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Final Report

Impact of Fines on Asphalt Mix Design

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Impact of Fines on Asphalt Mix Design

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16. Abstract
Pavement engineers have known for some time that the particle shape and surface texture of aggregates play a significant role in the constructability, drivability, strength, and durability of asphalt concrete pavements. Superpave™ recommends use of a variety of aggregate tests to ensure minimum desirable aggregate characteristics or "consensus properties" in order to assure an acceptable level of performance. For fine aggregates, the recommended method is AASHTO TP33 (ASTM C1252)—*Test Method for Uncompacted Void Content of Fine Aggregate (as Influenced by Particle Shape, Surface Texture, and Grading).* In this investigation, three methods for classifying aggregate particle shape and texture—AASHTO TP33 (ASTM C1252), ASTM D3389 (Index of Particle Shape and Texture), and the flow rate method—were evaluated. These methods were used to rank four natural river sands and a crushed granite from good to poor performance based on the criteria established in each method. Test results indicate that all methods easily distinguished the crushed aggregate from the natural river sands. The AASHTO TP33 (ASTM C1252) and the flow rate methods were found to be somewhat less sensitive to slight differences in particle shape and texture than ASTM D3398. The flow rate test was also found to be dependent on the gradation of the aggregate while the index values determined by ASTM D3398 and AASHTO TP33 (ASTM C1252) seemed to be less dependent on grading. All the test methods were found to be repeatable, each having low coefficients of variation for all the aggregates tested. One of the objectives of this study was to show that increased amount of mineral fillers can be accommodated in asphalt mixtures without adversely affecting its rutting (permanent deformation performance). Results of this study clearly indicate that within the range of mineral filler content and type used in this study, increasing the amount of mineral filler has beneficial effect on the rutting performance. However, although the rutting performance is enhanced, it should be noted that at higher mineral filler content, the asphalt content is reduced, which may have a detrimental effect on other mixture properties, such as fatigue, thermal cracking, and raveling.

17. Key Words
aggregate tests, asphalt pavements, pavement strength, mineral filler, rutting, fatigue, thermal cracking, raveling

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EXECUTIVE SUMMARY

Pavement engineers have known for some time that the particle shape and surface texture of aggregates play a significant role in constructability, drivability, strength and durability of asphalt concrete pavements. Superpave^{TM} recommends use of a variety of aggregate tests to ensure minimum desirable aggregate characteristics or "consensus properties" in order to assure an acceptable level of performance. For fine aggregates, the recommended method is AASHTO TP33 (ASTM C1252) -- *Test Method for Uncompacted Void Content of Fine Aggregate (as Influenced by Particle Shape, Surface Texture, and Grading).*

In this investigation, three methods for classifying aggregate particle shape and texture -- AASHTO TP33 (ASTM C1252), ASTM D3389 (*Index of Particle Shape and Texture*) and the flow rate method -- were evaluated. These methods were used to rank four natural river sands and a crushed granite from good to poor performance based on the criteria established in each method. Test results indicate that all methods easily distinguished the crushed aggregate from the natural river sands. The AASHTO TP33 (ASTM C1252) and the flow rate methods were found to be somewhat less sensitive to slight differences in particle shape and texture than ASTM D3398. The flow rate test was also found to be dependent on the gradation of the aggregate while the index values determined by ASTM D3398 and AASHTO TP33 (ASTM C1252) seemed to be less dependent on grading. All the test methods were found to be repeatable, each having low coefficients of variation for all the aggregates tested.

In order to evaluate the effect of particle shape and texture, and mineral filler content on mix performance, one natural sand (Cape Fear) which was ranked as "average performing" was selected and blended with the crushed granite. To investigate the effect of increased amounts of mineral filler on the design and performance of mixtures, a standard NC Department of Transportation (NCDOT) surface course gradation was modified to contain 4, 6, 8 and 12 percent mineral filler. Each mineral filler content gradation was produced from a 100 percent crushed granite aggregate and a blend containing 80 percent crushed aggregate and 20 percent natural sand, giving eight total aggregate gradation blends.

Asphalt-aggregate mixtures were designed using the Marshall procedure, with the optimum asphalt contents selected to yield mixtures with 5.0% air voids as per NCDOT specifications. Increase in the amount of mineral filler was found to decrease the optimum asphalt content if 5.0% air voids is used as the optimum selection criteria. Marshall stability and unit weight increased with increase in mineral filler content. The addition of 20 percent natural fines was found to decrease asphalt content and increase Marshall stability. The Corps of Engineers gyratory testing machine (GTM) was also used to design and evaluate the shear performance of the mixtures. Increases in mineral filler content were found to reduce the optimum asphalt content selected by the GTM. The shear strength of the mixtures also decreased with an increase in mineral filler. The addition of natural fines generally resulted in lower optimum asphalt contents and inferior performance in shear when compared to mixtures containing 100 percent crushed aggregate.

The Repeated Shear Test at Constant Height (RSCH) was performed on mixtures containing 4, 8 and 12 percent mineral filler with 100 percent crushed aggregate and 80/20 blends of crushed and natural sand. The mixtures were compacted using Superpave™ gyratory compactor to 5.0 percent air voids at the optimum asphalt contents selected based on the results from Marshall mix design. Within the range of mineral filler contents used in this study, an increase in mineral filler content of a mixture was found to decrease its permanent deformation while increasing the mixture shear resilient modulus.

One of the objectives of this study was to show that increased amount of mineral fillers can be accommodated in asphalt mixtures without adversely affecting its rutting (permanent deformation performance). Results of this study clearly indicates that within the range of mineral filler content and type used in this study, increasing the amount of mineral filler has beneficial effect on the rutting performance. However, although the rutting performance is enhanced, it should be noted that at higher mineral filler content, the asphalt content is reduced which may have a detrimental effect on other mixture properties such as fatigue, thermal cracking, and raveling. Further investigation of the effect of increased mineral filler content on other properties is therefore warranted.

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1. INTRODUCTION

The crushed stone industry faces increasing difficulty in marketing fine aggregates with high percentages of material passing the 75 μm sieve. Twenty two companies, participating in a recent survey, reported about 22.5 million tons of fines stockpiled at their sites accounting on an average, for about 13% of their total annual aggregate production. These companies also reported about 6.5 million tons of fine aggregates unsold every year. Almost 50% of fine aggregate production is regular screenings, and 50% is washed screenings out of which 20% of the material passing the 75 μm sieve or mineral filler is waste. The unused mineral filler has to be either stockpiled or disposed of in landfills. If plausible ways of usage of mineral fillers are not found, it could cause serious environmental problems. The current uses of mineral filler include the following:

1. Asphalt related applications such as hot mix asphalt concrete (HMA).
2. Agricultural industry applications such as aglime, fertilizer filling, and livestock feed.
3. Miscellaneous applications such as industrial fillers, paint fillers, etc.

The bulk of the usage of mineral fines is in the production of HMA. Highway pavement engineers have known for some time that the amount of mineral filler used in asphalt concrete mixes, and its shape and surface texture play a significant role in determining the workability, strength, durability, and drivability of asphalt concrete pavements. Angular and rough aggregate particles like those produced from crushing operations generally produce mixtures that are stronger and more resistant to permanent deformation than mixtures containing round and smooth aggregates from natural river sands. However, crushed fines are usually blended with natural sands to increase the workability of the mix.

There are several test procedures (or variations thereof) currently available for use by the state highway agencies to determine the particle shape and surface texture characteristics of the fine aggregates. Three of these test methods are ASTM C1252 (*Standard Method for Uncompacted Void Content of Fine Aggregate (as Influenced by Particle Shape, Surface Texture,* *and Gradation*)), ASTM D3398 (*Standard Method for Index of Aggregate Particle Shape and Texture*)(*1*), and the flow rate method (*2,3*). Khandal, et al. (*4*) have reported that most state highway agencies, however, control fine aggregate particle shape and texture in HMA mixtures by limiting the amount of natural sands rather than with criteria based on one of the above tests. Current North Carolina Department of Transportation (NCDOT) specifications allow no more than 20 percent natural sand by the weight of total mineral filler in the HMA. In order to assure an acceptable level of performance, for fine aggregates, Superpave™ recommends use of AASHTO TP33 (ASTM C1252) (*Test Method for Uncompacted Void Content of Fine Aggregate (as Influenced by Particle Shape, Surface Texture, and Grading)*) (*5*).

With regards to the amount, most highway agencies allow 2 to 8 percent mineral filler passing the 75 μm sieve based on dry sieve analysis. Invariably, most of these mixtures are expected to contain a higher percentage of fines (1 to 2 percent) if a wash sieve analysis was performed on the same graded aggregates. Current NCDOT specifications (*6*) for aggregate gradation are based on washed sieve analysis which also requires 2 to 8 percent mineral filler passing the 75 μm sieve. If increased amount of mineral filler can be accommodated in asphalt mixtures without adversely affecting its performance, it could lead to substantial environmental benefits.

It is therefore of interest to investigate if the amount of fines in asphalt mixtures based on the washed sieve analysis could be increased from a maximum of about 8 percent as currently specified, without adversely affecting the performance of the mixture. At the same time, it is also of interest to investigate the influence of the mineral filler type (crushed versus natural river sands, or combinations thereof) on asphalt mix design and the mix permanent deformation performance. In this investigation, the effects of mineral filler type and amount on mix design and permanent deformation are evaluated using the Marshall and Corps of Engineers (gyratory) (*7*) mix design methodologies, and the SHRP Superpave™ shear test device, respectively.

1.1 Objectives

The specific objectives of this research investigation are the following:

1. To evaluate commonly used methods that measure the particle shape and texture of fine aggregates.
2. To determine the effect of type and amount of mineral filler on the design of an asphalt concrete surface course mixture.
3. To evaluate the effect of increased amount of mineral filler on the shear performance of an NCDOT surface course mixture using the Corps of Engineer Gyratory Testing Machine and the SHRP Superpave™ shear tester.

1.2 Research Approach and Methodology

There are two basic fine aggregate (sand) types used in asphalt concrete mixtures: natural and crushed (manufactured). The amount of fine aggregate that can be accommodated in an asphalt concrete mixture depends on its characteristics, particle shape and texture. Asphalt mixtures containing natural aggregates (especially the natural river sands) are generally more susceptible to rutting, shoving and bleeding than mixtures containing 100 percent crushed fine aggregate. However, mixtures containing 100 percent crushed fine aggregate are more difficult to place and compact than mixtures containing at least some percentage of natural fine aggregate. Since the addition of natural sands increases the workability of a mixture, most contractors will add the maximum allowable amount of natural sand.

Because not all natural fine aggregates have rounded and smooth particle shape and texture, the performance of a natural sand in an asphalt mixture will also depend on the quality of the natural sand used. In order to preclude poor performance, most highway agencies limit the amount of natural sand allowed in their mixtures rather than specifying the amount based on their characteristics. For example, the current NCDOT specifications allow for a maximum of 20% (by weight) natural sand which can be used in heavy duty asphalt concrete surface course mixtures irrespective of the particle shape or texture consideration. There is therefore, a need to quantify the shape and texture in order to specify use of the fine aggregates on a more rational basis.

There are three test procedures for quantifying (indexing) the particle shape and texture of fine aggregates. These are AASHTO TP33 (ASTM C1252), ASTM D3398, and the flow rate method. In this investigation, the three indexing procedures were used to characterize four natural sands and one crushed fine aggregate (granite) commonly used in North Carolina to evaluate their effectiveness in ranking the fine aggregates based on their performance. Based on the results obtained, one natural sand was selected for combining with crushed fine aggregate to evaluate the effect of mineral filler type and amount on the asphalt concrete mix design and mix shear performance.

2. MATERIALS USED

The properties of the materials used in this investigation are presented in this section. These properties include the materials description, aggregate gradation, bulk specific gravities, and the properties of asphalt cement used.

2.1 Aggregates

For the evaluation of particle shape and texture indexing tests, four natural sands used in this study were obtained from the Brewer, Cape Fear, Marston, and Pelcher quarries in North Carolina. The crushed granite (granite washed screenings) was obtained from a quarry located in Raleigh, North Carolina. A sieve analysis was performed on each aggregate in accordance with ASTM C 117 (*Standard Method for Materials Finer than 75 μm (No. 200) Sieve in Mineral Aggregates by Washing*) and ASTM C 136 *(Standard Method for Sieve Analysis of Fine and Coarse Aggregates*)(*8*). Results of the sieve analysis are shown in Table 1 and Figure 1.

TABLE 1 Sieve Analysis Results

Sieve Size	Percent Passing				
(mm)	Brewer	Cape Fear	Marston	Pelcher	Granite
19	100	100	100	100	100
12.5	100	100	100	99.8	100
9.5	100	100	100	98.9	100
4.75	100	99.8	99.9	95.4	98.4
2.36	99.8	92.9	98.1	89.1	81.4
1.18	95.7	73.0	91.2	77.5	60.4
0.6	69.1	41.4	66.0	47.1	43.1
0.3	30.7	13.2	32.9	12.4	31.4
0.15	8.9	3.9	10.9	3.3	11.0
0.075	2.9	2.0	3.0	1.5	2.3

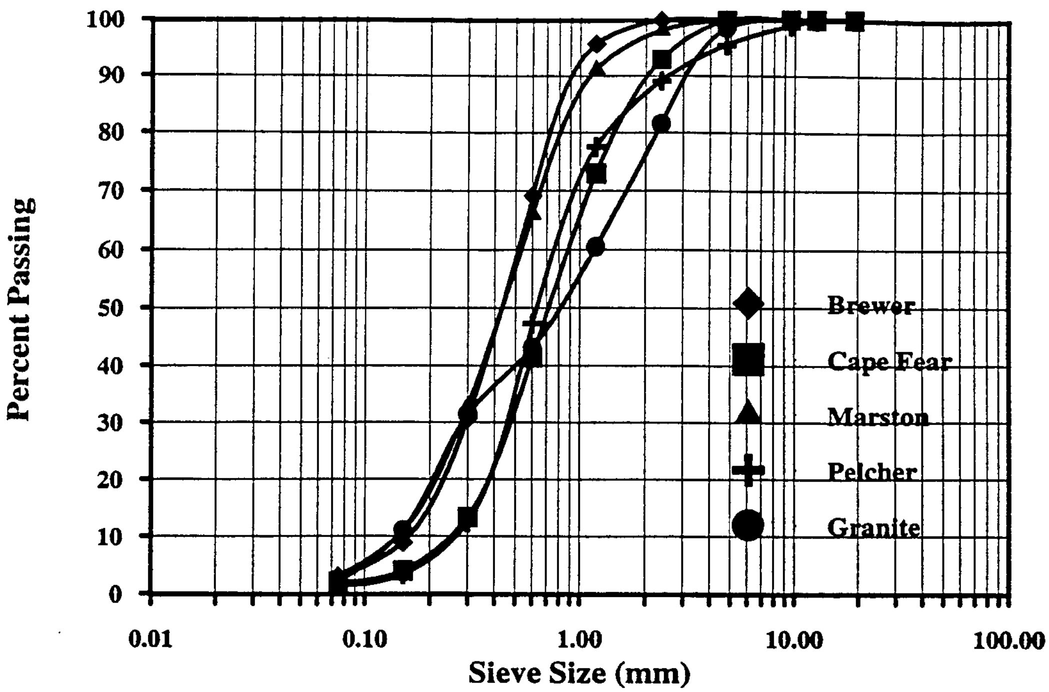

FIGURE 1 Sieve Analysis Results For the Natural and Crushed Fine Aggregates

From Figure 1, it can be seen that the natural sands are fairly uniformly graded with nominal maximum aggregate size of 2.36 mm for Brewer, Cape Fear, and Marston sands and 4.75 mm nominal aggregate size for Pelcher sand. The crushed granite is well graded with a 4.75 mm nominal maximum aggregate size.

Table 2 shows the bulk specific gravity of the aggregates determined in accordance with ASTM C128 (*Standard Method for Specific Gravity and Absorption of Fine Aggregate*)(*8*).

TABLE 2 Bulk Specific Gravities

Aggregate Type	Bulk Specific Gravity
Sand - Brewer	2.520
Sand - Cape Fear	2.561
Sand - Marston	2.529
Sand - Pelcher	2.570
Granite Screenings	2.624
Granite 78M	2.590

For the preparation of the asphalt-aggregate mixtures, crushed granite aggregate was used. Table 3 and Figure 2 show the aggregate gradation analysis results for the crushed coarse and fine granite aggregates as received from the quarry in two standard NCDOT aggregate sizes: 78M and washed screenings. The 78M aggregate has a nominal maximum size of 12.5 mm and the washed screenings has a maximum nominal size of 4.75 mm, as indicated earlier. Bulk specific gravities of both aggregate size fractions are given in Table 2.

