefore, these Figures demonstrate that serious error can result when the job-mix formula design is represented by single curves as shown in Figure 13. Instead, because of the influence of tolerances in paving mixture properties, the single lines in Figure 13 should be expanded into bands as illustrated by Figures 4 to 12.

2. **Influence of Tolerances on Ranges of Test Values For Paving Mixture Properties**

Table 13 demonstrates the influence of ASTM and AASHTO tolerances on the range of each of 8 paving mixture properties for A-HL3 with

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particle indices of 14.0, 11.5 and 9.0. The lowest, highest and job-mix formula values are posted for each of the eight properties. In the right hand column, the range or difference between the highest and lowest values for each property is listed. Similar information is given in Table 14 for B-HL3 with particle indices of 14.0, 11.5 and 9.0, and in Table 15 for HL6 with particle indices of 14.0, 11.5 and 9.0.

In Tables 13, 14 and 15, the grading, job-mix, lower, upper, lower-upper, or upper-lower, responsible for the lowest or highest value has been indicated. While the lowest and highest values are normally associated with either lower-upper or upper-lower gradings, in many cases the difference between these and one of the other gradings is small.

The right hand columns of Tables 13, 14 and 15 demonstrate that the range between the highest and lowest values for each of these eight paving mixture properties due to the tolerances, is quite substantial in every case.

3. Influence of Tolerances on Ranges of Test Values for Paving Mixture Properties Above and Below the Corresponding Job-Mix Formula

In view of the substantial range of test values on paving mixture properties that are listed in the right hand column of each of Tables 13, 14 and 15, the question arises as to whether most of this range of values lies above or below the corresponding job-mix formula. Answers to this question are provided in Table 16 for A-HL3 with particle indices of 14.0, 11.5 and 9.0, for B-HL3 with particle indices of 14.0, 11.5 and 9.0 and for HL6 with particle indices of 14.0, 11.5 and 9.0.

Values are tabulated in Table 16 for the amount by which lowest and highest values are below and above the corresponding job-mix formula value for each of the eight paving mixture properties listed for each of the nine paving mixtures included. The mean value $\bar{x}$, the standard deviation σ, and $\bar{x} + 2\sigma$ are given for each column of figures at the bottom of Table 16.

The following information is provided by the $\bar{x} + 2\sigma$ values in the bottom row of Table 16:

1. for air voids, the higher range of values, 3.4 per cent, is above the job-mix formula value
2. for VMA, the greater range of values, 2.99 per cent, is below the job-mix value
3. for Marshall stability, the greater range of values, 1138 pounds, is below the job-mix formula value
4. for flow index, the higher range of values, 6.9 units of 0.01 inch, is above the job-mix value
5. for modulus of stiffness, the greater range of values, 6481 psi, is below the job-mix formula value
6. for bulk specific gravity of the Marshall briquettes, the range of values, 0.070, both below and above the job-mix formula, is equal

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7. for 100 per cent laboratory compacted density, the range of values, 4.4 lb/ft^3, both below and above the job-mix formula, is equal
8. for filler/bitumen ratio by weight, the higher range of values, 0.69, is above the job-mix formula value.

The data of Table 16 emphasize the substantial margin by which job-mix formula values can fail to represent the actual test values for paving mixture properties, because of the uncertainties introduced by paving mixture tolerances.

4. Influence of Restraints on Lower-Upper and Upper-Lower Grading Curves

The principal difference between the A-HL3 and B-HL3 paving mixtures was that the lower-upper and upper-lower grading curves for the B-HL3 paving mixtures were required to cross the No. 4 sieve at the same 55 per cent passing that had been established by the grading curves for the corresponding job-mix formulae, Table 2. The lower-upper and upper-lower grading curves for the A-HL3 paving mixtures were not subject to this restraint, Table 1.

A comparison of the ranges of test values for paving mixture properties for A-HL3 in Table 13, with those for B-HL3 in Table 14 show differences that appear to be relatively small for paving mixtures containing aggregates with a particle index of 14.0, but become successively larger for paving mixtures containing aggregates with particle indices of 11.5 and 9.0 respectively. Consequently, Student's t test was applied to the data of Tables 13 and 14 to determine whether or not these differences are statistically significant. Table 17 indicates how this comparison was made for A-HL3 and B-HL3 paving mixtures containing aggregates with a particle index of 9.0.

Columns two and three from the left in Table 17 contain the actual range of values for each test property for A-HL3 and B-HL3 paving mixtures made with aggregates having a particle index of 9.0 that are listed in Tables 13 and 14, respectively. To give each of these ranges of values the same weight numerically, each value for A-HL3 in column 2 from the left in Table 17 was assigned a value of 100 in column 4 from the left. Each value for the B-HL3 paving mixtures in column 5 from the left bears the same numerical relationship to the corresponding value in column 4 from the left, that this value in column 3 from the left bears to the corresponding value in column 2 from the left. From this point on, the standard method for conducting the calculations for Student's t test was followed (5), as illustrated at the bottom of Table 17.

Any table of Student's t test values versus number of degrees of freedom indicates that a Student's t test value of 3.53 for 6 degrees of freedom is highly significant in a statistical sense. Consequently, for weaker paving mixtures containing aggregate with a particle index of 9.0, forcing the extreme grading curves within the ASTM or AASHTO tolerance bands, eg. lower-upper and upper-lower, to have the same per cent passing the No. 4 sieve as the job-mix formula (the B-HL3 paving mixtures), in general can be expected to result in a narrower range of

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test values for paving mixture properties than those for paving mixtures for which this restraint does not apply (the A-HL3 paving mixtures). Calculations similar to those illustrated in Table 17, indicate that this also applies in a somewhat lesser degree to stronger paving mixtures containing more stable aggregates with a particle index of 11.5. However, for very strong paving mixtures containing highly stable aggregates with a particle index of 14.0, Student's t test calculations indicate no overall statistically significant difference between the ranges of values for each paving mixture property, regardless of whether these restraints were applied to the lower-upper and upper-lower grading curves or not.

Therefore, the information provided in this section implies that in general, the locations of extreme grading curves within the AASHTO and ASTM grading band, eg. lower-upper and upper-lower, can have a very marked effect on reducing (B-HL3) or increasing (A-HL3) the range of test values for paving mixture properties for weaker paving mixtures made with more or less rounded aggregates having a low particle index (9.0-). On the other hand, the range of test values for paving mixture properties for highly stable paving mixtures made very largely with crushed aggregates with a high particle index (14.0+), appears to be independent of the locations of extreme grading curves, eg. lower-upper and upper-lower, within this tolerance band. As the particle indices of the aggregates in paving mixtures gradually decrease from 14.0 to 9.0 or less, and more particularly from 11.5 to 9.0 or less, that is, as the paving mixtures themselves become less and less stable, varied locations of the extreme grading curves within the tolerance bond are associated with an increasingly wider range of test values for paving mixture properties.

5. Statistical Evaluation of Range of Test Values Associated With Each Paving Mixture Property Due to Tolerances

ASTM and AASHTO tolerances specify permissible ranges only for aggregate gradation and asphalt content for asphalt paving mixtures. It was the principal purpose of this paper to investigate the effect of these tolerances on the corresponding ranges of values for air voids, VMA, Marshall stability, flow index, as well as other properties of asphalt paving mixtures.

The results of this investigation are summarized in Table 18, which provides the mean value $\bar{x}$, standard deviation σ, mean value minus two standard deviations $\bar{x} - 2\sigma$, and mean value plus two standard deviations $\bar{x} + 2\sigma$, for the **range** of test values for each of nine paving mixture properties listed in Table 18, that are caused by ASTM and AASHTO tolerances from job-mix formulae.

The right hand columns of Tables 13, 14 and 15 indicate the range of values determined for each paving mixture property for the nine job-mix formulae and their tolerances included in this investigation, 3 A-HL3 3 B-HL3 and 3 HL6. The nine values listed in these three tables for each paving mixture property were averaged to provide the mean value $\bar{x}$ shown opposite each paving mixture property in Table 18, and they also furnished the basis for the corresponding value for the standard deviation σ that is given in Table 18.

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It should be emphasized that the values listed in the two right hand columns of Table 18 are not actual test values. Instead, they indicate the minimum and maximum **ranges** of values from those provided by any job-mix formula for dense graded asphalt concrete **because of the influence of AASHTO and ASTM tolerances**, or at least for the job-mix formulae and tolerances investigated in this study.

The statistical working range of values in many applications is considered to be $\bar{x} \pm 2\sigma$, since this includes 95 per cent of all test data. Consequently, the second column from the right in Table 18, $\bar{x} - 2\sigma$, indicates the minimum range of test values found for each paving mixture property due to the extreme range of grading curves and asphalt contents permitted by AASHTO and ASTM tolerances, while the right hand column $\bar{x} + 2\sigma$ indicates the maximum range of test values measured for each paving mixture property. For example, at the present time, specifications often stipulate that the limits for per cent voids are to be from 3 to 5 per cent. This represents a permissible range of air voids of 2 per cent. It is of interest that the $\bar{x} - 2\sigma$ value for the minimum range of air voids indicated by this investigation is 2.1 per cent, Table 18. However, the maximum range of air voids, $\bar{x} + \sigma$, listed in Table 18 is 5.62 per cent. This means that for some paving mixture project for which AASHTO or ASTM tolerances were designated, if the minimum acceptable air voids value being enforced were 2.0 per cent, the minimum air voids range that might be encountered during the control of this paving project could be from 2.0 to 4.1 per cent, while the maximum range could be from 2.0 to 7.62 per cent.

Similarly, for paving mixtures for which AASHTO and ASTM tolerances have been specified, during the control of a paving mixture being constructed, Table 18 indicates that the **variation** in test values for:

(a) VMA, could range from a minimum of 0.97 to a maximum of 4.57 per cent

(b) Marshall stability, could range from a minimum of 467 pounds to a maximum of 1407 pounds

(c) Flow index, could range from a minimum of 5.20 to a maximum of 10.2 units of 0.01 inch.

Similar information is contained in Table 18 for the minimum and maximum range of test values that could be anticipated for several other paving mixture properties listed.

The manner in which either the minimum or maximum range of values listed in the two right hand columns in Table 18 would be divided below and above the corresponding value provided by the job-mix formula, can be determined by means of the data at the bottom of Table 16. For example, Table 18 indicates that the maximum range of values to be expected for Marshall stability is 1407 pounds, while Table 16 shows that $\bar{x} + 2\sigma$ for Marshall stability ranges from 1138 pounds below any corresponding job-mix formula to 728 pounds above. Consequently, the maximum range of Marshall stability, 1407 pounds, indicated by Table 18, would be split into $\frac{1138}{1138 + 728} \times 1407 = 858$ pound less than, and $\frac{728}{1138 + 728} \times 1407 = 549$ pounds more than the Marshall stability for

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any corresponding job-mix formula. Similarly, the minimum range of Marshall Stability, 467 pounds indicated by Table 18, would be divided into $\frac{1138}{1138 + 728}$ x 467 = 285 pounds less than, and $\frac{728}{1138 + 728}$ x 467 = 182 pounds more than the Marshall stability given by any corresponding job-mix formula.

6. **Influence of Tolerances on Filler/Bitumen Ratios**

Filler/bitumen ratios frequently appear to be considered a relatively constant factor in asphalt paving mixture design. However, the data in Tables 4 to 12, and the summarized data in Tables 13 to 15, demonstrate that the ASTM and AASHTO tolerances for aggregate gradation and asphalt content, can introduce very drastic variations into filler/bitumen ratios.

All of the A-HL3 and B-HL3 job-mix formulae were designed to have a filler/bitumen ratio of 0.9 by weight. Nevertheless, Table 13 shows that because of the AASHTO and ASTM tolerances, filler/bitumen ratios can range from a minimum of 0.38 to a maximum of 1.53 for A-HL3 surface course paving mixtures, while for the B-HL3 surface course mixtures, Table 14 indicates that the filler/bitumen ratios can range from 0.35 to 1.56.

The HL6 base course job-mix formulae were designed to have a filler/bitumen ratio of 0.6, but Table 15 demonstrates that because of the ASTM and AASHTO tolerances, the filler/bitumen ratios can range from a minimum of 0.039 to a maximum of 1.29, that is from 6.5 per cent to 215 per cent of the filler/bitumen ratio for the corresponding job-mix formula.

Table 18 shows that the minimum range of values for filler/bitumen ratio is 1.04, while the maximum range is 1.24. These ranges in Table 18 merely express in a different way the message that has been indicated by the data from Tables 13, 14 and 15.

The very wide range in filler/bitumen ratios that have been indicated, which result from the ASTM and AASHTO tolerance of $\pm$ 3.0 per cent passing No. 200 sieve, as well as the tolerance of $\pm$ 0.5 per cent in asphalt content, have a very marked effect on the corresponding values for air voids, VMA, Marshall stability and flow index of paving mixtures.

7. **Influence of Tolerances on Pavement Compaction Requirements**

Most specifications for the compaction of asphalt pavements during construction require rolling to 97 per cent or to some similar percentage of laboratory compacted density.

At present, compaction of a pavement by rolling in the field is often controlled by a nuclear densimeter. However, a nuclear device only gives a pavement density reading in pounds per cubic foot. It does not indicate directly the per cent of laboratory compacted density that has been achieved. Until a value for 100 per cent laboratory compacted density has been provided, there is no target with which the nuclear density reading can be compared. This is needed to determine whether

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rolling can be stopped because the specified density, for example 97 per cent of laboratory compacted density, has been achieved, or if more rolling is required.

Quite often, the target value employed is 100 per cent of the laboratory compacted density of the job-mix formula. The target may also be 100 per cent of laboratory compacted density provided occasionally by compaction tests in a field laboratory.

That either of these methods for establishing the target value for 100 per cent of laboratory compacted is of questionable value, is indicated by the test data in Tables 4 to 12, which indicate very clearly that because of AASHTO and ASTM tolerances, 100% of laboratory compacted density becomes a moving target. This moving target occurs because of the substantial influence that AASHTO and ASTM tolerances from the job-mix formula can have on the value for 100 per cent laboratory compacted density.

In Table 6 for example, 100 per cent laboratory compacted density for the job-mix formula is 148.3 lb/ft^3, and 97 per cent of this density is $0.97 \times 148.3 = 143.9$ lb/ft^3. This would be the target for compaction on many paving projects. However, the lowest value for 100 per cent laboratory compacted density for any paving mixture in Table 6 is 145.1 lb/ft^3. If this latter paving mixture were compacted to the target density of 143.9 lb/ft^3, it would be compacted to $\frac{143.9}{145.1} \times 100 = 99.2$ per cent of its own laboratory compacted density, which is far in excess of the normally specified compaction requirement of 97 per cent of laboratory compacted density.

On the other hand, in the same Table 6, the maximum value for 100 per cent laboratory compacted density for any paving mixture is 152.6 lb/ft^3. If this particular paving mixture were compacted to the target density of 143.9 lb/ft^3, it would have been compacted to only $\frac{143.9}{152.6} \times 100 = 93.6$ per cent of its laboratory density. This demonstrates what tolerances or variations in the composition of a paving mixture can do to field density determinations that are based on the density of the job-mix formula as the target density. They can result in accepting field compaction that is too low, or they can result in a blood, sweat and tears rolling effort in an attempt to achieve a pavement density that may be almost impossible to attain.

