

Evaluation of Stone-on-Stone Contact in Stone-Matrix Asphalt

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The presence of stone-on-stone contact and a relatively low percentage of fine aggregate are two characteristics of stone-matrix asphalt (SMA). Although it is known that the stone skeleton in SMA is primarily responsible for its high rutting resistance, a method to quantitatively determine stone-on-stone contact has not been used in the United States. A simple laboratory method was developed to determine stone-on-stone contact in SMA with conventional hot-mix asphalt parameters such as voids in mineral aggregate, voids in coarse aggregate, and dry-rodded weight of coarse aggregate. Tests were conducted to evaluate the effect of percent passing the 4.75-mm sieve on the susceptibility of mix stability to change in void content. It was observed that mixes with a low percent passing the 4.75-mm sieve were less sensitive to low air void contents. Mixtures with a low percent passing the 4.75-mm (No. 4) sieve (30 percent or less) tended to have stone-on-stone contact.

Stone-matrix asphalt (SMA) has proven to be a rut-resistant and cost-effective surface layer material in Europe for more than 20 years. A number of SMA projects have been constructed in the United States since 1991 to evaluate its performance, and these projects will continue to be monitored for several years. Unlike conventional hot-mix asphalt (HMA), SMA mixtures are characterized as stone-on-stone contact (1). SMA derives its strength primarily from the stone-on-stone skeleton developed in the mix (2-4). The stone-on-stone skeleton is shown schematically in Figure 1, which also shows the coarse aggregate contact for an SMA gradation and the less coarse aggregate contact for a dense-graded mixture. Though there has been much discussion about SMA mixtures having stone-on-stone contact, a method needs to be selected to actually determine quantitatively whether stone-on-stone contact exists. (5). Also, because performance of SMA has been shown to be significantly affected by aggregate gradation (6), there is a need to evaluate the effect of percent passing the 4.75-mm sieve on stability of SMA mixes.

OBJECTIVE

The objectives of this study were to develop a method to measure stone-on-stone contact in SMA mixes and to evaluate the effect of stone-on-stone contact on the stability of mixes.

SCOPE

The results presented in this paper were obtained from two studies; one was conducted to evaluate stone-on-stone contact in SMA

(with gravel and limestone aggregates), and the other was conducted to evaluate the effect of percent passing the 4.75-mm sieve on stability of mixes (with limestone aggregates). To evaluate stone-on-stone contact in SMA mixes, studies were carried out with gravel and limestone aggregates and 0.3 percent European cellulose fibers. Mixes were made by varying the percent of materials passing the 4.75-mm sieve, starting at 50 percent and going down to 15 percent. Two types of void were plotted against percent passing the 4.75-mm sieve: the void in mineral aggregates (VMA), and the void in coarse aggregates (VCA). VCAs were calculated in a way similar to VMAs by replacing percent of aggregates in the mix with percent of coarse aggregates in the calculation. The curves for VMA and VCA versus percent passing the 4.75-mm sieve were compared with that for the VCA obtained from the dry-rodded test of coarse aggregates to determine whether stone-on-stone contact existed.

Marshall stability was measured for gravel and limestone mixes (in the stone-on-stone contact study), and gyratory test properties were measured for limestone mixes (in the evaluation of effect of percent passing the 4.75-mm sieve). These properties were measured at different percents passing the 4.75-mm sieve and at different asphalt (air void) contents. Comparisons of changes in stability and gyratory properties with changes in air void content were made for the different mixes.

TEST PLAN

To obtain optimum resistance to rutting, it is believed that stone-on-stone contact in the coarse aggregate portion of the SMA mixture is required. In the past, stone-on-stone contact has been very subjective and has only been evaluated by visual observation from cored samples. There is a need to develop a method to quantify when stone-on-stone contact occurs to ensure that it is sufficient to provide the desired properties.

It was decided that stone-on-stone contact could be evaluated from the VMA and VCA curves. Stone-on-stone contact is considered to begin at the point at which the VCA plot begins to curve as the amount of material passing the 4.75-mm sieve is reduced. It also is considered to begin at the point at which the VMA begins to increase as the percent passing the 4.75-mm sieve is reduced. A third measure of stone-on-stone contact is when the voids in the dry-rodded condition are equal to or greater than the VCA in the SMA mixture.

Two types of aggregates, gravel and limestone, were used for this study. Coarse and fine aggregates refer to materials retained on and passing the 4.75-mm sieve, respectively. Mixes were produced with various percents of material passing the 4.75-mm sieve: 50, 40, 30, 25, 20, and 15 percent. The gradations are shown in Table 1. The binder used for the mixes was an AC-20 asphalt cement from Chevron, Inc., U.S.A. (Mobile, Ala.).

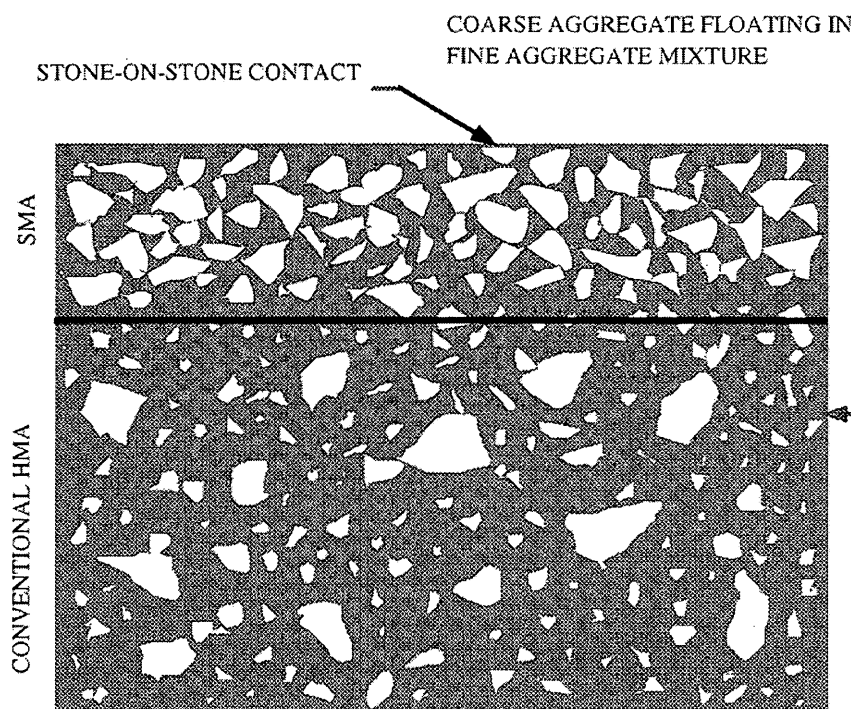


FIGURE 1 Section showing difference in stone-on-stone contact between SMA and conventional HMA.

