Factors that Affect the Voids in the Mineral Aggregate of Hot-Mix Asphalt

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To determine the maximum density line that would best predict the voids in the mineral aggregate (VMA) of a mix, 101 mix designs were analyzed. The line drawn from the origin to the actual percent passing the nominal maximum aggregate size provided the best correlation with the measured VMA of the mixes. Differences between mix gradation and the maximum density line at the 2.36-mm (No. 8) sieve size and finer gave the best prediction of the VMA of a mix. Additionally, 24 laboratory mix designs were evaluated to determine the effect on the VMA of a mix of four variables considered important in obtaining VMA: gradation, quantity of aggregate <75μ [passing the 75μ (No. 200) sieve], size distribution of aggregate <75μ, and the angularity of the fine aggregate. Gradation provided the largest changes in VMA for all mixes. The quantity and size of aggregate <75μ caused significant changes to VMA, especially for the finer gradations. The angularity of the fine aggregate caused significant changes to mix VMA, especially for the coarser gradations.

Voids in the mineral aggregate (VMA) are a property of hot-mix asphalt (HMA) that controls the minimum asphalt content of mixes and ensures good durability of HMA pavements. VMA specifications were developed by McLeod (*1,2*) and Lefebvre (*3*) in the late 1950s using a 75-blow Marshall design and empirical observation of pavement performance. The bulk specific gravity (G_{sb}) of the aggregate was used by McLeod and Lefebvre and has also been used by the authors to calculate the VMAs of HMAs.

The specification of VMA for HMA has gained wide acceptance and is recommended by FMWA (*4*), the Asphalt Institute (*5*), and the Strategic Highway Research Program (*6*).

The Colorado Department of Transportation (CDOT) proposed and implemented a VMA mix design specification for the 1993 construction season. This report was written to provide guidance to CDOT suppliers in adjusting mix properties to change the VMA of their mixes to meet the 1993 VMA mix design specification.

This study was done in two phases. In Phase 1, gradations and VMAs of HMAs used during 1992 were analyzed to determine the most effective way to use the maximum density line to develop HMAs with adequate VMA. In Phase 2, a laboratory study was performed to identify mix properties that affect the VMA of an HMA. This report summarizes the full report (*7*) written for CDOT.

PHASE 1—ANALYSIS OF 1992 MIX DESIGNS

In general the further a gradation is from the maximum density line, the higher the measured VMA is. However, this is not always true. In addition numerous methods are used to draw the maximum density line.

The purpose of the Phase 1 analysis was to determine which maximum density line, if any, could be used to best forecast the VMA in an HMA. The best method to draw the maximum density line could then be used by contractors to develop gradations that would have a high probability of meeting the VMA specifications.

Definitions Used in Analysis

Actual Gradation

Analyzed were 101 of the mixes designed by CDOT during the 1992 construction season. The actual gradation of each HMA and its VMA measured using G_{sb} were known.

Power Gradation Plot

A 0.45 power plot of an HMA's aggregate gradation consists of the sieve sizes in microns (μ), raised to the 0.45 power plotted on the x axis and the percent passing each sieve size plotted on an arithmetic y axis. Theoretically an aggregate having a gradation that plots as a straight line on this type of graph will have the maximum density achievable and thus the lowest VMA (*8,9*).

Maximum Density Lines

Six maximum density lines, that is, straight lines on a 0.45 power plot drawn using various end points, were evaluated as tools to predict the VMA of an HMA. These six maximum density lines are shown in Figure 1.

Five maximum density lines were drawn from the origin. Their equation is

$$P = \frac{Y_{\text{end}}}{(X_{\text{end}})^n} \times d^n \qquad (1)$$

where

P = maximum density line Y coordinate at the d sieve size,
X_{end} = sieve size of maximum density line end coordinate (microns),
Y_{end} = end point Y coordinate at sieve size X (percent),
d = sieve opening size being evaluated (microns), and
n = exponent of 0.45 (*8,9*).

The sixth maximum density line is commonly referred to as the Texas reference gradation line. The Texas reference gradation line is drawn from the actual percent passing the largest sieve to retain

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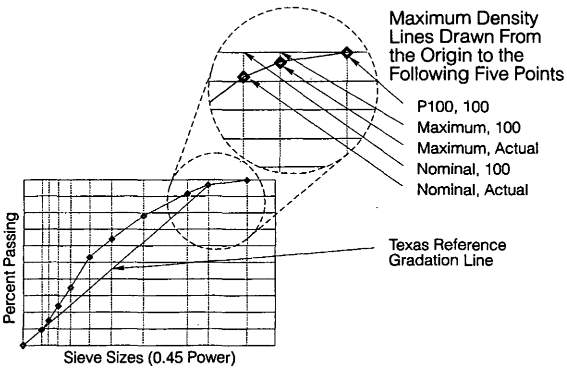

FIGURE 1 Six maximum density lines evaluated.

