Designing Stone Matrix Asphalt Mixtures Volume III – Summary of Research Results

Final Report

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Executive Summary

The National Center for Asphalt Technology (NCAT) has developed and validated a mix design procedure for stone matrix asphalt (SMA). This work was funded by the National Cooperative Highway Research Program (NCHRP) under project number NCHRP 9-8 and was completed in 1998.

This project involved 15 tasks that included the following topics: literature review, material and mixture properties, appropriate laboratory tests, development of a mix design procedure, field evaluation of the mix design procedure, development of quality control/quality assurance procedures, development of construction guidelines, verification of mixing and compaction temperatures, verification of density requirements, and the accuracy and precision of nuclear density gauges for SMA pavements.

The results of this study have been published in five volumes. Volume I - Literature Review summarizes available literature on SMA up to 1998. This review includes over 100 papers presented primarily during the time period 1989 to 1998.

Volume II(a) - Research Results presents the results of the initial research performed measure the critical material and mixture properties of SMA. This report also describes work accomplished to evaluate the ability of different laboratory tests to characterize SMA mixtures. This work included finding a method of identifying when stone-on-stone contact is achieved within SMA mixtures. This report also presented the first tentative SMA mixture design procedure.

Volume II(b) - Research Results presents the results of work accomplished to finalize the tentative mixture design procedure for SMA. Additional work reported in this volume consisted of analyzing mixture properties that were designed with the finalized mixture design procedure. This testing included indirect tensile creep and wheel track testing.

Volume II(c) -Research Results, presents the results of work to verify that the mixtures designed by the final mixture design procedure could be produced and placed in the field. Additional work consisted of developing quality control/quality assurance procedures, evaluating SMA gradations with varying nominal maximum aggregate sizes, developing SMA construction guidelines, verifying laboratory mixing and compaction temperatures, verifying in-place density requirements, and evaluating the accuracy of nuclear density gauges for determining the in-place density of SMA pavements.

Volume III - Summary of Research Results is provided to summarize all of the research effort for the NCHRP 9-8 study. This volume was intended to give a general overview of the entire research effort and includes summaries for material properties, aggregate skeleton testing, mortar testing, mixture design testing, mixture design analysis, the effect of flat and elongated particles, aggregate breakdown analysis, mixing and compaction testing, permeability evaluation, evaluation of nominal maximum aggregate sizes, mixture performance evaluation, field evaluation of the mixture design procedure, field density requirements, and the accuracy of nuclear density gauges.

Volume IV - Mixture Design Method, Construction Guidelines, and Quality Control/Quality Assurance Procedures provides the deliverables of the study. As the title indicates, this report contains the final SMA mixture design procedure, guidelines for the construction of SMA, and quality control/quality assurance procedures to be used during construction. This report also provides draft AASHTO standard test methods for tests developed during the course of the research, an example SMA mixture design using the final mixture design procedure, and an example of blending SMA gradations based on volumes.

Volume V - Appendix For Phase II Work provides detailed summaries of field validation projects and the data from Phase II experiments.

CHAPTER 1 - INTRODUCTION AND RESEARCH APPROACH

1.1 PROBLEM STATEMENT AND RESEARCH OBJECTIVE

Stone Matrix Asphalt (SMA) has been used in Europe for over 20 years. Within the United States, SMA has been used successfully since 1991. Some states routinely use SMA even though a standard mixture design procedure is not available. If a good mixture design procedure is adopted, it should be possible to improve the performance of SMA. A procedure that provides guidance on material properties, aggregate gradation, determination of optimum asphalt content, and mixture properties is needed.

As a result of this need, the National Cooperative Highway Research Program (NCHRP) contracted with the National Center for Asphalt Technology (NCAT) in 1994 to develop a mixture design procedure for SMA. The emphasis of this study was to develop a straightforward procedure for SMA that is repeatable and that can be used by any agency or laboratory that is equipped to do hot mix asphalt (HMA) testing. This design procedure was envisioned as one method with two separate compaction options. The design can be accomplished with either a flat-faced, static base Marshall hammer or a Superpave gyratory compactor (SGC). Therefore, the objective of this project was to develop a mixture design procedure for SMA.

1.2 SCOPE OF STUDY

In order to achieve the overall goal of developing a quality mixture design procedure for SMA, much research was accomplished. Two distinct phases of research were performed (Phase I and Phase II). Phase I research involved developing a SMA mixture design procedure and necessitated two “parts” (Phase I - Part 1 and Phase I - Part 2). Phase I - Part 1 began in April 1994 and had as its main goal the development of a tentative SMA mixture design method. This was done by evaluating critical material and mixture properties of SMA and the selection of laboratory tests to evaluate the selected material and mixture properties.

Phase I - Part 2 began in early 1995 and was performed to build on the results of Phase I - Part 1. The main objectives of this research were to evaluate and modify the tentative mixture design procedure and to analyze SMA mixtures with the revised method to make any necessary refinements.

Phase II of the research began in 1996 and was performed to field validate the proposed mixture design procedure established in Phase I research. Additionally, Phase II developed Quality Control/Quality Assurance (QC/QA) and construction guidelines for the construction of SMA.

1.3 RESEARCH APPROACH

The research approach taken to accomplish the objective of this project was to divide the project into 15 different tasks. Tasks 1 through 4 were accomplished under Phase I - Part 1, Tasks 5 through 7 were accomplished for Phase I - Part 2, and Tasks 8 through 15 were performed under Phase II. Following are brief overviews of the different tasks.

Task 1- State of the Art

Task 1 was accomplished to summarize the available information developed for SMA. Current mix design procedures, specifications, and construction procedures were obtained from all available sources, in particular, available published literature.

Task 2 - Critical Material and Mixture Properties

This task entailed evaluating aggregate, mortar, and mixture properties. The important aggregate properties such as Los Angeles Abrasion, flat and elongated particles, absorption, soundness, and crushed content and their specifications were studied. In addition, the effects of aggregate type, shape, and gradation on SMA mixtures were studied.

Mortar testing under this task essentially looked at the applicability of the Superpave binder equipment and their testing procedures for evaluating SMA mortars. Both the total mortar (material passing 2.36 mm sieve, asphalt cement, and stabilizing additive) and fine mortars (material passing the 0.075 mm sieve, asphalt cement, and stabilizing additive) were evaluated. The total mortars were considered to be more like a mixture and were tested at low, intermediate, and high temperatures using the bending beam rheometer, resilient modulus, indirect tensile test, and the Brookfield viscometer. The fine mortars were considered to be a binder and were tested with the Superpave binder equipment and test procedures.

Evaluation of mixture properties consisted of determining the volumetric properties, moisture susceptibility, creep properties, and draindown characteristics of SMA mixtures.

Task 3 - Selection of Laboratory Tests

Testing under this task was performed to determine what laboratory tests could be used to evaluate SMA mixtures. Testing was conducted for the aggregate skeleton, additional mortar testing, and SMA mixture testing. The aggregate skeleton testing consisted of finding a method for identifying when stone-on-stone contact is achieved within an SMA mixture.

Mortar testing under this task was again conducted on both the total and fine mortars. The primary purpose of this testing was to determine the potential of the tests listed under Task 2 to measure desirable properties of SMA mortars.

The SMA mixture testing was accomplished to evaluate the effect of changing volumetric properties on SMA. A dynamic, confined creep test was used for this evaluation.

Task 4 - Interim Report

The requirement of Task 4 was to submit an interim report summarizing the work in Tasks 1-3. This report included a tentative mixture design procedure for SMA.