TABLE 1 Gradation of Aggregates

Sieve Size	Percent Passing					
	A	B	MIX C	D	E	F
12.5 mm (1/2 inch)	100	100	100	100	100	100
9.50 mm (3/8 inch)	75	70	65	63	60	58
4.75 mm (No. 4)	50	40	30	25	20	15
2.36 mm (No. 8)	40	32	25	21	18	15
1.18 mm (No. 16)	34	28	22	19	16	15
0.60 mm (No. 30)	30	25	20	18	15	15
0.30 mm (No. 50)	22	19	17	16	15	14
150 μ m (No. 100)	15	15	14	14	13	12
75 μ m (No. 200)	10.0	10.0	10.0	10.0	10.0	10.0

LIMESTONE AGGREGATES USED IN GYRATORY TESTS

Sieve Size	Percent Passing					
	A	B	MIX C	D	E	F
12.5 mm (1/2 inch)	100	100	100	100	100	100
9.50 mm (3/8 inch)	83	80	78	77	74	72
4.75 mm (No. 4)	50	40	35	30	25	20
2.36 mm (No. 8)	38	30	27	24	20	16
1.18 mm (No. 16)	28	24	22	20	17	15
0.60 mm (No. 30)	22	19	16	16	14	14
0.30 mm (No. 50)	17	15	14	14	12	12
150 μ m (No. 100)	12	12	11	11	11	11
75 μ m (No. 200)	10.0	10.0	10.0	10.0	10.0	10.0

Samples were prepared using 0.3 percent cellulose fiber (a typical cellulose made in Europe) and agricultural lime as the filler. Mix designs were performed with the mechanical Marshall compactor (50 blows) by preparing and compacting samples with asphalt content varied in 0.5 percent increments. Three samples were made for each asphalt content. The optimum asphalt content was chosen as the asphalt content that produced 3.0 percent air voids. VMA and VCA were calculated for the compacted samples. VCA was calculated by replacing percent of aggregates in the mix (used in VMA calculations) by percent of coarse aggregates in the calculations. The equations used for calculating VMA and VCA were:

$$\text{VMA} = 100 - \frac{V_{\text{agg}}}{V_T} (100)$$

$$\text{VCA} = 100 - \frac{V_{\text{CA}}}{V_T} (100)$$

where

V_{agg} = volume of aggregate calculated using bulk specific gravity,

V_T = total volume of compacted mixture, and

V_{CA} = volume of coarse aggregate calculated using bulk specific gravity.

To measure the VCA with no fine aggregates, the coarse aggregate was placed in a container and dry rodded to maximum density in accordance with ASTM C29. The aggregates were rodded when the container was one-third full, two-thirds full, and full. The VCA in the dry-rodded condition represents stone-on-stone contact. The VMA and VCA at the optimum asphalt content were then plotted against the percent passing the 4.75-mm sieve and compared with

the VCA for a mix without any fine aggregates. The point at which the VCA in the mixture was equal to the VCA in the dry-rodded condition was the point at which it was assumed that stone-on-stone contact existed. Other measures of stone-on-stone contact were the points at which the VMA curve starts upward as the percent passing the 4.75-mm sieve is reduced, and the point at which the VCA curve began to flatten. A schematic of the test plan is shown in Figures 2 and 3.

To observe the effects of reducing the percent passing the 4.75-mm sieve, Marshall stability tests were conducted on the mixes having different asphalt contents (voids). A different set of mixes containing limestone aggregates were compacted in the Corps of Engineers gyratory testing machine (GTM) at various asphalt (air void) contents to observe the effect of percent passing the 4.75-mm sieve on the gyratory shear index (GSI) and the gyratory shear (Sg). The gradations of the limestone aggregates are shown in Table 1.

TEST RESULTS AND ANALYSIS

The results of VMA and VCA measurements for different mixes are shown in Tables 2 and 3. The variations of VMA and VCA with percent passing the 4.75-mm sieve are shown in Figures 4 and 5 for gravel and limestone, respectively. The VCA for the dry-rodded weight is also shown as an indication of the point where stone-on-stone contact begins to occur. For gravel, the VCA plot began to curve at 30 percent, the VMA curve started to increase at 30 percent (as the percent passing the 4.75-mm sieve was reduced), and the VCA of mix crossed the VCA line (dry rodded) at 26 percent. For gravel, the data show that stone-on-stone contact began at 26 to 30 percent passing the 4.75-mm sieve and was present for any percent less than 26 to 30. For limestone, the VCA plot began to curve and the VMA started to increase at 25 percent (as the percent passing the 4.75-mm sieve was reduced), whereas the VCA curve of the SMA mix crossed the VCA line (dry rodded) at 32 percent. For