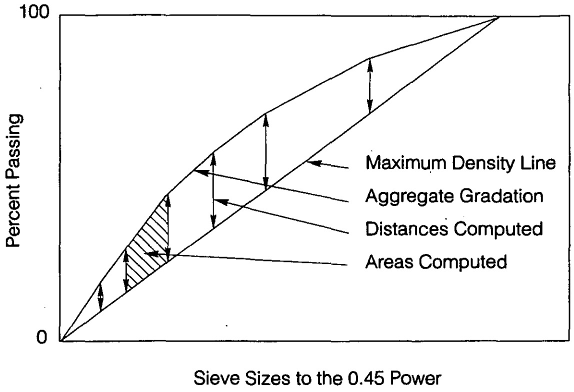

FIGURE 2 Areas and distances between mix gradations and maximum density lines.

any material to the actual percent passing the 75μ (No. 200) sieve (Figure 1). The equation of the Texas reference gradation line is

$$P = \frac{(100 - P75\mu)}{(D^n - 75^n)} \times (d^n - 75^n) + P75\mu \qquad (2)$$

where variables are the same as for Equation 1 and D is sieve opening size of the largest sieve to retain any material (microns) and $P75\mu$ is percent aggregate passing the 75μ (No. 200) sieve.

Distance

The absolute value of the difference in percent passing between the actual gradation and one of the maximum density lines at a given sieve size is defined as the distance. The distances summed over various ASTM D 3515 standard sieve sizes is defined as the sum of the distances. Actual gradations that were close to a maximum density line had a sum of the distances at all screens as low as 5. Actual gradations far away from a maximum density line had a sum of the distances at all screens as high as 150.

Correlation Analysis

It was thought that a person analyzing the gradation of an HMA would evaluate, by observation, the sum of the distances on a 0.45 power plot between their chosen maximum density line and the actual gradation of the HMA at the standard sieve sizes.

To simulate the visual process mathematically, the sum of the distances between the 6 maximum density lines and 101 actual gradations were calculated as shown in Figure 2. The sum of the distances for various screen sizes were then correlated to the measured VMA of the HMAs. Linear regression was used for the correlation, and the coefficients of determination, r^2, were calculated.

Nominal Maximum Size

VMA specifications have been recommended by others as a function of the nominal maximum aggregate size (*2,4,6,10*). The nominal maximum aggregate size is defined as one size larger than the first sieve size to retain more than 10 percent of the aggregate.

Results

Accounting for Various Aggregate Sizes

The data base of 101 actual gradations contained four nominal maximum aggregate sizes. The gradations were grouped by their nominal maximum aggregate sizes, and the average VMA for each group was calculated. The differences between the average VMA values for each group were remarkably similar to the differences in VMA specifications recommended by others (*2,4,6,10*).

Differences in VMA that appear to be related to the nominal maximum aggregate size have to be accounted for. Whenever data were analyzed that included gradations with various nominal maximum aggregate sizes, the data were normalized by subtracting the measured VMA from the VMA that would have been specified for that particular gradation.

For example, a mix having a ¾-in. nominal maximum aggregate size has a CDOT specified minimum VMA of 13 percent. If the VMA of the mix was measured at 13.5 percent air voids, the normalized VMA of the mix would be 0.5 percent. A mix having a ⅜-in. nominal maximum aggregate size will have a CDOT specified minimum VMA of 15 percent and, if the VMA of the mix measured 14.5 percent, the normalized VMA for the mix would be –0.5 percent air voids. By removing the contribution of nominal maximum aggregate size to VMA, one can evaluate the contribution of the relationship between the gradation and the maximum density lines.

Simple Analysis

In an attempt to determine which method of drawing the maximum density line best predicted the VMA of 101 HMA designs evaluated by the state of Colorado in 1992, regression analyses were performed. Regression was performed between the measured VMA and the sum of the distances.

Sums of the distances were calculated between the 101 actual gradations and six maximum density lines. The four different nominal maximum aggregate sizes were analyzed as individual groups and as one large group (normalized as explained previously). In addition the distances between the six maximum density lines and the 101 actual gradations were summed for various ranges of sieve sizes, for example, the percent differences at all screens between the 2.36-mm (No. 8) and the 75μ (No. 200) sieve sizes.