TABLE 3 Sieve Analysis Results for Crushed Granite Aggregate

Sieve Size	Percent Passing	
(mm)	Granite Screenings	Granite 78M
19	100	100
12.5	100	99.1
9.5	100	80.3
4.75	98.4	28.5
2.36	81.4	5.3
1.18	60.4	0.7
0.6	43.1	0
0.3	31.4	0
0.15	11.0	0
0.075	2.3	0

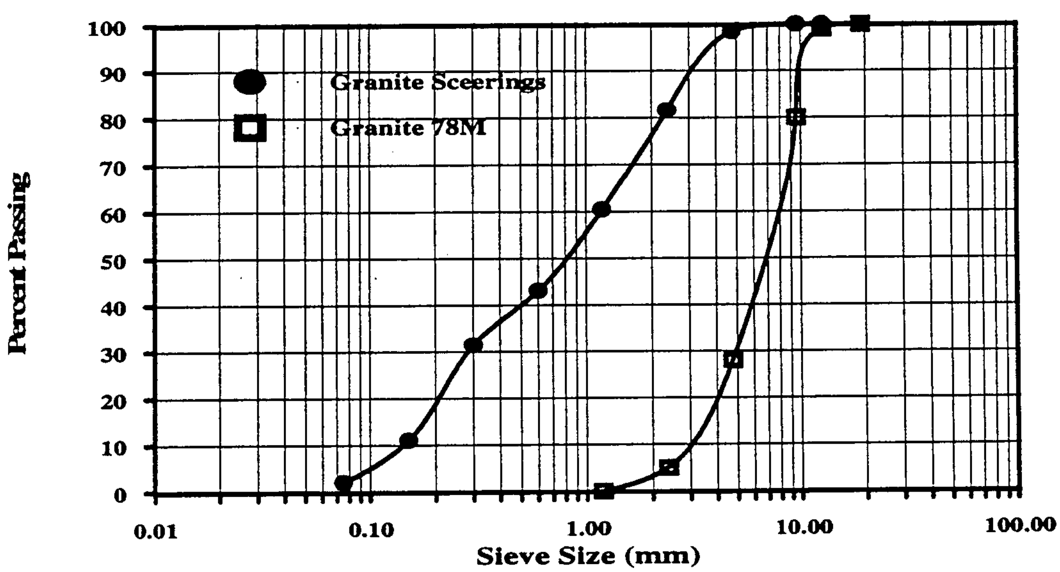

FIGURE 2 Sieve Analysis Results For Granite Aggregates

2.2 Asphalt Cement

The asphalt cement used in this study was supplied by local petroleum company and was viscosity graded as AC-20. The AC grade was verified in accordance with ASTM D2171 (*Standard Method for Viscosity of Asphalt Cements by Vacuum Capillary Viscometer*) (*1*). The penetration of the asphalt cement was determined by ASTM *D5 (Standard Method for Penetration of Bituminous Materials*) (*1*). The binder was also tested in accordance with Superpave™ specifications given in AASHTO TP5 (*Standard Test Method for Determining the Rheological Properties of Asphalt Binder Using a Dynamic Shear Rheometer (DSR)*) and AASHTO MP1 (*Standard Specification for Performance Graded Asphalt Binder*) (*5*). The results of these tests are given in Table 4.

TABLE 4 Asphalt Cement Properties

Absolute Viscosity (ASTM D2171)	2143 poises
Penetration 77°F (ASTM D5)	77 dmm
DSR Testing - Original Binder G*/sin δ @58°C, 10 rad/sec	2.01 kPa
DSR Testing - RTFO Aged G*/sin δ @58°C, 10 rad/sec	6.01 kPa
DSR Testing - PAV Aged G*sin δ @ 22°C, 10 rad/sec	2400 kPa

3. PARTICLE SHAPE AND TEXTURE INDEXING TESTS

The five natural and crushed fine aggregates were characterized using three particle shape and texture indexing tests. The test procedures and results are presented in the following sections.

3.1 AASHTO TP33 (ASTM C1252) (*Standard Test Method for Uncompacted Void Content of Fine Aggregate (as Influenced by Particle Shape, Surface Texture, and Gradation)*

This method uses the uncompacted void content of fine aggregate as an index for particle shape and texture. AASHTO TP33 (ASTM C1252) allows three procedures based on aggregate gradation used. Method A uses a graded sample batched using individual size fraction on weight basis shown in Table 5.

TABLE 5 Standard Gradation Used for AASHTO TP33 (ASTM C1252) Method A

Individual Size Fraction	Mass (gm)
2.36 mm (#8) to 1.18 mm (#16)	44
1.18 mm (#16) to 600 μm (#30)	57
600 μm (#30) to 300 μm (#50)	72
300 μm (#50) to 150 μm (#100)	17
Total	190

Method B allows use of three individual size fractions weighing 190 g each (2.36 mm to 1.18 mm, 1.18 mm to 600 μm, and 600 μm to 300 μm). The test is conducted on each size fraction individually, and the individual results are averaged together to obtain the average uncompacted voids. In Method C, the uncompacted voids are determined on 190 g of the as-received fine aggregate finer than 4.75 mm.

When this study was initiated, the National Aggregate Association (NAA) Method A, which is essentially ASTM C1252 Method A, was to be used as one of the indexing procedures. From Table 5, it can be seen that 44 g of material is needed for the 2.36 mm to 1.18 mm size fraction. From the sieve analysis of the natural sands given in Table 1 and Figure 1, it can be seen that the Marston and Brewer sands have about 98 to 99 percent of their gradations passing the 1.18 mm sieve. This would mean that in order to run ASTM C1252 Method A (NAA Method A), a substantial amount of sieving would be required to obtain a small test sample in the 2.36 mm to 1.18 mm size range. Furthermore, if Method A is used, particle sizes not included in the required gradation, but that are prominent in the as-received gradation may have a significant effect on uncompacted voids. When fine natural sands are blended with crushed aggregates for use in asphalt concrete mixtures, the entire gradation of natural sand is generally used. For these reasons, Methods A and B were not used in this study. Instead, Method C, the procedure using as-received gradation was used for the determination of uncompacted voids.

The specific details for performing the test can be found in AASHTO TP33 or ASTM C1252. In general, the test consists of a standard mass of fine aggregate flowing from a 1 quart mason jar with an aluminum funnel-shaped cap screwed onto the end. The aggregate falls from the jar 115 mm into a steel mold whose volume is calibrated using water. Once all the aggregate has fallen from the jar, the mold is carefully stricken off so as not to cause any settlement of the aggregate particles in the mold. The weight of the steel mold and fine aggregate specimen are determined and the uncompacted voids are calculated using the following equation:

$$U = \frac{V - \left(\frac{F}{G}\right)}{V}(100) \qquad (1)$$

where,

V = volume of steel mold (ml),

F = net mass of the fine aggregate in the mold (grams),

G = bulk specific gravity of the fine aggregate, and

U = uncompacted voids in the fine aggregate (%).

Aggregate particles that are round and smooth would allow for easy compaction and, therefore, have low uncompacted voids as opposed to highly angular and rough aggregate particles that would yield higher uncompacted voids. The gradation of the aggregate also affects uncompacted voids. Aggregates that are well graded would have lower uncompacted voids than an aggregate containing uniform size particles. Therefore, well graded aggregates with high uncompacted voids would generally produce asphalt mixtures that are relatively strong and resistant to permanent deformation, but are more difficult to compact and handle than mixtures made from uniform size aggregates with lower uncompacted voids (*9*).

3.2 ASTM D3398 *(Standard Method for Index of Aggregate Particle Shape and Texture)*

This test procedure also measures the voids in an aggregate sample, but the voids are determined after the sample is compacted in a standard mold with a standard tamper at two different compactive efforts. The compaction levels are 10 and 50 blows from the standard tamper. The voids at the two compaction levels are used in a nomograph (*1*), or a corresponding equation, in order to determine the particle index. The theory behind this test is based on the fact that particles with different surface texture and shape will compact to different void contents at a given compactive effort. Aggregate particles which are round and smooth will have lower void content at a given compactive effort than particles which are angular and rough. The decrease in voids with an increasing compactive effort will also be greater for a round and smooth particle when compared to the decrease in void content of angular and rough particles.

The test specification allows for use of various aggregate particle sizes (up to 38.1 mm), by increasing the size of the mold and tamper. Molds may be as large as 200 mm in diameter or as small as 50 mm in diameter. The tests performed in this study utilized a mold 152.4 mm (6 inches) in diameter and 177.8 mm (7 inches) in height. The volume of the mold was calibrated in milliliters by determining the mass of water the mold contained and multiplying this mass by the specific gravity of water at the test temperature. The tamper used for compacting the aggregate in the mold is also based on the size of the aggregate sample to be tested. The tamper used in this study was 10.6 mm (0.42 inch) in diameter, 407 mm (16 inches) in height and had a mass of 275 grams. It consists of an outer sleeve in which the actual tamper slides. The vertical drop of the tamper is 50 mm (2 inches) and is controlled by a slot and pin arrangement made into the sleeve.

Unlike AASHTO TP33 (ASTM C1252 Method C), which determines the uncompacted voids for the as-received gradation, this test determines the particle index on each individual size fraction which is present in the original gradation in amounts of 10% or more, and a weighted average is calculated to obtain the particle index for the entire gradation. Table 6 shows the size fractions that can be used for testing.

TABLE 6 Aggregate Size Fractions Used in ASTM D3398

Size Fraction Passing	Size Fraction Retained
37.5 mm	25.0 mm
25.0 mm	19.0 mm
19.0 mm	12.7 mm
12.5 mm	9.5 mm
9.5 mm	4.75 mm
4.75 mm	2.36 mm
2.36 mm	1.18 mm
1.18 mm	600 µm
600 µm	300 µm
300 µm	150 µm
150 µm	75 µm

At least 1.8 kg of each size fraction to be tested is washed with water over a 75 µm sieve. The samples are then dried to a constant mass at 110°C. The specific gravity is also determined for each size fraction individually in accordance with ASTM C127 or C128. The aggregate size fractions are then placed into the mold in 3 layers, with each layer being compacted by 10 blows of the tamper before the addition of another layer. Each blow is applied by holding the rod vertically over the sample with the end 50 mm (2 in) above the sample, and releasing it so that it falls freely. After the final layer is compacted, small amounts of material are added to bring the level of the aggregate to the top of the mold and the excess material is then stricken off with a straightedge. The mass of the aggregate in the mold is determined and the process is repeated using 50 blows per layer from the tamping rod. The percentage of voids in the aggregate sample is then determined using the following equations:

$$V_{10} = \left[1 - \left(\frac{M_{10}}{sv}\right)\right](100) \qquad (2)$$

$$V_{50} = \left[1 - \left(\frac{M_{50}}{sv}\right)\right](100) \qquad (3)$$

where,

V_{10} = voids in aggregate compacted at 10 drops per layer (%),

V_{50} = voids in aggregate compacted at 50 drops per layer (%),

M_{10} = average mass of aggregate in the mold compacted at 10 blows per layer (gm),

M_{50} = average mass of aggregate in the mold compacted at 50 blows per layer (gm),

s = bulk dry specific gravity of the aggregate size fraction being tested and,

v = volume of the mold (ml).

In this study, at least three replicate tests were performed on each size fraction and compactive effort and the values for compacted voids were averaged. The uncompacted voids for 10 and 50 blows can then be used to determine the particle index using the nomograph given in the ASTM D3398 specification, or its corresponding equation:

$$I_a = 1.25V_{10} - 0.25V_{50} - 32.0 \qquad (4)$$

where,

I_a = particle index,

V_{10} = compacted voids at 10 blows per layer (%), and

V_{50} = compacted voids at 50 blows per layer (%).

The particle indices for the different size fractions were then combined using a weighted average which takes into account the percentage of the individual size fractions in the total aggregate gradation. As discussed earlier, the voids in a compacted aggregate sample will be lower for round and smooth particles than for angular and rough particles. For this reason, the particle index for round and smooth particles will also be lower than for angular and rough particles. The particle index for well graded aggregates will also be lower than for uniform sized aggregates. For a given gradation, aggregates with lower particle indices will generally produce asphalt mixtures which are more workable, but also are more prone to permanent deformation and possess relatively less strength than mixtures produced from aggregates with higher particle indices (*9*).

3.3 The Flow Rate Method

The flow rate method used in this study is not a standard test method, but is based on the work reported by Rex and Peck (*2*) and Jimenez (*3*). The test procedure and apparatus are similar to that used for AASHTO TP33 (ASTM C1252). The advantage of this test is that it can be performed on the portion of an as-received aggregate gradation that passes a 2.36 mm (#8) sieve, or on the individual size fractions within the gradation. About 500 grams of aggregate is placed into a 1 pint Mason jar and a funnel-shaped lid with a 12.5 mm (1/2 inch) opening is screwed onto the mouth of the jar. A cork is placed in the 12.5 mm opening and the jar is inverted onto a ring stand or similar clamping device. The cork is then removed and the time required for aggregate to pour from the jar is measured. The flow rate of the aggregate can be calculated using the following equation:

$$f = \frac{\left(\frac{m}{s}\right)}{t} \qquad (5)$$

where,

f = flow rate of the aggregate (cc/sec),

m = mass of the aggregate (gm),

$s =$ bulk specific gravity of the aggregate, and

$t =$ aggregate flow time (seconds).

If the flow rate is determined for the individual size fractions in the gradation, then the flow rates are combined using weighted averages based on the amount that the individual sizes are present in the gradation to be used. The flow rate for the aggregate gradation can be compared to the flow rate of a reference material to calculate a shape and texture index (STI). The reference material used in this study was No. 9 lead shot. The flow time of 500 grams of shot was determined as was the specific gravity, and flow rate of the shot was found to be 11.90 cc/sec. The flow rate of the reference material can then be divided by the flow rate of the aggregate to obtain the STI for the aggregate.

$$STI = \frac{f_r}{f} \qquad (6)$$

where,

$STI =$ shape and texture index,

$f_r =$ flow rate of reference material (cc/sec), and

$f =$ flow rate of the aggregate (cc/sec)

In general, for a given gradation, the flow rate for an aggregate with round and smooth particles will be higher than that of an aggregate with highly angular and rough particles. Similarly, the flow rate for uniform sized aggregate will be higher as compared to a well graded aggregate. Therefore, mixtures containing aggregates of a given gradation with high STI values will generally be more resistant to permanent deformation, but would be more difficult to compact than mixtures containing aggregates with lower STI values.

3.4 Fine Aggregate Indexing Test Results

Detailed test results for each of the five fine aggregates and for each indexing test procedure are given in Appendix A. Table 7 summarizes the average results of the particle shape and index tests for the four natural sands and the crushed granite. The uncompacted voids determined from AASHTO TP33 (ASTM C1252) ranges from 41.8% for the Cape Fear sand to 47.0% for the crushed granite. The STI values for the flow rate test are all less than 1.0 for the natural sands, meaning that all the natural sands had flow rates higher than that of the lead shot reference material. The particle index determined from ASTM D3398 ranges from a low of 12.4 for the Marston sand to a high of 17.0 for the crushed granite. The STI values of 2.1 for the crushed granite are much higher than those of the natural sands. The STI values for the natural sands ranges from 0.87 for the Pelcher sand to 0.74 for the Marston sand. Results in Table 7 are graphically illustrated in Figures 3 and 4 which show the relationship between uncompacted void contents and the particle index (I_a) and the shape and texture Index (STI).