The compaction data in any one of the Tables 4 to 12 indicate the serious errors that can result from basing the field compaction requirement on the job-mix formula, on any other single compacted density, or on any target density other than that measured on the paving mixture at the exact location where the nuclear density reading has been taken. For example, in Table 4 which contains data for a job-mix formula and tolerances for A-HL3 with a particle index of 14.0, there are 10 paving mixtures for which 100 per cent laboratory compacted density is less than that for the job-mix formula, 149.3 lb/ft^3, and 4 paving mixtures for which 100 per cent laboratory compacted density is more than that for the job-mix formula. If the target for field compaction were 97 per cent of the job-mix formula laboratory compacted density, 0.97

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x 144.9 = 144.9 lb/ft^3, each of the 10 mixes would have to be compacted to more than 97 per cent of its laboratory compacted density to achieve the target density of 144.9 lb/ft^3, and the range of compaction would be from 97.1 to 98.4 per cent of the laboratory compacted densities for these 10 paving mixtures. On the other hand, each of the 4 paving mixtures would be compacted to less than 97 per cent of its laboratory compacted density, and the compaction range would be from 95.4 to 96.9 per cent of the laboratory compacted density of these 4 mixes. Consequently on the basis of the data in Table 4, because of the influence of tolerances, which merely reflect the differences from batch to batch in paving mixture composition, using 97 per cent of the job-mix formula density as the target for field compaction could result in field compaction actually ranging from 95.4 to 98.4 per cent of the target density.

Expressed in another way, based on the data for the 15 paving mixtures in Table 4, if each of these 15 mixes were to be compacted to 97 per cent of its own laboratory compacted density, this compaction requirement would range from 95.6 to 98.6 per cent of the laboratory compacted density of the job-mix formula, which is 149.4 lb/ft^3. For example, using the lowest 147.3 lb/ft^3, and the highest, 151.9 lb/ft^3, laboratory compacted densities listed in Table 4, 97 per cent of 147.3 lb/ft^3 = 142.9 lb/ft^3, which is $\frac{142.9}{149.4}$ x 100 = 95.6 per cent of the laboratory compacted density of the job-mix formula, while 97 per cent of 151.9 lb/ft^3 = 147.3 lb/ft^3, which is $\frac{147.3}{149.4}$ x 100 = 98.6 per cent of the job-mix formula laboratory compacted density. This demonstrates that neither the laboratory compacted density of the job-mix formula, nor of any other single paving mixture sample, nor of periodically selected paving mixture samples, can provide a satisfactory target density for controlling pavement compaction by rolling during construction.

Therefore, because of the tolerances, or differences in paving mixture composition from batch to batch or from time to time, while nuclear devices are highly useful for monitoring the density of hot-mix pavements being achieved by rolling during construction, the ultimate question as to whether or not any particular point on a pavement has been compacted to the specified per cent of laboratory compacted density, can only be answered by comparing the in-place density with the laboratory compacted density determined on a pavement sample taken from the same point on the pavement.

V: GENERAL COMMENTS

1. Because the aggregate grading curves selected for the paving mixtures for this investigation represent extreme ranges of gradation within the AASHTO and ASTM tolerances, it might be argued that the ranges of test values for paving mixture properties listed in Table 18 are wider than would be indicated by tests on normal paving mixture production on a large paving project.

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2. In reply to this, it can be pointed out that for this investigation the aggregate particle index for every size range in each paving mixture was the same. This was done to remove any influence that variations in aggregate characteristics in a paving mixture might have on paving mixture properties. Since in most paving mixtures being actually laid, the aggregate characteristics often vary substantially from sieve size to sieve size, this could be expected to widen the range of test values on paving mixture properties in comparison with those for paving mixtures for which the aggregate particle index was held constant.

3. For two of the three groups of paving mixtures for this study, B-HL3 and HL6, restraints were placed on the locations of the lower-upper and upper-lower grading curves. They were forced to pass through the same per cent passing the No. 4 sieve, 55 per cent, as the grading curve for the corresponding job-mix formula. It has been shown, Table 17, that these restraints narrowed the range of test values for each paving mixture property for paving mixtures (B-HL3) made with aggregates with particle indices of 11.5 and 9.0, relative to similar paving mixtures (A-HL3) that were free from these restraints. Since ordinary paving mixtures in the field are not subject to these restraints in gradation, this would tend to widen the range of test values for their paving mixture properties.

4. In the introduction, three examples were referred to which indicate that many paving mixtures being laid at the present time have gradation curves and asphalt contents that lie outside even the rather generous AASHTO and ASTM tolerances. This would also widen the range of test values on the paving mixture properties of these paving mixtures.

5. Whether in total, the influence of the three factors discussed in Items 2, 3 and 4 above, is equal to, exceeds, or falls short of the range of values for each paving mixture property listed in Table 18, which were determined on paving mixtures with the extreme grading curves within the ASTM and AASHTO tolerances that were used in this investigation, is a question that can be answered only by a substantial amount of inspection data for each of these paving mixture properties that have been carefully obtained on each of a relatively large number of pavement construction projects.

6. Because of the relatively wide range of paving mixture test values listed in Table 18, that are associated with AASHTO and ASTM tolerances, or that could result from the normal variation in composition of the paving mixture on any job, it is clearly very difficult for a field laboratory to maintain effective control over a paving operation. When a paving mixture goes off-specification at a mixing plant, a long section of off-specification pavement will very often have been laid before the fault is discovered and corrected. This is particularly true of today's high production hot-mix plants. These considerations would appear to support the use of end result specifications with realistic tolerances, and statistical quality control, wherein the contractor would assume full responsibility for the quality of the paving mixture and paving operations, and would be penalized on a graduated scale for any pavement section (lot) that was found to be off-specification.

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SUMMARY

1. It was the purpose of this paper to investigate the influence of the AASHTO and ASTM tolerances covering variations in gradation and asphalt content, on other paving mixture properties such as VMA, air voids, Marshall stability and flow index.

2. Based on rather limited inspection data available, it is shown that many paving mixtures being placed at the present time would fall outside of the ASTM and AASHTO tolerances which are the most generous known to the writer.

3. Two HL3 dense graded surface course paving mixtures, A-HL3 (Table 1) and B-HL3 (Table 2), and one HL6 (Table 3) base course paving mixture were studied in this investigation.

4. Five gradations were employed for each paving mixture, Figure 3, the gradation for the job-mix formula, plus each of four extreme limits of gradation, labelled lower, upper, lower-upper, and upper-lower, at the boundaries established by the AASHTO and ASTM tolerances.

5. The A-HL3 and B-HL3 paving mixtures differed in that for the B-HL3 paving mixtures, the gradations for the lower-upper and upper-lower grading curves were forced to pass through the same 55 per cent passing the No. 4 sieve as the job-mix formula, while the grading curves for the A-HL3 paving mixtures were not subject to this restraint. This same restriction was also applied to the HL6 base course paving mixtures.

6. The A-HL3 paving mixtures consisted of three different groups, each of which was made with a different aggregate type:

   (a) crushed aggregate with a particle index of 14.0
   (b) rounded aggregate with a particle index of 9.0
   (c) intermediate aggregate with a particle index of 11.5.

   The B-HL3 and HL6 paving mixtures were likewise made with these three different aggregates.

7. The asphalt cement employed throughout was 150/200 penetration complying with Ontario's specification.

8. Paving mixtures were compacted into Marshall briquettes, employing triplicate specimens, which were tested for bulk specific gravity, air voids, VMA, Marshall stability and flow index. The averaged test values obtained are listed in Tables 4 to 12.

9. These data are summarized in Tables 13 to 15, which demonstrate that for each job-mix formula and its four tolerances, the range between the lowest and highest values for each paving mixture property is quite substantial.

10. For each paving mixture, the range of test values for each paving mixture property below and above the corresponding value for the job-mix formula is indicated in Table 16.

11. By applying Student's t test to the test results for the A-HL3 and B-HL3 paving mixtures, Table 17, it is shown that the differences in test data between A-HL3 and B-HL3 paving mixtures are very significant

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statistically for the less stable paving mixtures made with rounded aggregates with a particle index of 9.0, but are not statistically significant for very stable paving mixtures made with crushed aggregates having a particle index of 14.0.

12. The range of test values found for each paving mixture property is summarized in Table 18.

13. Figures 4 to 12 demonstrate that the single curve approach to the design of paving mixtures illustrated by Figure 13, can be quite misleading when paving mixture tolerances are also considered.

14. It is shown that the ASTM and AASHTO tolerances can have a drastic effect on the filler/bitumen ratios for paving mixtures, and therefore on the paving mixture properties that are influenced by the filler/bitumen ratio.

15. The data obtained in this investigation indicate that the densities of paving mixtures within the tolerance range can be substantially different than the density of the corresponding job-mix formula. Therefore, while nuclear devices are highly useful for monitoring the density of hot-mix pavements being attained by rolling during construction, whether or not any particular point on a pavement has been compacted to the specified per cent of laboratory compacted density, can only be answered by comparing the in-place density with the laboratory compacted density determined on a pavement sample taken from the same point on the pavement.

16. Whether the range of test values for paving mixture properties due to AASHTO and ASTM tolerances listed in Table 18, is representative, too high, or too low, in comparison with inspection data on paving mixtures being laid, can only be determined by obtaining substantial inspection data on a number of pavement construction projects.

17. Because of the wide range of test values due to tolerances, or to variations in paving mixture composition from time to time, it is not easy for a field laboratory to maintain effective control over a paving operation. With the high capacity of many hot-mix plants, a long stretch of off-specification pavement may be laid before a fault is detected and corrected. This would appear to support the use of end result specifications with realistic tolerances, and statistical quality control, wherein the contractor would assume full responsibility for the quality of the paving mixture and the paving operations, and would be penalized on a graduated scale for any pavement section (lot) that was found to be off-specification.

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TABLE I

SIEVE ANALYSES FOR THREE A-HL3 JOB-MIX FORMULAE AND THEIR TOLERANCES

(a) For crushed aggregate paving mixtures - particle index 14.0

Sieve Size	Job-Mix Formula	Lower	Upper	Lower Upper	Upper Lower
		Per Cent Passing			
1/2 inch	100	100	100	100	100
3/8 "	80	73	87	73	87
No. 4 Sieve	55	48	62	48	62
" 8 "	51	45	57	45	51
" 16 "	49	43	55	43	43
" 30 "	40	35	45	40	35
" 50 "	22	17	27	27	17
" 100 "	9	5	13	13	5
" 200 "	5.75	2.75	8.75	8.75	2.75

(b) For Intermediate aggregate paving mixtures - particle index 11.5

Sieve Size	Job-Mix Formula	Lower	Upper	Lower Upper	Upper Lower
		Per Cent Passing			
1/2 inch	100	100	100	100	100
3/8 "	80	73	87	73	87
No. 4 Sieve	55	48	62	48	62
" 8 "	54	48	60	48	54
" 16 "	53	47	59	47	47
" 30 "	40	35	45	40	35
" 50 "	21	16	26	26	16
" 100 "	7	3	11	11	3
" 200 "	5.74	2.74	8.74	8.74	2.74

(c) For rounded aggregate paving mixtures - particle index 9.0

Sieve Size	Job-Mix Formula	Lower	Upper	Lower Upper	Upper Lower
		Per Cent Passing			
1/2 inch	100	100	100	100	100
3/8 "	80	73	87	73	87
No. 4 Sieve	55	48	62	48	62
" 8 "	53	47	59	47	53
" 16 "	52	46	58	46	46
" 30 "	47	42	52	42	42
" 50 "	22	17	27	27	17
" 100 "	8	4	12	12	4
" 200 "	5.54	2.54	8.54	8.54	2.54

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TABLE 2

SIEVE ANALYSES FOR THREE B-HL3 JOB-MIX FORMULAE AND THEIR TOLERANCES

(a) For crushed aggregate paving mixtures - particle index 14.0

Sieve Size	Job-Mix Formula	Lower	Upper	Lower Upper	Upper Lower
		Per Cent Passing			
1/2 inch	100	100	100	100	100
3/8 "	80	73	87	73	87
No. 4 Sieve	55	48	62	55	55
No. 8 "	51	45	57	51	45
No. 16 "	49	43	55	49	43
No. 30 "	39	34	44	44	34
No. 50 "	23	18	28	28	18
No. 100 "	7	3.0	11	11	3.0
No. 200 "	5.74	2.74	8.74	8.24	2.74

(b) For intermediate aggregate paving mixtures - particle index 11.5

Sieve Size	Job-Mix Forumla	Lower	Upper	Lower Upper	Upper Lower
		Per Cent Passing			
1/2 inch	100	100	100	100	100
3/8 "	80	73	87	73	87
No. 4 Sieve	55	48	62	55	55
No. 8 "	54	48	60	54	48
No. 16 "	53	47	59	53	47
No. 30 "	40	35	45	45	35
No. 50 "	24	19	29	29	19
No. 100 "	7	3.0	11	11	3.0
No. 200 "	5.85	2.85	8.85	8.85	2.85

(c) For rounded aggregate paving mixtures - particle index 9.0

Sieve Size	Job-Mix Formula	Lower	Upper	Lower Upper	Upper Lower
		Per Cent Passing			
1/2 inch	100	100	100	100	100
3/8 "	80	73	87	73	87
No. 4 Sieve	55	48	62	55	55
No. 8 "	53	47	59	53	47
No. 16 "	52	46	58	52	46
No. 30 "	47	42	52	52	42
No. 50 "	27	22	32	32	22
No. 100 "	7	3	11	11	3
No. 200 "	5.23	2.23	8.23	8.23	2.23

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TABLE 3

SIEVE ANALYSES FOR THREE HL6 JOB-MIX FORMULAE AND THEIR TOLERANCES

(a) For crushed aggregate paving mixtures - particle index 14.0

Sieve Size	Job-Mix Formula	Lower	Upper	Lower Upper	Upper Lower
		Per Cent Passing			
3/4 inch	100	100	100	100	100
1/2 "	80	72	88	72	88
3/8 "	70	63	77	63	77
No. 4 Sieve	55	48	62	55	55
No. 8 "	45	39	51	51	39
No. 16 "	40	34	46	46	34
No. 30 "	30	25	35	35	25
No. 50 "	16	11	21	21	11
No. 100 "	5	1	9	9	1
No. 200 "	3.6	0.6	6.6	6.6	0.6

(b) For intermediate aggregate paving mixtures - particle index 11.5

Sieve Size	Job-Mix Formula	Lower	Upper	Lower Upper	Upper Lower
3/4 inch	100	100	100	100	100
1/2 "	80	72	88	72	88
3/8 "	70	63	77	63	77
No. 4 Sieve	55	48	62	55	55
No. 8 "	50	44	56	53.5	44
No. 16 "	46	40	52	52	40
No. 30 "	35	30	40	40	30
No. 50 "	18	13	23	23	13
No. 100 "	5	1	9	9	1
No. 200 "	3.49	0.49	6.49	6.49	0.49