VMA correlated best to the sums of the distances between the 75μ (No. 200) and the 2.36-mm (No. 8) screens between the mix gradations and the maximum density line drawn from the origin to the actual percent passing the nominal maximum aggregate size ($r^2 = 0.29$ for all mixes considered as a group) (Table 1). The gradation of the fine aggregate is very influential in the measured VMA.

Possible reasons for the low correlations found between the VMA and the various sums of the distances between an HMA's gradation and the six maximum density lines that were evaluated are discussed in the next section.

Qualifying Statements

Distances

In data analyzed by Huber and Shuler (*5*) (Table 2), correlations between VMA and the sum of the distances between actual gradations and maximum density lines were poor when the data bases contained small sums of the distances at all screens (less than 80), and correlations were excellent when the data bases contained large sums of the distances at all screens (up to 150).

The indexes of determination, r^2, reported in this study using the 101 gradations from 1992 are low. All of the gradations analyzed in this study had low sums of the distances at all screens (less than 80) because they were produced within the very narrow CDOT Master Range specified in 1992.

It is possible to conclude that when gradations follow the maximum density line closely factors such as aggregate angularity are more critical in controlling VMA than when the gradations lie further from the maximum density line.

Age of Data

It should be noted that data gathered in the 1990s by CDOT and others (*12*) have gradations that commonly are closer to the maximum density line than data gathered in the 1950s (*3,9*). Apparently changes have occurred during the past 35 years to promote the production of aggregate gradations that are closer to the maximum density line.

Other Work

The excellent correlations between VMA and the sums of distances between mix gradations and maximum density lines obtained by Goode and Lufsey (*9*) used data from HMAs produced using one aggregate source. The Lefebvre data (*3*) was generated from HMAs using two aggregate sources. These correlations would be expected to drop as different aggregate sources with a variety of particle shapes were used. CDOT and D'Angelo and Ferragut (*11*) used data from HMAs produced from a wide variety of aggregate sources, and the VMA data have correspondingly lower correlations to the sums of the distances between mix gradations and the various maximum density lines.

Data in work by Lefebvre (*3*) and Goode and Lufsey (*9*) are from small nominal maximum aggregate size mixes, predominantly 12.5 mm (½ in.). Distances between actual gradations and the maximum

TABLE 1 Coefficients of Determination, r^2, for VMA Versus Distance from Actual Gradation to Maximum Density Line

Figure 1 Reference Line	Nominal Maximum Aggregate Size (mm)	Bracketed Ranges of Sieve Sizes			
		All Sieves	No. 4 to No. 50 Sieves	No. 8 to No. 200 Sieves	No. 30 to No. 200 Sieves
Nominal[a], Actual	All	0.14	0.20	0.29	0.28
	19.0	0.14	0.19	0.19	0.15
	12.5	0.01	0.02	0.04	0.04
Nominal, 100	All	0.05	0.12	0.19	0.22
	19.0	0.14	0.18	0.19	0.15
	12.5	0.04	0.01	0.00	0.00
Maximum[b], Actual	All	0.05	0.12	0.23	0.27
	19.0	0.10	0.13	0.19	0.30
	12.5	0.21	0.10	0.10	0.06
Maximum, 100	All	0.04	0.12	0.23	0.27
	19.0	0.10	0.13	0.19	0.30
	12.5	0.20	0.10	0.10	0.06
P100[c], 100	All	0.14	0.19	0.27	0.29
	19.0	0.14	0.19	0.19	0.15
	12.5	0.00	0.03	0.08	0.16
Texas Reference	All	0.03	0.12	0.14	0.13
	19.0	0.21	0.19	0.18	0.22
	12.5	0.02	0.13	0.10	0.02

[a] Nominal - First ASTM D 3515 sieve size above the largest sieve passing less than 90 % of the material.

[b] Maximum - Second ASTM D 3515 sieve size above the largest sieve passing less than 90 % of the material.

[c] P100 - Smallest ASTM D 3515 sieve size passing 100 % of the material.