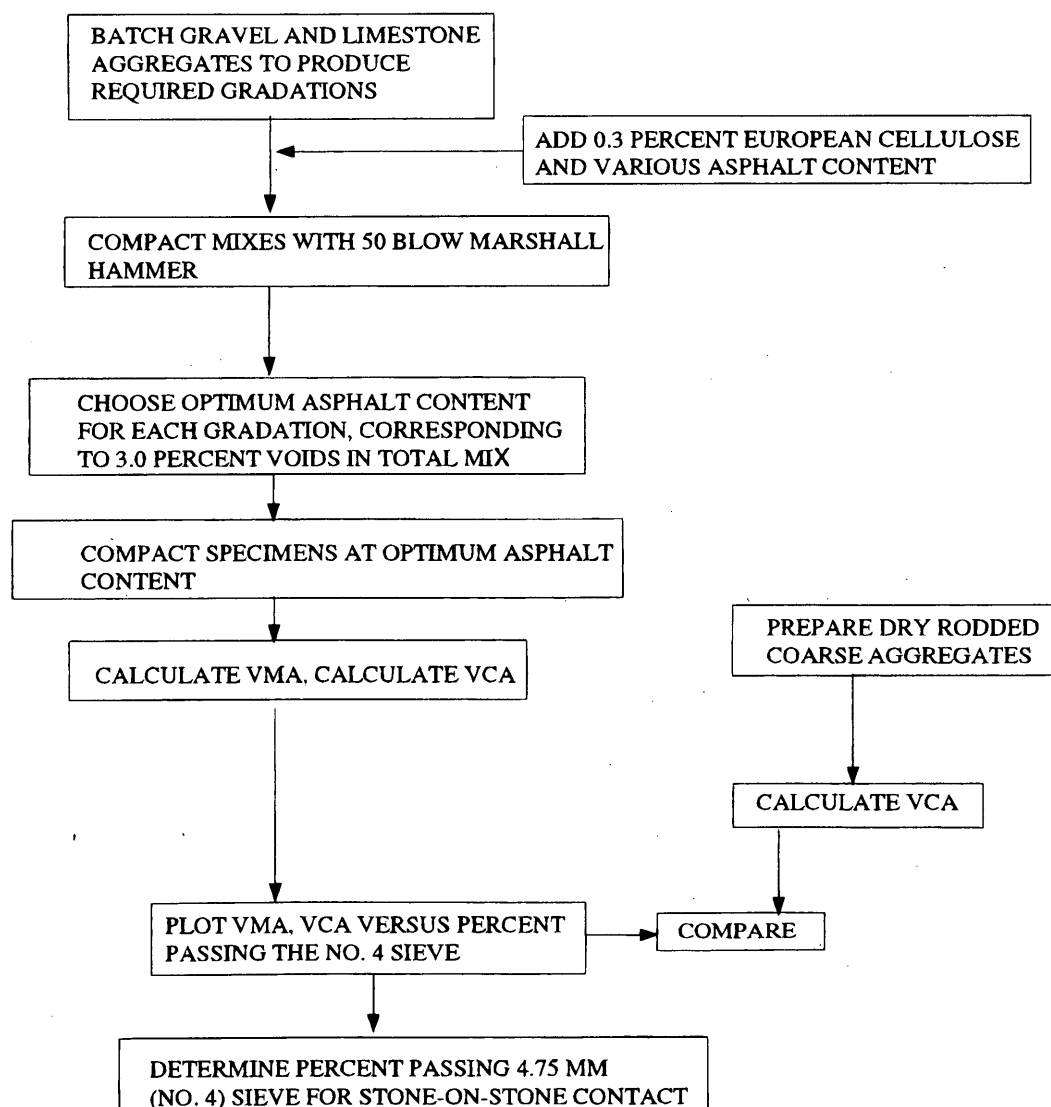


FIGURE 2 Test plan for evaluation of stone-on-stone contact.

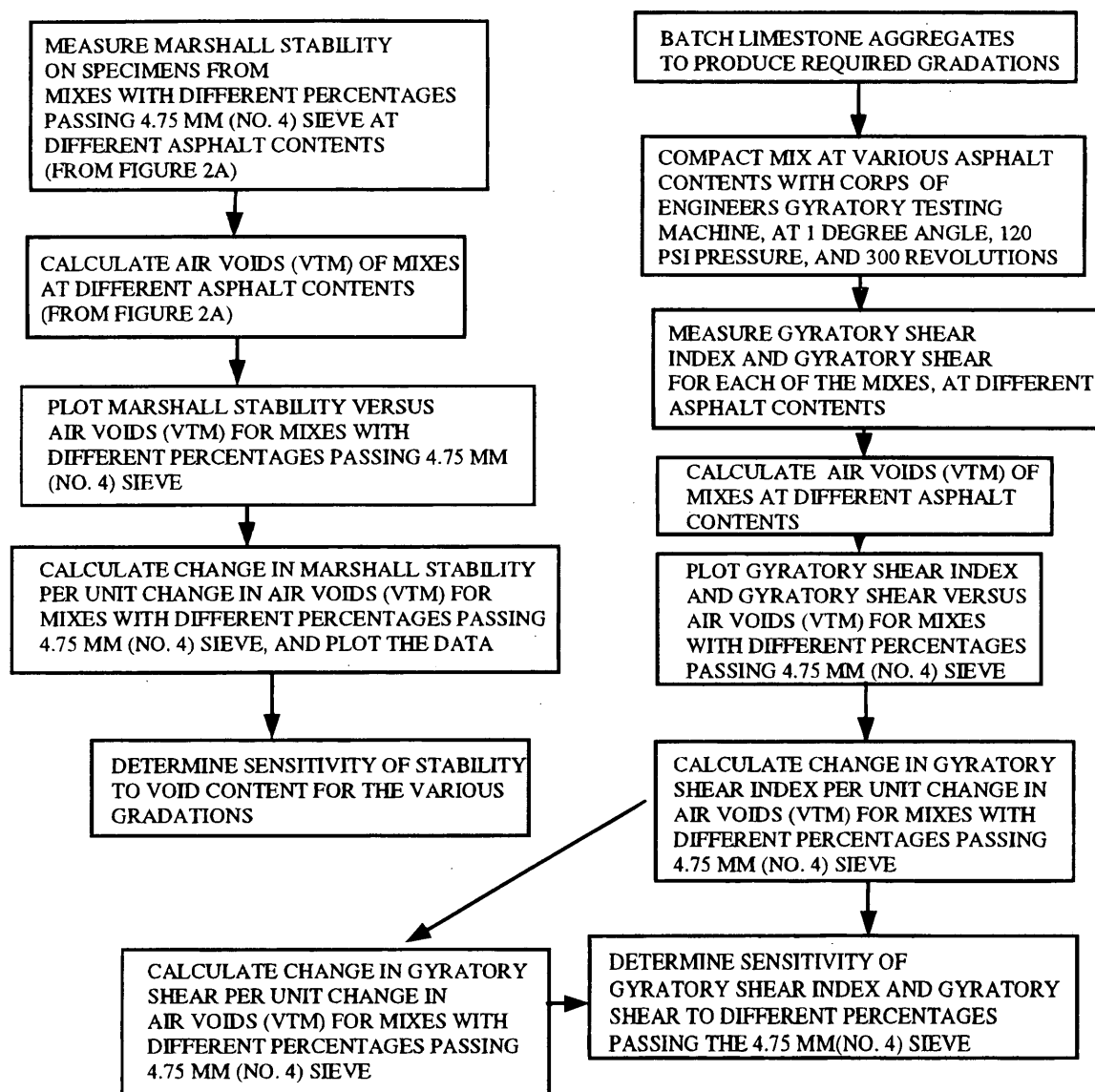


FIGURE 3 Test plan for evaluation of effect of percent passing 4.75-mm (No. 4) sieve on mix stability.

limestone, stone-on-stone contact began at 25 to 32 percent passing the 4.75-mm sieve.