Task 5 - Mixture Design Procedure

The main goal of Task 5 was to finalize the mixture design procedure proposed under Tasks 1-4. This was accomplished by adapting the Superpave volumetric design procedure for SMA, establishing a method for determining the proper laboratory mixing and compaction temperature for SMA, establishing fine mortar specification criteria, and further evaluating the design procedure.

Task 6 - Mixture Analysis

Task 6 was completed to analyze the properties of mixtures produced using the design method established under Task 5. Testing included under this task was the Indirect Tensile Creep and wheel tracking.

Task 7 - Final Report

The requirement of this task was to produce a final report documenting the research effort under Phase I of the project. An updated mixture design method was provided in this report.

Task 8 - Field Evaluation of SMA Mix Design Procedures

This task entailed going to various SMA construction projects throughout the United States and collecting actual field data. For this phase, a mobile laboratory was used to develop much of the data. Within the mobile laboratory was equipment to compact specimens using both the Marshall hammer and the Superpave gyratory compactor (SGC), determine the maximum specific gravity of the SMA mixtures, and determine the draindown characteristics of the SMA mixtures.

Task 9 - Develop Quality Control/Quality Assurance Procedures for SMA Mixtures

During this task information from several states involved with SMA construction along with information developed during Task 8 were used to develop the Quality Control/Quality Assurance (QC/QA) procedures. The QC/QA procedures also included a trouble shooting guide to aid in determining the specific cause of potential problems.

Task 10 - Laboratory Testing

Testing included in this task were designed to extend some of the results produced in Phase I of the research. Specific testing focused on various maximum aggregate sizes, determination of the effects of flat or elongated particles using the SGC, and Direct Tension Testing of SMA fine mortars.

Task 11 - Develop SMA Construction Guidelines

The purpose of this task was to develop SMA construction guidelines to assist producers during the production and placement of SMA mixtures. The guidelines included guidance on aggregate handling, fiber handling, plant operations, laydown operations, and compaction. These guidelines were developed based on the experience of the NCAT staff, state DOTs, FHWA, contractor personnel, and information gathered during Task 8.

Task 12 - Verify Laboratory Mixing and Compaction Temperatures

This task was accomplished to further the research effort of Task 5 with regards to establishing a procedure for determining the mixing and compaction temperatures for SMA mixtures. Testing was conducted on SMA fine mortars (minus fibers) in the Brookfield viscometer and on SMA mixtures using a workability device developed during the study.

Task 13 - Verify Density Requirements

At the present time, most SMA projects are being compacted to in-place air void contents of 5 to 6 percent. This appears to be acceptable, but there is some evidence that indicates that SMA mixtures are permeable to water at a lower air void content than are dense-graded mixtures. Task 13 investigated this possibility using laboratory and field permeability tests.

Task 14 - Accuracy and Precision of Nuclear Gauge for Determining Field Density

By nature, SMA mixtures have a rough surface texture. As a result, the use of nuclear density gauges to determine in-place density is questionable. Therefore this task evaluated the accuracy of nuclear gauges for determining the density of SMA mixtures.

Task 15 - Preparation of Reports

The requirement of this task was to produce a final report documenting the total research effort. Included within this report were the final mixture design procedure, the QC/QA procedures, and the guidelines for SMA construction.

CHAPTER 2 - FINDINGS OF RESEARCH

2.1 LITERATURE REVIEW

Known by several similar names, such as Splittmastixasphalt in Europe where the material was first developed and Stone Matrix Asphalt when it was adopted in the USA, this durable, deformation-resisting mix has become generically known by its initials SMA. Stone Matrix Asphalt is, in fact, not a particularly good translation of the German word as it fails to convey the sense of crushed stone, which is an essential feature of the mix. However, the convenient SMA form of the name will be used in this review.

SMA is a simple idea: find a hard, durable, quality stone, fracture it into roughly cubical shape and of a size consistent with the proposed layer thickness, and then glue the stones together with a durable, moisture-resistant mortar of just the right quantity to give stone-on-stone contact among the coarse aggregate particles. For the asphalt technologist, the trick is getting the various parameters right. This is where the recipes come in. Most European specifications are reflections of mix ingredients and proportions that seem to work quite well. Many specifications are based on Germany's work (10).

It was not until about 1990 that interest in SMA was sparked in North America, following a study tour (26) of five European countries by a group of pavement specialists from the U.S. The favorable reaction of the team to SMA soon caught the attention of the trade press and several articles on SMA followed, especially after SMA projects were constructed first in Canada in late 1990 (24) and then in several U.S. states in 1991. Technical reports and published papers of substance relating to North American experience began to appear in late 1991.

In 1990, news about SMA began to circulate through exchanges of technical information between local technologists and Europeans. During the European study tour (26), U.S. pavement specialists had the opportunity to see SMA in action and hear about it through presentations such as the one by Liljedhal (8). Armed with European experience and specifications (1, 2, 4, 5, 6, 7, 9, 10, 11, 12), decision-makers in the U.S. deemed SMA worthy of trials. The first project was in Wisconsin and was reported in the trade press by Scherocman (14).

Gradations appear extensively throughout the papers reviewed. In the first project in the U.S., Scherocman (14) noted that the gradation followed the "30-20-10 rule", which is a useful guideline for specifiers and designers of SMA who are lacking model procedures. The rule indicates that the aggregate gradation should have 30% passing the 4.75 mm (#4) sieve, 20% passing the 2.36 mm (#8) sieve, and 10% passing the 75 µm (#200) sieve.

Other projects followed the one in Wisconsin and were also reported in the trade press before more detailed reports were published by research bodies or state highway departments (21, 22, 23, 25, 27, 28, and 29). To help potential users of SMA, Bukowski

(20) produced the FHWA's work plan, which contained a summary of the first five SMA projects that had been built in the U.S. in 1991.

Several reports in the U.S. in 1991 and 1992 dealt with the U.S. SMA projects. Little (16), Brown (40), and Stuart (35) all performed comparative mix designs for Georgia DOT, which also produced a report (31) and supplemental specifications (32). Missouri's experience was reported by McDaniel (34). Scherocman (46, 50) and Brown (40, 48) reported on others, in addition to several items in the trade press. Brown, et. al., (97) reported an evaluation of over 85 SMA projects. The practical problem of producing an SMA with cellulose fibers in a drum mixer without losing fibers in the exhaust gas dust collection system was addressed by Karnemaat, Vreibel, and Van Deusen (54) early in 1993 but this was based on experience with the earlier Michigan projects.

Carpenter (77), Brown and Mallick (84), and Brown and Haddock (99) have addressed mixture volumetrics and achievement of the stone-on-stone contact that SMA is supposed to provide in service. Brown and Mallick (84) and Brown, et. al., (98) suggest a design procedure that is intended to answer this problem.

Brown, et. al, (95) performed a study in 1997 stating that the amount of filler finer than 20µm did not matter. They based this conclusion on mortar characterizations using the Superpave binder equipment and procedures.

According to Bellin (41), type of filler is not named in specifications or requests for proposals in Germany. He indicates that ground limestone is used and that baghouse fines are not used much. Scherocman (46) noteD that baghouse fines are not normally returned into the SMA production line in Europe.

One of the questions facing mix designers is how to deal with the design of the mortar. Milster (53), in a telling photograph, illustrates the difference in stiffening effects between the mortar fractions of an SMA and a dense-graded mix. Bellin (41) reported that the Schellenberg draindown test is used in Germany to ensure that the mix does not lose its cementing mortar. Details of the test are reported by Stuart (35). In the United Kingdom, Walsh (70) references another test, while Brown and Mallick (84) proposed a test method, which has been accepted in the FHWA's Model Material and Construction Guidelines (81).