TABLE 2 Relationship of Correlation Between VMA and Distance Between Maximum Density Line and Actual Gradation for Various Ranges

	Sum of Distances Between the Actual Gradation and the Maximum Density Line Drawn from the Origin to:			
	Maximum Size		Nominal Maximum Size	
Data Base	Range	r^2	Range	r^2
1992 CDOT	15 - 80	0.122	15 - 70	0.144
D'Angelo (11)	30 - 70	0.208	10 - 35	0.001
Goode (9)	40 - 120	0.915	20 - 50	0.004
Lefebvre (3)	50 - 150	0.815	30 - 100	0.232

density line drawn through the gradation at the nominal maximum aggregate size to the origin and summed for sieve sizes from 75µ (No. 200) to 2.36 mm (No. 8) were correlated to the measured VMA. The 1992 CDOT data base's 9.5-mm (3/8-in.) nominal maximum aggregate size mixes showed significantly higher correlations ($r^2 = 0.42$) than did the larger maximum aggregate size mixes. Gradations with smaller nominal maximum aggregate sizes appear to have better correlations between VMA and the sum of distances than gradations with larger nominal maximum aggregate sizes.

Before definite conclusions can be drawn about the best method to use in drawing the maximum density line, a larger data base, containing several different nominal maximum aggregate sizes, should be examined.

Summary

Gradation is important in the effort to influence VMA. Increasing the sum of the distance between a gradation and the maximum density line increases the chance that an HMA will possess adequate VMA.

The recommended maximum density line is drawn from the origin to the actual amount of material passing the nominal maximum aggregate size.

It is especially important to look at the sum of the distances at the 2.36-mm (No. 8) and smaller sieve sizes since the sums of the distances between mix gradations and recommended maximum density line had the best correlation to VMA in this region. All methods of analysis evaluated in this study showed that the amount of aggregate passing the smaller sieve sizes had the greatest effect on VMA.

However, because correlations were low, the only way to be certain of the VMA is to produce a sample and measure its VMA. The maximum density line is used only as a rule-of-thumb to provide guidance in increasing VMA.

PHASE 2—LABORATORY EXPERIMENT

An experiment was performed to determine the effect of varying several aggregate properties that were considered likely to affect VMA. The variables evaluated were the aggregate gradation, the particle size distribution of material passing the 75µ (No. 200) sieve (<75µ), the quantity of <75µ material, and the angularity of the material passing the 4.75-mm (No. 4) sieve.

Variables Investigated

Gradation

The HMA examined had a maximum aggregate size of 19.0 mm (3/4 in.). Three gradations (fine, coarse, and straight when plotted on a 0.45 power gradation chart) were used (Figure 3). The fine gradation was the finest gradation allowed by the 1992 CDOT master range. The coarse gradation was 4 percent to 6 percent coarser than allowed by the 1992 CDOT master range.

<75µ Size Material

Two sizes of <75µ material were used in the study. One <75µ material source was a quarried manufactured granite; the other was a natural source. The hydrometer analysis (ASTM D 422) results for both <75µ materials are shown in Figure 4. Sodium hexametaphosphate was used as a dispersing agent in the hydrometer analysis. Hydrated lime was used at 1 percent by weight of the aggregate for all HMA.

The coarse <75µ material had 55 percent passing the 20µ size, whereas the fine <75µ material had 75 percent passing the 20µ size. Both sources of <75µ material are characterized as fine, but one was finer than the other.

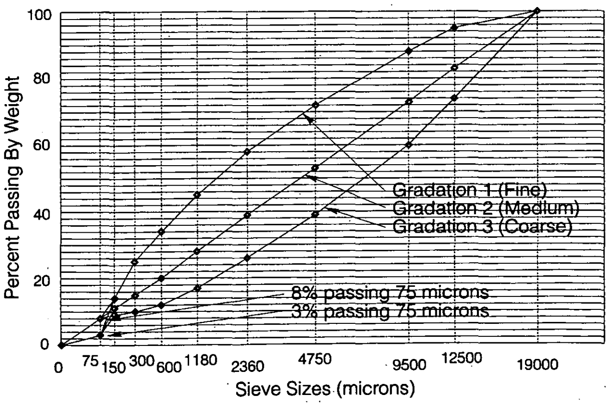

FIGURE 3 Three gradations and two levels of material passing 75µ sieve.