TABLE 7 Average Test Results for the Particle Indexing Tests

Aggregate Type	AASHTO TP33 (ASTM C1252) Uncompacted Voids (%)	ASTM D3398 Particle Index (I_a)	Flow Rate STI
Sand - Brewer	45.3	13.8	0.77
Sand - Cape Fear	41.8	13.0	0.83
Sand - Marston	42.6	12.4	0.74
Sand - Pelcher	46.0	15.7	0.87
Crushed - Granite	47.7	17.0	2.10

3.4.1 Discussion of Indexing Test Results

Based on the results of the indexing tests given in Table 7, a relative predictive performance ranking can be assigned to each aggregate as shown in Table 8. The rankings range from 1 (best performing) to 5 (worst performing). As expected, the crushed granite is ranked as performing the best in all tests. The Pelcher sand was ranked by all the test methods as

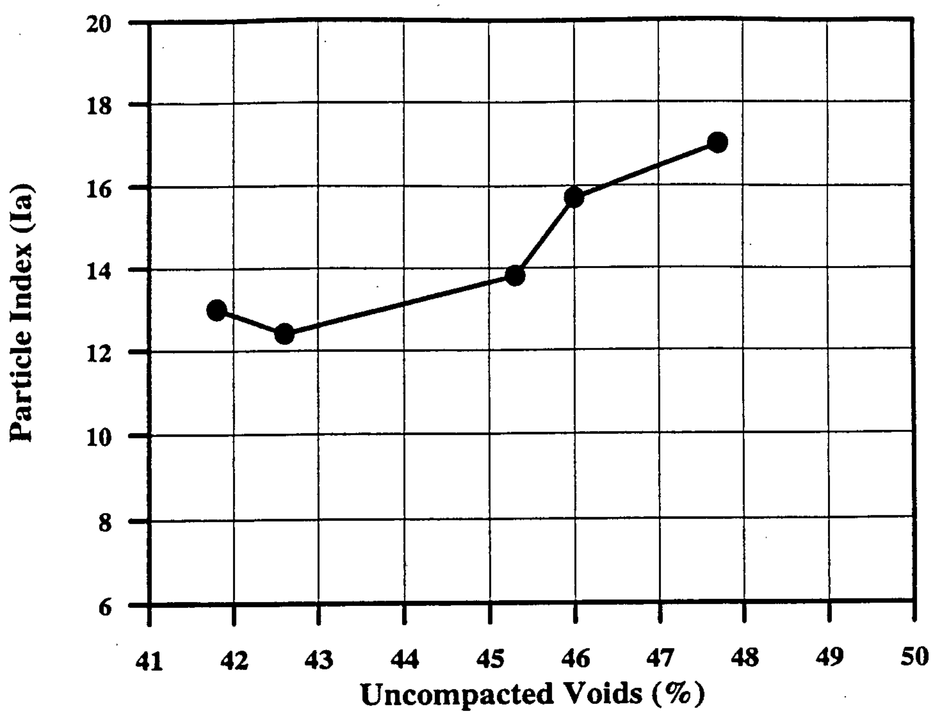

FIGURE 3 Particle Index (I_a) versus Uncompacted Voids

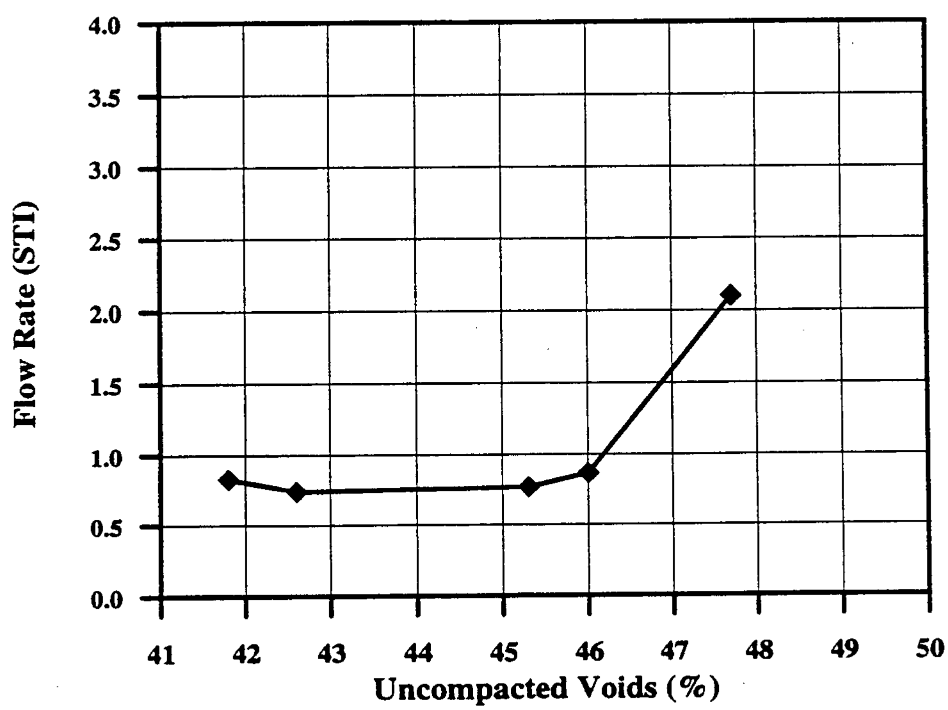

FIGURE 4 Flow Rate (STI) versus Uncompacted Voids

performing second best among all the aggregates, also making it the best performing natural sand. For the Brewer, Cape Fear, and Marston sands, the relative rankings from each test procedure is different. However, at least 2 test procedures (ASTM D3398 and the flow rate method) indicated Marston sand to be the worst. AASHTO TP33 (ASTM C1252) ranks Marston sand the second worst performing sand. Therefore, in general, among the natural sands, Pelcher is the best performing followed by Brewer, Cape Fear, and with Marston showing the worst performance.

TABLE 8 Relative Performance Ranking Based on the Particle Indexing Tests

Aggregate Type	AASHTO TP33 (ASTM C1252)	ASTM D3398	Flow Rate	Average
Sand - Brewer	3	3	4	3.3
Sand - Cape Fear	5	4	3	4.0
Sand - Marston	4	5	5	4.7
Sand - Pelcher	2	2	2	2.0
Crushed - Granite	1	1	1	1.0

Comparison of the actual index values indicates that there is a 58% difference (percentage based on higher value) in the STI between the crushed granite and the best performing (Pelcher) natural sand in the flow rate test ranking. However, there is only a 15% difference in the STI between the best and worst ranked sands as determined by the flow rate. The difference in the percent voids for the best and worst performing natural sands as ranked by AASHTO TP33 (ASTM C1252) is even lower at 9%. However, there is a 21% difference between the particle index (I_a) for the best and worst performing sands, as determined by ASTM D3398. This analysis of maximum and minimum values and maximum percent differences suggests that ASTM D3398 maybe the most sensitive of the three test procedures. The flow rate and AASHTO TP33 (ASTM C1252) tests may not detect slight differences in particle shape and texture in similar aggregates, as can be seen in Figures 3 and 4. However, these figures clearly illustrate that the highest voids value (crushed granite) is associated with the highest particle index and STI values.

It may also be noted that the flow rate method seems to be more sensitive to the gradation of the aggregate than the other test methods. The performance ranking from the flow rate method ranks the aggregates from well graded (#1--Granite) to more uniform graded (#5--Marston). The ASTM tests seem to rate the performance of aggregates independently of the gradation. The Cape Fear sand, which is fairly well graded, was ranked as among the worst performing by both ASTM tests. However, the Pelcher sand, which is also a well graded, was ranked as the best performing natural sand.

Table 9 shows the coefficient of variation (CV) for the data obtained from each test method. The CV values are based on 6 replicate tests in the flow rate and AASHTO TP33 (ASTM C1252) tests. In ASTM D3398, actual CV values are difficult to calculate so the CV values for this test method are the average coefficient of variations based on three measurements of particle index at each compaction level for each size fraction. The CV values for all the test methods are relatively small, with the maximum CV being 1.9% calculated for the flow rate test of the crushed granite. The CV values seem independent of aggregate type and test method. The AASHTO TP33 (ASTM C1252) exhibits the lowest CV values of the three test procedures with an average CV value of 0.42%.

TABLE 9 Coefficients of Variation for the Test Methods

Aggregate type	Coefficient of Variation (%)		
	AASHTO TP33 (ASTM C1252)	**ASTM D3398**	**Flow Rate**
Sand - Brewer	0.37	1.1	0.35
Sand - Cape Fear	0.50	0.34	0.33
Sand - Marston	0.44	0.23	0.66
Sand - Pelcher	0.43	0.22	0.33
Crushed - Granite	0.34	0.91	1.90
Average	0.42	0.56	0.71

In terms of the effort expended for each test procedure, the flow rate test was found to be the simplest and quickest to perform. The flow time and bulk specific gravity of the aggregate are the only measurements required for the calculation of flow rate. The measurement of flow time using a stop watch is the largest source of variation for the test, which generally reduces with experience. The equipment for the flow rate test is relatively inexpensive with the Mason jar and funnel cap available from commercial suppliers. AASHTO TP33 (ASTM C1252) uses similar equipment as the flow rate test method except that a 100 ml nominal volume cylindrical mold is required. The mold was fabricated in a local machine shop and was relatively inexpensive. AASHTO TP33 (ASTM C1252) is also relatively quick and simple to perform, with the source of measurement variation being the determination of the net mass of the aggregate in the mold. If care is taken in transferring the mold from the apparatus to the balance to avoid the loss of aggregate particles, this source of variation is easily reduced. It was found that if the sides of the mold are tapped lightly after the aggregate is stricken off, the loss of fines and therefore measurement variation is greatly minimized. ASTM D3398 was found to be the most difficult of the three tests to perform. The compaction of three layers of aggregate in the mold at two compaction levels, with a least three replicate tests, is very time consuming. The equipment for ASTM D3398 is also relatively the most expensive. The mold and tamper used in this study had to be fabricated in a local machine shop since it was not available from commercial suppliers.

3.4.2 Conclusions

Based on the results of this study, several specific conclusions can be drawn:

1. The flow rate and AASHTO TP33 (ASTM C1252) methods appear to be less sensitive to slight differences in particle shape and texture as compared to the ASTM D3398 test method.
2. All test methods easily distinguish crushed granite aggregate from natural sands.
3. The flow rate method seems to be more dependent on the aggregate gradation than ASTM D3398 and AASHTO TP33 (ASTM C1252).
4. All test methods studied had good repeatability with low coefficients of variation.
5. The flow rate method was the least time consuming and easiest test to perform and had the lowest equipment cost associated with it.
6. ASTM D3398 was the most difficult and time consuming of the three tests studied. It also had the largest equipment cost associated with it.

4. EFFECT OF MINERAL FILLER TYPE AND AMOUNT ON MIXTURE DESIGN

In Section 3, particle shape and surface texture characteristics of four natural sands and a crushed granite were evaluated based on three test procedures. Test results indicate (Table 8) that among the natural sands, Pelcher sand was the best performing followed by the Brewer, Cape Fear and Marston sands.

To investigate the effect of mineral filler type and amount on the mix design process, the average performing natural Cape Fear sand and the crushed granite were selected for further investigation. It may be re-iterated here that to ensure adequate mix performance NCDOT specifications allow for up to 20 percent (by weight) of natural sand to be used in heavy duty asphalt concrete mixtures, irrespective of the particle shape and surface texture characteristics of the natural sand. At the same time NCDOT specifications also limit the amount of mineral filler content to a maximum of 8 percent by the weight of aggregate. In this investigation, the amount of mineral filler content of 4, 6, 8 and 12 percent were evaluated using a 100 percent crushed granite and an 80/20 blend of crushed granite and the Cape Fear sand combination to determine the effect of mix design and permanent deformation performance of mixtures.

4.1 Selection of Aggregate Gradation

The gradation selected for use in the mixture performance phase of this study confirms to an NCDOT I-1 surface course gradation, which is shown in Figure 5. The NCDOT specification allows for 2 to 8 percent material passing the 75 µm sieve. Four different gradations were investigated in the mixture design phase. These four gradations contained 4, 6, 8, and 12 percent material passing the 75 µm sieve. From Figure 5 it can be seen that all the gradations comply with the NCDOT I-1 specification except for the one with 12 percent mineral filler. In order to avoid mixture instability, the gradation curves were rotated up slightly on the end as opposed to just increasing the amount of mineral fillers using a fixed gradation.

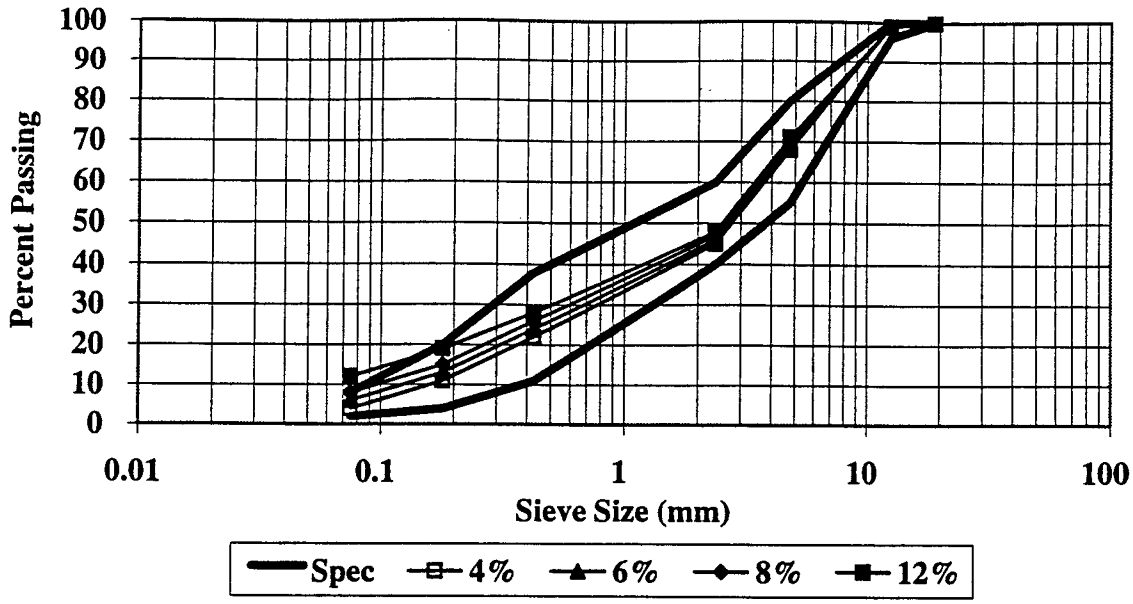

FIGURE 5 Gradations Used for Mixture

Figure 6 shows the gradations plotted on a 0.45 power chart with the Superpave™ aggregate gradation control points and restricted zone. It can be noted that all the gradations, except for the one with 12 percent mineral filler, meet the specification. All gradations avoid the restricted zone by passing above it.

The four gradations shown in Figures 5 and 6 were used to prepare aggregate blends for asphalt mixtures using a 100 percent crushed fines and an 80/20 blend containing crushed and natural fines, for a total of eight different aggregate blends.

4.2 Marshall Mix Design

The Marshall mix design was performed in accordance with ASTM *D1559 (Resistance to Plastic Flow of Bituminous Mixtures Using Marshall Apparatus).* The density and voids of the specimens were determined using ASTM D2726 *(Bulk Specific Gravity and Density of Compacted Bituminous Mixtures Using Saturated Surface-Dry Specimens)* and ASTM *D2041 (Theoretical Maximum Specific Gravity and Density of Bituminous Paving Mixtures).*

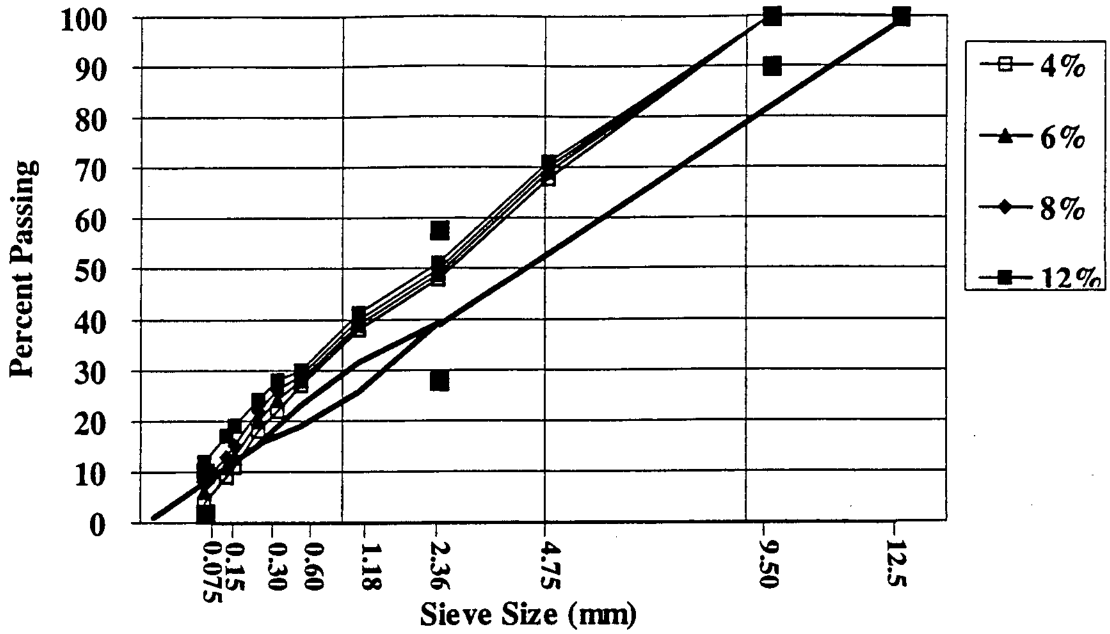

FIGURE 6 Mixture Gradations on 0.45 Power Chart

The Marshall specimens were compacted using 50 blows compaction, as required by the NCDOT specification for an I-1 mixture. Four asphalt contents and 3 replicate specimens per asphalt content were used for a total of 12 specimens for each aggregate blend. A total of 96 specimens were tested as shown in Table 10. Current NCDOT mixture design procedures require selection of the optimum asphalt content at 5% air voids, if the requirements for stability, flow, and voids filled with asphalt (VFA) are met. This method was used for the selection of optimum asphalt content in this study.