Brown, et. al., (98) looked at the effect of different stabilizing additives on draindown. They concluded that fibers (mineral or organic) did a better job of preventing draindown than did polymers.

Harders (67) used the Ring and Ball softening point test in evaluating the effect of stabilizers. Richter (19) also used this test among others that are less familiar. Serfass and Samanos (33), and Schröder and Kluge (51) have also used the softening point test. According to Schröder and Kluge, mortar compositions with softening points between 85 and 100°C provide the right viscosity and impact strength. Sometimes fibers and polymers are combined, as noted by Reinke (59) and Fujita (86); and a multigrade asphalt has also been used as reported in the trade press (56) and by Kriech and Haddock et al (57, 61).

A review of the literature indicates that there are no clearly defined approaches to SMA mix design, nor are there performance-related mix tests that designers and practitioners can embrace with confidence. Despite these apparent drawbacks, SMAs in the U.S. appear to be living up to their reputation as a rut-resisting mix.

2.2 MATERIAL PROPERTIES

2.2.1 Aggregate Properties

Several different types of aggregates were used during the study and included traprock, granite (two different sources), limestone (two different sources), Florida limestone (sometimes called limerock), blast furnace slag, and siliceous gravel. These aggregates were selected because they provided a range of qualities from excellent to marginal.

The coarse aggregate for an SMA mixture must be sufficiently strong to carry the imposed loads since these mixtures are designed to have stone-on-stone contact. Presently the aggregate test that is commonly used for determining the toughness of the aggregate particles is the L.A. Abrasion test. Based on the data accumulated during the study, coarse aggregates used within SMA should have L.A. Abrasion values of less than 30 percent loss. SMA mixtures using aggregates with higher L.A. Abrasion values have been used successfully but care must be used when using these softer aggregates. Higher Abrasion values resulted in excessive aggregate breakdown during laboratory compaction.

Since the coarse aggregate must carry the load, fractured faces are required to provide a coarse aggregate structure with high internal friction. If the fractured face count is significantly less than 100 percent for the coarse aggregate, the SMA mixture is almost certainly going to be less resistant to shoving and rutting. This requirement for fractured faces eliminates the use of uncrushed gravels and will also eliminate many crushed gravels if the fractured face count is not high enough to meet the desired requirements.

The amount of aggregate absorption can affect the performance of SMA mixtures just as it does dense graded mixtures. Low absorptive aggregates are preferred but some locations, due to availability of aggregates, may be required to use aggregates with higher absorption values. When high absorptive aggregates are used, the optimum asphalt content should be selected on the high side but within the specification limits to allow for some additional absorption of the asphalt cement during placement and during the life of the pavement.

The angularity of fine aggregates was measured during the project using the NAA flow test (AASHTO TP33, Method A). The test results ranged from 44.6 to 49.9 percent. Based on the testing conducted, it was recommended that a value of 45 seemed reasonable for the fine aggregate requirement.

2.2.2 Mineral Filler Properties

Eleven different mineral fillers were used during the course of this project. These fillers included: limestone dust, marble dust, traprock dust, southeastern flyash, Georgia flyash, aglime, diabase, wimpey, Dankalk, Oyta, and Faxekalk. These mineral fillers were selected because they cover the range of mineral fillers that have been used within SMA. Characterization testing conducted to evaluate the different fillers was particle size distributions, the modified Rigden's voids test, and surface area measurements.

Fine mortar (mineral filler, stabilizing additives, and asphalt cement) testing was used to evaluate the influence of the different mineral fillers on SMA mixtures. During the fine mortar testing, the influence of the amount of mineral filler passing the 0.02 mm sieve, the modified Rigden's voids, and the surface area of the fillers were all evaluated. Based on this testing, it was determined that the amount of material passing the 0.02 mm sieve did not influence the mortar properties, the modified Rigden's voids correlated well with mortar testing results, and the surface area did not influence mortar properties.

It was decided that a good screening test for fillers is to ensure the percent voids does not exceed 50 when measured with the Rigden's voids. Fillers that exceed 50 cause the mortar to be excessively stiff and difficult to work.

2.2.3 Asphalt Binder Properties

The effect of different asphalt binders was not a major part of this study. However, three different binder types were used: AC-20, AC-20M1 (SBS modified), and AC-20M2 (polyolefin modified). The three binder performance grades (PG) were 64-22 for the non-modified, 70-28 for the SBS modified, and 70-22 for the polyolefin modified.

Based on all of the information obtained during the study, the asphalt cement for SMA mixtures should be graded using the Superpave binder grading system (PG graded). The asphalt cement should be selected based on the climate in which it will be used. Guidance for adjusting the performance grade of asphalt binders for either traffic speed or traffic level is provided in AASHTO MP2," Standard Specification for SUPERPAVE Volumetric Mix Design," Section 5.5.

2.2.3.1 Effects of High Temperature Testing

Though the type asphalt binder was not a major part of the study, a subtask of Task 11 was to evaluate the effect of high temperatures on asphalt binders. This subtask was included because high temperatures are sometimes needed for SMA, especially on occasions when polymer additives are used.

Testing to determine the effects of high temperatures on asphalt binders included aging six different asphalt binders (three modified and three unmodified) using six different temperatures in a thin film oven. For each set of aged asphalts, the Superpave binder tests were conducted to determine the properties after aging.

Based on this testing, it was shown that for each of the Superpave binder tests (except the direct tension) that at a temperature between 180 and 195°C a significant change in the test results was exhibited. Therefore it was recommended that SMA mixtures not be heated to temperatures above 176°C (350°F).

2.2.4 Stabilizing Additives

Three major stabilizing additive types were used during the laboratory part of this project and included: cellulose fibers, mineral fibers (slag wool and rock wool), and polymers (SBS and polyolefin). Testing performed to evaluate the different stabilizing additives was the testing of the fine mortars using the Superpave binder equipment and test procedures. For the study, cellulose was added at 0.3 percent of total mixture mass and mineral fibers were added at 0.4 percent. Several different types and percentages of polymer were used. This testing indicated that at higher temperatures the mineral fibers stiffen the asphalt binders the least followed by cellulose fiber, SBS, and the polyolefin. At intermediate temperatures both the cellulose and mineral fibers stiffen about the same or slightly more than no stabilizer. The polyolefin is less stiff than the fibers but slightly more stiff than the SBS stabilizer. Testing at low temperatures showed that the mineral fibers stiffened the asphalt binders the most. The cellulose and polyolefin stabilized mortars have about the same stiffness and the SBS stabilized mortars were the least stiff.

2.3 AGGREGATE SKELETON TESTING

Since one objective in the design of SMA is to produce a mixture with stone-on-stone contact, it was essential that a method be available to define this condition within the coarse aggregate fraction. Therefore, work was performed to evaluate the ability of five different methods to determine when stone-on-stone contact exists in the coarse aggregate fraction. The five methods used to determine the voids in coarse aggregate (VCA) included: the Marshall hammer, dry-rodded test, Superpave gyratory compactor (SGC), vibrating table, and Kango (vibrating) hammer. A summary of VCA testing results are presented in Table 2.1.