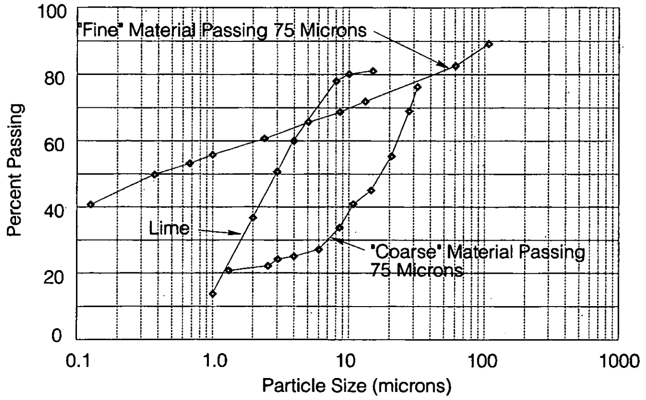

FIGURE 4 Hydrometer size analysis of material passing 75μ sieve.

<75μ Material Quantity

Two quantities of <75μ material were selected: 3 percent and 8 percent. These values were typical of those observed during the 1992 construction season and represented the maximum range allowed by the CDOT specifications for project-produced material.

Fine Aggregate Angularity

Mixes with two angularities of the fine aggregate fraction were evaluated. The HMA contained either 0 percent or 20 percent of the total aggregate weight as natural sand passing the 4.75-mm (No. 4) sieve. The particle shape and texture of the fine aggregate were measured using the National Aggregate Association's (NAA) test, Method A (*12,13*). The results of this test are reported as the uncompacted air void content of the aggregate. More angular aggregates will tend to have higher uncompacted air void contents. The uncompacted air void content of the aggregates used in Phase 2 of this experiment were 49.4 percent for the quarried material and 41.6 percent for the natural sand. Typical angularities of material from Pennsylvania (*13*) are shown in Figure 5 for comparison.

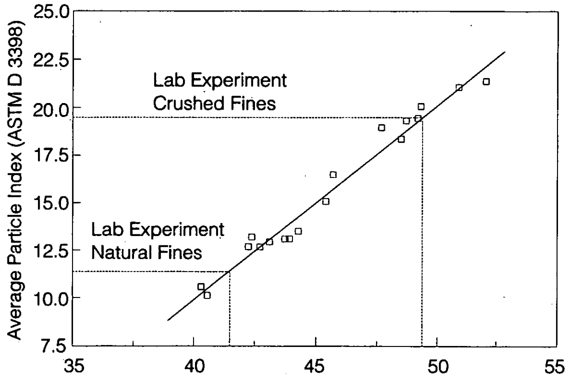

FIGURE 5 Uncompacted air void content versus aggregate angularity (*12*).

Mix Design Methodology

Twenty-four mix designs were evaluated, including all combinations of three gradations, two types of <75μ material, two quantities of <75μ material, and two levels of aggregate angularity.

Each aggregate was split into its individual standard sieve sizes, as defined by ASTM D 3515, then washed and oven-dried before recombination.

Each mix design sample was compacted using the Texas gyratory compactor (ASTM D 4013). Each mix design was evaluated at four asphalt contents with three samples compacted at each asphalt content. The bulk specific gravity (AASHTO T 166) and stability (AASHTO T 246) of each sample were measured. The theoretical maximum specific gravity (AASHTO T 209) was determined for each of the 24 mix designs.

Results

Data Extremes

The VMA of the 24 mix designs had a wide range of measured values. Optimum asphalt contents, selected at 4.0 percent air voids, ranged from 4.2 percent to 7.0 percent. The corresponding VMAs ranged from 12.5 to 18.1 percent. The data are summarized in Table 3.

It was hypothesized that the mixed with the highest VMA would be the fine gradation containing 100 percent crushed aggregate and 3 percent coarse <75μ material. The mix with the lowest VMA contained 80 percent crushed material and 8 percent <75μ material as expected; however, the mix had the coarse gradation and the coarse <75μ material. Since both types of <75μ material used in the study are classified as fine, it was hypothesized that a coarser source of <75μ material may have increased the highest VMA measured.

Effect of Component Variables on VMA

By changing the gradation from the coarse gradation to the straight-line gradation, the measured VMA increased (Table 4). This was not attributed to testing variability since all of the straight gradation HMAs had higher VMAs than their corresponding coarse gradations. However, it should be emphasized that only one coarse gradation was examined in this experiment. In Colorado's experience, it has been difficult to obtain adequate VMA when an HMA's gradation lies on the coarse side of the maximum density line. It was hypothesized that coarser HMAs can result in higher VMA, and this was confirmed in Phase 1 of the study. However, the single gradation studied in the laboratory experiment did not confirm this hypothesis.

When the effects of the individual component variables were analyzed, several localized changes in VMA were identified, as shown in Table 4. The fine aggregate angularity changed the VMA by 1 percent for the straight and coarse gradations, but angularity had only a slight effect on the VMA of the fine gradation.