TABLE 10 Mixture and Test Variables for Marshall Mix Design

Test Variables	Levels of Treatment	No. of Levels
Asphalt contents (AC)	4, 5, 6, and 7% by wt. of mix	4
Number of specimens at each AC	---	3
Crushed/natural sand combinations	100% crushed & 80/20 blend crushed/natural sand	2
Mineral filler content	4, 6, 8, and 12%	4
Total number of specimens	---	96

Detailed results of the Marshall mix design for the 8 aggregate blends are presented in Appendix B. Average mix design results as a function of mineral filler contents are presented in Tables 11 and 12 for the 100 percent crushed granite and the 80/20 crushed/natural sand blend, respectively, along with the NCDOT specifications. The data in Table 11 suggest that increasing the amount of mineral filler decreases asphalt content, increases stability and increases the bulk specific gravity of mixtures containing 100 percent crushed granite at 5% air voids. There appears to be no correlation between mineral filler content and Marshall flow or VFA in mixtures containing 100 percent crushed granite. In Table 12 for the 80/20 aggregate blend it can be seen that increases in mineral filler also decreases asphalt content, decreases VFA, and increases Marshall stability. However, increases in mineral filler do not appear to greatly affect Marshall flow and bulk specific gravity.

TABLE 11 Marshall Mix Design Results - 100% Crushed Granite

Mix Properties	Mineral Filler Content			
	4%	6%	8%	12%
Optimum Asphalt Content (%)	6.2	5.6	5.2	4.8
Marshall Stability (kN) (5.782 kN min.)	11.56	12.90	12.90	14.18
Marshall Flow (7 - 18)	15.0	13.8	13.2	15.7
Air Voids (%)	5.0	5.0	5.0	5.0
Voids Filled with Asphalt (60-75%)	72.0	71.0	70.0	71.0
Unit Weight (kg/m^3)	2272.4	2285.3	2293.3	2315.7

TABLE 12 Marshall Mix Design Results - 80/20 Aggregate Blend

Mix Properties	Mineral Filler Content			
	4%	6%	8%	12%
Optimum Asphalt Content (%)	5.7	5.2	5.2	4.3
Marshall Stability (kN) (5.782 kN min.)	12.01	14.01	13.79	19.13
Marshall Flow (7 - 18)	13.5	13.0	12.8	13.0
Air Voids (%)	5.0	5.0	5.0	5.0
Voids Filled with Asphalt (60-75%)	69.0	68.0	68.0	63.0
Unit Weight (kg/m^3)	2291.7	2306.0	2296.5	2320.5

Comparison of test results in Tables 11 and 12 clearly shows the effect of crushed fines versus the blend of crushed/natural sand. For a given air void content, the addition of natural sand to an aggregate gradation appears to reduce asphalt content, VFA and Marshall flow, while increasing Marshall stability and unit weight. The increase in Marshall stability with the addition of natural sand is surprising, but probably due to increase in compaction facilitated by rounded particle shape and smooth surface texture of the natural sand. The increase in compaction is evident in the unit weight values which are higher for blended aggregate as compared to the 100 percent crushed granite. It should be noted that for mixtures containing 12 percent mineral filler, the optimum asphalt contents are fairly low. For mixtures containing 12 percent 80/20 blended mineral filler, the VFA of 63 percent is out of the specification criteria of 65-78 percent for the Marshall mix design criteria, but it is within the NCDOT I-1 specifications.

4.3 Mix Design Using Corps of Engineers Gyratory Testing Machine

The Corps of Engineers gyratory testing machine (GTM) was used in this study to 1) compare the optimum design asphalt contents with those obtained using the Marshall procedure, and 2) to measure the compaction stability and shear properties of mixtures during specimen fabrication. The procedure used in this study (*7*) consisted of compacting a specimen to volume equilibrium under a constant pressure of 830 kPa and 1° angle of gyration. The compaction was stopped every 50 gyrations and specimen height and roller pressure were measured. When the density of the specimen increased by less than 8 kg/m^3 in 50 gyrations, the specimen was considered to be at volume equilibrium and the final roller pressure was measured. Most of the specimens compacted in this study required between 150 to 250 gyrations to obtain volume equilibrium. Six asphalt contents and 2 replicate specimens per asphalt content were evaluated for a total of 12 specimens for each aggregate blend. A total of 96 specimens were tested as shown in Table 13.

Using the measurements taken during specimen fabrication, several parameters such as Gyratory Stability Index (GSI), Gyratory Shear Modulus(G_G), Gyratory Shear Factor (GSF) and

Unit Weight Aggregate Only (UWAO) were computed. An explanation of these parameters and their derivation can be found elsewhere (7). As per the manufacturer's recommendations, the asphalt content that maximized G_G or GSF and UWAO, but produced a stable mixture, was selected as the optimum asphalt content.

TABLE 13 Mixture and Test Variables for Gyratory Mix Design

Test Variables	Levels of Treatment	No. of Levels
Asphalt contents (AC)	3.5, 4, 4.5, 5, 5.5, and 6% by wt. of mix	6
Number of specimens at each AC	---	2
Crushed/natural sand combinations	100% crushed & 80/20 blend crushed/natural sand	2
Mineral filler content	4, 6, 8, and 12%	4
Total number of specimens	---	96

Tables 14 and 15 show the average results of the GTM design for the 100 percent crushed granite aggregate and 80/20 aggregate blend, respectively. Detailed test results are enclosed in Appendix C. Table 14 shows that for crushed granite aggregate, an increase in the amount of mineral filler does not have significant effect on the optimum asphalt content except at the 12 percent filler content for which the asphalt content is reduced by one-half percent to 4.0 percent. However, the gyratory shear modulus and the GSF both significantly decrease with increase in mineral filler content while increasing the unit weight of the aggregates. The increase in mineral filler content from 4 to 8 percent (optimum asphalt content is the same at 4.5 percent for 4 to 8 percent filler content) seems to reduce the structural stability of the mixture (the gyratory shear modulus reduces from 23.44 MPa to 15.17 MPa) at the given asphalt content (4.5 percent).

TABLE 14 Gyratory Mix Design Results - 100% Crushed Granite

Mix Properties	Mineral Filler Content			
	4%	6%	8%	12%
Optimum Asphalt Content (%)	4.5	4.5	4.5	4.0
Gyratory Stability Index (GSI)	1.00	1.00	1.00	1.00
Unit Weight Aggregate Only (kg/m^3)	2298.1	2270.8	2304.5	2346.2
Gyratory Shear Modulus (MPa)	23.44	19.31	15.17	7.58
Gyratory Shear Factor (GSF)	2.7	2.2	1.7	0.8

TABLE 15 Gyratory Mix Design Results - 80/20 Aggregate Blend

Mix Properties	Mineral Filler Content			
	4%	6%	8%	12%
Optimum Asphalt Content (%)	4.5	4.5	4.0	4.0
Gyratory Stability Index (GSI)	1.00	1.00	1.00	1.00
Unit Weight Aggregate Only (kg/m^3)	2269.2	2270.8	2285.3	2298.1
Gyratory Shear Modulus (MPa)	15.17	15.17	17.93	13.10
Gyratory Shear Factor (GSF)	1.8	1.8	1.9	1.6

For the 80/20 aggregate blend, trends in the measured properties (Table 15) are not well defined as was the case for the mixtures containing crushed granite. However, in general, asphalt content reduces by about one-half percent for the 8 and 12 percent mineral filler content; gyratory shear modulus and GSF decreases at high filler content (12 percent). The unit weight of aggregate only increases with increase in mineral filler content.

Comparison of the gyratory shear modulus and GSF between mixtures containing crushed granite versus 80/20 aggregate blend show that both parameters at 4 and 6 percent filler content are higher for crushed granite as compared to the 80/20 aggregate blend. However, this trend reverses for the 8 and 12 percent filler content with the values of the gyratory shear modulus and GSF being lower for the crushed granite versus the 80/20 aggregate blend. One possible explanation for this behavior could be differences in effective asphalt content. The effective asphalt content in mixtures with 8 and 12 percent mineral filler, 100 percent crushed granite may be lower than for the 80/20 aggregate blend. This is because crushing operations can yield aggregate particles with higher number of fractured faces and therefore greater particle surface area than particles found in natural sands. However, since volumetric analysis is not required in the GTM design procedure, an effective asphalt content was not calculated for the mixtures.

4.4 Conclusions

Based on the results of the Marshall and gyratory mix designs, the following conclusions can be made:

1. For a given air void content, increasing the amount of mineral filler decreased the optimum asphalt content in mixtures as determined by the Marshall mix design method, while increasing Marshall stability and unit weight.
2. For a given air void content, the optimum asphalt content as determined by the Marshall mix design method was found to be lower by as much as 0.5 percent for the mixtures containing 20 percent Cape Fear natural sand as compared to mixtures containing 100 percent crushed granite aggregate.
3. Increase in mineral filler content does not significantly affect the optimum asphalt content in mixtures as determined by the GTM design method except at 12 percent filler content, for which the optimum asphalt content reduces by 0.5 percent.
4. The GTM design method clearly show that in general, the gyratory shear modulus and gyratory shear factor decrease with increase in mineral filler content, indicative of increased potential for rutting (permanent deformation) in mixtures.
5. For a given air void content, the addition of 20 percent natural sand to crushed granite aggregate results in a reduction in the values of the gyratory shear modulus and gyratory shear factor as compared to those determined for mixtures containing 100 percent crushed aggregate.
6. For the GTM design method, in general, the optimum asphalt contents for both aggregate blends containing all mineral filler contents are much lower compared to the optimum asphalt contents obtained using the Marshall mix design procedures. The difference ranges from a low of approximately 0.5 percent at higher filler contents, to a high of approximately 1.5 percent for the lower filler contents. The gyratory design asphalt contents seem to be unreasonably low. Based on the past NCDOT practice, these asphalt contents may not be acceptable due to the possibility of early distresses such as raveling, fatigue and thermal cracking.

5. REPEATED SIMPLE SHEAR TEST AT CONSTANT HEIGHT

To evaluate the effect of increased amount of mineral filler content on the shear permanent deformation performance, mixtures containing the two aggregate blends and the optimum asphalt content selected based on Marshall mix design, were subjected to repeated shear test at constant height (RSCH) using the Superpave™ simple shear test device (SST). The Superpave™ gyratory compactor (SGC) was used to fabricate the RSCH specimens because it can be set to compact specimens to a specified height, which is useful for targeting a given air void level. The compacted specimens were 150 mm in diameter and 130 mm in height. The ends of each specimen were sawn off and then the specimen was sawn in the middle to produce two test specimens. It should be noted that the air voids of the sawn test specimens were almost always found to be about 1.5% less than the air voids determined for the same specimens before they were sawn. For this reason, the specimens compacted using the SGC were compacted to 6.5% air voids so that the void content of the sawn test specimens would be 5.0±0.5%. The final dimensions of the shear test specimens were 150 mm in diameter and 57 mm in height. The RSCH tests were conducted on specimens containing 4, 8, and 12 percent mineral fillers as shown in Table 16.

TABLE 16 Mixture and Test Variables for RSCH Test

Test Variables	Levels of Treatment	No. of Levels
Asphalt contents (AC)	Optimum determined from Marshall mix design	1
Number of replicate specimens	---	4
Crushed/natural sand combinations	100% crushed & 80/20 blend crushed/natural sand	2
Mineral filler content	4, 8, and 12%	3
Test temperature	60°C	
Total number of specimens	---	24

The test procedures outlined in the AASHTO TP7 (*Standard Test Method for Determining the Permanent Deformation and Fatigue Cracking Characteristics of Hot Mix Asphalt (HMA) Using SST Device, Procedure F*) was used for the RSCH tests. A stress amplitude of 68±5 kPa was used for the repeated controlled shear testing with a 0.1 second loading time followed by a 0.6 second rest period. Testing temperature was 60°C. The axial load required to maintain the specimen at constant height, shear load, and axial and shear deformations (resilient and permanent) were recorded as a function of the number of loading cycles.

5.1 RSCH Test Results

Figure 7 shows the permanent deformation vs. number of load cycles relationships for mixtures containing 4, 8 and 12 percent mineral filler. Mixtures Containing 100 percent crushed granite aggregate and an 80/20 aggregate blend of crushed and natural sand are denoted as "M" and "N" in Figure 7, respectively. The permanent deformation curves shown for each mixture are the average permanent deformations based on 4 replicate test specimens.

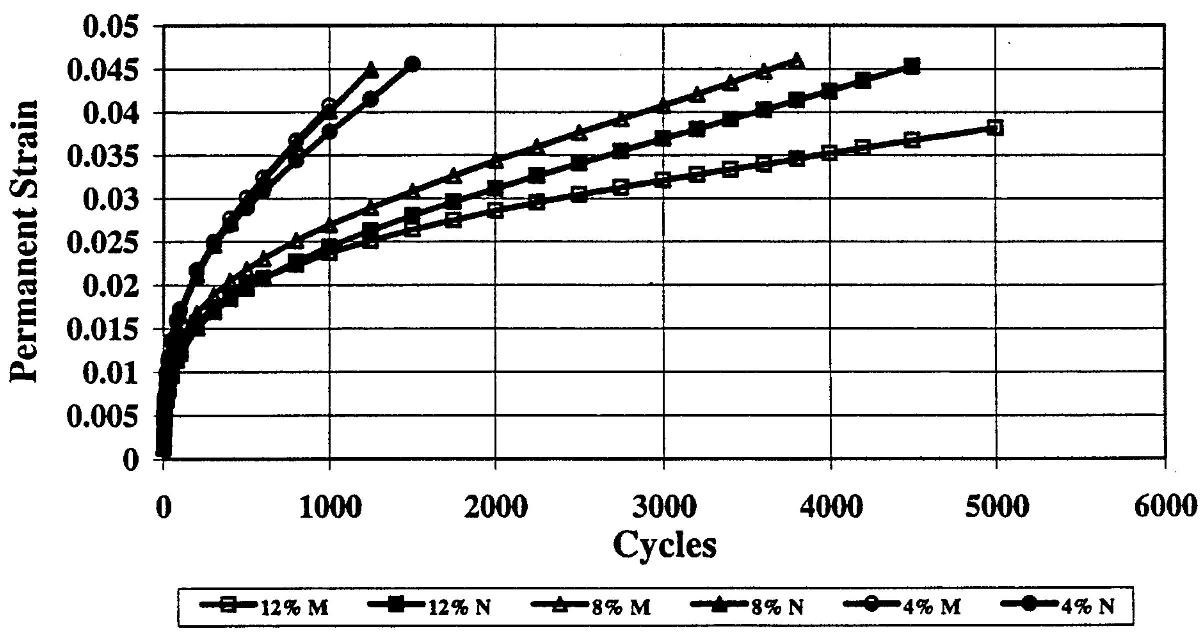

FIGURE 7 Shear Permanent Deformations

Based on Figure 7 following observations can be made in general:

1. Mixtures containing 100 percent crushed granite show lower accumulation of permanent strain at a given number of cycles as compared to the mixtures containing the 80/20 blend of

crushed and natural sand. These results are consistent with the notion that increasing the amount of natural sands with round particle shape and smooth surface texture, will produce mixtures which are more susceptible to rutting and shoving.

2. Increasing the amount of mineral filler in the mixtures reduces the accumulation of the permanent strain considerably, at least for the mineral filler amounts used in this study.
3. It may be noted that the difference in performance between the two aggregate blends at the lower filler content (4 percent) is small and increases with increase in filler content. For the 8 and 12 percent filler contents, the difference in performance of mixtures containing the two aggregate blends at a fixed strain level of 4 percent is approximately 67 and 40 percent (percentage based on the higher value), respectively.
4. The RSCH test is sufficiently sensitive to reflect the presence of as little as 20 percent of natural sand in total aggregate gradation.

At first glance, the second finding in this investigation seems to be in contradiction to the general belief that increasing fines content in asphalt mixtures should lead to increased rutting potential. However, for the range of mineral fillers and aggregate gradations considered in this investigation, results from the Marshall stability test also show increasing stability values with increasing mineral filler contents (Tables 11 and 12), results consistent with those obtained from the RSCH test. It should be noted that for the range of mineral filler contents considered, the unit weight of the mixture containing optimum asphalt content increases with increase in the mineral filler content (Tables 11 and 12). Consequently, the mass viscosity of the mixtures will also increase resulting in reduced shear susceptibility (lower permanent strain).

The average initial resilient shear moduli for each mixture type is presented in Table 17. In general, an increase in the amount of mineral filler in mixture increased the shear resilient modulus of the mixtures. With regards to the type of the mineral filler, mixtures containing 20 percent natural sand show a higher resilient moduli values as compared to the mixtures containing 100 percent crushed granite. This result although surprising, is probably due to the fact that average unit weight of mixtures containing natural sand is higher compared to mixtures containing crushed granite, a trend consistent with the results of Marshall mix design (Tables 11 and 12).

TABLE 17 Shear Resilient Modulus from RSCH Test

Aggregate Type	Mineral Filler Content (%)	Shear Resilient Modulus (MPa)
100% Crushed Granite	12	35.9
80/20 Blend	12	37.5
100% Crushed Granite	8	33.2
80/20 Blend	8	29.4
100% Crushed Granite	4	22.8
80/20 Blend	4	29.3

5.2 Conclusions

Based on the RSCH test results, following conclusions can be made for the mixtures and mineral filler percentages used in this study:

1. For a given air void content, an increase in the amount of mineral filler decreases the amount of permanent deformation that a mixture undergoes during repeated load shear test.
2. For a given mineral filler and air void content, the addition of 20 percent natural sand to a mixture increases the amount of permanent deformation a mixture undergoes during repeated load shear test (lower resistance to permanent deformation).
3. In general, mixtures containing 20 percent natural sand exhibit higher shear resilient modulus due to increased unit weight, at the same time exhibiting lower resistance to permanent deformation.