(c) For rounded aggregate paving mixtures - particle index 9.0

Sieve Size	Job-Mix Formula	Lower	Upper	Lower Upper	Upper Lower
3/4 inch	100	100	100	100	100
1/2 "	80	72	88	72	88
3/8 "	70	63	77	63	77
No. 4 Sieve	55	48	62	55	55
No. 8 "	49	43	55	55	43
No. 16 "	47	41	53	53	41
No. 30 "	36	31	41	41	31
No. 50 "	19	14	24	24	14
No. 100 "	4	1	8	8	1
No. 200 "	3.23	0.23	6.23	6.23	0.23

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TABLE 4

TEST DATA ON A-HL3 PAVING MIXTURES CONTAINING CRUSHED AGGREGATE - PARTICLE INDEX 14.0

Gradation / Test	Job-Mix Formula			Lower			Upper			Lower - Upper			Upper - Lower		
Asphalt Content % (total mix)	5.5	6.0	6.5	5.5	6.0	6.5	5.5	6.0	6.5	5.5	6.0	6.5	5.5	6.0	6.5
* Air Voids %	4.0	2.9	2.4	4.6	3.5	2.7	3.8	2.8	2.3	2.2	1.7	1.6	5.0	3.7	2.9
**VMA %	14.9	15.2	15.7	15.3	15.4	15.9	14.9	15.1	15.7	13.2	13.9	14.8	15.9	16.0	16.4
Bulk Spec. Grav.	2.388	2.395	2.391	2.378	2.386	2.386	2.389	2.397	2.391	2.435	2.428	2.415	2.360	2.370	2.371
100% Lab. Density lb/ft^3	149.0	149.4	149.2	148.2	148.9	148.9	149.1	149.6	149.2	151.9	151.5	150.7	147.3	147.9	148.0
Theor. Max. Spec. Gr.	2.487	2.467	2.450	2.493	2.472	2.452	2.483	2.467	2.448	2.485	2.461	2.441	2.490	2.470	2.454
Marshall Stability lb at 140°F	2512	1909	1565	2022	1802	1709	2592	1949	1549	2142	1728	1510	1658	1792	2090
Flow Index (units of 0.01 inch)	8.0	10.9	11.0	7.7	9.7	10.0	8.7	12.0	13.0	12.0	15.0	16.0	9.0	8.0	8.5
***Stiffness Modulus at 140°F, psi	12560	7006	5691	10504	7431	6836	11917	6497	4766	7140	4608	3775	7369	8960	9835
Ave. Aggregate Spec. Gr.	2.653	2.653	2.653	2.652	2.652	2.652	2.653	2.653	2.653	2.651	2.651	2.651	2.652	2.652	2.652
% Asphalt Absorption (wt. of aggregate)	0.92	0.90	0.94	1.00	1.00	0.99	0.85	0.90	0.90	0.99	0.98	1.00	0.90	0.80	0.79
Filler/Bitumen Ratio by weight	0.98	0.90	0.83	0.47	0.43	0.40	1.50	1.37	1.26	1.50	1.37	1.26	0.47	0.43	0.40

* % Air voids derived from ratio of bulk specific gravity to theoretical maximum specific gravity.

** % VMA based on the aggregate's ASTM bulk specific gravity

*** Calculated from - Modulus of stiffness = $\frac{40 \text{ Marshall Stability}}{\text{Flow Index}}$

NOTE - Compaction by 75 blows on each face by Marshall double compactor.

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TABLE 5

TEST DATA ON A-HL3 PAVING MIXTURES CONTAINING INTERMEDIATE AGGREGATE - PARTICLE INDEX 11.5

Gradation / Test	Job-Mix Formula			Lower			Upper			Lower-Upper			Upper-Lower		
sphalt Content % (total mix)	5.5	6.0	6.5	5.5	6.0	6.5	5.5	6.0	6.5	5.5	6.0	6.5	5.5	6.0	6.5
Air Voids %	4.0	3.1	2.6	4.7	3.9	3.0	3.3	2.7	2.3	1.8	1.3	1.0	5.6	4.2	3.9
*VMA %	14.4	14.9	15.6	15.1	15.3	15.8	14.0	14.7	15.4	12.5	13.3	14.2	16.2	16.1	16.7
ulk Spec. Grav.	2.387	2.387	2.379	2.367	2.373	2.372	2.401	2.393	2.386	2.441	2.431	2.419	2.336	2.350	2.345
00% Lab. Density b/ft^3	148.9	148.9	148.4	147.7	148.1	148.0	149.8	149.3	148.9	152.3	151.7	150.9	145.8	146.6	146.3
heor. Max. pec. Gr.	2.486	2.462	2.442	2.485	2.470	2.446	2.483	2.460	2.443	2.487	2.464	2.445	2.474	2.454	2.440
arshall tability lb at 140°F	1610	1618	1226	1866	1328	1144	1629	1568	950	1807	1327	978	1085	1219	1287
low Index (units f 0.01 inch)	7.0	9.9	10.3	7.0	7.0	7.8	8.7	10.3	11.0	12.0	14.0	14.0	7.0	7.0	7.0
** Stiffness Modulus t 140°F, psi	9200	6537	4761	10663	7589	5867	7490	6089	3455	6023	3791	2794	6200	6966	7354
ve. Aggregate pec. Gr.	2.635	2.635	2.635	2.634	2.634	2.634	2.637	2.637	2.637	2.636	2.636	2.636	2.633	2.633	2.633
Asphalt Absorption wt. of aggregate)	1.2	1.1	1.1	1.2	1.2	1.1	1.1	1.0	1.0	1.2	1.1	1.1	1.0	1.0	1.0
iller/Bitumen atio by weight	0.99	0.90	0.83	0.47	0.43	0.39	1.50	1.37	1.26	1.50	1.37	1.26	0.47	0.43	0.39

* % Air voids derived from ratio of bulk specific gravity to theoretical maximum specific gravity.
** % VMA based on the aggregate's ASTM bulk specific gravity.
*** Calculated from - Modulus of stiffness = $\frac{40 \text{ Marshall Stability}}{\text{Flow Index}}$

NOTE - Compaction by 75 blows on each face by Marshall double compactor.

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TABLE 6

TEST DATA ON A-HL3 PAVING MIXTURES CONTAINING ROUNDED AGGREGATE - PARTICLE INDEX 9.0

Test \ Gradation	Job-Mix Formula			Lower			Upper			Lower - Upper			Upper - Lower		
Asphalt Content % (total mix)	5.3	5.8	6.3	5.3	5.8	6.3	5.3	5.8	6.3	5.3	5.8	6.3	5.3	5.8	6.3
* Air Voids %	4.2	3.1	2.7	4.7	3.7	3.2	3.7	2.7	2.2	1.0	1.0	0.8	5.8	4.6	3.5
**VMA %	15.1	15.1	15.7	15.7	15.8	16.4	14.5	14.7	15.4	12.3	13.3	14.2	16.4	16.4	16.5
Bulk Spec. Grav.	2.366	2.377	2.373	2.351	2.360	2.356	2.381	2.389	2.380	2.446	2.431	2.420	2.326	2.338	2.348
100% Lab. Density lb/ft3	147.6	148.3	148.1	146.7	147.3	147.0	148.6	149.1	148.5	152.6	151.7	151.0	145.1	145.9	146.5
Theor. Max. Spec. Gr.	2.471	2.452	2.439	2.468	2.452	2.435	2.472	2.455	2.433	2.471	2.456	2.440	2.470	2.451	2.433
Marshall Stability lb at 140°F	1040	953	720	888	845	595	1450	1200	845	1200	913	680	651	846	697
Flow Index (units of 0.01 inch)	8.0	9.2	8.5	6.0	6.3	6.2	7.5	8.3	10.0	10.2	13.0	14.8	6.3	6.3	8.0
***Stiffness Modulus at 140°F, psi	5200	4143	3388	5920	5365	3839	7733	5783	3380	4706	2809	1838	4133	5371	3485
Ave. Aggregate Spec. Gr.	2.639	2.639	2.639	2.641	2.641	2.641	2.637	2.637	2.637	2.642	2.642	2.642	2.635	2.635	2.635
% Asphalt Absorption (wt. of aggregate)	0.70	0.72	0.81	0.63	0.68	0.70	0.75	0.80	0.72	0.66	0.73	0.79	0.74	0.74	0.75
Filler/Bitumen Ratio by weight	0.99	0.90	0.82	0.45	0.41	0.38	1.53	1.39	1.28	1.53	1.39	1.28	0.45	0.41	0.38

* % Air voids derived from ratio of bulk specific gravity to theoretical maximum specific gravity.

** % VMA based on the aggregate's ASTM bulk specific gravity.

*** Calculated from - Modulus of stiffness = $\frac{40 \text{ Marshall Stability}}{\text{Flow Index}}$

NOTE - Compaction by 75 blows on each face by Marshall double compactor.

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TABLE 7

TEST DATA ON B-HL3 PAVING MIXTURES CONTAINING CRUSHED AGGREGATE - PARTICLE INDEX 14.0

Test \ Gradation	Job-Mix Formula			Lower			Upper			Lower - Upper			Upper - Lower		
Asphalt Content % (total mix)	5.5	6.0	6.5	5.5	6.0	6.5	5.5	6.0	6.5	5.5	6.0	6.5	5.5	6.0	6.5
* Air Voids %	4.7	2.9	2.8	5.5	4.6	3.1	4.7	3.4	2.8	5.5	4.2	1.0	3.7	3.1	2.5
**VMA %	15.4	14.9	15.9	15.8	16.0	15.9	15.4	15.4	16.1	16.3	16.2	14.5	14.1	14.8	15.5
Bulk Spec. Grav.	2.376	2.402	2.386	2.362	2.369	2.384	2.374	2.388	2.382	2.350	2.365	2.426	2.409	2.403	2.395
100% Lab. Density lb/ft^3	148.3	150.0	149.0	147.5	147.9	148.8	148.2	149.1	148.7	146.7	147.6	151.5	150.4	150.0	149.5
Theor. Max. Spec. Gr.	2.494	2.473	2.454	2.500	2.483	2.461	2.491	2.472	2.450	2.488	2.470	2.450	2.502	2.480	2.456
Marshall Stability lb at 140°F	1982	2287	1486	1725	1738	1819	2034	1702	1280	1661	1741	1810	2365	1662	1226
Flow Index (units of 0.01 inch)	8.9	10.6	12	9.0	9.5	10.3	9.5	11.0	14.0	8.2	9.0	9.7	10.5	13.5	16.2
***Stiffness Modulus at 140°F, psi	8908	8630	4953	7667	7318	7064	8564	6189	3657	8102	7738	7464	9010	4924	3027
Ave. Aggregate Spec. Gr.	2.653	2.653	2.653	2.652	2.652	2.652	2.653	2.653	2.653	2.652	2.652	2.652	2.651	2.651	2.651
% Asphalt Absorption (wt. of aggregate)	1.0	1.0	1.0	1.2	1.2	1.2	0.99	1.0	0.94	0.94	0.95	0.94	1.2	1.2	1.1
Filler/Bitumen Ratio by weight	0.99	0.90	0.83	0.47	0.43	0.39	1.50	1.37	1.26	1.50	1.37	1.26	0.47	0.43	0.39

* % Air voids derived from ratio of bulk specific gravity to theoretical maximum specific gravity.

** % VMA based on the aggregate's ASTM bulk specific gravity.

*** Calculated from - Modulus of stiffness = $\frac{40 \text{ Marshall Stability}}{\text{Flow Index}}$

NOTE - Compaction by 75 blows on each face by Marshall double compactor.

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TABLE 8

TEST DATA ON B-HL3 PAVING MIXTURES CONTAINING INTERMEDIATE AGGREGATE - PARTICLE INDEX 11.5

Gradation / Test	Job-Mix Formula			Lower			Upper			Lower - Upper			Upper - Lower		
Asphalt Content % (total mix)	5.6	6.1	6.6	5.6	6.1	6.6	5.6	6.1	6.6	5.6	6.1	6.6	5.6	6.1	6.6
* Air Voids %	3.8	3.1	2.4	5.4	3.7	3.1	3.8	3.2	3.0	3.3	2.7	2.1	4.6	4.1	2.9
**VMA %	14.7	15.0	15.6	16.0	15.5	16.0	14.6	15.3	16.1	14.0	14.7	15.2	15.5	16.1	16.1
Bulk Spec. Grav.	2.389	2.392	2.388	2.354	2.378	2.378	2.390	2.384	2.374	2.407	2.400	2.399	2.368	2.362	2.376
100% Lab. Density lb/ft^3	149.1	149.3	149.1	147.0	148.5	148.5	149.2	148.8	148.2	150.3	149.8	149.8	147.8	147.5	148.3
Theor. Max. Spec. Gr.	2.483	2.469	2.447	2.489	2.471	2.445	2.485	2.464	2.447	2.489	2.467	2.450	2.482	2.463	2.446
Marshall Stability lb at 140^{o}F	1435	1185	845	872	1267	811	1480	992	782	1384	979	847	1294	941	858
Flow Index (units of 0.01 inch)	9.2	10.3	12.3	7.2	8.0	9.7	9.0	11.8	12.0	9.8	12.2	16.2	7.7	7.7	9.5
***Stiffness Modulus at 140^{o}F, psi	6239	4602	2748	4844	6335	3344	6578	3363	2607	5649	3210	2091	6722	4888	3613
Ave. Aggregate Spec. Gr.	2.643	2.643	2.643	2.644	2.644	2.644	2.643	2.643	2.643	2.643	2.643	2.643	2.644	2.644	2.644
% Asphalt Absorption (wt. of aggregate)	1.1	1.15	1.1	1.1	1.2	1.2	1.1	1.1	1.1	1.2	1.1	1.2	1.0	1.0	1.1
Filler/Bitumen Ratio by weight	0.99	0.90	0.83	0.48	0.44	0.40	1.49	1.36	1.25	1.49	1.36	1.25	0.48	0.44	0.40

* % Air voids derived from ratio of bulk specific gravity to theoretical maximum specific gravity.

** % VMA based on the aggregate's ASTM bulk specific gravity.

*** Calculated from - Modulus of stiffness = $\frac{40 \text{ Marshall Stability}}{\text{Flow Index}}$

NOTE - Compaction by 75 blows on each face by Marshall double compactor.