The VMA of the fine gradation was more sensitive to the amount of <75μ material than were the coarse or straight gradations. Whereas the VMA of the fine gradation rose 1.6 percent when the amount of <75μ material was reduced from 8 percent to 3 percent, the straight and coarse gradations were affected significantly less. It is therefore necessary to keep the overall gradation of a mix in mind

TABLE 3 Test Results from Laboratory Experiment

% Crush	Gradation	% <75μ	Size <75μ	VMA at 4% A.V.[a]	AC Cont. @ 4% A.V.	Stability		
						@ 4% A.V.	@ 2% A.V.	Drop
100	Fine	3	Fine	17.9	6.8	50	38	20
100	Fine	3	Coarse	18.1	7.0	46	22	24
100	Fine	8	Fine	16.9	6.0	44	25	19
100	Fine	8	Coarse	15.7	5.7	48	37	21
100	Straight	3	Fine	14.0	4.9	53	40	13
100	Straight	3	Coarse	15.1	5.3	49	40	9
100	Straight	8	Fine	14.0	4.7	43	28	15
100	Straight	8	Coarse	13.8	4.6	51	29	22
100	Coarse	3	Fine	13.9	4.8	42	35	7
100	Coarse	3	Coarse	13.8	4.6	49	44	5
100	Coarse	8	Fine	13.3	4.3	44	40	4
100	Coarse	8	Coarse	13.2	4.1	39	34	5
80	Fine	3	Fine	17.7	6.8	35	29	6
80	Fine	3	Coarse	17.5	6.5	33	28	5
80	Fine	8	Fine	16.7	6.0	39	22	17
80	Fine	8	Coarse	15.7	5.6	38	27	11
80	Straight	3	Fine	13.5	4.7	43	36	7
80	Straight	3	Coarse	13.1	4.5	42	37	5
80	Straight	8	Fine	13.1	4.3	42	30	12
80	Straight	8	Coarse	13.0	4.4	40	23	17
80	Coarse	3	Fine	12.6	4.3	42	35	7
80	Coarse	3	Coarse	12.6	4.2	41	39	2
80	Coarse	8	Fine	12.7	4.2	42	37	5
80	Coarse	8	Coarse	12.5	4.2	38	29	9

[a] A.V. - Air Voids

when recommending changes to the mix in an attempt to increase its VMA.

Sensitivity of Mix Stability to Changes in Air Voids

The inevitable small changes in the air void content of an HMA will cause large changes in the Hveem stability of a sensitive mix. It has been shown that HMA designed in the laboratory does not always represent the material produced in the field (*11*).

Air voids of field-produced material can drop 1 percent or 2 percent from the HMA design. It is desirable that an HMA be stable so that this change in air voids does not cause a large drop in Hveem stability. For this reason, an attempt was made to identify the properties of HMA that relate to the sensitivity of stability.

The Hveem stability and the air voids versus asphalt content were examined to try to identify properties of an HMA that ensured a high VMA to address durability concerns while simultaneously maintaining a flat Hveem stability versus air voids curve to address permanent deformation concerns. Sensitive mixes are shown in Figure 6(*a*), and stable mixes are shown in Figure 6(*c*).

Effect of Component Variables on Sensitivity to Stability

For this analysis the sensitivity of the HMA to changes in air voids was defined by the drop in Hveem stability when the air voids were lowered from 4.0 percent to 2.0 percent. The 24 mix designs tested showed a wide range of sensitivity. When the air voids dropped from 4 percent to 2 percent, the corresponding stability drops were as low as 2 and as high as 24. These data are presented in Table 3.

Of the variables investigated, mix gradation showed the best correlation to the drop in Hveem stability of an HMA caused by a lowering of air voids. Coarse-graded HMAs were the least sensitive and fine-graded HMAs were the most sensitive to a lowering of air voids (Table 5). Although the stability values dropped less for the HMA

TABLE 4 Changes in VMA for Individual Variables at Optimum Asphalt Content for Different Gradations

Variable	Percent Change in VMA			
	Fine	Straight	Coarse	All
<75μ matl. - 8% to 3%	+1.6	+0.5	+0.3	+0.8
<75μ matl. - Fine to Coarse	-0.5	+0.1	-0.1	-0.2
Angularity - 80% to 100% Crushed	+0.3	+1.1	+1.0	+0.8
Gradation - Coarse to Straight	*	*	*	+0.6
Gradation - Straight to Fine	*	*	*	+3.3