The VMA content began to increase as the fine aggregate content was reduced when stone-on-stone contact began. Once coarse aggregate contact was made, a decrease in percent passing the 4.75-mm sieve did not result in an equal decrease in the VCA, and thus the VMA increased. From this point, removal of fine aggregates did not contribute to further densification of the coarse aggregate portion of the mix, and thus increased the VMA. Also, VCA in the dry-rodded condition was near the VCA for 30 percent passing (26 for gravel and 32 for limestone) the 4.75-mm sieve in both the mixes. Thus for these two mixtures, it can be assumed that stone-on-stone contact existed at less than 30 percent passing the 4.75-mm sieve and did not exist at more than 30 percent passing the 4.75-mm sieve.

The dry-rodded test seems to be a good method to determine the density of the coarse aggregate required for stone-on-stone contact.

This is a simple test that can readily be conducted in most laboratories. It is believed that stone-on-stone contact occurs when the density of the coarse aggregate in the SMA mixture is equal to or higher than that measured in the dry-rodded test. This is because irrespective of the amount of fines present in a mix, the density of the rigid stone-on-stone skeleton should be approximately the same as that achieved in the dry-rodded condition. When the VCA of the dry-rodded aggregate and the density of the coarse aggregate in an SMA mix are the same, it means that the coarse aggregate in the SMA mix is at least as closely packed as that in the dry-rodded mix. Because the VCA in the dry-rodded mix represents a stone-on-stone condition, it is concluded that a similar condition exists in the SMA mix.

This study identified three possible ways to ensure stone-on-stone contact in the coarse aggregate portion of SMA mixtures. The first way was to develop a plot of VCA versus percent passing the 4.75-mm sieve. In this series of tests, the percent passing the 4.75-

TABLE 2 Summary of Volumetric and Marshall Stability Properties of Gravel Mixes

PERCENT PASSING ASPHALT 4.75 MM (NO. 4) SIEVE	CONTENT (%)	TMD	VTM	VMA	VCA	MARSHALL STABILITY (N)
50	5.0	2.435	3.4	14.0	57.0	12,298
	5.5	2.418	2.2	14.0	57.0	10,800
	6.0	2.400	1.7	14.6	57.3	8,520
	6.5	2.384	1.4	15.4	57.7	7,520
	5.1	2.431	2.9	13.8	56.9	-
40	5.0	2.435	3.6	14.2	48.5	10,213
	5.5	2.418	2.2	14.0	48.4	9,524
	6.0	2.401	1.7	14.6	48.8	7,986
	6.5	2.384	1.2	15.3	49.2	7,035
	5.2	2.429	2.9	14.0	48.4	-
30	4.5	2.449	5.1	14.6	40.2	10,169
	5.0	2.431	4.6	15.2	40.7	9,213
	5.5	2.414	3.3	15.2	40.6	7,453
	6.0	2.397	2.0	15.0	40.5	7,924
	5.4	2.418	2.8	14.4	40.1	-
25	5.7	2.414	4.0	15.9	36.9	7,613
	6.0	2.404	2.7	15.4	36.6	7,369
	6.5	2.386	2.2	16.1	37.1	7,924
	7.5	2.353	1.6	17.6	38.2	7,231
	5.9	2.407	3.2	15.6	36.7	-
20	4.5	2.446	7.5	16.9	33.5	7,582
	5.0	2.428	6.7	17.2	33.7	7,364
	5.5	2.411	5.5	17.1	33.7	7,422
	6.0	2.394	4.4	17.2	33.8	7,564
	6.6	2.374	3.9	18.1	34.4	-
15	6.0	2.409	6.7	18.7	30.9	6,987
	6.5	2.392	5.8	18.9	31.1	6,489
	7.0	2.375	5.3	19.5	31.6	6,213
	7.5	2.359	4.0	19.4	31.5	6,533
	8.0	2.343	2.9	19.5	31.5	-
DRY RODDED COARSE AGGREGATE	-	-	-	-	37.6	-
- DATA NOT AVAILABLE						1 N = 0.225 LBF

mm sieve was decreased to a point at which the straight line relationship began to curve. This curve was caused by the development of stone-on-stone contact, which prevented a closer packing of the coarse aggregate as the amount of fine aggregate was reduced. This occurred at approximately 30 percent passing the 4.75-mm sieve for the two mixtures evaluated (Figures 4 and 5).

A second method that appeared to have some possibility of identifying the occurrence of stone-on-stone contact in the coarse aggregate fraction is the VMA plot. These data can be generated at the same time as the VCA data, so no extra testing is required. As the percent passing the 4.75-mm sieve was decreased, the VMA plot was essentially flat until stone-on-stone contact began to develop; then the VMA began to increase. This increase in VMA resulted because the coarse aggregate cannot be moved closer together with a reduction in the percent of fine aggregate when stone-on-stone contact exists. This method can be used to estimate the point at which stone-on-stone contact occurs in a way similar way to the VCA method. This method also shows that stone-on-stone contact occurs at approximately 30 percent passing the 4.75-mm sieve. Both of these methods require a significant amount of testing.

A third method used in this study to measure stone-on-stone contact involved using the dry-rodded test for voids in coarse aggregate. Only coarse aggregate is used in this test, and the dry-rodded condition is a measure of stone-on-stone contact. As long as the density of the coarse aggregate in an SMA mixture is equal to or greater than the dry-rodded density, stone-on-stone contact should exist. The compacted condition of the coarse aggregate can be quantified by VCA or by the density of the coarse aggregate. This is a very simple test that involves very little time. As shown in Figures 4 and 5, this method gives about the same results as the VCA and VMA methods described previously. These methods of measuring stone-on-stone contact seem promising, but more data need to be generated, and other possible methods should be evaluated.