6. SUMMARY AND CONCLUSIONS

This study was carried out to evaluate commonly used methods that measure particle shape and texture characteristics of fine aggregate; and to investigate the effect of fines type and increased mineral filler content on asphalt mix design methods and mix resistance to permanent deformation.

Three methods for classifying aggregate particle shape and texture -- AASHTO TP33 (ASTM C1252), ASTM D3389 (*Index of Particle Shape and Texture*) and the flow rate method -- were evaluated. These methods were used to rank four natural river sands and a crushed granite from good to poor performing based on the criteria established in each method.

In order to evaluate the effect of particle shape and texture, and mineral filler content on mix performance, one natural sand (Cape Fear) which was ranked as "average performing" was selected and blended with the crushed granite. To investigate the effect of increased amounts of mineral filler on the design and performance of mixtures, a standard NC Department of Transportation (NCDOT) surface course gradation was modified to contain 4, 6, 8 and 12 percent mineral filler. Each mineral filler content gradation was produced from a 100 percent crushed aggregate and a blend containing 80 percent crushed aggregate and 20 percent natural sand, giving total of eight aggregate gradation blends.

Asphalt-aggregate mixtures were designed using the Marshall procedure, with the optimum asphalt contents selected to yield mixtures with 5.0% air voids as per the NCDOT specifications. The Corps of Engineers gyratory testing machine (GTM) was also used to design and evaluate the shear performance of the mixtures.

The Repeated Shear Test at Constant Height (RSCH) was performed on mixtures containing 4, 8 and 12 percent mineral filler with 100 percent crushed aggregate and 80/20 blends of crushed and natural sand. These mixtures were compacted using Superpave™ gyratory compactor to 5.0 percent air voids at the optimum asphalt contents selected based on the results from Marshall mix design. Based on the results obtained in this study, the following specific conclusions can be made:

1. The flow rate and AASHTO TP33 (ASTM C1252) methods appear to be less sensitive to slight differences in particle shape and texture as compared to the ASTM D3398 test method.
2. All test methods easily distinguish crushed granite aggregate from natural sands.
3. The flow rate method seems to be more dependent on the aggregate gradation than ASTM D3398 and AASHTO TP33 (ASTM C1252).
4. All test methods studied had good repeatability with low coefficients of variation.
5. The flow rate method was the least time consuming and easiest test to perform and had the lowest equipment cost associated with it.
6. ASTM D3398 was the most difficult and time consuming of the three tests studied. It also had the largest equipment cost associated with it.
7. For a given air void content, increasing the amount of mineral filler decreased the optimum asphalt content in mixtures as determined by the Marshall mix design method, while increasing Marshall stability and unit weight.
8. For a given air void content, the optimum asphalt content as determined by the Marshall mix design method was found to be lower by as much as 0.5 percent for the mixtures containing 20 percent Cape Fear natural sand as compared to mixtures containing 100 percent crushed granite aggregate.
9. Increase in mineral filler content does not significantly affect the optimum asphalt content in mixtures as determined by the GTM design method except at 12 percent filler content, for which the optimum asphalt content reduces by 0.5 percent.
10. The GTM design method shows that in general, the gyratory shear modulus and gyratory shear factor decrease with increase in mineral filler content, indicative of increased potential for rutting (permanent deformation) in mixtures. However, it should be noted that this trend is in conflict with the actual mix shear permanent deformation performance.
11. For a given air void content, the addition of 20 percent natural sand to crushed granite aggregate results in a reduction in the values of the gyratory shear modulus and gyratory shear

factor as compared to those determined for mixtures containing 100 percent crushed aggregate.

12. For the GTM design method, in general, the optimum asphalt contents for both aggregate blends containing all mineral filler contents are much lower compared to the optimum asphalt contents obtained using the Marshall mix design procedures. The difference ranges from a low of approximately 0.5 percent at higher filler contents, to a high of approximately 1.5 percent for the lower filler contents. The gyratory design asphalt contents seem to be unreasonably low. Based on the past NCDOT practice, these asphalt contents may not be acceptable due to the possibility of early distresses such as raveling, fatigue and thermal cracking.
13. For a given air void content, an increase in the amount of mineral filler decreases the amount of permanent deformation that a mixture undergoes during repeated load shear test.
14. For a given mineral filler and air void content, the addition of 20 percent natural sand to a mixture increases the amount of permanent deformation a mixture undergoes during repeated load shear test (lower resistance to permanent deformation).
15. Mixtures containing 20 percent natural sand in general, exhibit higher shear resilient modulus due to increased unit weight, at the same time exhibiting lower resistance to permanent deformation.

One of the important objective of this study was to show that increased amount of mineral fillers can be accommodated in asphalt mixtures without adversely affecting its rutting (permanent deformation performance). Results of this study clearly indicate that within the range of mineral filler content and type used in this study, increasing the amount of mineral filler has beneficial effect on the rutting performance. However, although the rutting performance is enhanced, it should be noted that at higher mineral filler content, the asphalt content is reduced which may have a detrimental effect on other mixture properties such as fatigue, thermal cracking, and raveling. Further investigation of the effect of increased mineral filler content on other properties is therefore warranted.

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APPENDIX A

TABLE A1 Results for AASHTO TP33 (ASTM C1252) Test Procedure

	Uncompacted Voids (%)						
Aggregate Type	Sample 1 Reading 1	Sample 1 Reading 2	Sample 2 Reading 1	Sample 2 Reading 2	Sample 3 Reading 1	Sample 3 Reading 2	Average
Sand- Brewer	45.56	45.36	45.40	45.00	45.20	45.24	45.29
Sand - Cape Fear	41.69	41.77	41.69	42.08	41.84	41.45	41.75
Sand - Marston	42.71	42.75	42.63	42.23	42.51	42.59	42.57
Sand - Pelcher	46.3	45.8	46.14	45.91	45.8	46.00	46.00
Crushed - Granite	47.56	-	47.64	-	47.87	-	47.69

TABLE A2 Results for ASTM D3398 Test Procedure

	Particle Index (I_a)						
Aggregate Type	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Sample 6	
	Sieve, mm 1.18 - 0.60	Sieve, mm 1.18 - 0.60	Sieve, mm 0.60 - 0.30	Sieve, mm 0.60 -0.30	Sieve, mm 0.30 - 0.15	Sieve, mm 0.30 - 0.15	Weighted Average
Sand- Brewer	14.00	13.89	13.38	12.90	14.38	14.32	13.8
Sand - Marston	11.69	11.72	12.43	12.43	12.68	12.68	12.4
	Sieve, mm 2.36 - 1.18	Sieve, mm 2.36 - 1.18	Sieve, mm 1.18 - 0.60	Sieve, mm 1.18 - 0.60	Sieve, mm 0.60 - 0.30	Sieve, mm 0.60 - 0.30	Weighted Average
Sand - Cape Fear	13.19	13.09	12.72	12.99	13.64	13.62	13.0
Sand - Pelcher	15.08	15.04	16.06	16.16	15.92	15.91	15.7
	Sieve, mm 4.75 - 2.36	Sieve, mm 4.75 - 2.36	Sieve, mm 2.36 - 1.18	Sieve, mm 2.36 - 1.18	Sieve, mm 1.18 - 0.60	Sieve, mm 1.18 - 0.60	Weighted Average
Crushed - Granite	15.08	15.35	17.66	17.39	17.40	17.29	17.0

TABLE A3 Results for Flow Rate Test Procedure

	Surface Texture Index					
Aggregate Type	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Average
Sand- Brewer	0.77	0.78	0.77	0.78	0.77	0.77
Sand - Cape Fear	0.83	0.83	0.83	0.83	0.83	0.83
Sand - Marston	0.74	0.75	0.74	0.74	0.74	0.74
Sand - Pelcher	0.91	0.87	0.88	0.87	0.87	0.87
Crushed - Granite	2.16	2.07	2.07	2.10	2.06	2.10

TABLE A4 Fine Aggregate Specific Gravity (ASTM C128)

Sieve Fraction (mm)	Aggregate Type				
	Sand-Brewer	Sand-Cape Fear	Sand-Marston	Sand-Pelcher	Granite
As Received	2.520	2.561	2.529	2.570	2.624
4.75 - 2.36	-	2.614	-	-	2.612
2.36 - 1.18	-	2.628	-	2.595	2.610
1.18 - 0.60	2.551	2.593	2.596	2.605	2.606
0.60 - 0.30	2.498	2.561	2.547	2.582	-
0.30 - 0.15	2.512	-	2.554	-	-

APPENDIX B

TABLE B1 Test Results for Marshall Mix Design – 100 percent Crushed Granite

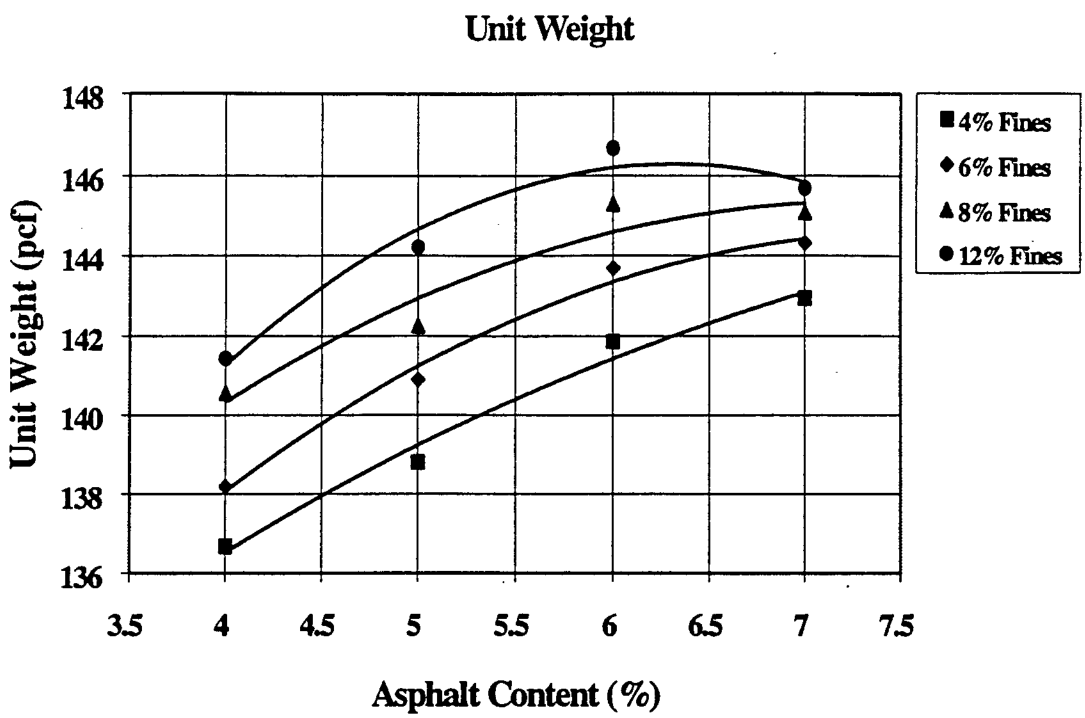
Asphalt Content (%)	Specimen No.	% Mineral Filler	Bulk Sp. Gravity	Air Void (%)	VMA (%)	VFA (%)	Stability kN	Flow
4	1	4	2.193	11.4	18.9	43.4	9.078	13.7
4	2	4	2.207	10.9	18.4	44.8	10.158	12.7
4	3	4	2.171	12.3	19.8	41.3	7.716	11.5
4	1	6	2.222	10.2	17.9	46.4	10.909	12.8
4	2	6	2.210	10.7	18.3	45.2	9.892	12.6
4	3	6	2.211	10.7	18.3	45.2	9.248	11.9
4	1	8	2.259	8.9	16.6	50.5	11.929	12.7
4	2	8	2.234	9.9	17.5	47.4	12.635	14.2
4	3	8	2.265	8.6	16.4	51.1	12.596	13.6
4	1	12	2.267	7.1	16.3	55.9	14.287	13.5
4	2	12	2.266	7.2	16.4	55.7	12.840	12.4
4	3	12	2.266	7.2	16.4	55.7	13.890	16.7
5	1	4	2.216	8.6	18.9	56.3	10.044	15.9
5	2	4	2.230	8.0	18.4	58.1	10.630	12.5
5	3	4	2.226	8.2	18.6	57.6	10.830	12.6
5	1	6	2.261	6.7	17.4	62.9	12.047	12.9
5	2	6	2.260	6.7	17.4	62.8	13.462	14.7
5	3	6	2.253	7.0	17.6	61.7	11.811	12.8
5	1	8	2.275	6.1	16.9	65.0	12.792	13.8
5	2	8	2.281	5.9	16.6	66.0	12.898	14
5	3	8	2.283	5.8	16.6	66.3	12.518	13.6
5	1	12	2.310	5.3	15.6	68.6	13.512	21.3
5	2	12	2.314	5.1	15.5	69.3	14.851	13.8
5	3	12	2.309	5.3	15.7	68.4	14.892	14.4
6	1	4	2.276	4.9	17.6	73.5	13.812	16
6	2	4	2.264	5.4	18.1	71.4	12.143	14.9
6	3	4	2.280	4.8	17.5	74.2	11.483	14.4
6	1	6	2.299	4.0	16.8	77.4	11.497	14.9
6	2	6	2.305	3.8	16.6	78.5	13.765	15
6	3	6	2.305	3.8	16.6	78.6	13.284	14.5
6	1	8	2.329	2.5	15.8	84.9	13.025	14.8
6	2	8	2.329	2.5	15.8	84.9	13.444	15.3
6	3	8	2.328	2.5	15.8	84.8	13.228	16.8
6	1	12	2.353	1.7	15.0	89.0	12.275	18.6
6	2	12	2.361	1.4	14.7	90.8	14.100	20.9
6	3	12	2.337	2.4	15.5	85.3	12.307	18.6

Table B1 (Contd.)

Asphalt Content (%)	Specimen No.	% Mineral Filler	Bulk Sp. Gravity	Air Void (%)	VMA (%)	VFA (%)	Stability kN	Flow
7	1	4	2.289	3.9	18.0	80.4	10.516	15.6
7	2	4	2.292	3.8	18.0	80.9	10.086	15.5
7	3	4	2.291	3.8	18.0	80.8	10.752	16.1
7	1	6	2.313	2.8	17.2	85.1	9.604	20
7	2	6	2.315	2.8	17.2	85.3	10.359	19.6
7	3	6	2.310	3.0	17.3	84.4	10.202	19.1
7	1	8	2.325	2.5	16.8	86.9	12.280	23.4
7	2	8	2.324	2.5	16.9	86.5	11.282	23.8
7	3	8	2.327	2.4	16.7	87.2	11.839	23.1
7	1	12	2.336	2.2	16.5	88.0	10.647	27
7	2	12	2.334	2.3	16.6	87.6	9.230	25

TABLE B2 Test Results for Marshall Mix Design – 80/20 Aggregate Blend

Asphalt Content (%)	Specimen No.	% Mineral Filler	Bulk Sp. Gravity	Air Voids (%)	VMA (%)	VFA (%)	Stability kN	Flow
5.5	8	1	2.314	4.1	15.7	73.6	16.454	13.7
5.5	8	2	2.298	4.8	16.3	70.4	15.607	11.7
5.5	8	3	2.318	4.0	15.6	74.3	15.428	14.8
6	8	1	2.327	2.9	15.7	81.5	15.785	14
6	8	2	2.336	2.5	15.4	83.4	17.168	15
6	8	3	2.334	2.6	15.5	83.0	16.499	15.5
6.5	8	1	2.346	1.4	15.5	90.8	15.964	17
6.5	8	2	2.348	1.3	15.4	91.4	14.983	16.5
6.5	8	3	2.344	1.5	15.5	90.4	15.206	17.6
4	12	1	2.293	6.8	15.2	55.0	22.073	13
4	12	2	2.309	6.2	14.6	57.5	20.111	14.6
4	12	3	2.303	6.4	14.8	56.6	19.709	13
4.5	12	1	2.335	4.4	14.1	68.6	21.850	13
4.5	12	2	2.322	5.0	14.6	65.9	20.958	13.5
4.5	12	3	2.320	5.1	14.7	65.4	18.461	12
5	12	1	2.378	2.0	13.0	84.7	19.040	13.5
5	12	2	2.349	3.2	14.1	77.4	20.066	13
5	12	3	2.341	3.5	14.3	75.7	19.977	14.5
5.5	12	1	2.364	1.8	14.0	86.9	18.282	15
5.5	12	2	2.355	2.2	14.3	84.4	18.951	15.8
5.5	12	3	2.345	2.6	14.6	82.2	16.945	15.2
6	12	1	2.361	1.2	14.5	91.5	15.161	17.8
6	12	2	2.359	1.3	14.6	90.8	14.804	17
6	12	3	2.353	1.6	14.8	89.4	13.645	17.2