* - Not possible to calculate

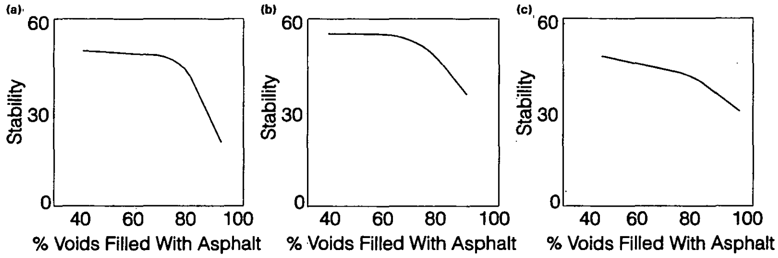

FIGURE 6 Voids filled with asphalt and stability of mixes: (*a*) fine gradation, (*b*) medium gradation, and (*c*) coarse gradation (data from 100 percent crushed material).

samples containing 20 percent natural sands, the stability values at 4 percent air voids were also consistently lower for the samples containing natural sand.

Influence of Voids Filled With Asphalt on Hveem Stability

Voids filled with asphalt (VFA) have been correlated with the rutting performance of HMA (*14,15*) and are considered to be an important mix design property (*10*). VFA were calculated for all 24 mix designs at all asphalt contents. The sensitivities of the mixes studied show a strong relationship to VFA, as shown in Figure 6. VFA of less than 75 percent to 80 percent appeared to be necessary to avoid having a mix whose stability is sensitive to asphalt content. Coarse-graded HMAs were the least sensitive and fine-graded HMAs were the most sensitive to VFA.

1993 EXPERIENCES

CDOT introduced a VMA specification for most HMA used during the 1993 construction season. The average asphalt content of 1993 mix designs increased by 0.46 percent over 1992 mix designs. CDOT has experienced better constructability of hot-mix bituminous pavements as a result of easier compaction and lower segregation of mixes. CDOT's materials engineers were pleased with the higher asphalt contents and better constructability of the 1993 HMAs and believe that mix quality improved from the 1992 HMAs. However, the opinion was expressed that the asphalt contents of mixes have not been raised enough.

CONCLUSIONS

On the basis of the analysis of 101 gradations from 1992 CDOT mixes and the laboratory experiment to determine the factors that influence VMA, the following conclusions were drawn.

1992 CDOT Mix Designs

- Because VMA did not correlate well to distances between mix gradations and maximum density lines, the only way to be certain of the VMA of a mix is to produce a sample and measure its VMA. The maximum density line is used only as a rule-of-thumb to provide guidance in increasing VMA.
- The recommended method for drawing the maximum density line is from the origin to the mix gradation at the nominal maximum aggregate sieve size.
- Gradations should be kept away from the recommended maximum density line throughout the sieve sizes smaller than the 2.36-mm (No. 8) sieve.
- A tight gradation specification by CDOT may have contributed to the poor correlations found between VMA and the percent difference between the actual gradations of mixes and the maximum density line.
- Aggregate gradations alone account for only a portion of the VMA attainable in an HMA. Aggregate angularity and quantity of <75μ material also affect the VMA of an HMA. Variations in these variables may have contributed to the low correlations found between mix gradations and VMA.

Laboratory Experiment

- Gradation affected the VMA of the mixes studied the most. The gradation on the fine side of the maximum density line had much more VMA than the gradation that followed the maximum density line. Producing coarse gradations that meet the VMA specifications historically has been difficult. The coarse gradation used in this experiment had lower VMA than the VMA of the gradation that followed the maximum density line. Although the coarse gradation in this study had low VMA, it is possible to achieve VMA on the coarse side of the maximum density line.

TABLE 5 Reduction in Stability when Air Voids Drop from 4 Percent to 2 Percent

	Average Reduction in Stability when Air Voids Drop from 4% to 2%		
Type of Aggregate	Fine	Straight	Coarse
100% Crushed	-15	-15	-6
80% Crushed	-11	-10	-6