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TABLE 9

TEST DATA ON B-HL3 PAVING MIXTURES CONTAINING ROUNDED AGGREGATES - PARTICLE INDEX 9.0

Test \ Gradation	Job-Mix Formula			Lower			Upper			Lower - Upper			Upper - Lower		
Asphalt Content % (total mix)	5.0	5.5	6.0	5.0	5.5	6.0	5.0	5.5	6.0	5.0	5.5	6.0	5.0	5.5	6.0
* Air Voids %	3.3	2.9	2.6	4.8	3.5	2.5	3.3	3.2	2.3	3.3	2.5	2.3	4.3	3.1	2.9
**VMA %	14.3	15.0	15.7	15.5	15.6	15.7	14.2	15.1	15.6	14.3	14.6	15.6	15.2	15.3	16.0
Bulk Spec. Grav.	2.390	2.380	2.375	2.358	2.366	2.377	2.391	2.377	2.375	2.391	2.394	2.380	2.364	2.373	2.365
100% Lab. Density lb/ft3	149.2	148.6	148.3	147.2	147.7	148.4	149.3	148.4	148.3	149.3	149.5	148.6	147.6	148.1	147.6
Theor. Max. Spec. Gr.	2.472	2.453	2.438	2.478	2.453	2.437	2.473	2.455	2.432	2.472	2.456	2.437	2.469	2.450	2.435
Marshall Stability lb at 140^{o}F	819	595	503	541	377	312	932	837	496	811	794	522	499	467	354
Flow Index (units of 0.01 inch)	7.3	8.4	9.5	7.0	6.8	11.0	8.7	10.2	14.2	8.8	9.8	13.7	6.2	8.1	8.7
***Stiffness Modulus at 140^{o}F, psi	4488	2833	2118	3091	2218	1135	4285	3282	1397	3686	3241	1524	3219	2306	1628
Ave. Aggregate Spec. Gr.	2.648	2.648	2.648	2.650	2.650	2.650	2.646	2.646	2.646	2.650	2.650	2.650	2.647	2.647	2.647
% Asphalt Absorption (wt. of aggregate)	0.41	0.39	0.46	0.48	0.36	0.42	0.45	0.47	0.39	0.38	0.42	0.42	0.36	0.36	0.42
Filler/Bitumen Ratio by weight	0.99	0.90	0.82	0.42	0.38	0.35	1.56	1.41	1.29	1.56	1.41	1.29	0.42	0.38	0.35

* % Air voids derived from ratio of bulk specific gravity to theoretical maximum specific gravity.

** % VMA based on the aggregate's ASTM bulk specific gravity.

*** Calculated from - Modulus of stiffness = $\frac{40 \text{ Marshall Stability}}{\text{Flow Index}}$

NOTE - Compaction by 75 blows on each face by Marshall double compactor.

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TABLE 10

TEST DATA ON HL6 PAVING MIXTURES CONTAINING CRUSHED AGGREGATE - PARTICLE INDEX 14.0

Test \ Gradation	Job-Mix Formula			Lower			Upper			Lower - Upper			Upper - Lower		
Asphalt Content % (total mix)	5.15	5.65	6.15	5.15	5.65	6.15	5.15	5.65	6.15	5.15	5.65	6.15	5.15	5.65	6.15
* Air Voids %	3.5	2.9	2.5	5.2	3.9	2.6	3.5	2.6	1.8	3.3	2.6	2.5	5.1	4.0	3.0
**VMA %	13.3	13.9	14.7	14.7	14.8	14.8	13.6	14.0	14.4	13.2	13.7	14.8	15.0	15.2	15.4
Bulk Spec. Grav.	2.420	2.416	2.408	2.379	2.389	2.401	2.416	2.417	2.418	2.425	2.424	2.406	2.373	2.381	2.389
100% Lab. Density lb/ft^3	151.1	150.8	150.3	148.5	149.1	149.9	150.8	150.9	150.9	151.4	151.3	150.2	148.1	148.6	149.1
Theor. Max. Spec. Gr.	2.509	2.489	2.468	2.509	2.487	2.466	2.503	2.483	2.462	2.507	2.489	2.468	2.501	2.481	2.464
Marshall Stability lb at 140°F	2690	2183	1853	1811	1652	1896	2367	2047	1567	2382	2025	1305	1987	1845	2407
Flow Index (units of 0.01 inch)	10.8	10.3	12.8	8.8	9.3	10.3	9.3	12.0	17.0	10.3	12.5	16.5	8.6	8.7	11.3
***Stiffness Modulus at 140°F, psi	9963	8478	5791	8232	7105	7363	10181	6823	3687	9250	6480	3164	9242	8483	8520
Ave. Aggregate Spec. Gr.	2.648	2.648	2.648	2.645	2.645	2.645	2.651	2.651	2.651	2.651	2.651	2.651	2.649	2.649	2.649
% Asphalt Absorption (wt. of aggregate)	1.1	1.1	1.1	1.2	1.1	1.1	0.99	0.97	0.94	1.1	1.1	1.1	0.84	0.96	0.99
Filler/Bitumen Ratio by weight	0.66	0.60	0.55	0.11	0.10	0.092	1.22	1.10	1.01	1.22	1.10	1.01	0.11	0.10	0.092

* % Air voids derived from ratio of bulk specific gravity to theoretical maximum specific gravity.

** % VMA based on the aggregate's ASTM bulk specific gravity.

*** Calculated from - Modulus of stiffness = $\frac{40 \text{ Marshall Stability}}{\text{Flow Index}}$

NOTE - Compaction by 75 blows on each face by Marshall double compactor.

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TABLE 11

TEST DATA ON HL6 PAVING MIXTURES CONTAINING INTERMEDIATE AGGREGATES - PARTICLE INDEX 11.5

Gradation / Test	Job-Mix Formula			Lower			Upper			Lower - Upper			Upper - Lower		
Asphalt Content % (total mix)	5.0	5.5	6.0	5.0	5.5	6.0	5.0	5.5	6.0	5.0	5.5	6.0	5.0	5.5	6.0
* Air Voids %	4.3	3.0	2.5	5.5	4.4	3.4	3.8	3.4	2.3	3.5	2.5	2.2	6.4	5.0	3.3
**VMA %	14.1	13.9	14.6	15.0	15.0	15.4	13.4	13.7	14.3	13.2	13.5	14.4	15.9	15.6	15.7
Bulk Spec. Grav.	2.389	2.406	2.399	2.363	2.377	2.379	2.406	2.411	2.408	2.413	2.418	2.405	2.339	2.360	2.369
100% Lab. Density lb/ft3	149.1	150.2	149.8	147.5	148.4	148.5	150.2	150.5	150.3	150.6	151.0	150.1	146.0	147.3	147.9
Theor. Max. Spec. Gr.	2.497	2.480	2.461	2.502	2.487	2.462	2.502	2.495	2.465	2.501	2.479	2.460	2.499	2.484	2.451
Marshall Stability lb at 140°F	1612	1737	1255	1123	1251	1159	1833	1476	1230	1860	1340	941	992	1173	1179
Flow Index (units of 0.01 inch)	7.5	8.5	9.0	7.0	6.9	8.0	8.0	9.5	11.3	9.5	10.0	12.3	7.0	6.8	7.3
***Stiffness Modulus at 140°F, psi	8597	8174	5578	6417	7252	5795	9165	6215	4354	7832	5360	3060	5669	6900	6460
Ave. Aggregate Spec. Gr.	2.641	2.641	2.641	2.642	2.642	2.642	2.640	2.640	2.640	2.641	2.641	2.641	2.641	2.641	2.641
% Asphalt Absorption (wt. of aggregate)	0.94	0.98	0.98	1.0	1.1	0.98	1.0	1.2	1.1	1.0	0.96	0.96	0.96	1.0	0.8
Filler/Bitumen Ratio by weight	0.66	0.60	0.55	0.093	0.084	0.077	1.23	1.12	1.02	1.23	1.12	1.02	0.093	0.084	0.077

* % Air voids derived from ratio of bulk specific gravity to theoretical maximum specific gravity.

** % VMA based on the aggregate's ASTM bulk specific gravity.

*** Calculated from - Modulus of stiffness = $\frac{40 \text{ Marshall Stability}}{\text{Flow Index}}$

NOTE - Compaction by 75 blows on each face by Marshall double compactor.

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TABLE 12

TEST DATA ON HL6 PAVING MIXTURES CONTAINING ROUNDED AGGREGATE - PARTICLE INDEX 9.0

Test / Gradation	Job-Mix Formula			Lower			Upper			Lower - Upper			Upper - Lower		
Asphalt Content % (total mix)	4.6	5.1	5.6	4.6	5.1	5.6	4.6	5.1	5.6	4.6	5.1	5.6	4.6	5.1	5.6
* Air Voids %	4.2	3.1	2.5	5.3	4.2	2.8	5.9	2.8	2.1	3.3	2.5	2.0	5.7	4.5	3.0
**VMA %	13.9	14.1	14.6	15.0	14.9	15.0	15.3	13.5	14.1	13.0	13.2	14.2	15.2	15.3	15.0
Bulk Spec. Grav.	2.385	2.392	2.391	2.357	2.372	2.381	2.344	2.405	2.401	2.410	2.409	2.403	2.347	2.356	2.377
100% Lab. Density lb/ft^3	148.9	149.3	149.3	147.1	148.1	148.6	146.3	150.1	149.9	150.5	150.4	150.0	146.5	147.1	148.4
Theor. Max. Spec. Gr.	2.489	2.469	2.453	2.490	2.475	2.451	2.490	2.475	2.452	2.493	2.472	2.453	2.488	2.468	2.451
Marshall Stability lb at 140°F	1163	992	660	731	599	633	1125	980	720	1305	937	737	489	637	617
Flow Index (units of 0.01 inch)	6.5	6.9	8.8	5.5	6.0	6.0	6.6	8.2	9.8	7.4	9.1	11.0	5.1	5.7	6.5
***Stiffness Modulus at 140°F, psi	7157	5751	3000	5316	3993	4220	6818	4780	2939	7054	4119	2680	3835	4470	3797
Ave. Aggregate Spec. Gr.	2.642	2.642	2.642	2.644	2.644	2.644	2.640	2.640	2.640	2.644	2.644	2.644	2.641	2.641	2.641
% Asphalt Absorption (wt. of aggregate)	0.52	0.52	0.55	0.51	0.58	0.48	0.57	0.64	0.57	0.56	0.53	0.5	0.55	0.5	0.5
Filler/Bitumen Ratio by weight	0.67	0.60	0.54	0.048	0.043	0.039	1.29	1.16	1.05	1.29	1.16	1.05	0.048	0.043	0.039

* % Air voids derived from ratio of bulk specific gravity to theoretical maximum specific gravity.
** % VMA based on the aggregate's ASTM bulk specific gravity.
*** Calculated from - Modulus of stiffness = $\frac{40 \text{ Marshall Stability}}{\text{Flow Index}}$

NOTE - Compaction by 75 blows on each face by Marshall double compactor.

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TABLE 13

RANGE OF TEST VALUES FOR EACH A-HL3 PAVING MIXTURE PROPERTY DUE TO TOLERANCES

Paving Mixture Property	Lowest Value	Job-Mix Formula	Highest Value	Range of Test Values Bet. Lowest & Highest
(a) Paving Mixtures Containing Crushed Aggregate - Particle Index 14.0				
% Air Voids	1.6 LU	2.9	5.0 UL	3.4
% VMA	13.2 LU	15.2	16.4 UL	3.2
Marshall Stability (lb. at 140°F)	1510 LU	1909	2592 U	1082.
Flow Index (units of 0.01 inch)	7.7 L	10.9	16.0 LU	8.3
Stiffness Modulus at 140°F psi	3775 LU	7006	12560 JM	8785.
Bulk Specific Gravity	2.360 UL	2.395	2.435 LU	0.075
100% Laboratory Density lb/ft^3	147.3 UL	149.4	151.9 LU	4.6
Filler/Bitumen Ratio by wt.	0.40 L	0.90	1.50 U	1.10
(b) Paving Mixtures Containing Intermediate Aggregate - Particle Index 11.5				
% Air Voids	1.0 LU	3.1	5.6 UL	4.6
% VMA	12.5 LU	14.9	16.7 UL	4.2
Marshall Stability (lb at 140°F)	950 U	1618	1866 L	916.
Flow Index (units of 0.01 inch)	7.0 L	9.9	14.0 LU	7.0
Stiffness Modulus at 140°F psi	2794 LU	6537	10663 L	7869.
Bulk Specific Gravity	2.336 UL	2.387	2.441 LU	0.105
100% Laboratory Density lb/ft^3	145.8 UL	148.9	152.3 LU	6.5
Filler/Bitumen Ratio by wt.	0.39 L	0.9	1.50 U	1.01
(c) Paving Mixtures Containing Rounded Aggregate - Particle Index 9.0				
% Air Voids	0.8 LU	3.1	5.8 UL	5.0
% VMA	12.3 LU	15.1	16.5 UL	4.2
Marshall Stability (lb at 140°F)	595 L	953	1450 U	855.
Flow Index (units of 0.01 inch)	6.0 L	9.2	14.8 LU	8.8
Stiffness Modulus at 140°F psi	1838 LU	4143	7733 U	5895.
Bulk Specific Gravity	2.326 UL	2.377	2.446 LU	0.120
100% Laboratory Density lb/ft^3	145.1 UL	148.3	152.6 LU	7.5
Filler/Bitumen Ratio by wt.	0.38 L	0.9	1.53 U	1.15

L - Lower U - Upper

LU - Lower Upper UL - Upper Lower

JM - Job-Mix

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TABLE 14

RANGE OF TEST VALUES FOR EACH B-HL3 PAVING MIXTURE PROPERTY DUE TO TOLERANCES

Paving Mixture Property	Lowest Value	Job-Mix Formula	Highest Value	Range of Test Values Bet. Lowest & Highest
(a) Paving Mixtures Containing Crushed Aggregate - Particle Index 14.0				
% Air Voids	1.0 LU	2.9	5.5 L	4.5
% VMA	14.1 LU	14.9	16.3 UL	2.2
Marshall Stability (lb. at 140°F)	1226 LU	2287	2365 LU	1139.
Flow Index (units of 0.01 inch)	8.2 UL	10.6	16.2 LU	8.0
Stiffness Modulus at 140°F psi	3027 LU	8630	9010 LU	5983.
Bulk Specific Gravity	2.350 UL	2.402	2.426 UL	0.076
100% Laboratory Density lb/ft^3	146.7 UL	150.0	151.5 UL	4.8
Filler/Bitumen Ratio by wt.	0.39 L	0.90	1.50 U	1.11
(b) Paving Mixtures Containing Intermediate Aggregate - Particle Index 11.5				
% Air Voids	2.1 LU	3.1	5.4 L	2.3
% VMA	14.0 LU	15.0	16.1 U	2.1
Marshall Stability (lb at 140°F)	782 U	1185	1480 U	698.
Flow Index (units of 0.01 inch)	7.2 L	10.3	16.2 LU	9.0
Stiffness Modulus at 140°F psi	2091 LU	4602	6722 UL	4631.
Bulk Specific Gravity	2.354 L	2.392	2.407 LU	0.053
100% Laboratory Density lb/ft^3	147.0 L	149.3	150.3 LU	3.3
Filler/Bitumen Ratio by wt.	0.40 L	0.90	1.49 U	1.09
(c) Paving Mixtures Containing Rounded Aggregate - Particle Index 9.0				
% Air Voids	2.3 U	2.9	4.8 L	2.5
% VMA	14.2 U	15.0	16.0 UL	1.8
Marshall Stability (lb at 140°F)	312 L	595	932 U	620.
Flow Index (units of 0.01 inch)	6.2 UL	8.4	14.2 U	8.0
Stiffness Modulus at 140°F psi	1135 L	2833	4488 JM	3353
Bulk Specific Gravity	2.358 L	2.380	2.394 LU	0.036
100% Laboratory Density lb/ft^3	147.2 L	148.6	149.5 LU	2.3
Filler/Bitumen Ratio by wt.	0.35 L	0.90	1.56 U	1.21