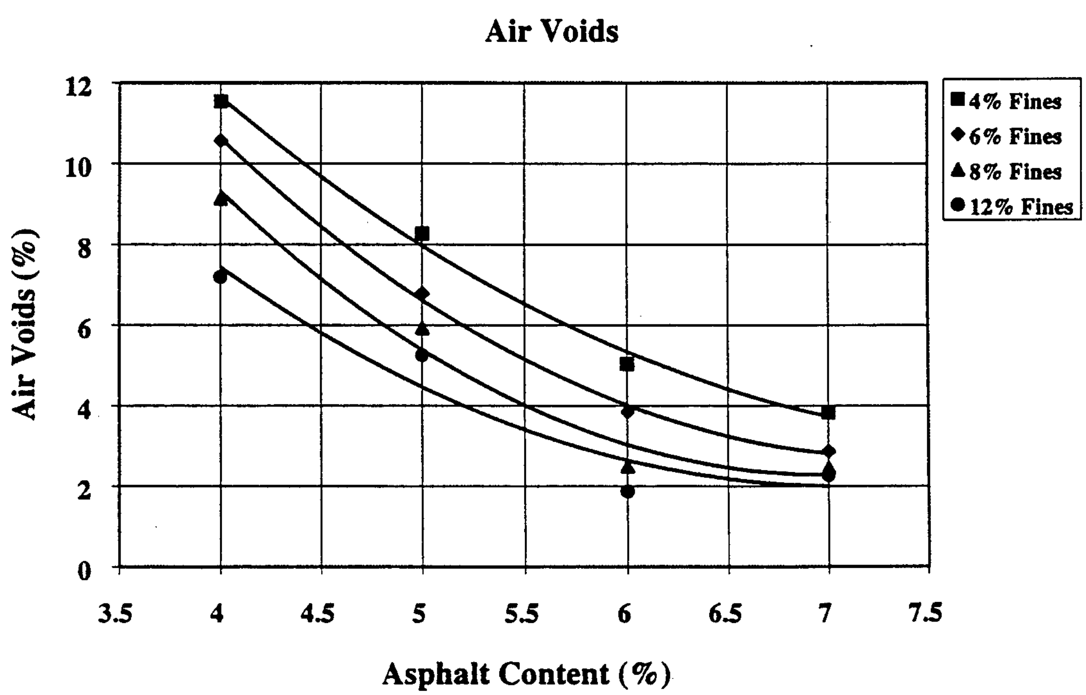
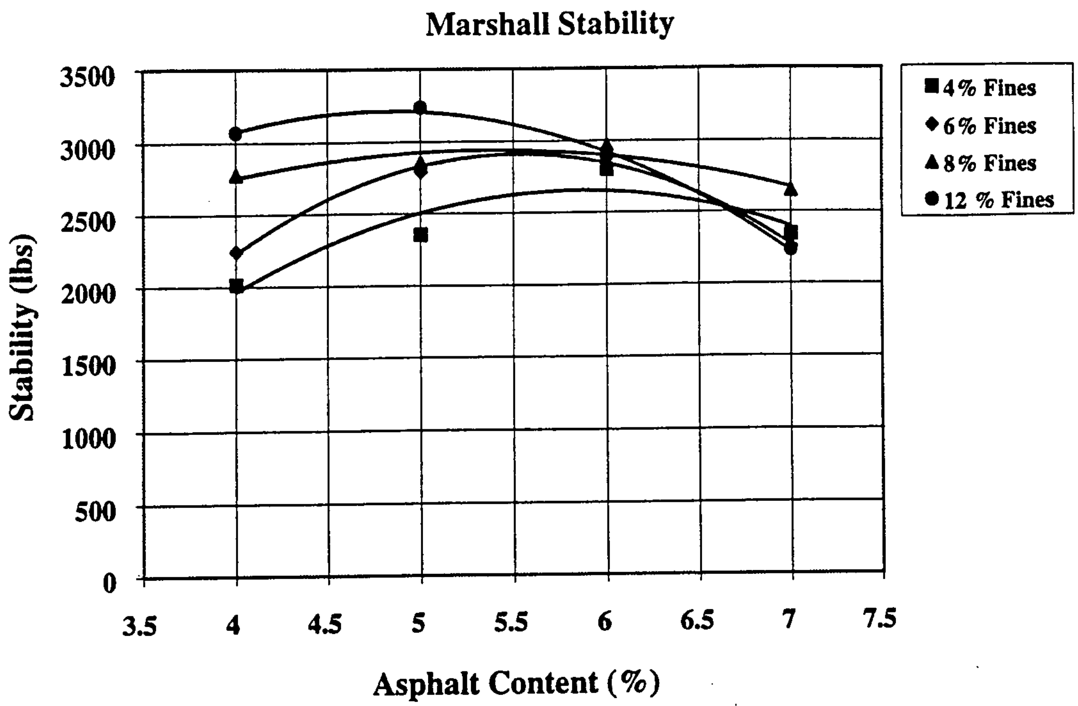


FIGURE B1 Unit Weight and Air Voids - 100% Crushed Fines



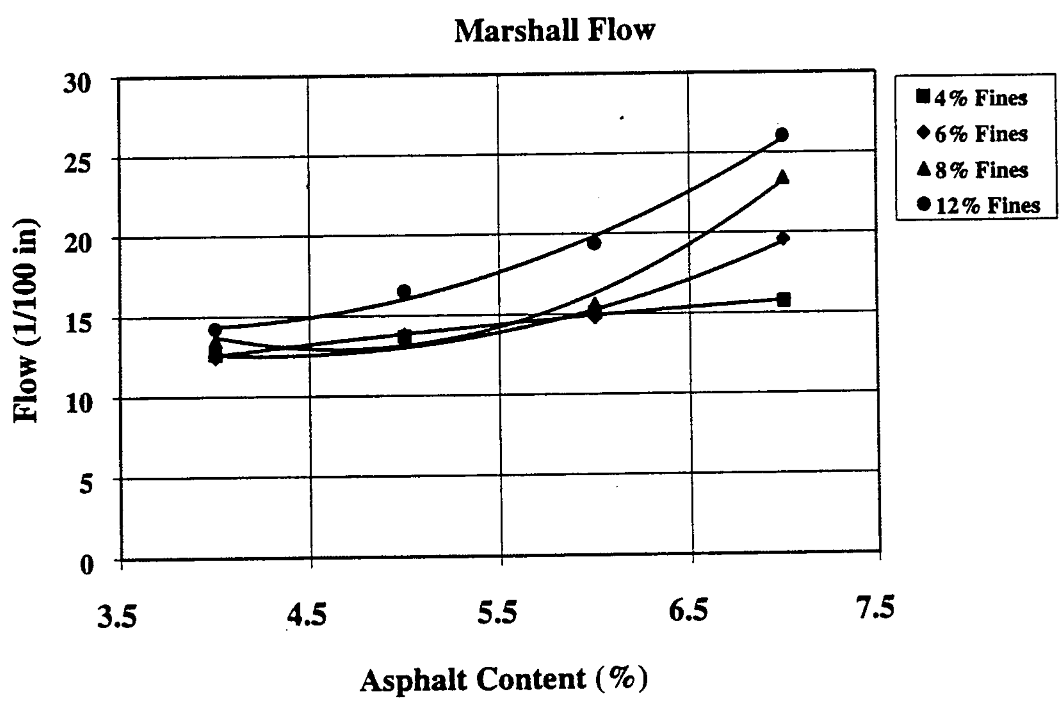


FIGURE B2 Marshall Stability and Flow - 100% Crushed Fines

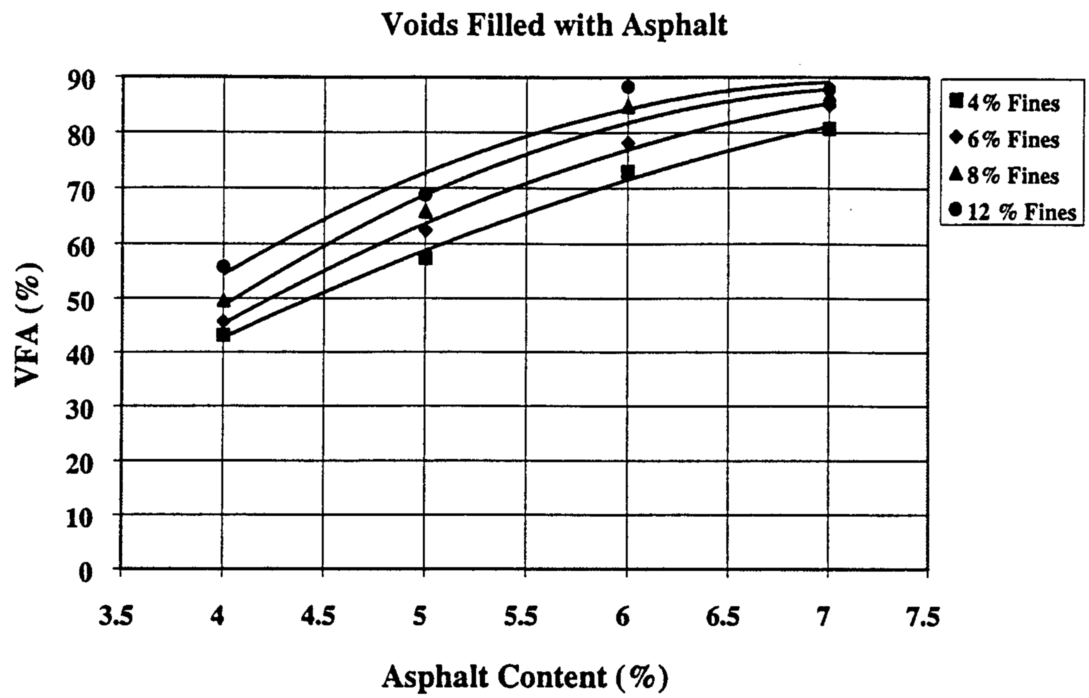
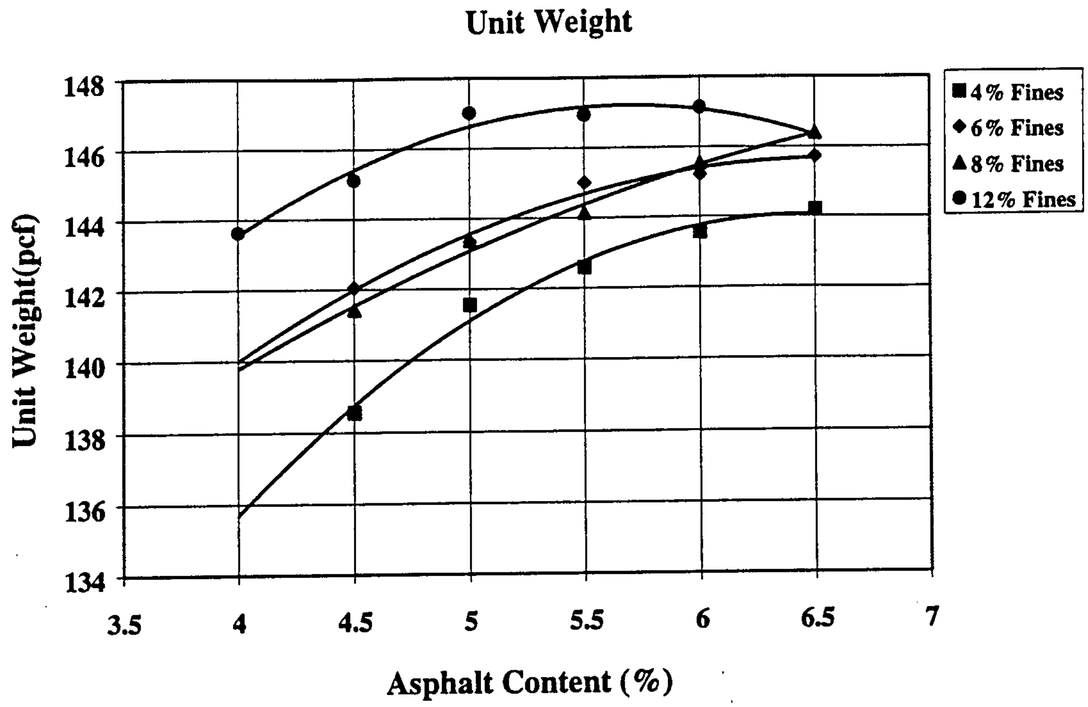


FIGURE B3 Voids Filled with Asphalt - 100% Crushed Fines



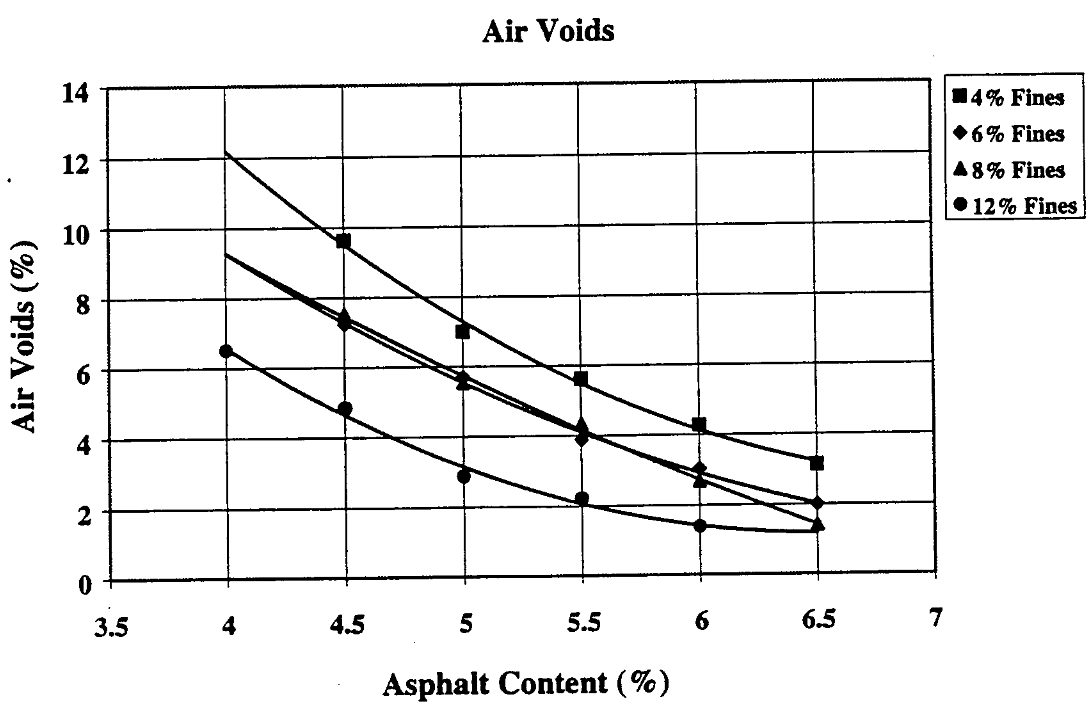
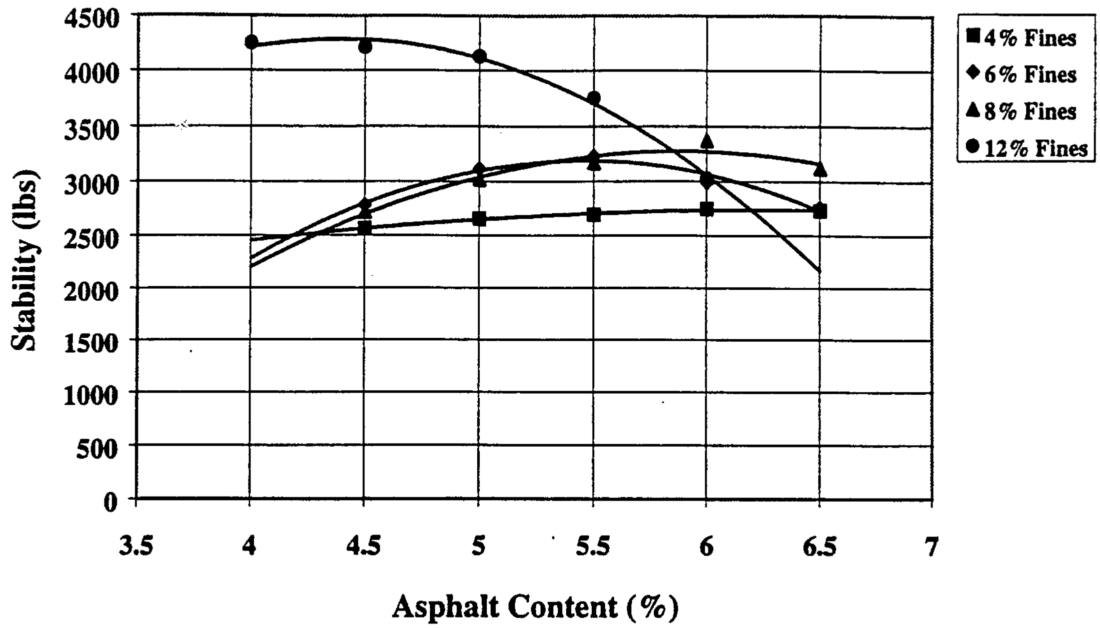