- The quantity of <75µ material in an HMA mixture significantly affects the VMA. Lower quantities of <75µ material produce higher VMAs. Higher quantities of <75µ material produce lower VMAs. The VMAs of gradations on the fine side of the maximum density line were affected more by the quantity of <75µ material than were the VMAs of gradations on the coarse side of the maximum density line.
- Aggregate angularity affected the VMA substantially. Higher quantities of crushed aggregates and more angular crushed aggregates will produce higher VMAs in HMAs. Higher quantities of rounded, natural sands and more rounded aggregates will result in lower VMAs. The VMAs of gradations on the coarse side of the maximum density line or following the maximum density line were more affected by the angularity of the fine aggregate than were the VMAs of HMAs with gradations on the fine side of the maximum density line.
- The determination of the effect on VMA by the size of the <75µ material was inconclusive. The sizes of <75µ material used in this study were both fine. Further study of this variable is required before conclusions can be drawn about the effect on VMA of the size of the <75µ material.
- The sensitivity of the Hveem stability of an HMA to changes in air voids is an important property that must be considered. Sensitivity was well correlated to gradation in the laboratory experiment: the coarser the gradation, the less sensitive the mix. A VMA content meeting the Asphalt Institute's specifications does not ensure a mix that is not sensitive; HMAs with high VMA can be sensitive to changes in air voids. The VFA should be limited to a maximum of 75 percent or 80 percent to reduce the chance of obtaining a mix with a stability that is sensitive to changes in air voids. This limit is more important for HMAs with gradations on the fine side of the maximum density line than for HMAs with gradations on the coarse side of the maximum density line.

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REFERENCES

1. McLeod, N. W. Relationships Between Density, Bitumen Content, and Voids Properties of Compacted Bituminous Paving Mixtures. *HRB Proc.*, Vol. 35, 1956, pp. 327–404.
2. McLeod, N. W. *Void Requirements for Dense-Graded Bituminous Paving Mixtures.* Special Technical Publication 252. ASTM, Philadelphia, Pa., 1959, pp. 81–112.
3. Lefebvre, J. Recent Investigations of Design of Asphalt Paving Mixtures. *Proc., Association of Asphalt Paving Technologists*, Vol. 26, 1957, pp. 321–394.
4. Heinz, R. E. *Asphalt Concrete Mix Design and Field Control.* FHWA Technical Advisory T 5040.27. FHWA, U.S. Department of Transportation, 1988, 27 pp.
5. Huber, G. A., and T. S. Shuler. Providing Sufficient Void Space for Asphalt Cement: Relationship of Mineral Aggregate Voids and Aggregate Gradation. *Effects of Aggregates and Mineral Fillers on Asphalt Mixture Performance:* Special Technical Publication 1147. ASTM, Philadelphia, Pa., 1992.
6. *Performance Based Specification to be Used in Mixture Design and Analysis Systems.* Draft working paper. Strategic Highway Research Program, National Research Council, Washington, D.C., 1991, 51 pp.
7. Aschenbrener, T., and MacKean, C. *Factors That Affect the Voids in the Mineral Aggregate in Hot Mix Asphalt.* CDOT-DTD-R-92-13. Colorado Department of Transportation, Denver, 1992, 58 pp.
8. Nijboer, L. W. *Plasticity as a Factor in the Design of Dense Bituminous Road Carpets.* Elsevier Publishing, New York, N.Y., 1948.
9. Goode, J. F., and L. A. Lufsey. A New Graphical Chart for Evaluating Aggregate Gradations. *Proc., Association of Asphalt Paving Technologies*, Vol. 31, 1962, pp. 176–207.
10. Huber, G. A. Marshall Mix Design Criteria Changes. *Asphalt: Magazine of the Asphalt Institute*, Winter 1991/1992, pp. 20–22.
11. D'Angelo, J. A., and T. Ferragut. Summary of Simulation Studies from Demonstration Project No. 74: Field Management of Asphalt Mixes, *Journal of the Association of Asphalt Paving Technologists*, Vol. 60, 1991, pp. 287–309.
12. Mogawer, W. S., and K. D. Stuart. Evaluation of Test Methods Used to Quantify Sand Shape and Texture. In *Transportation Research Record 1362*. TRB, National Research Council, Washington, D.C., 1992, pp. 28–37.
13. Kandhal, P. S., J. B. Motter, and M. A. Khatar. Evaluation of Particle Shape and Texture: Manufactured Versus Natural Sands. In *Transportation Research Record 1301*. TRB, National Research Council, Washington, D.C., 1991, pp. 48–56.
14. Huber, G. A., and G. H. Heiman. Effect of Asphalt Concrete Parameters on Rutting Performance: A Field Investigation. *Proc., Association of Asphalt Paving Technologists*, Vol. 56, 1987 pp. 33–61.
15. Ford, M. C., Jr. Asphalt Mix Characteristics and Related Pavement Performance. *Proc., Association of Asphalt Paving Technologists*, Vol. 57, 1988, pp. 519–544.