Effect of Percent Passing the 4.75-mm Sieve on Mixture Stability

As stone-on-stone contact is gradually achieved in a mix, with a decrease in percent passing the 4.75-mm sieve, the mix becomes

TABLE 3 Summary of Volumetric and Marshall Stability Properties of Limestone Mixes

PERCENT PASSING ASPHALT 4.75 MM (NO. 4) SIEVE	CONTENT (%)	TMD	VTM	VMA	VCA	MARSHALL STABILITY (N)
50	4.0	2.640	4.3	13.6	56.8	14,156
	4.5	2.619	3.3	13.8	56.9	12,867
	5.0	2.588	1.9	14.0	57.0	10,675
	5.5	2.567	1.1	14.5	57.3	8,511
	4.6	2.605	2.9	14.0	57.0	-
40	4.0	2.640	4.8	14.0	48.4	-
	4.5	2.619	4.0	14.5	48.7	11,480
	5.0	2.588	2.1	14.2	48.5	9,702
	4.8	2.606	3.2	14.4	48.6	-
30	4.0	2.629	5.3	14.8	40.4	9,320
	4.5	2.608	4.1	14.9	40.4	8,556
	5.0	2.588	2.9	14.9	40.4	8,013
	4.9	2.592	3.0	14.8	40.3	-
25	4.5	2.619	5.4	15.7	36.7	9,614
	5.0	2.598	3.1	14.7	36.0	8,924
	5.5	2.577	2.4	15.3	36.5	7,711
20	4.0	2.635	7.1	16.3	33.0	8,502
	4.5	2.613	5.8	16.3	33.0	8,298
	5.0	2.592	4.3	16.0	32.8	7,787
	5.5	2.572	3.2	16.2	32.9	7,542
	5.6	2.568	3.1	16.3	33.1	-
15	5.0	2.606	6.4	17.4	29.8	7,800
	5.5	2.585	5.1	17.4	29.8	7,689
	6.0	2.565	3.9	17.5	29.8	7,120
	6.5	2.545	3.3	18.0	30.3	7,342
	7.0	2.525	2.4	18.3	30.5	-
DRY RODDED COARSE AGGREGATE	-	-	-	-	42.2	-

- DATA NOT AVAILABLE

1 N = 0.225 LBF

less sensitive to a change in air voids. The presence of fines in a mix is similar to the presence of silt or clay in soil and results in a buildup of pore pressure under loading at low void contents (near saturation). However, in the case of stone-on-stone contact with a smaller amount of fines, the mix behaves more like a free-draining soil, having less pore-pressure effects. This causes the mix to be less sensitive to a change in asphalt content, just as a soil that drains freely is less sensitive to moisture content.

Marshall stability tests were conducted on the gravel and limestone mixes at different asphalt (voids) contents to observe the effect of percent passing the 4.75-mm sieve on the sensitivity of the mixes. Although Marshall stability may not be a good indicator of field stability, this test was chosen because it is a relatively simple test with which to evaluate change in stability with change in asphalt content (7). The results of the tests are summarized in Tables 2 and 3. Insufficient stability data were available for analysis of the limestone aggregate for 25, 30, and 40 percent passing the 4.75-mm sieve. Figures 6 and 7 show the effect of voids on Marshall stability for the different mixes. Marshall stability was observed to decrease significantly with a decrease in air void content for mixes with 50, 40, and 30 percent passing the 4.75-mm sieve. Conversely, stability remained almost constant with a change in air void content for mixes with low percent passing the 4.75-mm sieve (20 and 25 percent).

The change in stability per unit change in voids was calculated for the different mixes and plotted in Figure 8. The change in stability decreased with a decrease in percent passing the 4.75-mm sieve, indicating that mixes become less sensitive to air void content at lower percents passing the 4.75-mm sieve. For gravel, the change in stability per unit change in air voids decreased from 2300 N for 50 percent passing the 4.75-mm sieve to about 75 N for 25 percent passing the 4.75-mm sieve. Below 25 percent, the change increased slightly but remained at about 150 N per percent voids at both 20 and 15 percent passing the 4.75-mm sieve. For limestone, the change was about 1700 N per percent voids at 50 percent passing the 4.75-mm sieve and decreased to about 200 N per percent voids at 15 percent passing the 4.75-mm sieve. These data appear to confirm that 30 percent passing the 4.75-mm sieve (the point at which stone-on-stone contact occurs) is the point that separates mixtures that are sensitive to changes in voids from mixtures that are not.

GSI and Sg of Limestone Compacted in the GTM

Additional limestone mixes were compacted in the GTM at various asphalt (void) contents. The compactions were performed at 120 psi vertical pressure, 1 degree vertical angle, and 300 revolutions. Dur-

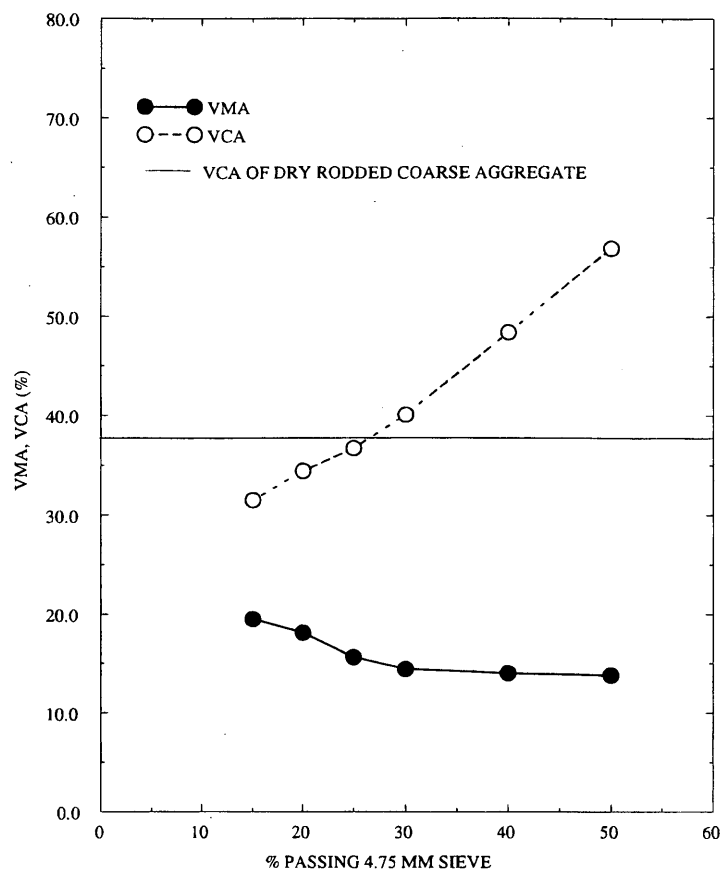


FIGURE 4 Variation of voids with percent passing 4.75-mm sieve for gravel mixes.