L - Lower U - Upper

LU - Lower Upper UL - Upper Lower

JM - Job-Mix

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TABLE 15

RANGE OF TEST VALUES FOR EACH HL6 PAVING MIXTURE PROPERTY DUE TO TOLERANCES

Paving Mixture Property	Lowest Value	Job-Mix Formula	Highest Value	Range of Test Values Bet. Lowest & Highest
(a) Paving Mixtures Containing Crushed Aggregate - Particle Index 14.0				
% Air Voids	1.8 U	2.9	5.2 L	3.4
% VMA	13.2 LU	13.9	15.4 UL	2.2
Marshall Stability (lb. at 140°F)	1305 LU	2183	2690 JM	1385.
Flow Index (units of 0.01 inch)	8.6 UL	10.3	17.0 U	8.4
Stiffness Modulus at 140°F psi	3164 LU	8478	10181 U	7017.
Bulk Specific Gravity	2.373 UL	2.416	2.425 LU	0.052
100% Laboratory Density lb/ft^3	148.1 UL	150.8	151.4 LU	3.3
Filler/Bitumen Ratio by wt.	0.092 L	0.60	1.22 U	1.128
(b) Paving Mixtures Containing Intermediate Aggregate - Particle Index 11.5				
% Air Voids	2.2 LU	3.0	6.4 UL	4.2
% VMA	13.2 LU	13.9	15.9 UL	2.7
Marshall Stability (lb at 140°F)	941 LU	1737	1860 LU	919.
Flow Index (units of 0.01 inch)	6.8 UL	8.5	12.3 LU	5.5
Stiffness Modulus at 140°F psi	3060 LU	8174	9165 U	6105.
Bulk Specific Gravity	2.339 UL	2.406	2.418 LU	0.079
100% Laboratory Density lb/ft^3	146.0 UL	150.2	151.0 LU	5.0
Filler/Bitumen Ratio by wt.	0.077 L	0.60	1.23 U	1.153
(c) Paving Mixtures Containing Rounded Aggregate - Particle Index 9.0				
% Air Voids	2.0 LU	3.1	5.9 U	3.9
% VMA	13.0 LU	14.1	15.3 U	2.3
Marshall Stability (lb at 140°F)	489 UL	992	1305 LU	816.
Flow Index (units of 0.01 inch)	5.1 UL	6.9	11.0 LU	5.9
Stiffness Modulus at 140°F psi	2680 LU	5751	7157 JM	4477.
Bulk Specific Gravity	2.344 U	2.392	2.410 LU	0.066
100% Laboratory Density lb/ft^3	146.3 U	149.3	150.5 LU	4.2
Filler/Bitumen Ratio by wt.	0.039 L	0.60	1.29 U	1.251

L - Lower U - Upper

LU - Lower Upper UL - Upper Lower

JM - Job-Mix

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TABLE 16

Range of Values Below and Above the Corresponding Job-Mix Formula Requirement

Particle Index	Air Voids Range % Below	Air Voids Range % Above	VMA Range % Below	VMA Range % Above	Marshall Stab. Range lb. Below	Marshall Stab. Range lb. Above	Flow Index Range 0.01 inch Below	Flow Index Range 0.01 inch Above	Stiffness Mod. Range psi Below	Stiffness Mod. Range psi Above	Bulk Spec. Gr. Range Below	Bulk Spec. Gr. Range Above	100% Lab. Comp. Density Range lb/ft^3 Below	100% Lab. Comp. Density Range lb/ft^3 Above	Filler/Bit. Ratio Range Below	Filler/Bit. Ratio Range Above
1.A-HL3																
14.0	1.3	2.1	2.0	1.2	399	683	2.9	4.1	2398	5554	0.035	0.040	2.1	2.5	0.50	0.60
11.5	2.1	2.5	2.4	1.8	668	248	2.9	4.1	3743	4126	0.051	0.054	3.1	3.4	0.51	0.60
9.0	2.3	2.7	2.8	1.4	358	497	3.2	5.6	2305	3590	0.051	0.069	3.2	4.3	0.52	0.63
2.B-HL3																
14.0	1.9	2.6	0.8	1.4	1061	78	2.4	5.6	5603	380	0.052	0.024	3.3	1.5	0.51	0.60
11.5	1.0	2.3	1.0	1.1	483	295	2.6	5.9	2511	2120	0.038	0.015	1.8	1.0	0.50	0.59
9.0	0.6	1.9	0.8	1.0	241	337	2.2	5.8	1698	1655	0.022	0.014	1.4	0.9	0.55	0.66
3.HL6																
14.0	1.1	2.3	0.7	1.5	878	507	1.7	6.2	5314	1703	0.043	0.009	2.7	0.6	0.51	0.62
11.5	0.8	3.4	0.7	2.0	796	123	1.7	3.8	5114	991	0.067	0.012	4.2	0.8	0.52	0.63
9.0	1.1	2.8	1.1	1.2	503	313	1.8	4.1	3071	1406	0.048	0.018	3.0	1.2	0.56	0.69
$\bar{x}$	1.4	2.5	1.37	1.40	599.	342.	2.4	5.0	3529	2392	0.045	0.028	2.8	1.80	0.52	0.62
σ	0.60	0.44	0.81	0.33	270.	193.	0.57	0.97	1476	1678	0.013	0.021	0.86	1.31	0.021	0.033
$\bar{x}+2\sigma$	2.6	3.4	2.99	2.06	1138	728	3.5	6.9	6481	5736	0.071	0.070	4.5	4.4	0.56	0.69

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TABLE 17

COMPARISON OF RANGE OF ASPHALT PAVING MIXTURE TEST VALUES PROVIDED BY TOLERANCES FOR A-HL3 AND B-HL3 BOTH WITH A PARTICLE INDEX OF 9.0

Paving Mixture Property	Actual Range Associated With A-HL3	Actual Range Associated With B-HL3	Corresponding Range Assoc. With A-HL3	Corresponding Range Assoc. With B-HL3	Difference Between A-HL3 & B-HL3 x	$(\text{Difference})^2$ x^2
% Air Voids	5.0	2.5	100	50.0	-50.0	2500.0
% VMA	4.2	1.8	100	42.9	-57.1	3260.4
Marshall Stability, lb at 140°F	855	620	100	72.5	-27.5	756.3
Flow Index, units of 0.01 inch	8.8	8.0	100	90.9	- 9.1	82.8
Stiffness Modulus at 140°F psi	5895	3353	100	56.9	-43.1	1857.6
Bulk Specific Gravity	0.120	0.036	100	30.0	-70.0	4900.0
Filler/Bitumen Ratio by wt.	1.15	1.21	100	105.2	+ 5.2	27.0
					$\Sigma x = -251.6$ $\bar{x} = -35.9$	$\Sigma x^2 = 13384.1$

$$\text{Standard deviation } S = \sqrt{\frac{n(\Sigma x^2) - (\Sigma x)^2}{n(n-1)}} = \sqrt{\frac{7(13384.1) - 63302.6}{(7)(6)}} = \sqrt{723.5} = 26.9$$

$$\text{Student's } t = \frac{(\bar{X} - \bar{x})\sqrt{n}}{S}$$

where assumed value for $\bar{X} = 0$
therefore $\bar{X} - \bar{x} = 35.9$ disregarding sign

$$t = \frac{35.9\sqrt{7}}{26.9} = \frac{(35.9)(2.65)}{26.9} = 3.53$$

Degrees of freedom = N-1 = 7-1 = 6

Differences between test values on paving mixture properties of A-HL3 and B-HL3 are statistically significant.

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TABLE 18

Statistical Analysis of the Ranges in Test Values for Properties of Nine Paving Mixtures

Paving Mixture Test Property	Mean Value of Range $\bar{x}$	Standard Deviation of Range σ	Mean Value of Range ± Two Standard Deviations $\bar{x} - 2\sigma$	$\bar{x} + 2\sigma$
% Air Voids	3.76	0.93	2.10	5.62
% VMA	2.77	0.90	0.97	4.57
Marshall Stability (lb at 140°F)	937	235	467	1407
Flow Index (units of 0.01 inch)	7.7	1.25	5.20	10.2
Stiffness Modulus at 140°F psi	6013	1714	2585	9441
Theor. Maximum Spec. Gr.	0.047	0.005	0.037	0.057
Bulk Specific Gravity	0.074	0.026	0.022	0.126
100% Lab. Comp. Density lb/ft^3	4.6	1.6	1.4	7.8
Filler/Bitumen Ratio by wt.	1.14	0.05	1.04	1.24

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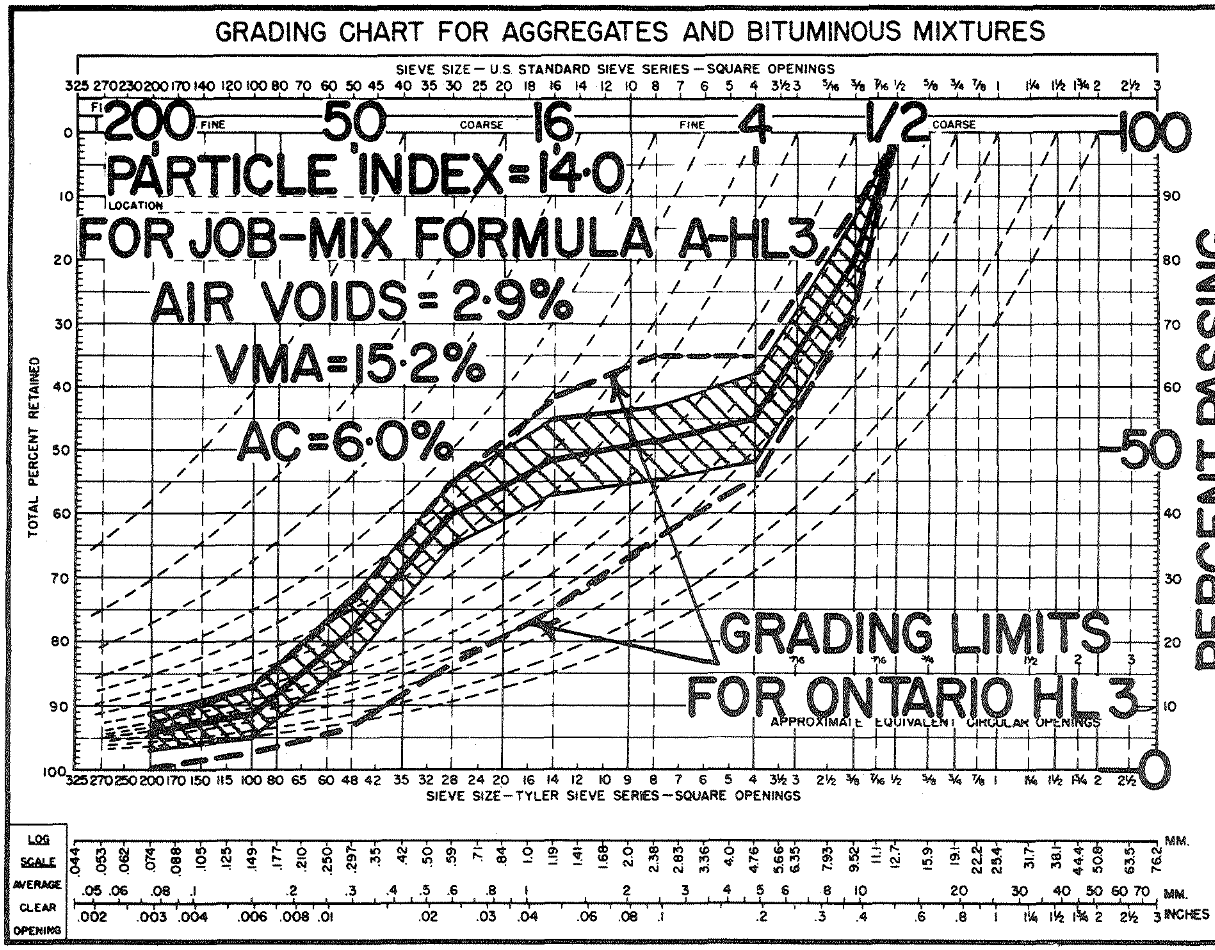

FIGURE I ILLUSTRATING ONTARIO GRADATION LIMITS FOR HL3, AND JOB-MIX FORMULA AND TOLERANCES FOR A-HL3 WITH A PARTICLE INDEX OF 14.0

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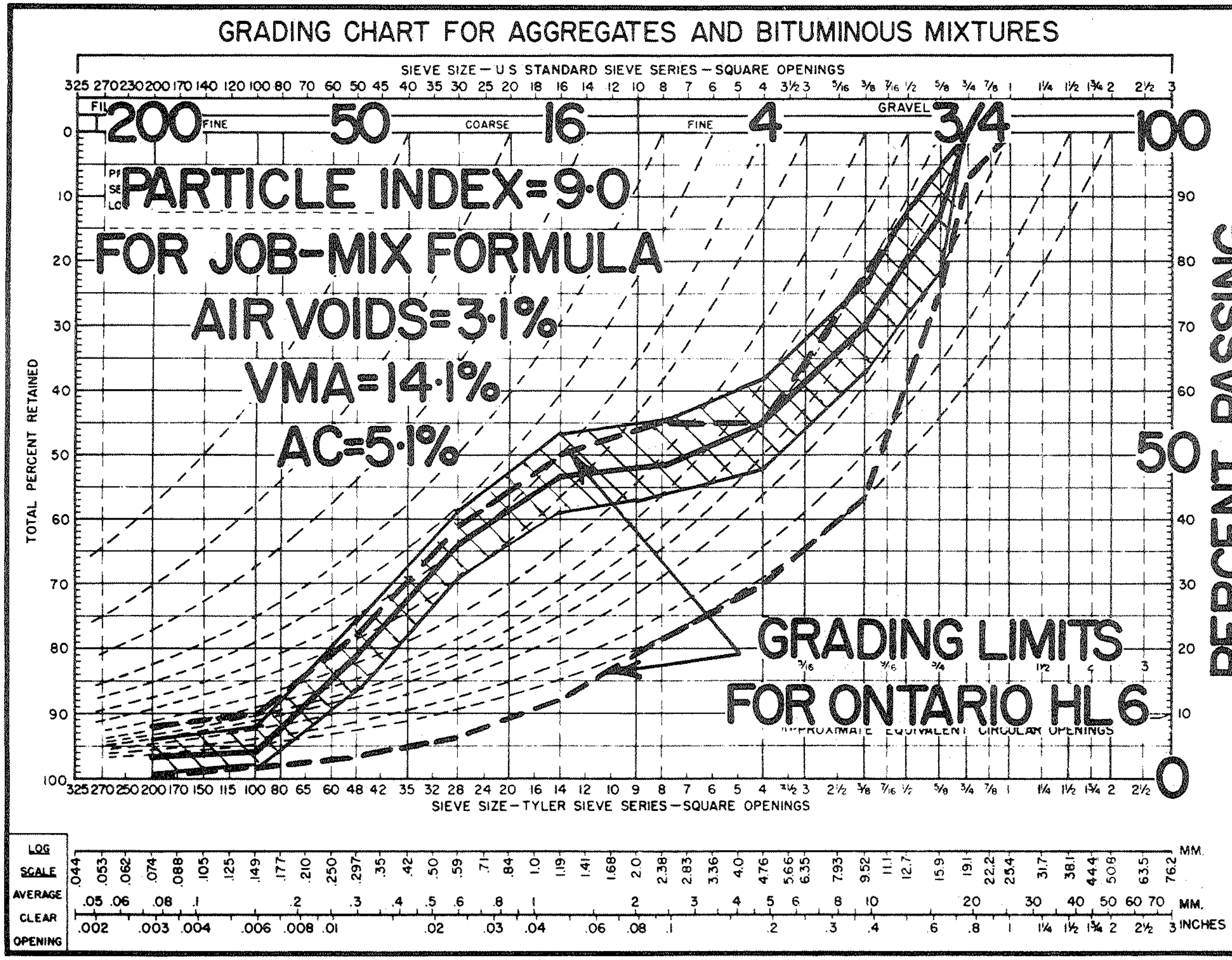