Table 2.1: Void in the Coarse Aggregate Test Results for the Coarse Aggregate Fraction Only						
Method		Granite	FL Limestone	Gravel	Limestone	Traprock
Marshall Hammer	Avg	32.1	26.9	33.4	29.9	35.6
	SD	0.55	0.50	0.82	0.45	0.85
SGC	Avg	34.7	30.3	37.2	36.6	39.2
	SD	1.30	0.84	0.40	0.25	0.42
Dry-Rodded	Avg	39.2	38.9	37.4	42.5	40.8
	SD	0.12	0.9	0.17	0.30	0.10
Vibrating Table	Avg	40.0	39.8	37.8	41.6	40.8
	SD	0.21	0.80	0.15	0.06	0.21
Kango Hammer	Avg	47.5	44.1	45.4	47.5	48.6
	SD	0.61	0.35	0.4	0.26	0.60
Avg - Average SD - Standard Deviation						

Based on the results of aggregate skeleton testing, it was decided that the dry-rodded condition was the easiest of the methods to use and provided reasonable results. It appeared to be the most appropriate method for determining the VCA at which stone-on-stone contact occurs.

2.4 MORTAR TESTING

Mortar testing was conducted in both main phases of the research project. During Phase I specification criteria was recommended for SMA mortars. Mortar testing during Phase II dealt with evaluating the specification criteria.

To attempt to fully understand the mortar characteristics, SMA mortars were first tested in two fractions during Phase I: the total and fine mortars. The total mortar fraction contained that portion of aggregate passing the 2.36-mm sieve, stabilizing additive(s), and asphalt cement. Because of the relatively coarser aggregates in the total mortar, it was considered to be similar to a mixture. Therefore, it was tested at low, intermediate, and high temperatures using the bending beam rheometer, resilient modulus, indirect tensile test, and Brookfield viscometer. The fine mortar fraction contained that portion of aggregate passing the 0.075-mm sieve (typically referred to as filler), stabilizing additive(s), and asphalt cement. Being of a finer nature, the fine mortar was considered a binder and was tested at low, intermediate, and high temperatures using the Superpave binder equipment before and after aging.

Based on the testing conducted on the two types of mortars, it was determined that the fine mortar properties were closely related to the total mortar properties (Figures 2.1 through 2.3). Based on this preliminary testing, it appeared that the fine mortar could be evaluated without the need for additional testing on the total mortar since these properties were related. During mix designs it would be much easier to prepare and test fine mortars than total mortars so therefore it was decided to continue testing on the fine mortars.

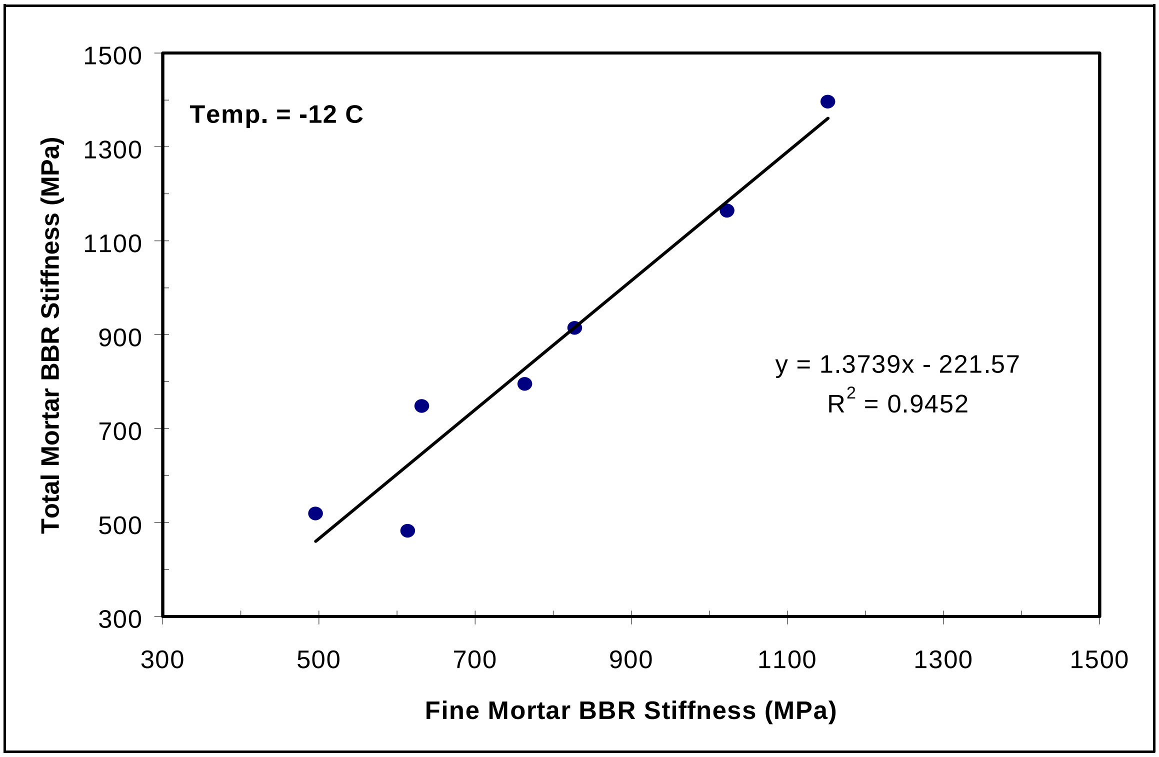

Figure 2.1: Relationship Between Total Mortar Stiffness and Fine Mortar Stiffness at -12C

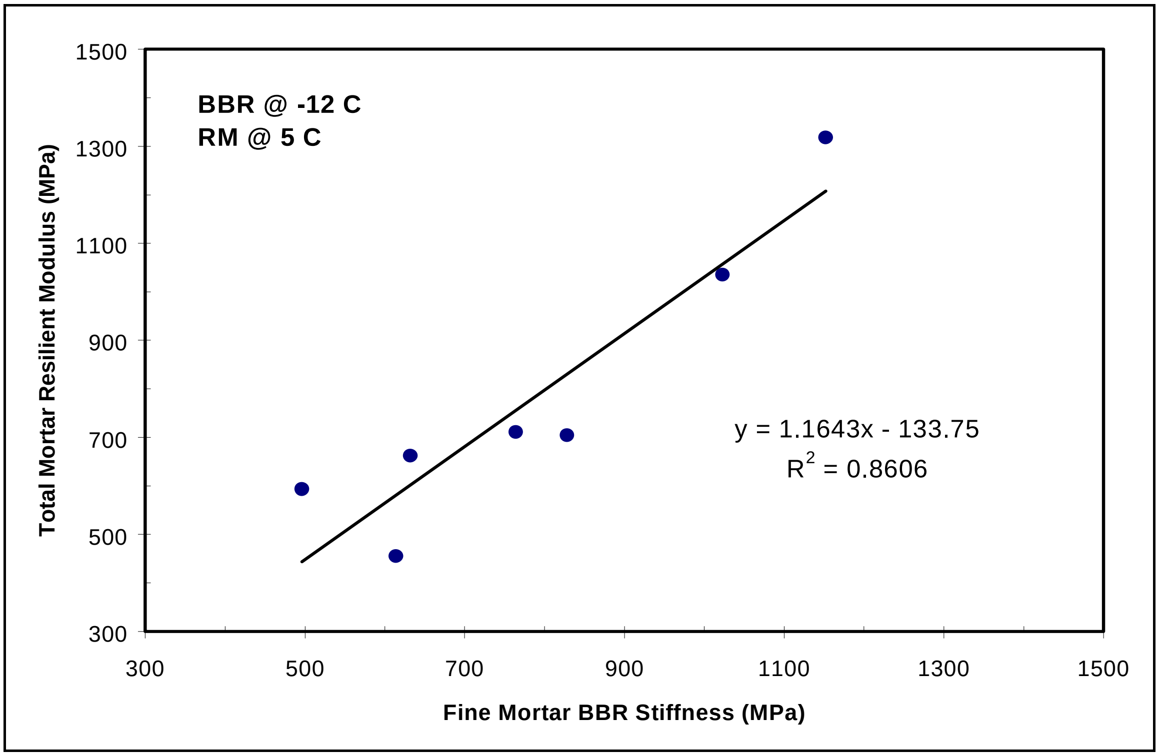

Figure 2.2: Relationship Between Total Mortar Resilient Modulus at 5 C and Fine Mortar Stiffness at -12 C

In order to characterize the influences of the different constituents of a SMA fine mortar, the test plan called for varying the type of filler, percent of filler, and type of stabilizing additives. The testing of these different mortars was conducted at high, intermediate, and low temperatures. The results of the testing is summarized in Table 2.2. This table shows whether significant trends were found in the test results for the high, intermediate, and low temperature testing.