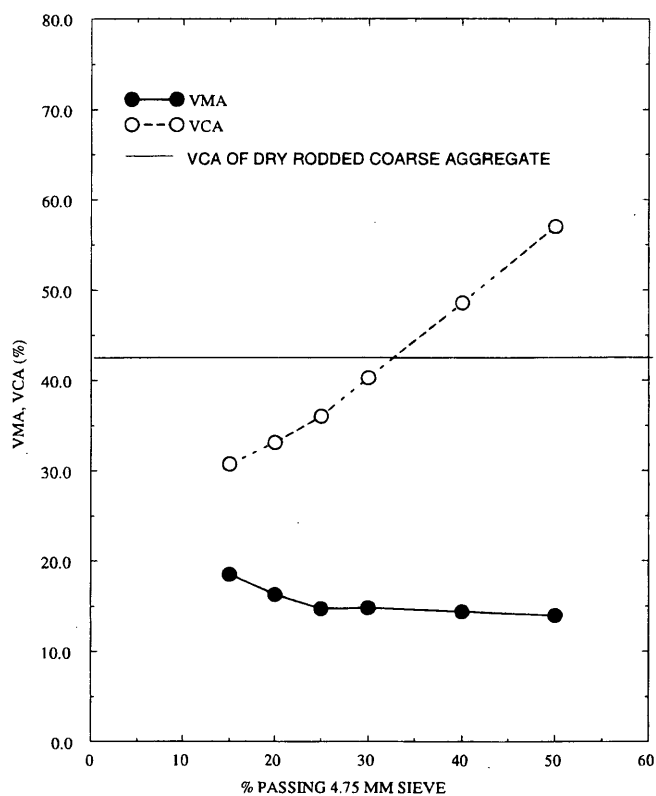


FIGURE 5 Variation of voids with percent passing 4.75-mm sieve for limestone mixes.

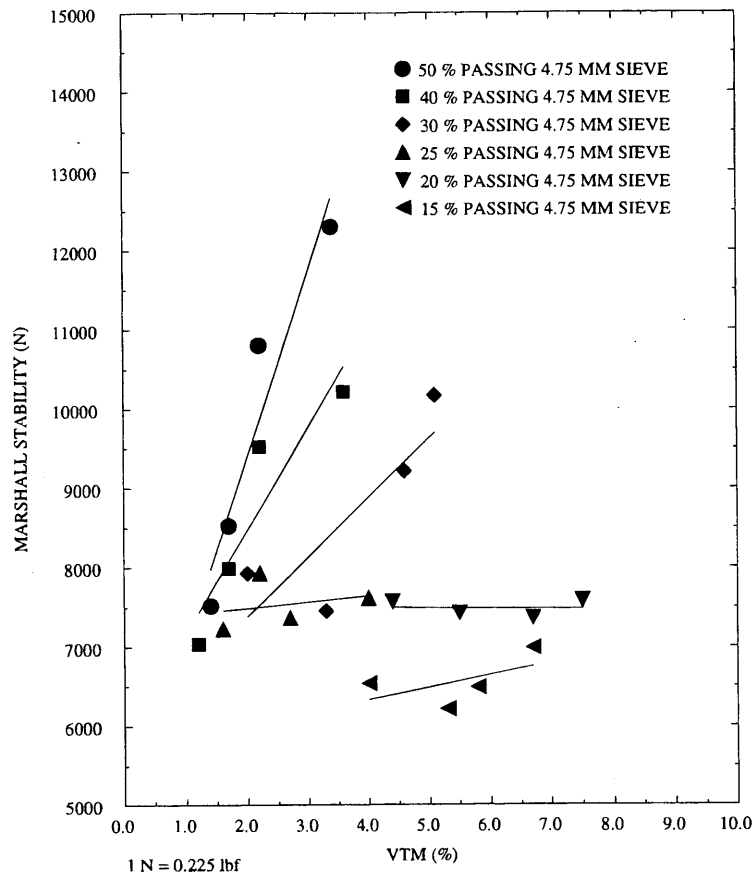


FIGURE 6 Plot of Marshall stability versus air voids for different gravel mixes.

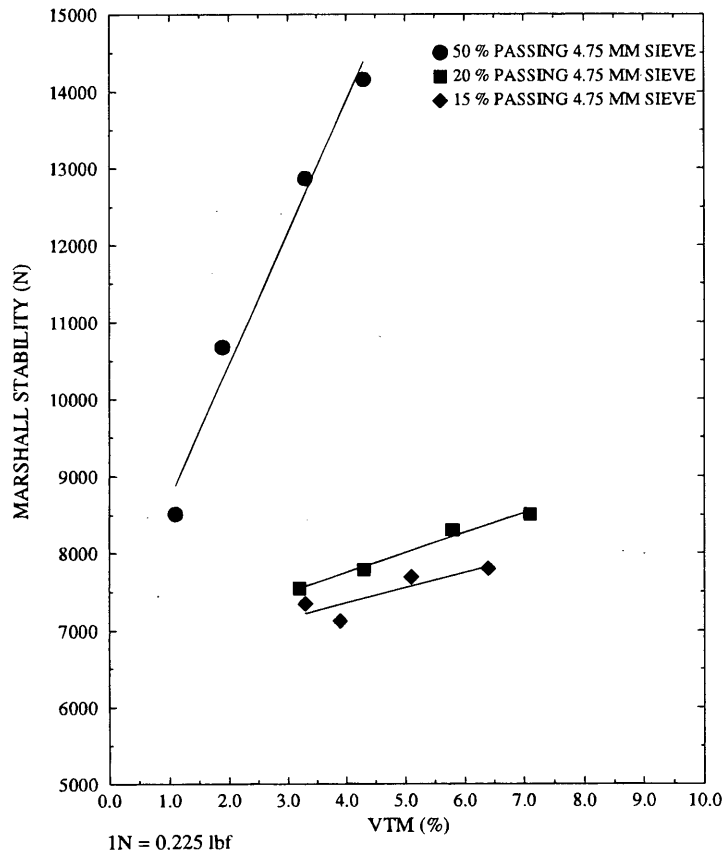


FIGURE 7 Plot of Marshall stability versus air voids for different limestone mixes.