FIGURE B4 Unit Weight and Air Voids - 80/20 Aggregate Blend

Marshall Stability



Marshall Flow

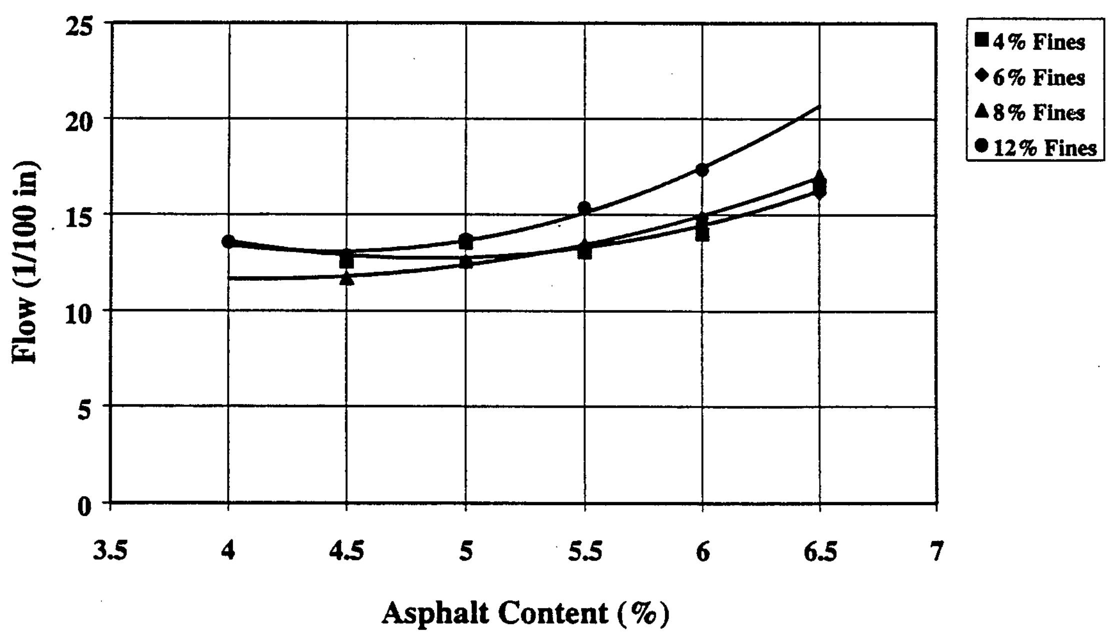


FIGURE B5 Marshall Stability and Flow - 80/20 Aggregate Blend

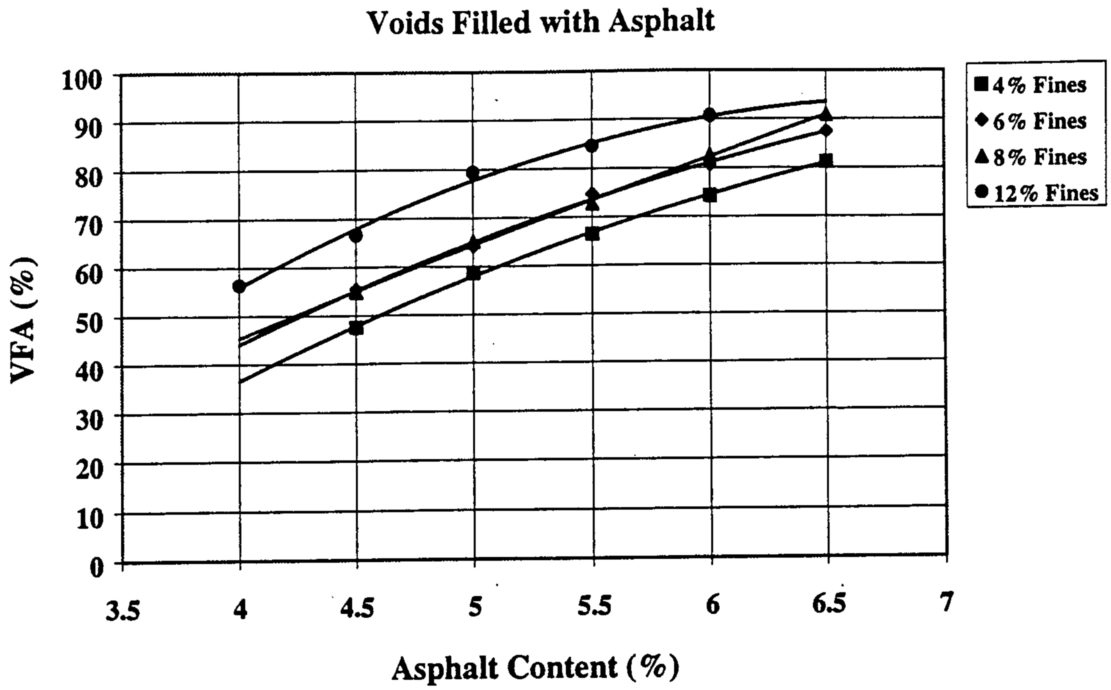


FIGURE B6 Voids Filled with Asphalt - 80/20 Aggregate Blend

APPENDIX C

TABLE C1 Test Results for GTM Mix Design – 100 percent Crushed Granite

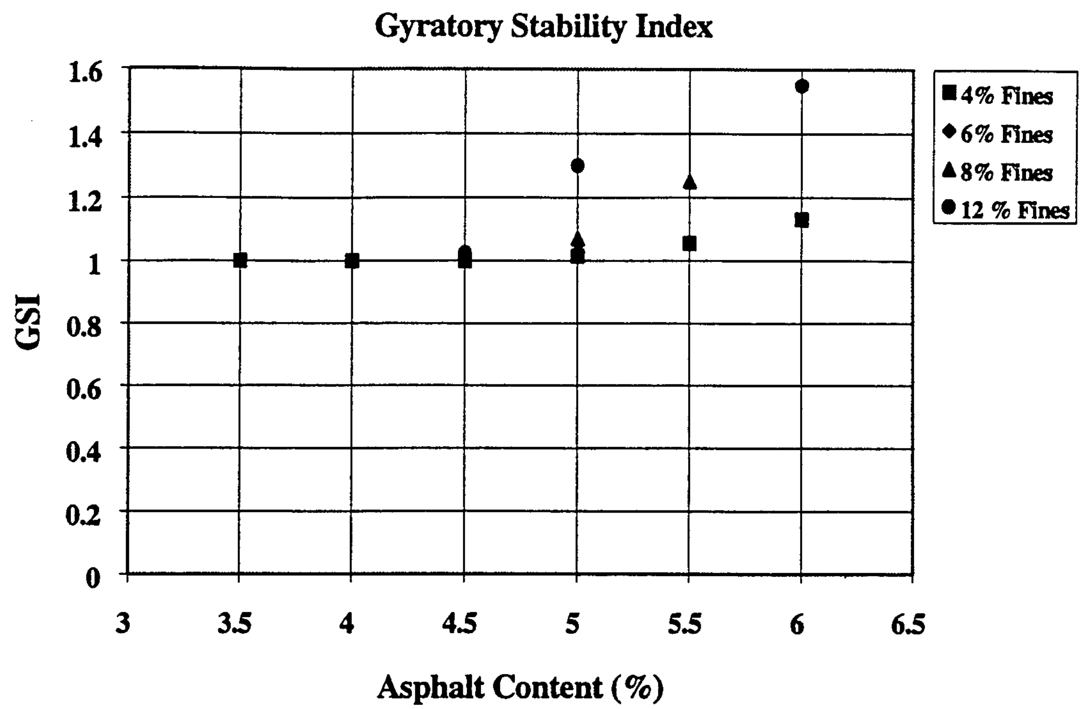
Asphalt Content	Specimen No.	% Mineral Filler	Sg	GSF	GSI	GEPI	Gg (MPa)	Eg (MPa)	UWTM kg/m^3	UWAO kg/m^3
3.5	1	4	130.700	3.42	1	1.7	30.3	90.9	2303.5	2222.9
3.5	2	4	77.100	2	1	1.7	17.9	53.6	2314.4	2233.5
4	1	4	120.570	3.15	1	1.7	28.3	85.0	2368.9	2274.0
4	2	4	122.290	3.2	1	1.7	27.9	83.8	2375.2	2280.1
4.5	1	4	100.040	2.619	1	1.7	23.9	71.7	2408.5	2296.2
4.5	2	4	78.897	2.06	1	1.7	18.3	54.9	2385.4	2278.1
5	1	4	90.380	2.366	1.03	1.8	19.8	59.4	2435.7	2313.9
5	2	4	87.920	2.3	1	1.7	20.4	61.1	2413.5	2292.6
5.5	1	4	74.260	1.94	1.08	1.8	15.0	45.0	2446.3	2311.7
5.5	2	4	101.160	2.64	1.03	1.8	21.5	64.6	2421.8	2288.7
6	1	4	66.670	1.7	1.14	1.7	13.5	40.4	2400.0	2256.1
6	2	4	45.428	1.2	1.12	1.7	9.4	28.3	2381.9	2238.9
3.5	1	6	46.583	1.219	1	1.6	11.5	34.4	2343.3	2261.3
4	1	6	101.300	2.65	1	1.7	23.5	70.4	2375.2	2280.1
4	2	6	112.030	2.93	1	1.7	26.0	77.9	2362.0	2267.5
4	3	6	52.142	1.3651	1	1.7	12.1	36.3	2356.7	2262.3
4	4	6	58.857	1.54	1	1.7	13.6	40.9	2347.8	2253.9
4.5	1	6	122.840	3.21	1	1.7	28.5	85.4	2405.6	2297.4
4.5	2	6	136.560	3.57	1	1.7	31.6	94.9	2384.3	2277.1
4.5	3	6	44.240	1.158	1	1.7	10.3	30.8	2370.3	2263.8
4.5	4	6	42.943	1.12	1	1.7	10.0	29.9	2360.3	2254.1
5	4	6	65.235	1.71	1.029	1.7	14.7	44.1	2381.1	2261.9
5.5	3	6	62.072	1.63	1.058	1.7	13.6	40.8	2395.9	2264.2
4	1	8	60.840	1.59	1	1.8	13.3	40.0	2473.9	2375.0
4	2	8	65.600	1.717	1	1.7	15.2	45.6	2416.2	2319.6
4	3	8	23.906	0.625	1	1.7	5.5	16.6	2370.0	2275.2
4	4	8	20.520	0.5374	1	1.6	5.1	15.2	2380.3	2285.1
4.5	1	8	32.940	0.86	1	1.7	7.6	22.9	2457.9	2347.4
4.5	3	8	116.210	3.04	1	1.7	27.7	83.2	2402.6	2294.6
4.5	4	8	109.250	2.86	1	1.7	25.3	76.0	2422.9	2314.1
4.5	2	8	39.560	1.03	1	1.7	9.2	27.5	2396.7	2288.8
4.5	3	8	39.770	1.04	1	1.6	9.8	29.4	2392.1	2284.6

Table C1 (Contd.)

Asphalt Content	Specimen No.	% Mineral Filler	Sg	GSF	GSI	GEPI	Gg (MPa)	Eg (MPa)	UWTM kg/m^3	UWAO kg/m^3
5	1	8	64.220	1.68	1.06	1.8	13.7	41.0	2408.7	2288.1
5	4	8	88.350	2.312	1.06	1.7	19.3	58.0	2403.7	2283.5
5	4	8	35.990	0.94	1.05	1.7	7.9	23.6	2398.1	2278.0
5	5	8	58.110	1.52	1.125	1.6	12.7	38.2	2393.6	2273.9
5.5	5	8	20.640	0.54	1.298	1.7	3.7	11.1	2406.4	2274.2
5.5	3	8	56.430	1.48	1.17	1.8	10.6	31.8	2458.7	2323.6
5.5	4	8	70.790	1.85	1.28	1.8	12.1	36.4	2455.0	2320.0
3.5	3	12	12.570	0.3292	1	1.7	3.0	9.0	2377.2	2294.1
3.5	4	12	19.360	0.50699	1	1.6	4.8	14.3	2378.2	2295.0
4	3	12	28.120	0.736	1	1.7	6.7	20.1	2400.3	2304.3
4	4	12	41.180	1.07	1	1.7	9.8	29.5	2396.7	2300.9
4.5	1	12	42.320	1.11	1	1.7	9.8	29.4	2468.1	2357.1
4.5	2	12	47.580	1.24	1.05	1.7	10.4	31.2	2489.7	2377.7
5	1	12	30.170	0.79	1.3	1.8	5.1	15.2	2492.1	2367.5
6	1	12	0.720	0.0188	1.43	2.0	0.1	0.3	2475.8	2327.2
6	2	12	0.715	0.0185	1.667	2.0	0.1	0.3	2456.6	2309.1

TABLE C2 Test Results for GTM Mix Design – 80/20 Aggregate Blend

Asphalt Content	Specimen No.	% Mineral Filler	Sg	GSF	GSI	GEPI	Gg (MPa)	Eg (MPa)	UWTM, kg/m^3	UWAO kg/m^3
4	1	4	40.653	1.06	1.00	1.80	8.9	26.7	2344.9	2251.1
4	2	4	42.352	1.11	1.00	1.75	9.5	28.6	2342.4	2248.7
4.5	1	4	49.524	1.30	1.00	1.70	11.5	34.4	2374.5	2267.7
4.5	2	4	77.432	2.03	1.00	1.70	17.9	53.8	2370.8	2264.2
5	1	4	91.936	2.41	1.03	1.70	19.6	58.7	2386.7	2267.3
5	2	4	134.384	3.52	1.03	1.70	30.3	90.8	2383.5	2264.2
5.5	1	4	166.538	4.36	1.03	1.70	37.5	112.5	2361.0	2231.3
5.5	2	4	151.081	3.96	1.09	1.80	32.2	96.5	2357.7	2228.1
4	1	6	70.389	1.84	1.00	1.70	16.3	48.9	2359.9	2265.5
4	2	6	83.199	2.18	1.00	1.70	19.3	57.8	2365.0	2270.4
4.5	1	6	61.357	1.61	1.00	1.70	14.2	42.7	2378.4	2271.5
4.5	2	6	58.907	1.54	1.00	1.75	13.3	39.8	2376.1	2269.3
5	1	6	63.285	1.66	1.06	1.65	14.2	42.7	2383.7	2264.4
5	2	6	84.537	2.21	1.03	1.70	19.0	57.1	2382.1	2262.9
5.5	1	6	67.145	1.76	1.06	1.75	14.3	42.9	2391.7	2260.3
5.5	2	6	74.529	1.95	1.06	1.70	16.3	48.9	2374.9	2244.4
4	1	8	59.636	1.56	1.00	1.65	14.2	42.7	2378.9	2283.7
4	2	8	94.199	2.47	1.00	1.65	22.5	67.5	2381.7	2286.4
4.5	1	8	45.508	1.19	1.03	1.80	9.7	29.1	2411.1	2302.7
4.5	2	8	56.404	1.48	1.03	1.70	12.7	38.1	2392.2	2284.6
5	1	8	116.495	3.05	1.03	1.75	25.5	76.5	2386.2	2266.8
5	2	8	62.945	1.65	1.06	1.80	13.1	39.2	2395.3	2275.5
5.5	1	8	41.139	1.08	1.17	1.80	7.7	23.2	2402.2	2270.2
5.5	2	8	38.449	1.01	1.19	1.85	6.9	20.7	2388.0	2256.7
3.5	1	12	42.995	1.13	1.00	1.65	10.3	30.8	2385.2	2301.8
3.5	2	12	70.359	1.84	1.00	1.65	16.8	50.4	2377.5	2294.3
4	1	12	48.181	1.26	1.00	1.75	10.8	32.5	2400.3	2304.3
4	2	12	59.953	1.57	1.00	1.60	14.8	44.3	2394.4	2298.6
4.5	1	12	55.478	1.45	1.03	1.80	11.8	35.4	2404.2	2296.1
4.5	2	12	60.161	1.58	1.03	1.70	13.5	40.6	2367.8	2279.5
5	1	12	51.753	1.35	1.09	1.75	10.7	32.2	2402.6	2282.4
5	2	12	61.696	1.62	1.11	1.75	12.5	37.4	2398.8	2278.8