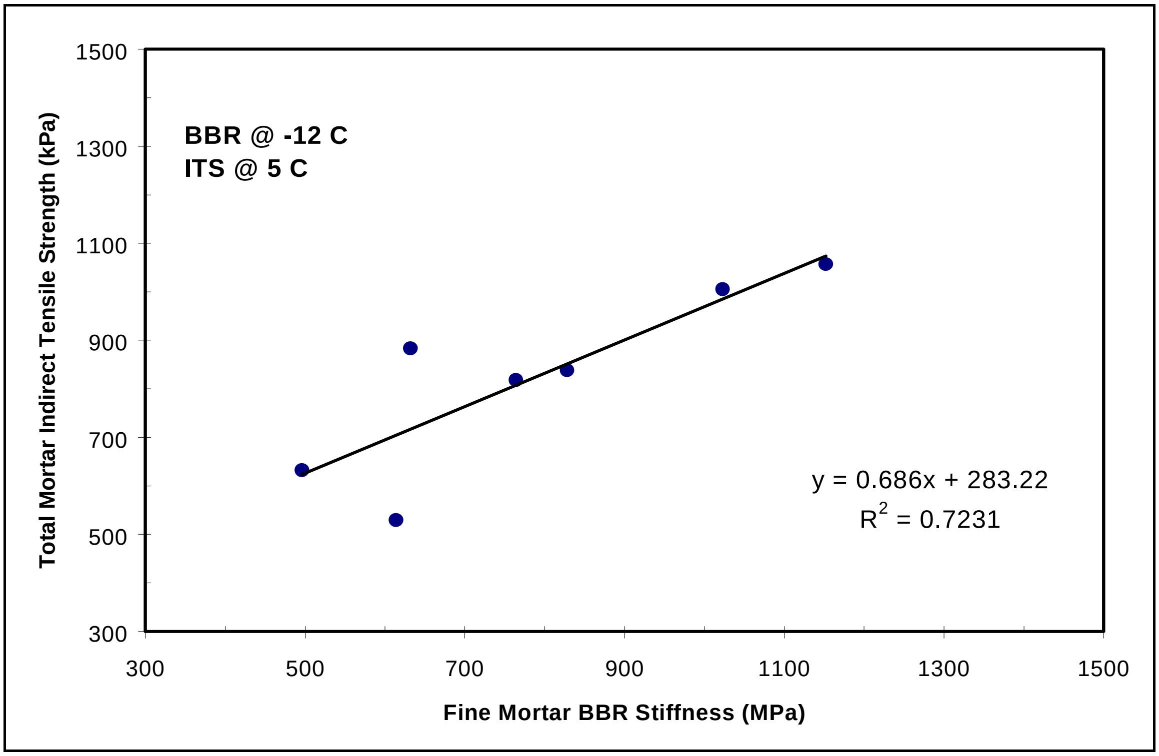

Figure 2.3: Relationship Between Total Mortar Tensile Strength at 5 C and Fine Mortar Stiffness at -12 C

Table 2.2: Summary of Fine Mortar Testing To Characterize SMA Mortars

Property	Significant Trend?		
	High Temperature Testing	Intermediate Temperature Testing	Low Temperature Testing
Filler Type	No	Yes	No
Filler Percent	Yes	Yes	Yes
Stabilizer Type	Yes	Yes	Yes
Filler Particle Sizes	Yes	No	No
Filler Particle Shape	No	No	No
Filler Surface Area	Yes	Yes	No

Based on these test results, it was concluded that the dynamic shear rheometer (DSR), bending beam rheometer (BBR), direct tensile test (DTT), and Brookfield viscometer (BV) could be used to characterize fine mortars. After comparing the data, it appeared that the mortars were typically at least 5 times stiffer than the asphalt binders. Therefore, a good starting point for writing a fine mortar specification was to specify the following:

Test	Test Method	Property	Specification
Original Mortars			
Dynamic Shear	TP 5	G*/Sinδ	5.0 kPa min.
RTFO Aged Mortars			
Dynamic Shear	TP 5	G*/Sinδ	11.0 kPa min.
RTFO and PAV Aged Mortars			
Bending Beam	TP 1	S	1500 MPa max.

Testing during Phase II was conducted on fine mortars from the eleven field projects visited during Task 8 to determine the applicability of these fine mortar specifications. For each of the eleven projects visited, fine mortars were fabricated at the NCAT laboratory to meet the job-mix-formula (JMF) percentages and tested using the Superpave binder equipment and testing protocols. Results of this testing indicated that the fine mortar specifications seem to be applicable. Figures 2.4 through 2.6 present the results of this testing in relation to the specifications.

These requirements provide a minimum stiffness of the fine mortar at high temperatures (original and RTFO DSR testing) to promote a stiff mortar to help in preventing permanent deformation. The requirements also address the cold temperature properties of the fine mortars (BBR testing) by limiting the creep stiffness (S) of the fine mortar.

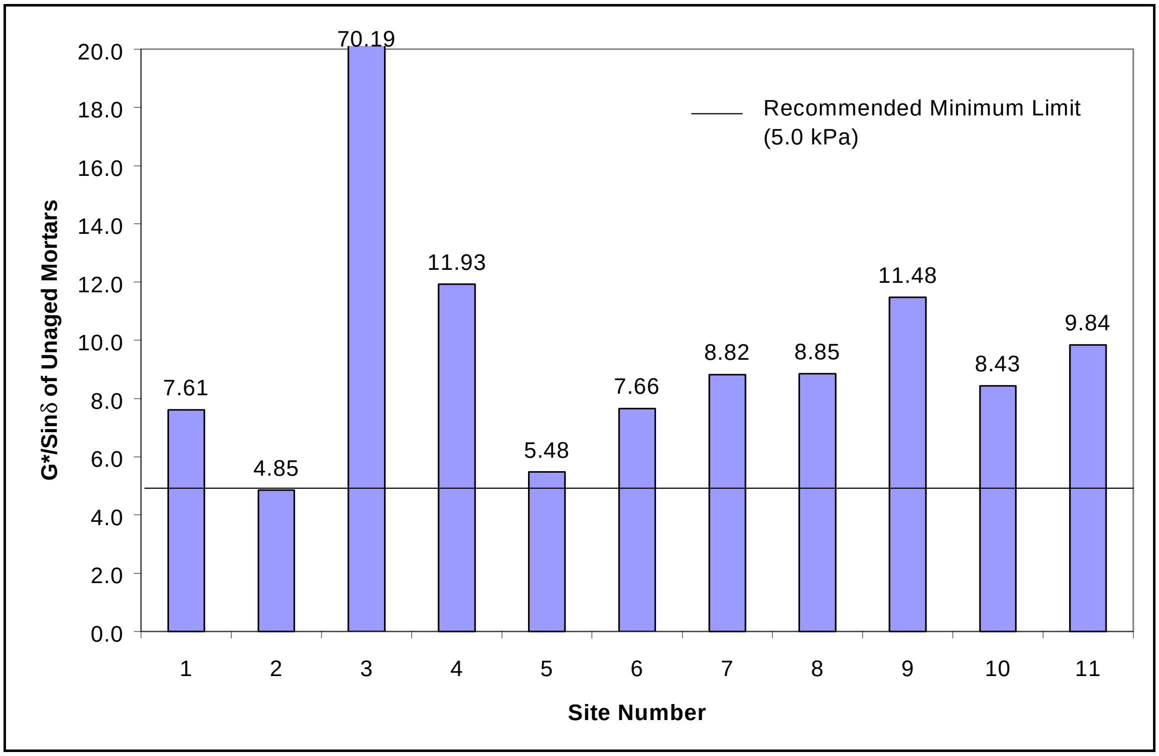

Figure 2.4: Results of Project High Temperature Fine Mortar Testing With DSR on Original Fine Mortars