FIGURE 2 ILLUSTRATING ONTARIO GRADATION LIMITS FOR HL6, AND JOB-MIX FORMULA AND TOLERANCES FOR HL6 WITH A PARTICLE INDEX OF 9.0

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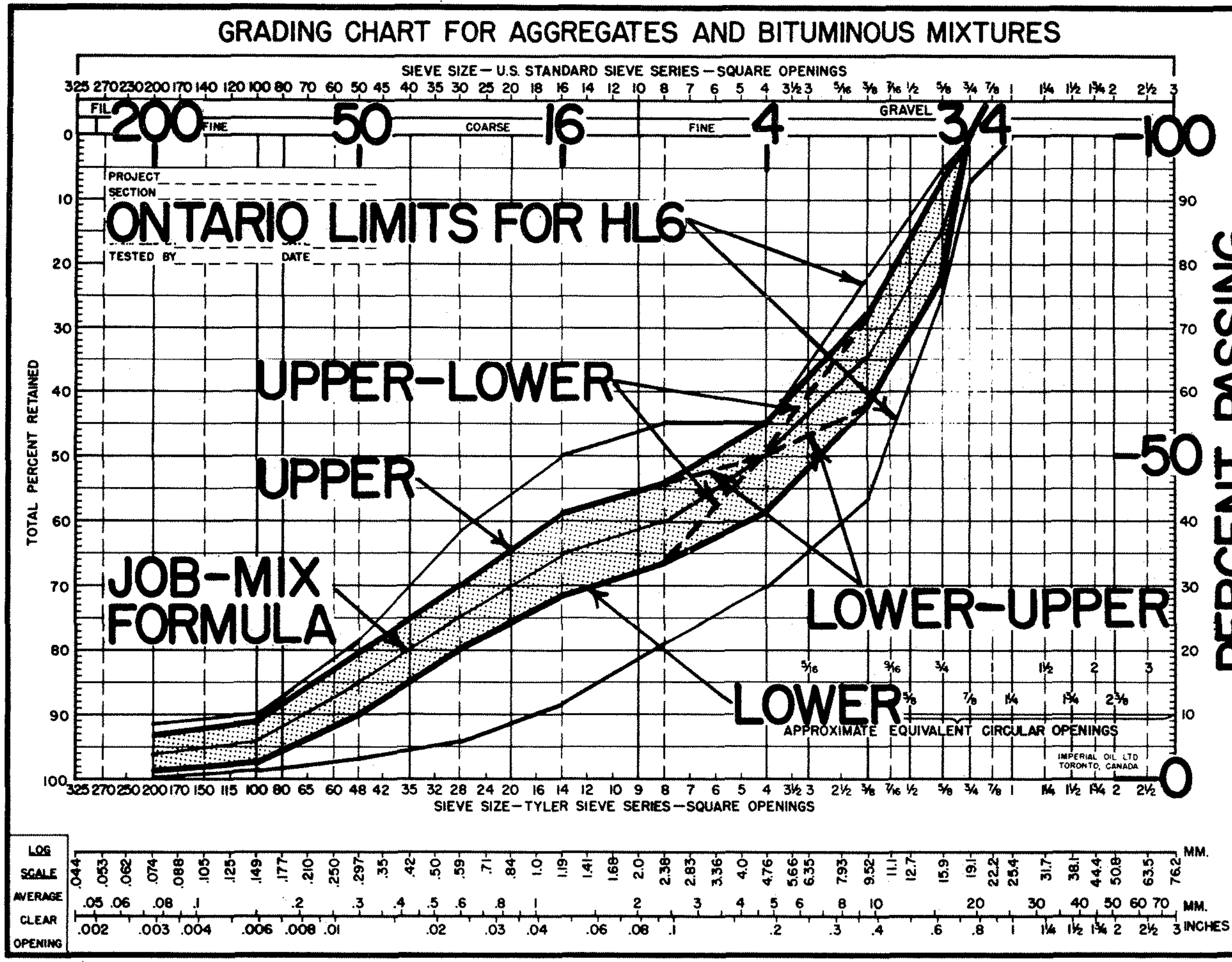

FIGURE 3 ILLUSTRATING THE LOCATIONS OF FIVE SEPARATE GRADING CURVES, JOB-MIX FORMULA, LOWER, UPPER LOWER-UPPER, AND UPPER-LOWER, WITHIN THE TOLERANCES' GRADING BAND FOR AN HL6 PAVING MIXTURE

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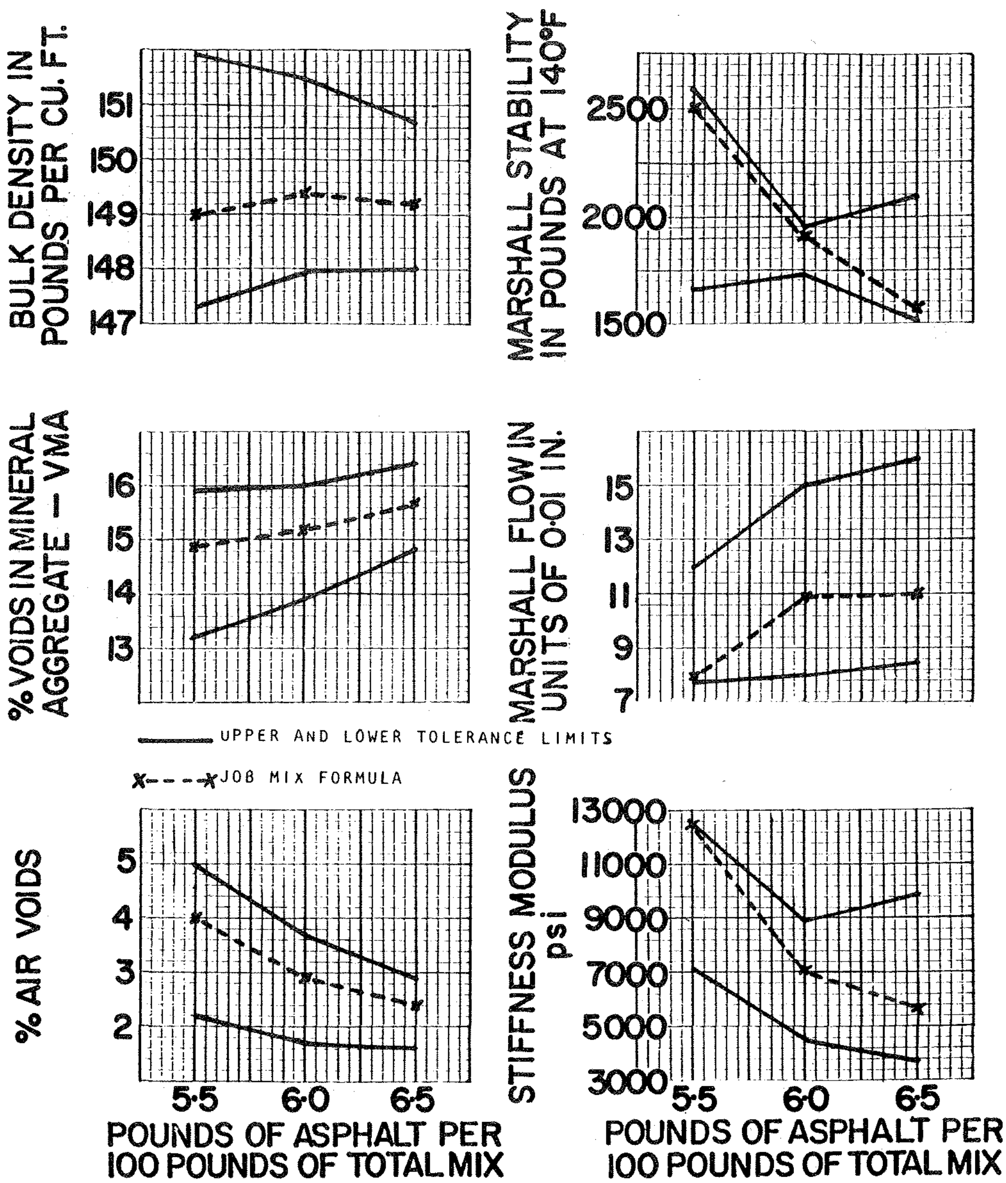

FIGURE 4 ILLUSTRATING INFLUENCE OF TOLERANCES ON THE PROPERTIES OF AN A-HL3 PAVING MIXTURE WITH A PARTICLE INDEX OF 14.0

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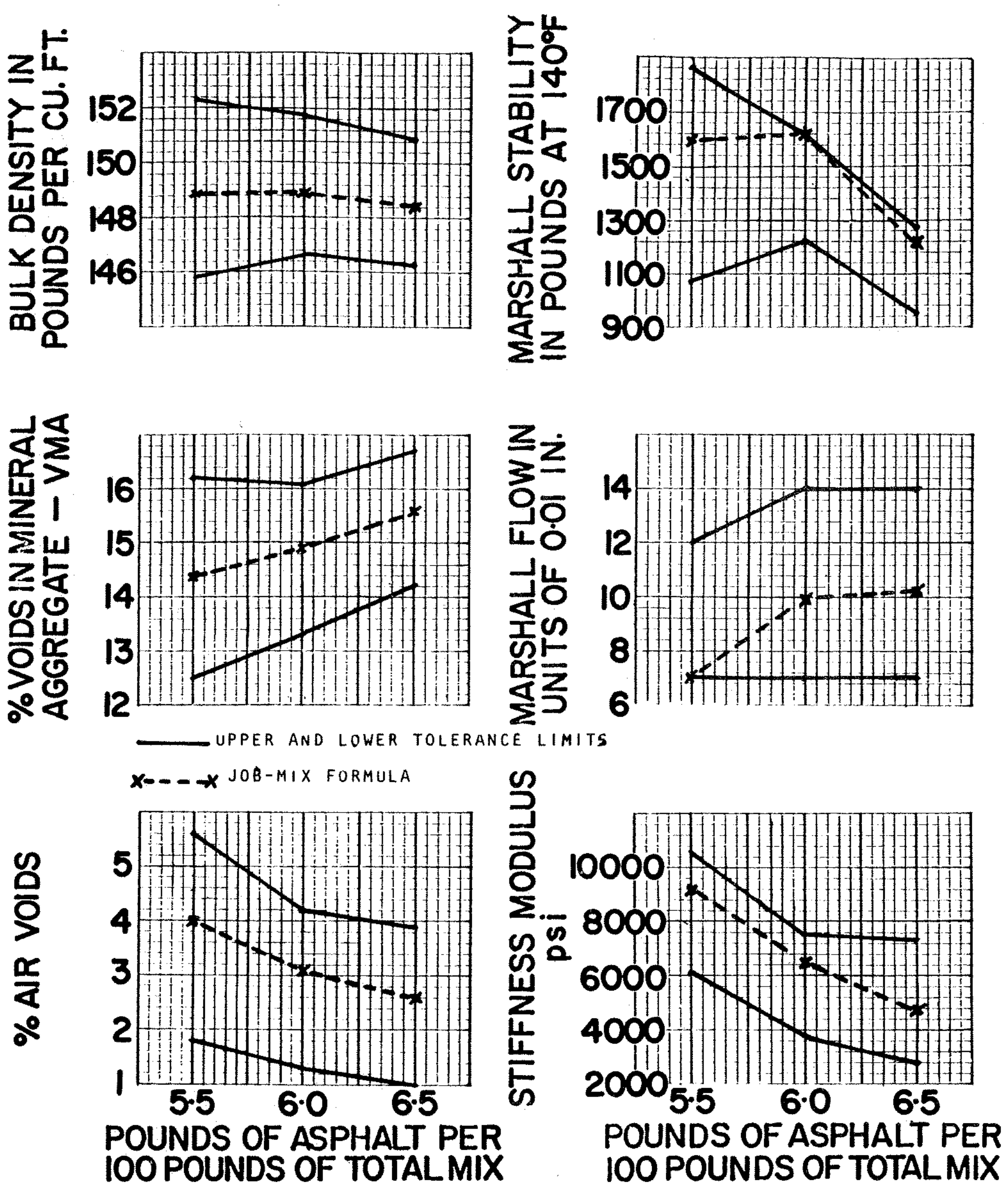