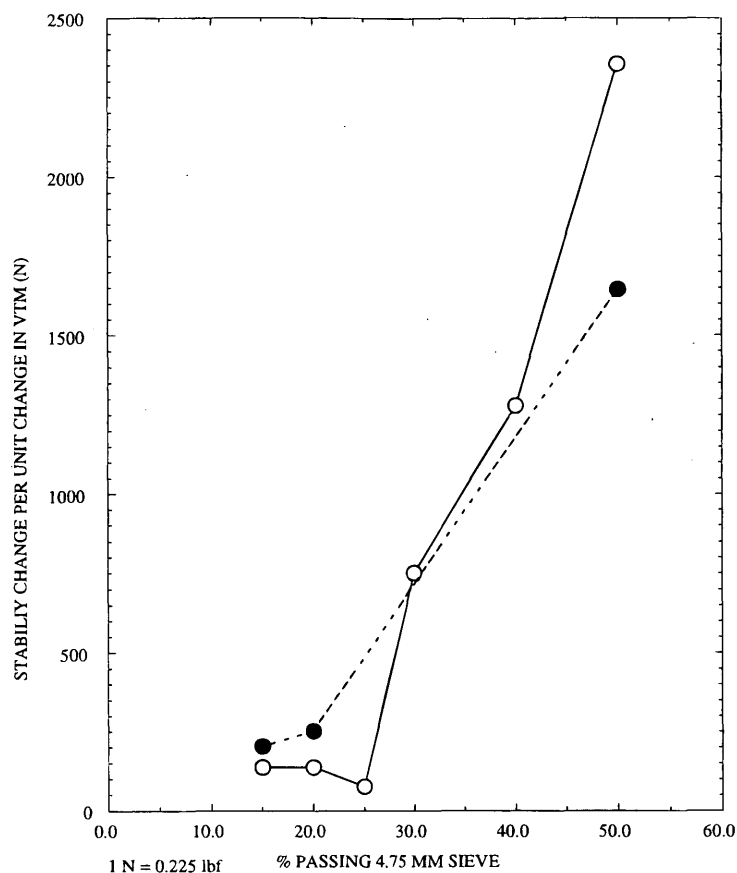


FIGURE 8 Change in Marshall stability per unit change in air void for different mixes.

ing compaction, two parameters were determined for each mix: GSI and S_g .

The GSI is a measure of mixture stability and is related to permanent deformation (7). It is determined by dividing the highest gyration angle by the initial angle. The gyration angle increases during compaction for unstable mixtures because of plastic flow of the HMA but does not increase significantly for stable mixtures. GSI values close to 1.0 have been shown to be typical for stable mixtures, and values significantly above 1.1 usually indicate unstable mixtures (7).

As the percent passing the 4.75-mm sieve is decreased, the coarse aggregates start moving closer to each other. As observed from the first phase of this study, stone-on-stone contact began to occur at 26 to 30 percent for gravel and at 25 to 32 percent for limestone. It was expected that at percents below the point of stone-on-stone contact, stability of mix would be less affected by air voids. GSI values for the mixes with different percents passing the 4.75-mm sieve and at different void contents are shown in Table 4. The results are plotted in Figure 9. The mixes with low percents passing the 4.75-mm sieve (20 and 25 percent) had GSI values very near 1 (around 1.05) at all voids contents. Mixes with 50, 40, 35, and 30 percent passing the 4.75-mm sieve showed an increase in GSI with a decrease in void content. This indicates that mixes with 30 percent and greater passing the 4.75-mm sieve became unstable at low void contents. Figure 11 shows the change in GSI values per unit change in void content. The change in GSI decreased when the percent passing the 4.75-mm sieve was decreased to 35 percent passing. The change was about 0.11 per percent voids at 50 percent, increased to about

0.12 per percent voids at 40 percent, and dropped considerably to about 0.01 per percent voids at 20 percent passing the 4.75-mm sieve.

S_g is a measure of the shear strength of the mix during compaction. This strength, measured at a high temperature [149°C (300°F)], is primarily a measure of aggregate properties because the viscosity of the asphalt is low and the mix has less cohesion (7). S_g values of the limestone mixes with different void contents are shown in Table 4. The results are plotted in Figure 10. The shear values decreased with a decrease in a void content for the mixes with 30, 35, 40, and 50 percent passing the 4.75-mm sieve. The S_g values dropped below 200 kPa at 3 percent and lower voids for mixes with 50 and 40 percent passing the 4.75-mm sieve. The change, although present, was less in the case of mixes with 35 and 30 percent passing the 4.75-mm sieve. However, for the mixes with low percent passing the 4.75-mm sieve (20 and 25 percent), the values remained almost constant (between 270 and 300 kPa) as the voids changed. Figure 11 shows a plot of change in S_g per unit change in void content. The change in S_g decreased with a decrease in percent passing the 4.75-mm sieve, from 66 kPa per percent voids at 40 percent to 3 kPa per percent voids at 20 percent passing the 4.75-mm sieve. It was expected that mixes with less than 30 percent passing the 4.75-mm sieve would be less sensitive to void content and hence would be able to maintain better resistance to rutting even when a gradual densification and resulting decrease in voids occurred. These data confirmed that mixtures with stone-on-stone contact are much less sensitive to air void content than mixtures without stone-on-stone contact.

TABLE 4 Summary of Gyrotory Properties of Limestone Mixes

PERCENT PASSING 4.75 mm (NO. 4) SIEVE	VOIDS IN TOTAL MIX (%)	GYRATORY SHEAR INDEX	GYRATORY SHEAR (kPa)
50	0.3	1.57	17.2
	0.5	1.53	120.6
	0.8	1.43	234.3
	4.5	1.10	268.7
40	0.3	1.47	10.3
	1.3	1.26	124.0
	2.3	1.23	155.0
	3.0	1.13	199.8
35	0.3	1.45	689.0
	1.7	1.10	172.2
	1.8	1.17	258.4
	3.6	1.08	258.4
30	0.2	1.25	124.0
	1.1	1.03	251.5
	1.7	1.06	289.4
	2.5	1.01	309.4
	4.2	1.10	296.3
25	0.7	1.04	272.1
	2.0	1.00	274.2
	3.3	1.00	274.9
	4.1	1.05	289.4
20	1.0	1.04	296.3
	2.0	1.01	296.3
	3.3	1.02	292.8
	3.7	1.00	310.7