2.5 MIXTURE DESIGN ANALYSIS

Early in Phase I, several aggregates were evaluated to determine the effect of aggregate type and gradation on SMA mixture properties. During this part of the study, mixture designs were performed with 50-blows of a flat-faced, static base Marshall hammer. The mix designs were conducted using several trial blends that varied the amount of material passing the 4.75 mm sieve until the VMA was 17 percent or higher and until stone-on-stone contact was achieved. The gradation for each mixture was then fixed and asphalt binder added to determine the optimum asphalt content.

The results of these mix designs were used to show that the concept of varying the percent passing the 4.75 mm sieve to obtain the minimum VMA requirement and the maximum VCA is viable. Figures 2.7 and 2.8 present a summary for the different mixtures when the percent passing the 4.75 mm sieve was varied. Figure 2.7 shows that as the percent passing the 4.75 mm sieve is decreased, VMA increases. Figure 2.8 illustrates that increases in the percent passing the 4.75 mm sieve likewise increased the VCA of the SMA mixtures.

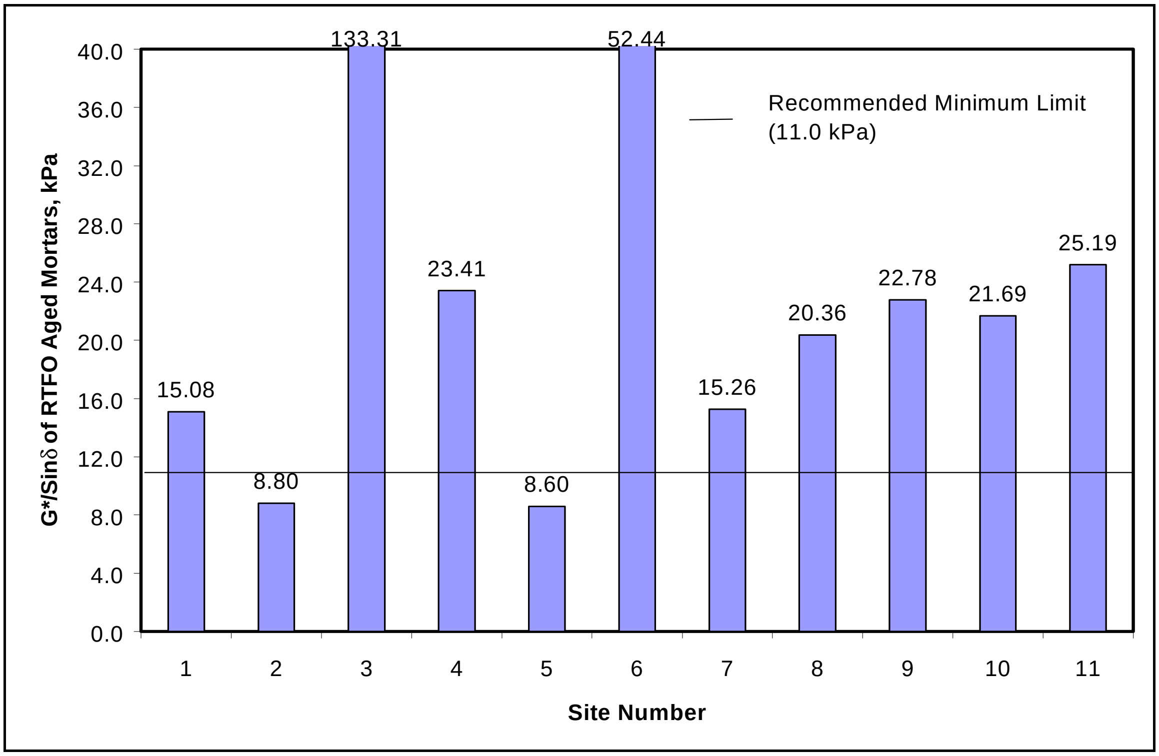

Figure 2.5: Results of Project High Temperature Fine Mortar Testing With the DSR on RTFO Aged Mortars

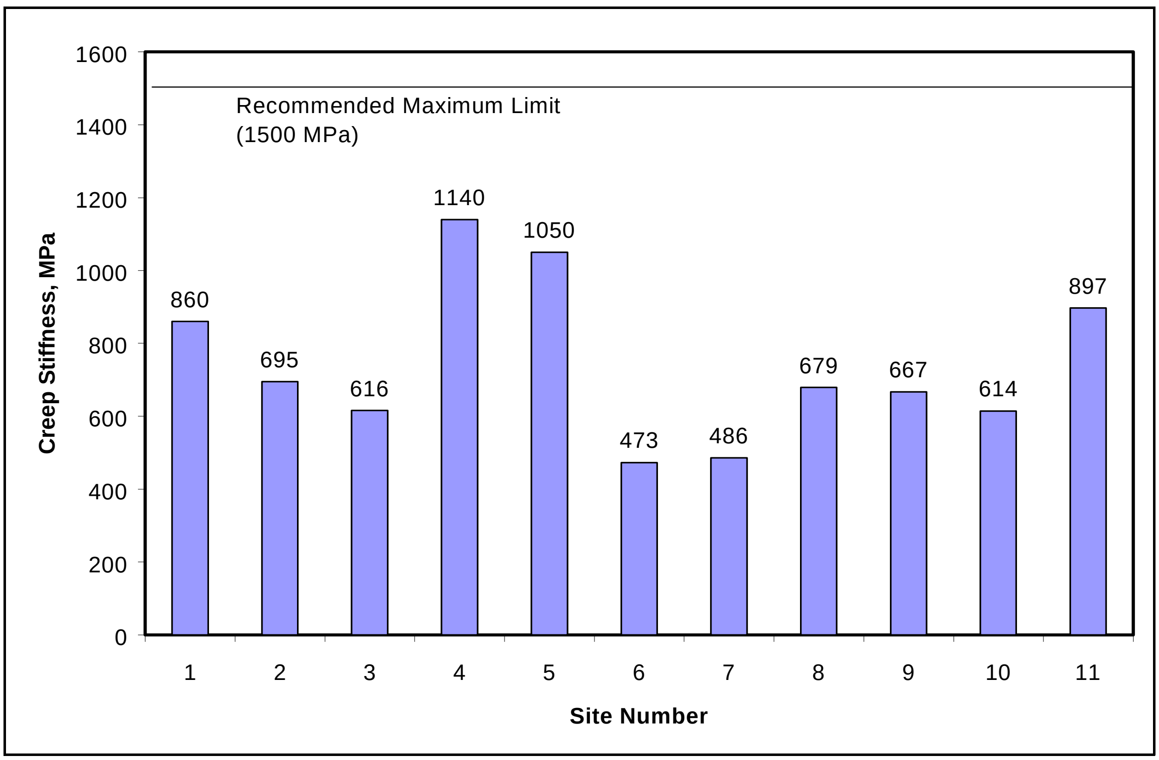

Figure 2.6: Results of Low Temperature Testing With the BBR on PAV Aged Mortars (Creep Stiffness