FIGURE 5 ILLUSTRATING INFLUENCE OF TOLERANCES ON THE PROPERTIES OF AN A-HL3 PAVING MIXTURE WITH A PARTICLE INDEX OF 11.5

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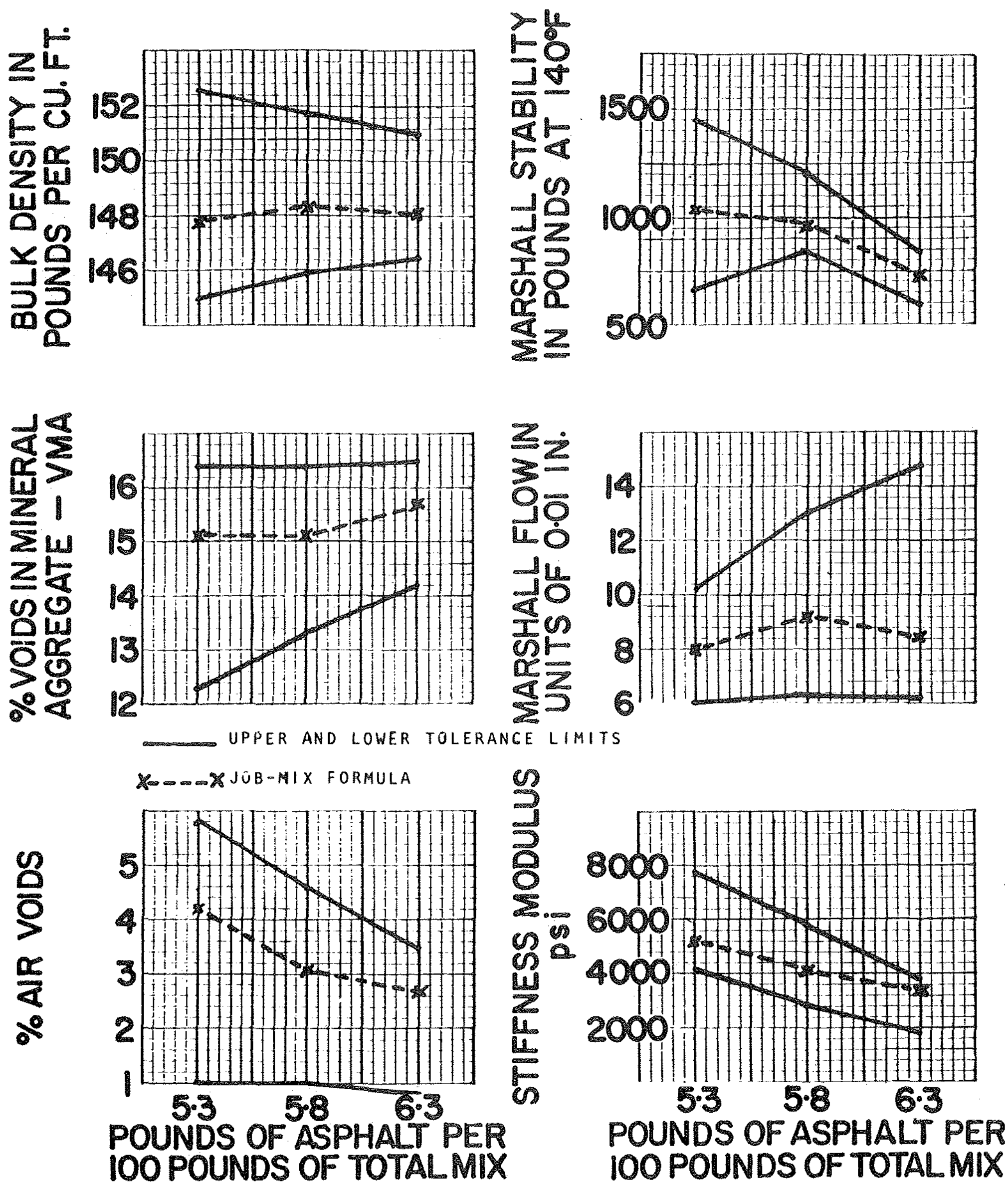

FIGURE 6 ILLUSTRATING INFLUENCE OF TOLERANCES ON THE PROPERTIES OF AN A-HL3 PAVING MIXTURE WITH A PARTICLE INDEX OF 9.0

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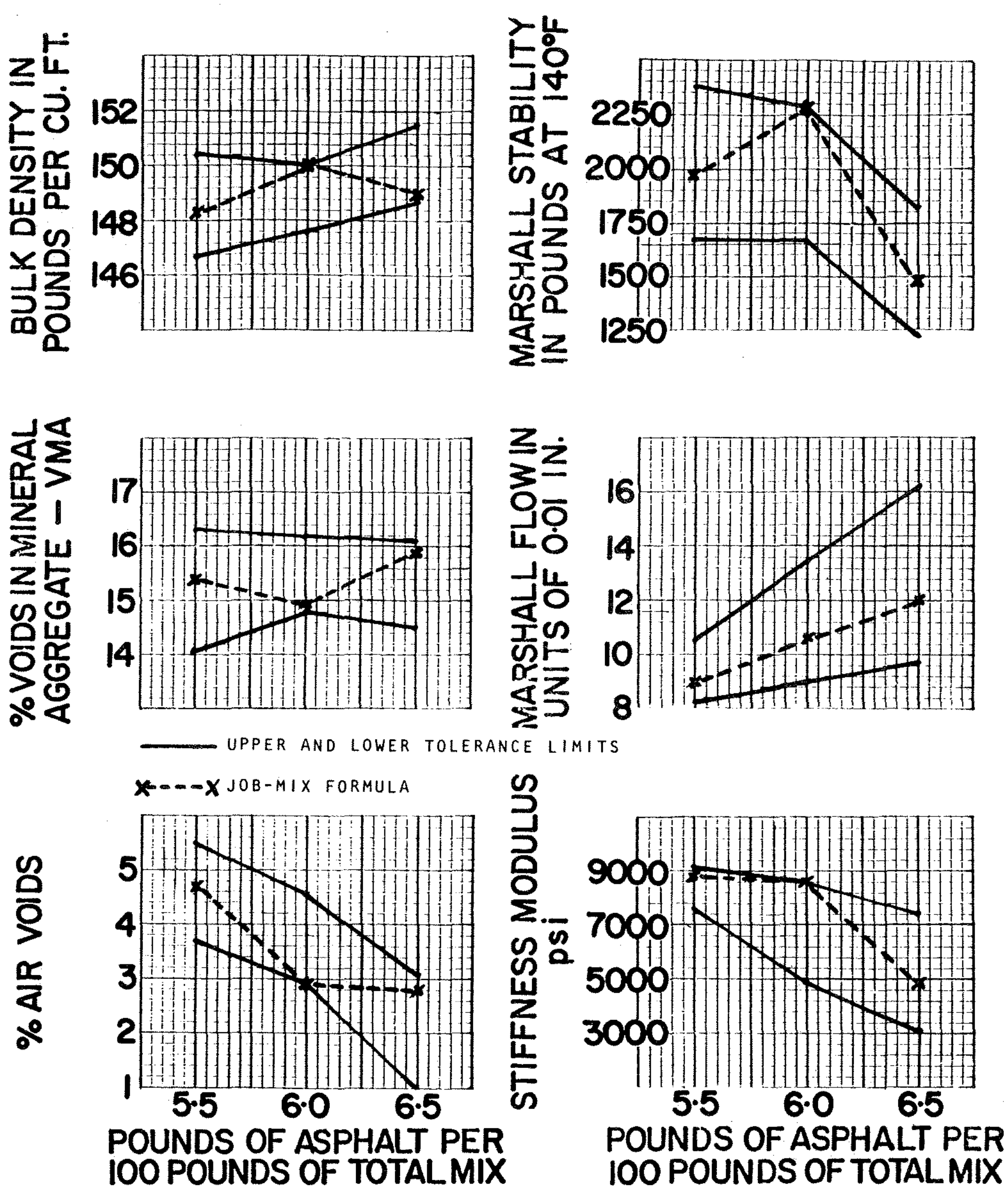

FIGURE 7 ILLUSTRATING INFLUENCE OF TOLERANCES ON THE PROPERTIES OF A B-HL3 WITH A PARTICLE INDEX OF 14.0

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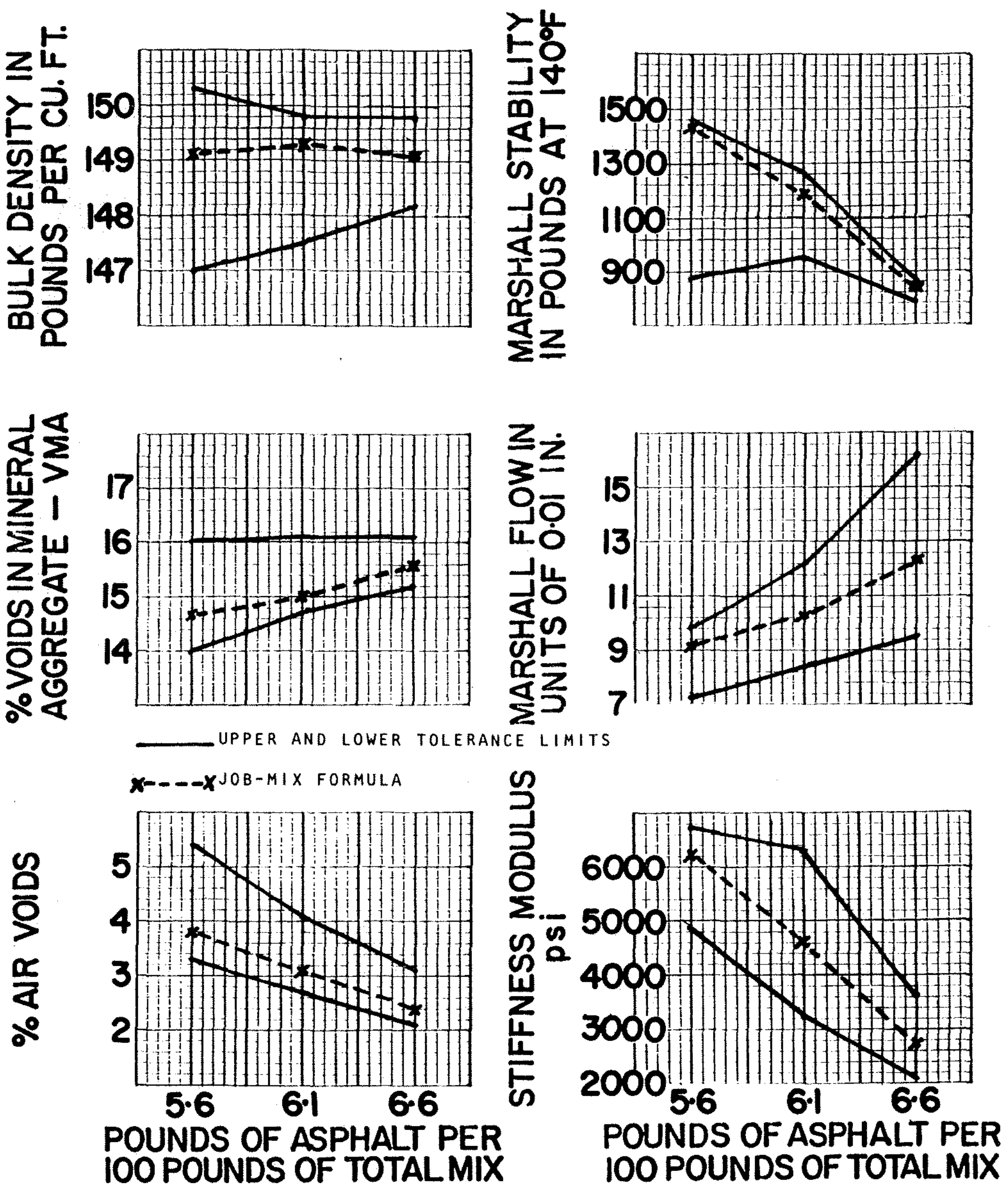

FIGURE 8 ILLUSTRATING INFLUENCE OF TOLERANCES ON THE PROPERTIES OF A B-HL3 PAVING MIXTURE WITH A PARTICLE INDEX OF 11.5

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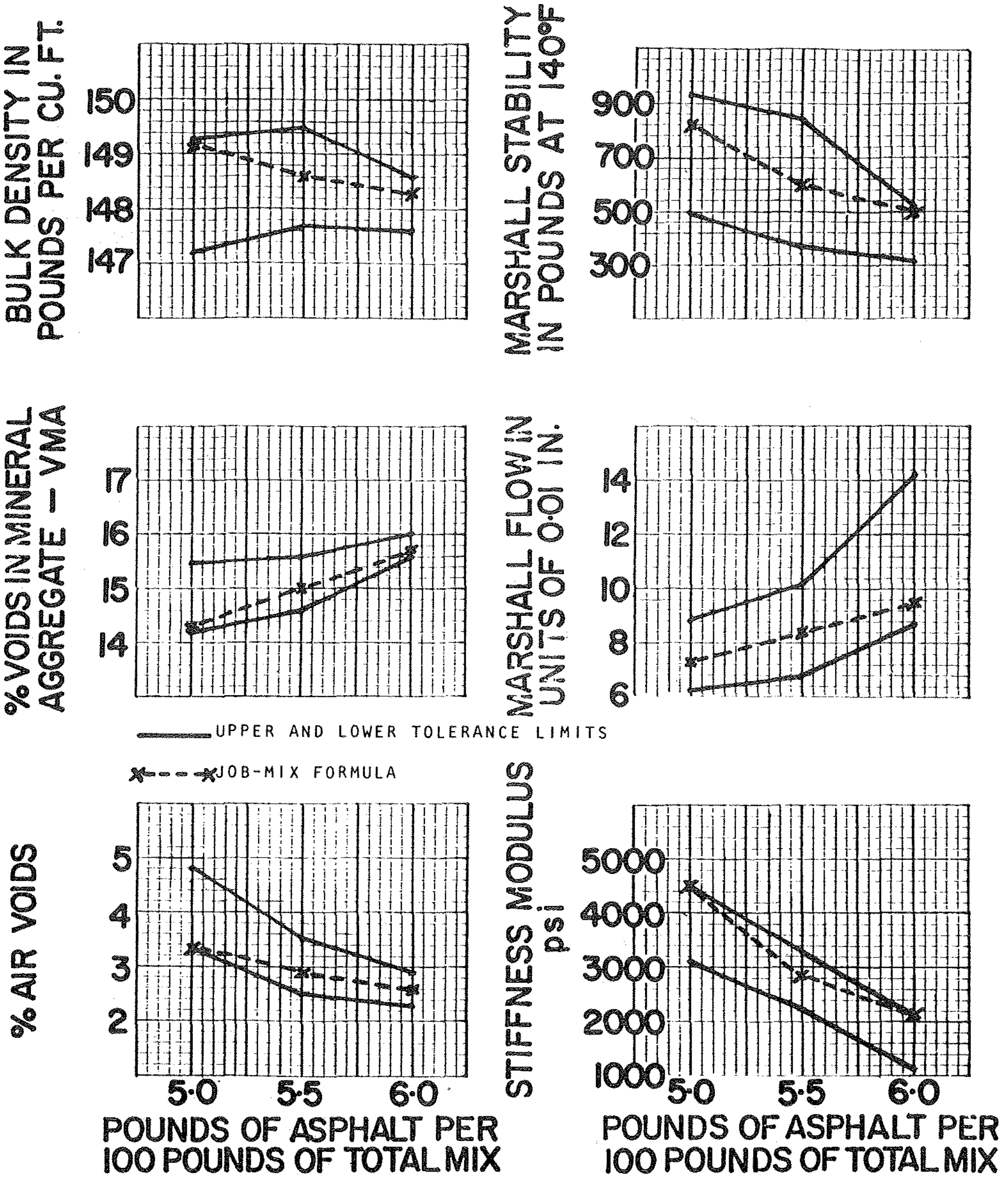