1 kPa = 0.145 psi

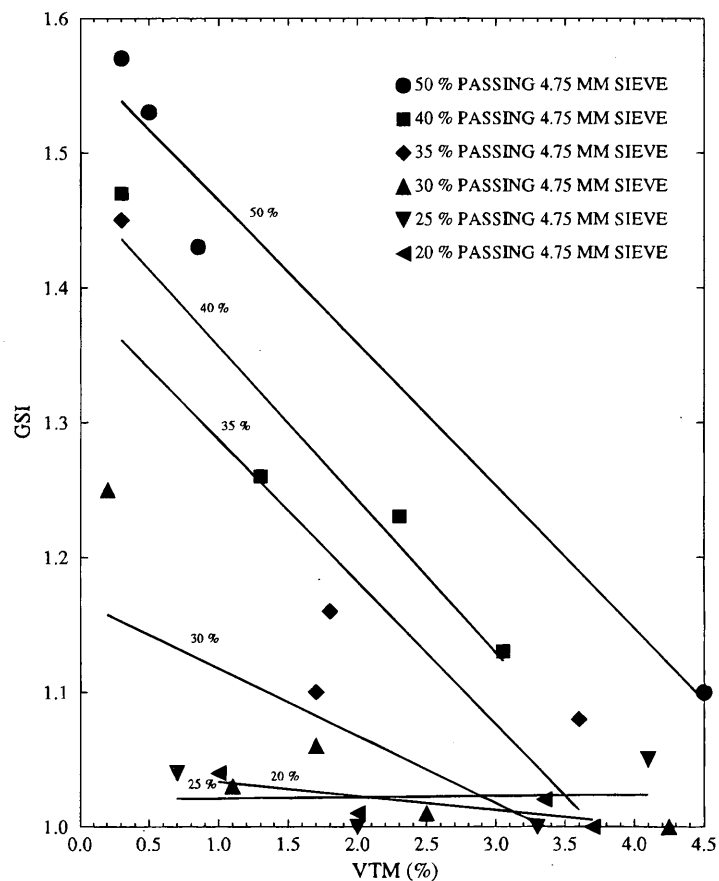


FIGURE 9 Plot of gyratory shear index (GSI) versus air voids for different mixes.

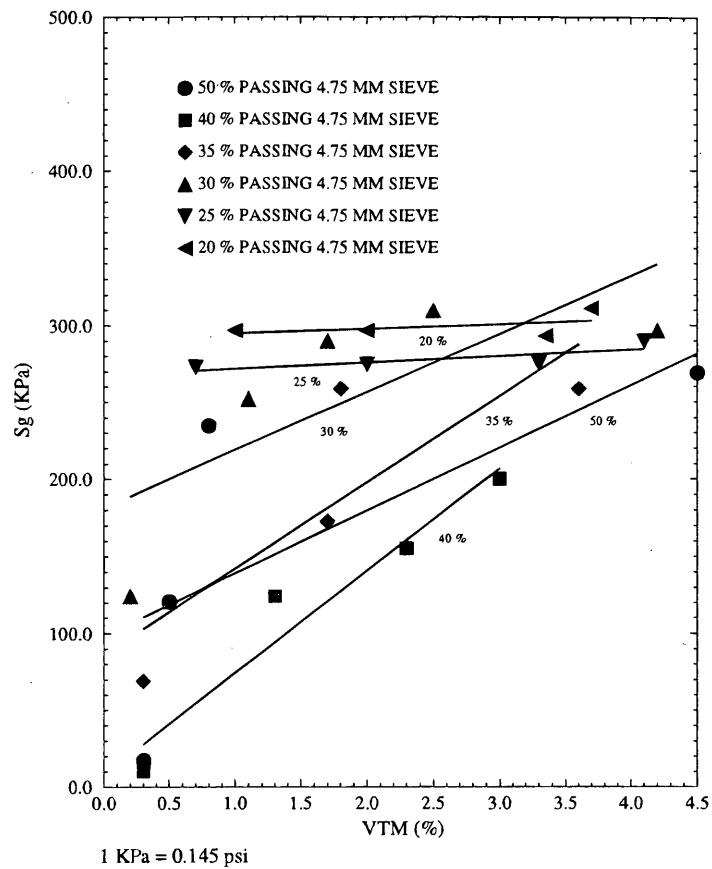


FIGURE 10 Plot of S_g versus air voids for different mixes.

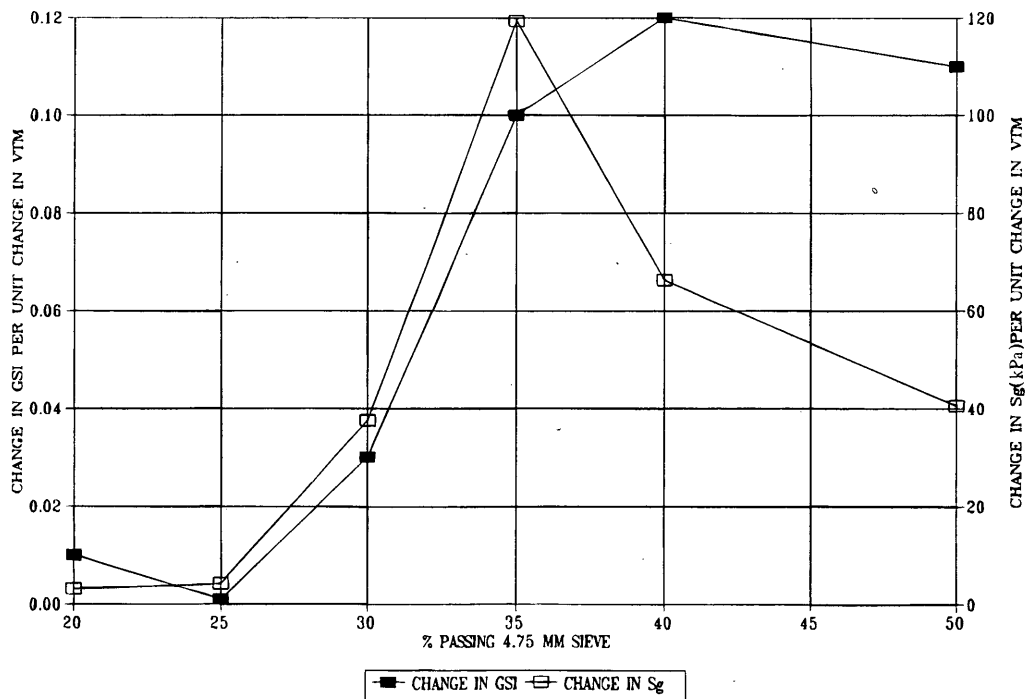


FIGURE 11 Change in GSI and S_g per unit change in air void for different mixes.

CONCLUSIONS

From the results of this study, it can be concluded that plots of VMA and VCA can be used to identify whether stone-on-stone contact exists. For the mixture evaluated in this study, stone-on-stone contact in the coarse aggregate portion began to occur at around 30 percent passing the 4.75-mm sieve. The dry-rodded test appears to be an easy way to determine the VCA necessary for stone-on-stone contact. These three methods appear to give similar results.

Stability tests indicate that mixes become less sensitive to a change in void content with a decrease in percent passing the 4.75-mm sieve and the resulting formation of stone-on-stone skeleton. As the percent passing the 4.75-mm sieve is decreased to 30 percent and lower for both gravel and limestone mixes, stone-on-stone contact occurs. These mixes with stone-on-stone contact were found to have very little or no change in stability, GSI, or gyratory shear strength with change in air voids.

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