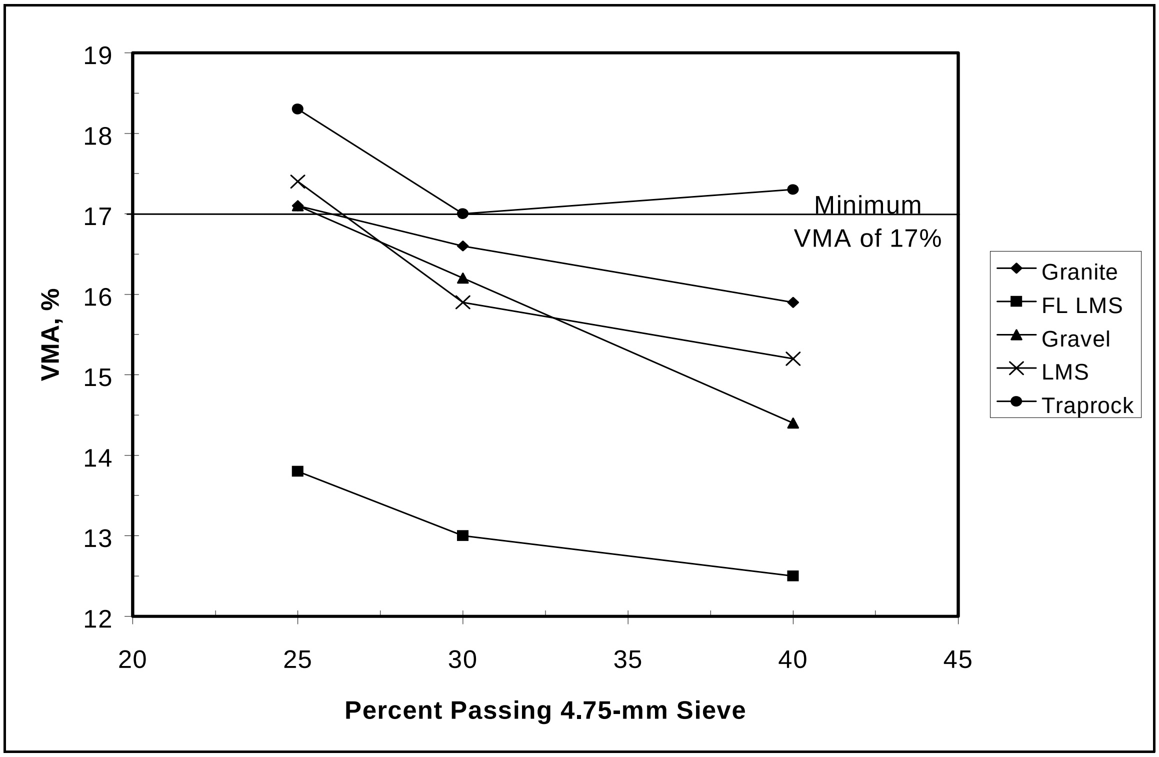

Figure 2.7: Summary of VMA versus Percent Passing 4.75 mm Sieve

The moisture susceptibility of each of the optimum mixtures as well as companion dense-graded mixtures were tested using AASHTO T283. This test procedure was modified slightly for the SMA mixtures in that they were compacted to an air void content of 6±1 percent. This air void content is more indicative of desired SMA pavement density at the time of construction. Also, no freeze-thaw cycle was used. Results of the moisture susceptibility testing indicated that for the testing conditions used, AASHTO T283 is applicable for SMA mixtures generally providing similar results as dense-graded mixtures.

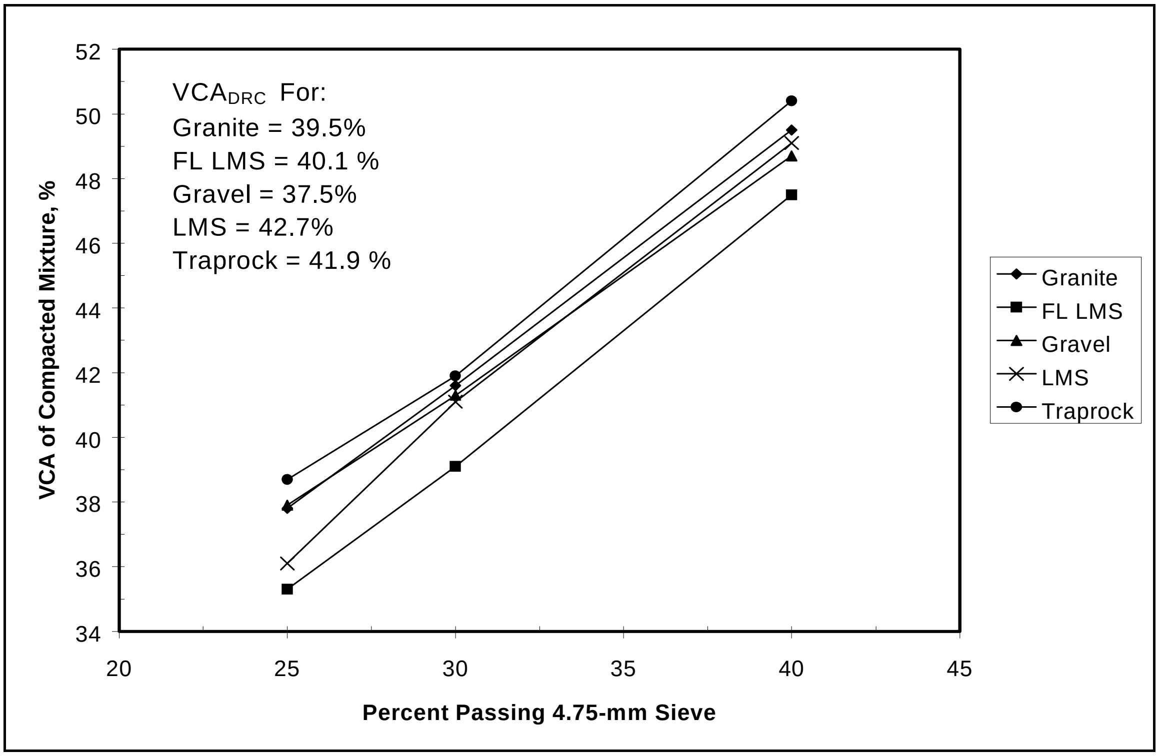

Figure 2.8: Summary of SMA Mixture VCA versus Percent Passing 4.75 mm Sieve

Work during Phase I using a number of aggregates and mortars was conducted in the laboratory to validate the tentative mix design procedure developed during the first part of Phase I. Based on this work, some problems were encountered. There was a significant amount of aggregate breakdown that occurred for some of the aggregates. As a result of this breakdown, VMA requirements were not always met. However, for the aggregates that did not experience excessive breakdown VMA requirements were easily met. Even with sufficient VMA values, the optimum recommended asphalt content by weight was sometimes less than the recommended minimum of 6 percent. This was seen for aggregates that had high specific gravities. It was suggested that the best approach was to specify a minimum VMA (17 percent) and not to be concerned about the asphalt content by weight.