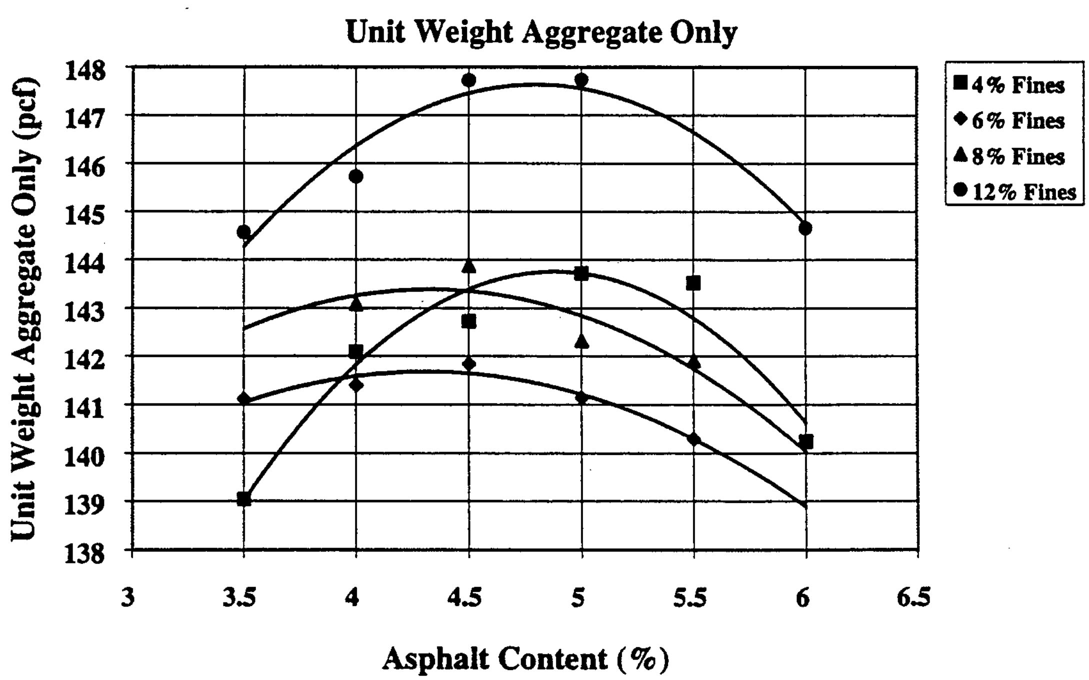
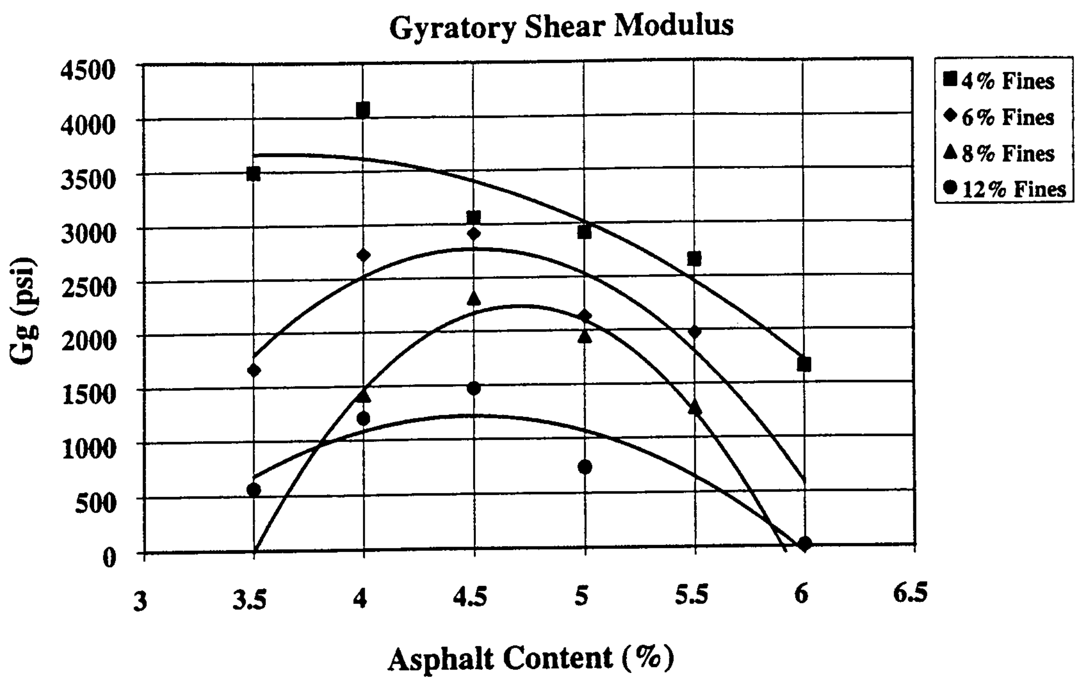


FIGURE C1 Gyratory Stability Index and Unit Weight Aggregate Only - 100% Crushed Fines



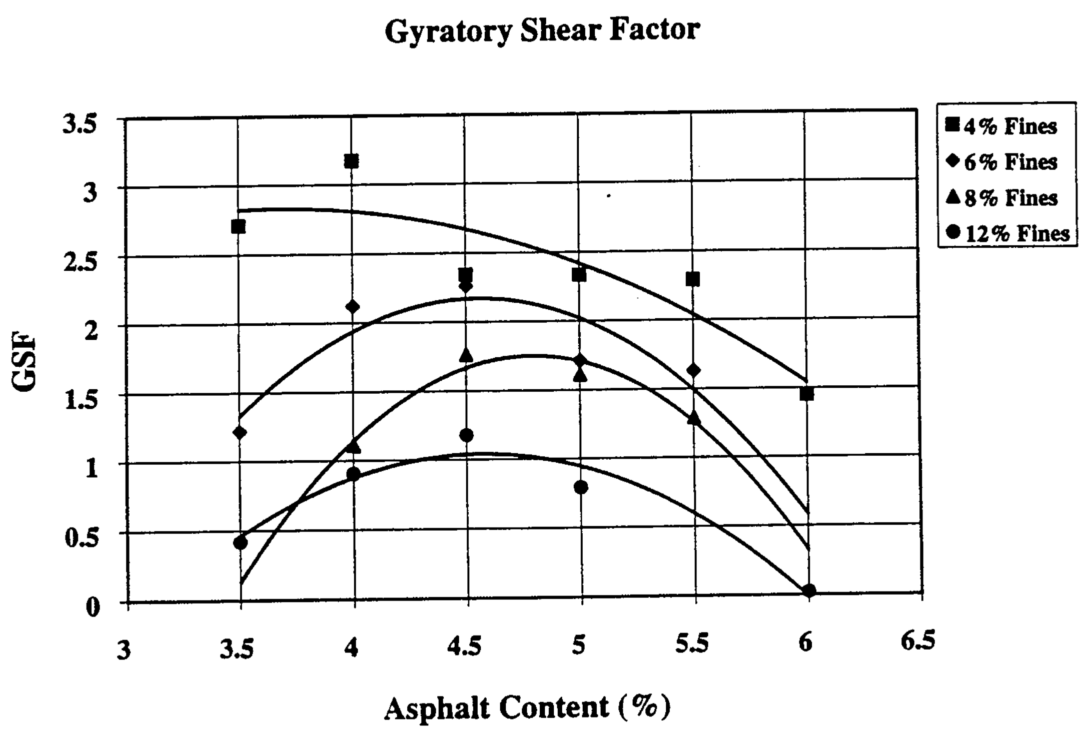
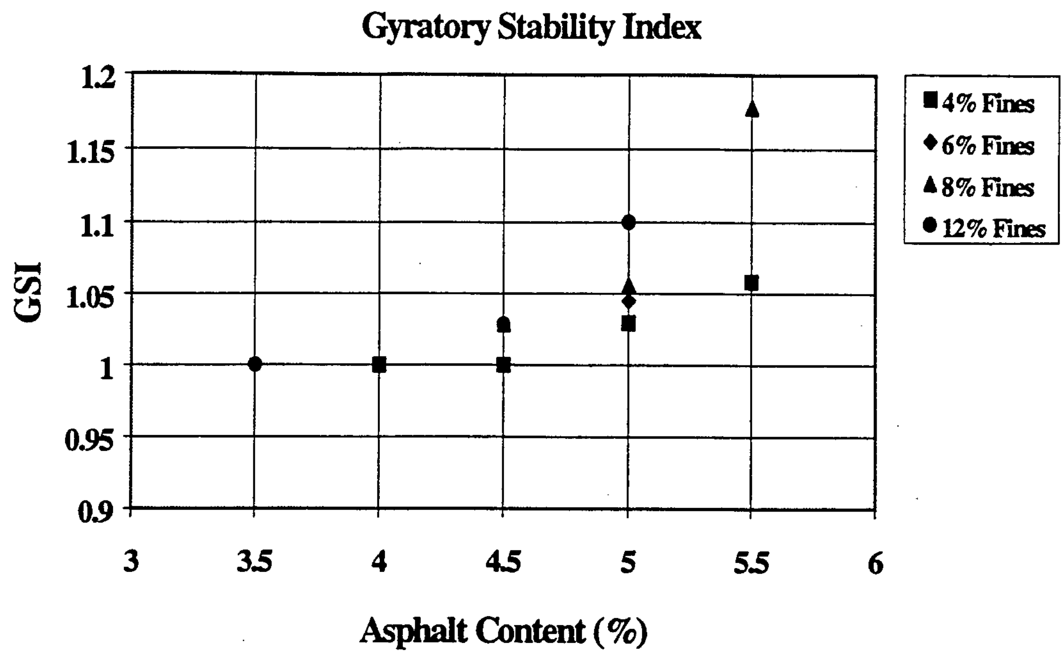


FIGURE C2 Gyratory Shear Modulus and Shear Factor - 100% Crushed Fines



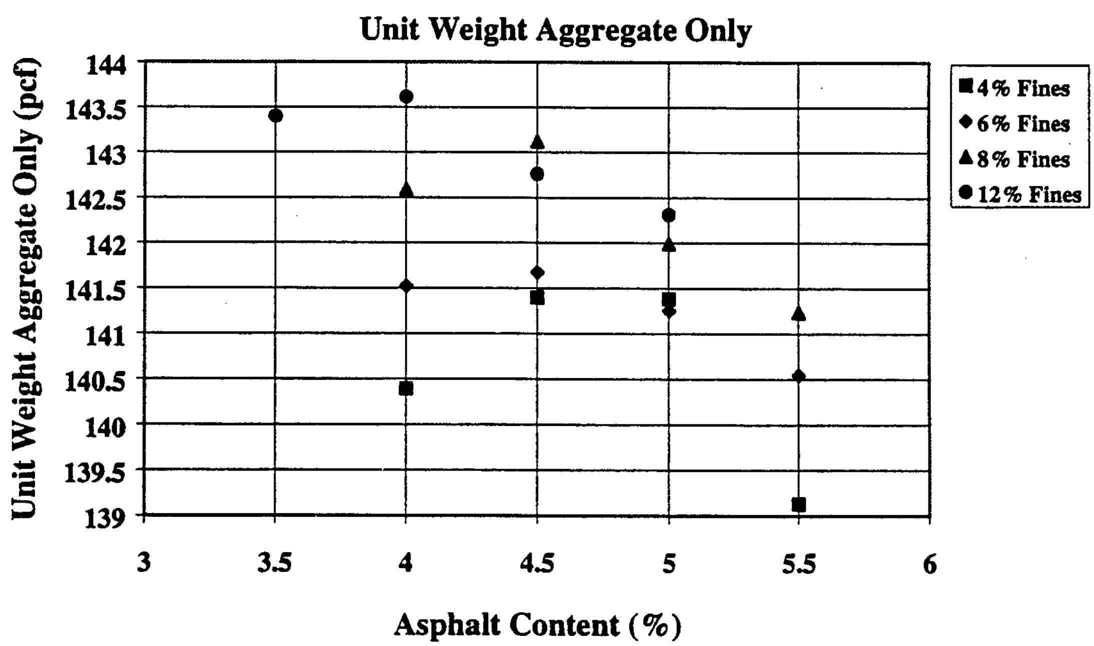
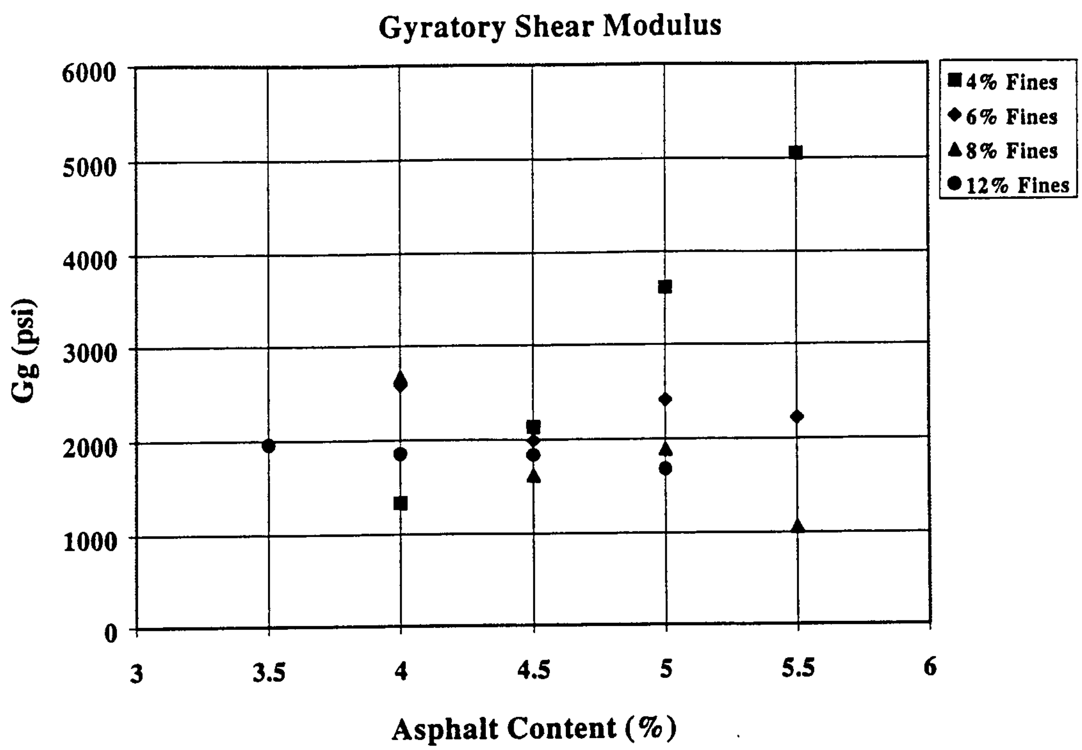


FIGURE C3 Gyratory Stability Index and Unit Weight Aggregate Only - 80/20 Aggregate Blend



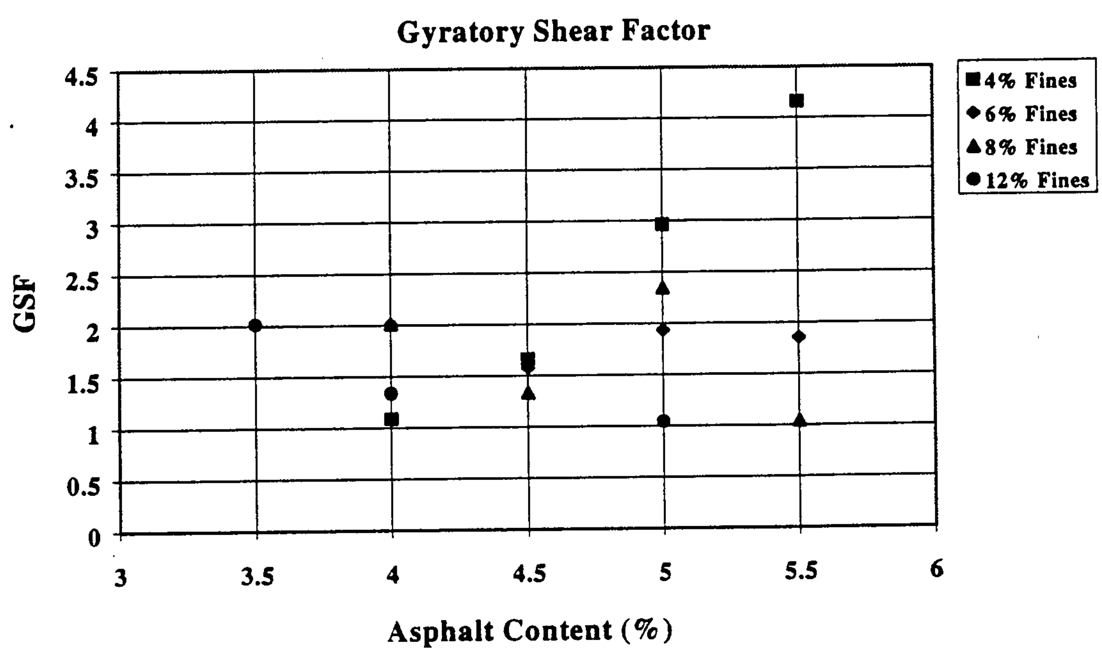


FIGURE C4 Gyratory Shear Modulus and Shear Factor - 80/20 Aggregate Blend