FIGURE 9 ILLUSTRATING INFLUENCE OF TOLERANCES ON THE PROPERTIES OF A B-HL3 PAVING MIXTURE WITH A PARTICLE INDEX OF 9.0

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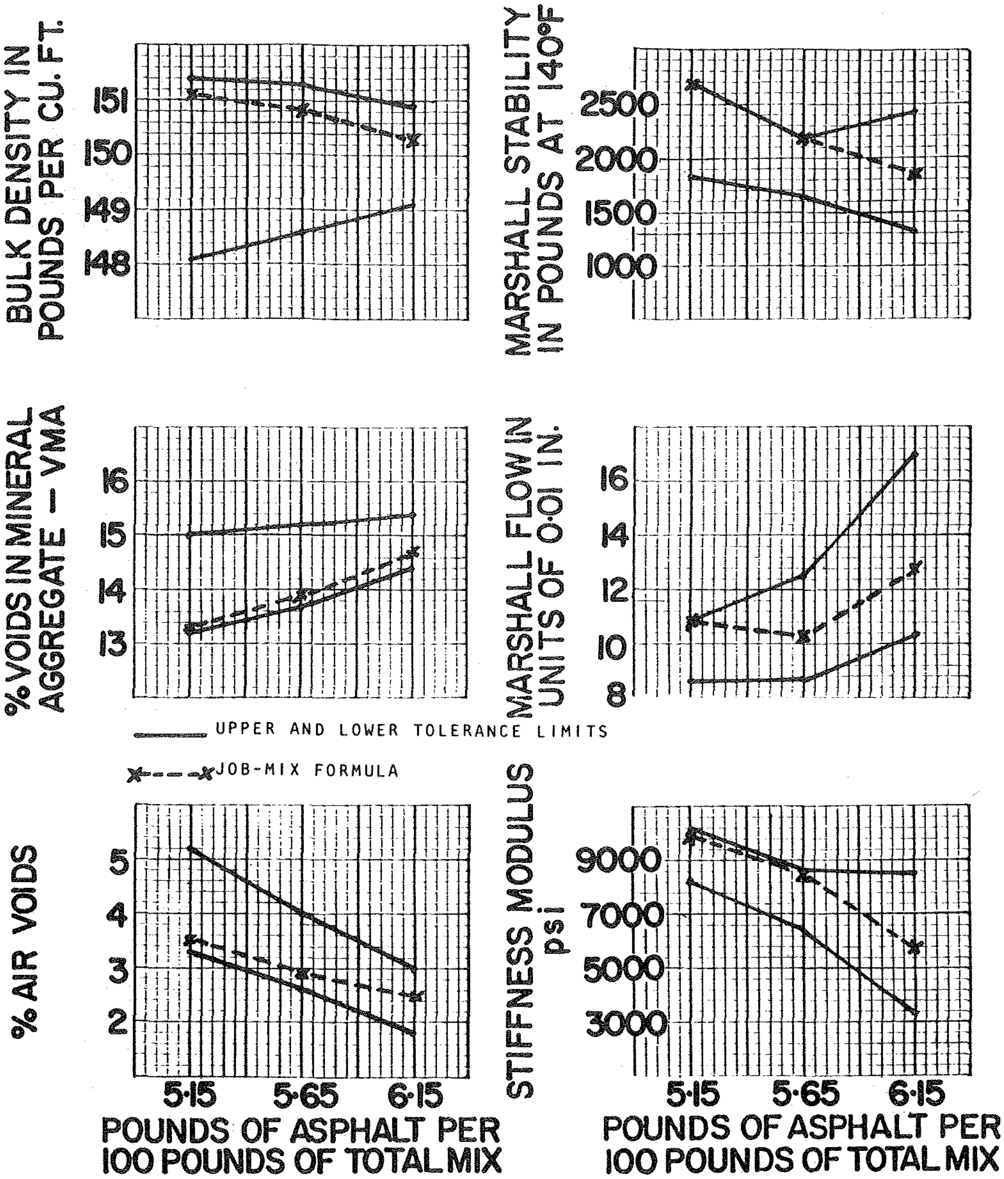

FIGURE 10 ILLUSTRATING INFLUENCE OF TOLERANCES ON THE PROPERTIES OF AN HL6 PAVING MIXTURE WITH A PARTICLE INDEX OF 14.0

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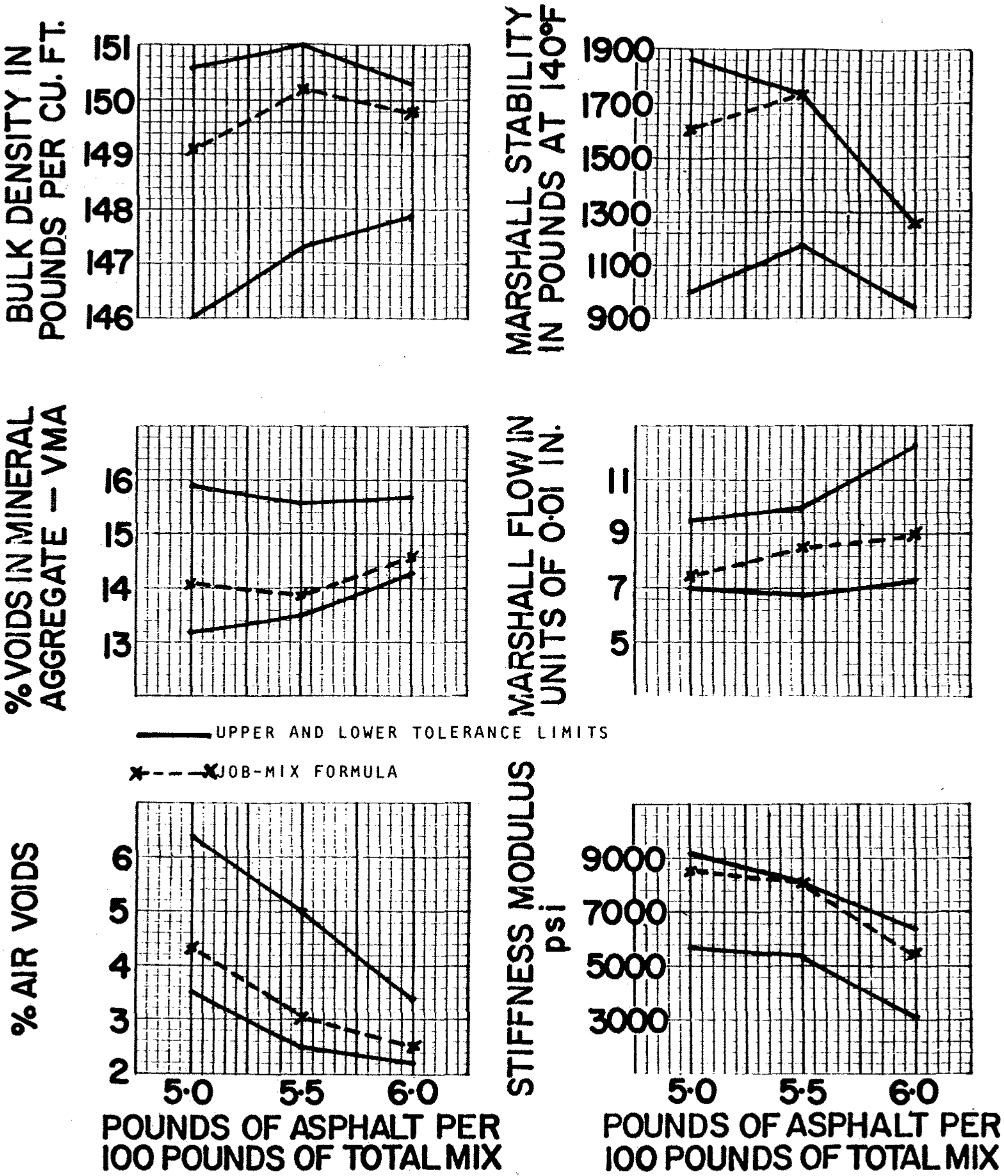

FIGURE 11 ILLUSTRATING INFLUENCE OF TOLERANCES ON THE PROPERTIES OF AN HL6 PAVING MIXTURE WITH A PARTICLE INDEX OF 11.5

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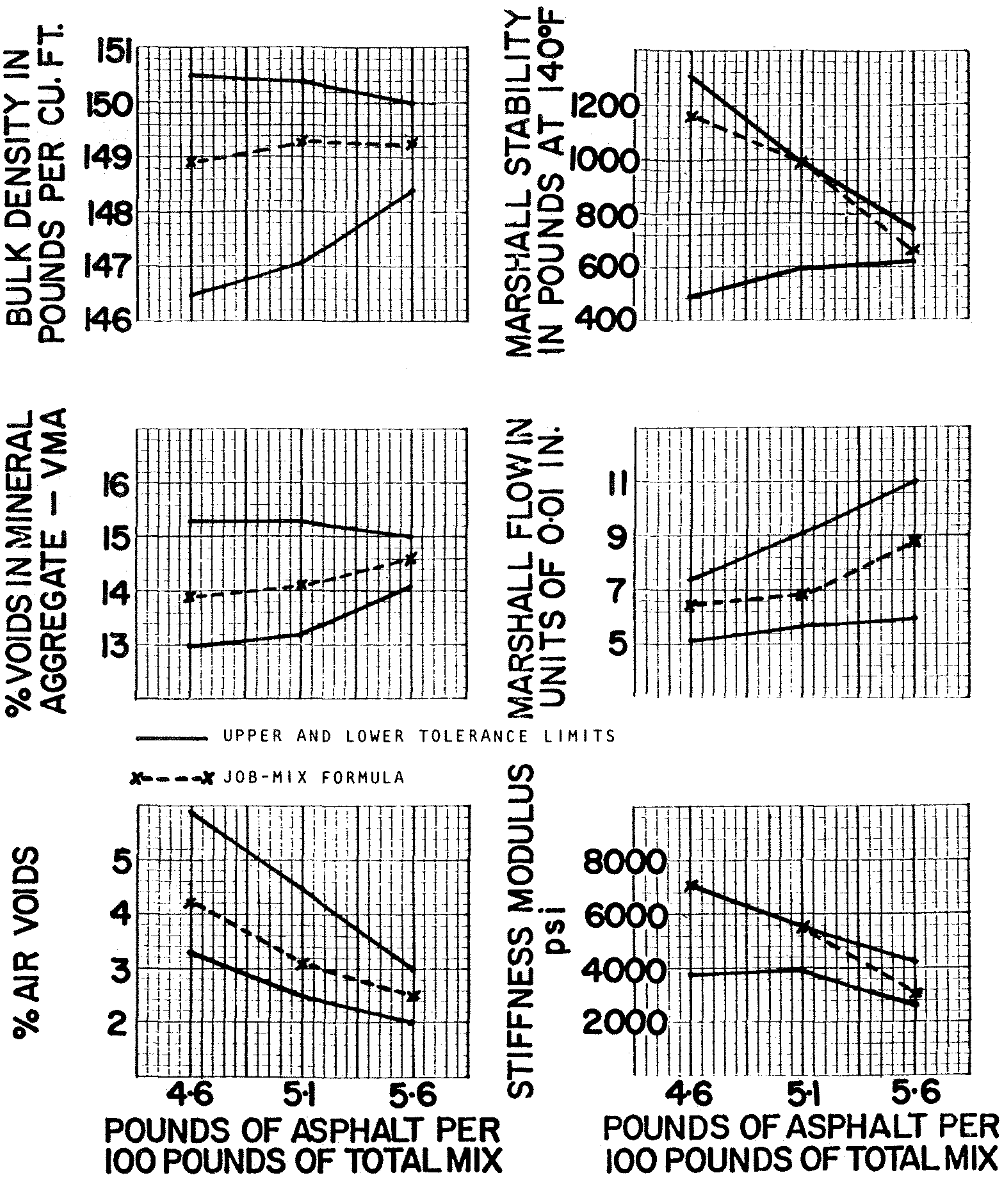

FIGURE 12 ILLUSTRATING INFLUENCE OF TOLERANCES ON THE PROPERTIES OF AN HL6 PAVING MIXTURE WITH A PARTICLE INDEX OF 9.0

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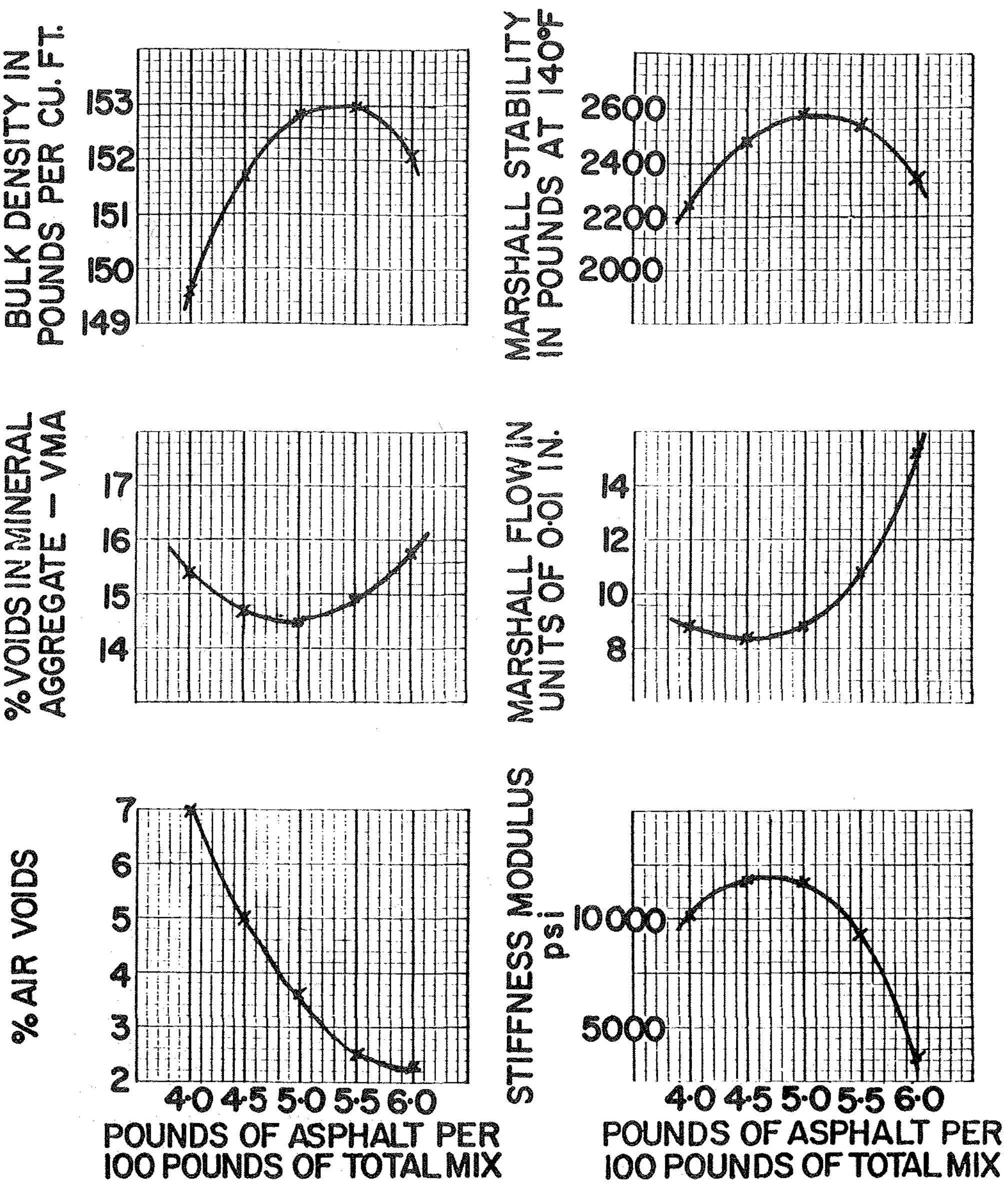

FIGURE 13 TYPICAL SINGLE CURVES ILLUSTRATING JOB-MIX FORMULA TEST VALUES FOR PROPERTIES OF A PAVING MIXTURE

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