Also during Phase I of the study, the volumetrics for SMA were compared between 50-blows of the Marshall hammer and 100 gyrations of the SGC (Figure 2.9). Based on the data, a good correlation existed between the two compactive efforts. It appeared that in the range of lower optimum asphalt contents, the Marshall hammer tended to give a higher optimum asphalt content for a given aggregate type and gradation. Conversely, in the range of higher optimum asphalt contents, the SGC produced higher optimum asphalt contents for a given aggregate type and gradation. (Results of later work during Phase II indicated that approximately 80 gyrations produced a similar density to 50-blows of the Marshall Hammer. See Section 2.12.2 of this volume.)

2.6 FLAT AND ELONGATED PARTICLES

The effect of flat and elongated particles within SMA was evaluated during both phases of the project. Work in both phases were similar with one major difference; Phase I looked at the influence of flat and elongated particles using 50-blows of the Marshall hammer while Phase II used the SGC.

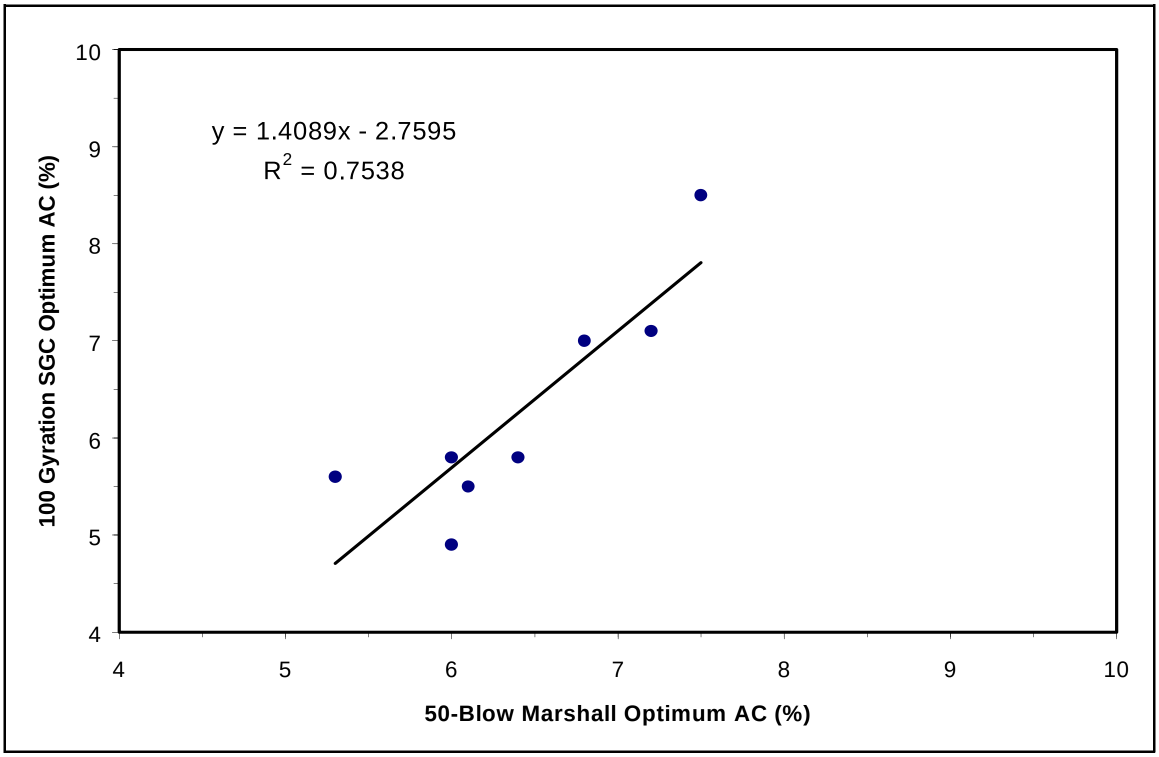

Figure 2.9: Correlation Marshall Hammer and SGC Optimum Asphalt Contents

For both phases of the study, a supply of aggregate that was quarried from the same ledge with one portion of the aggregate being crushed to produce a high percentage of flat and elongated particles and another portion crushed to produce a lower percentage. SMA mix designs using the proposed mix design procedure were accomplished with the Marshall hammer on gradations of varying percentages of the two aggregate types. Using the optimum asphalt content determined during the mix designs, specimens were compacted with both 50-blows of the Marshall hammer and 100 gyrations of the SGC to evaluate the effect of flat and elongated particles on volumetric properties. This evaluation showed that the VMA did increase as the amount of flat and elongated particles were increased (Figure 2.10).

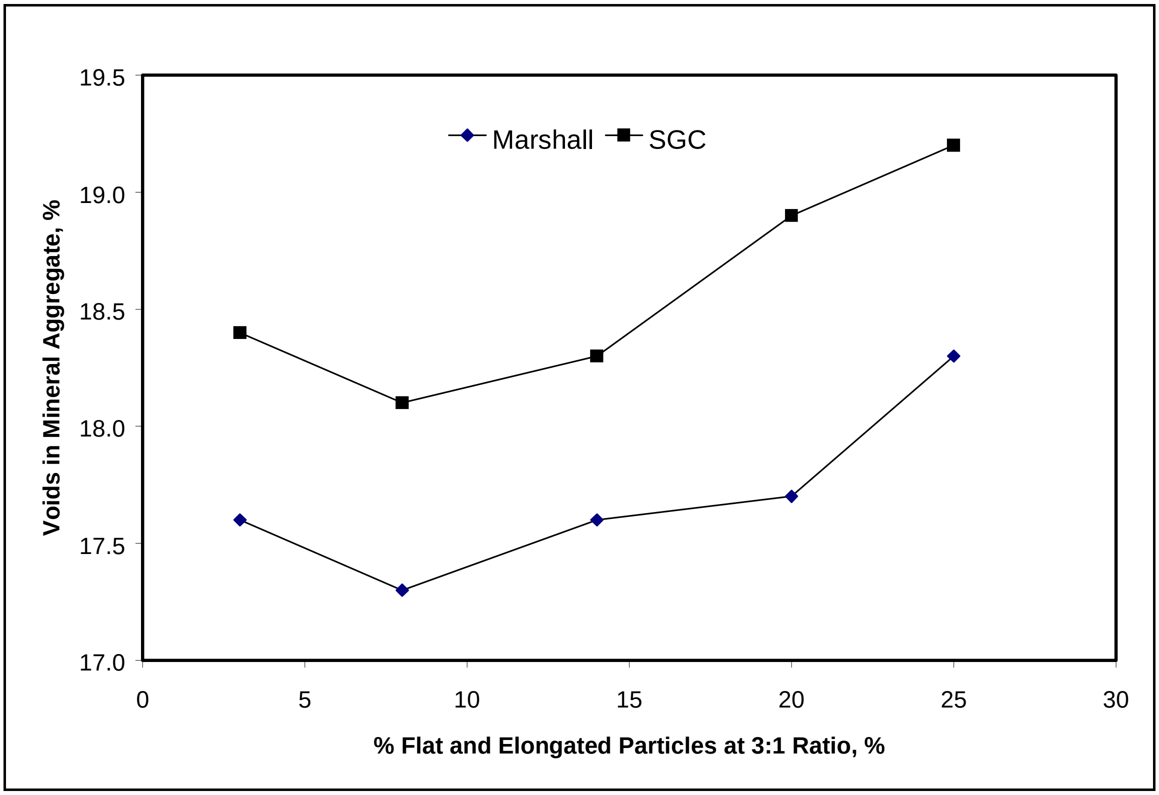

Figure 2.10: Effect of Flat and Elongated Particles on VMA

Next specimens were compacted with both compactors using a single gradation to evaluate the effect of flat and elongated particles on aggregate breakdown. For both compactors, as the percentage of flat and elongated particles increased the amount of aggregate breakdown also increased (Figure 2.11).

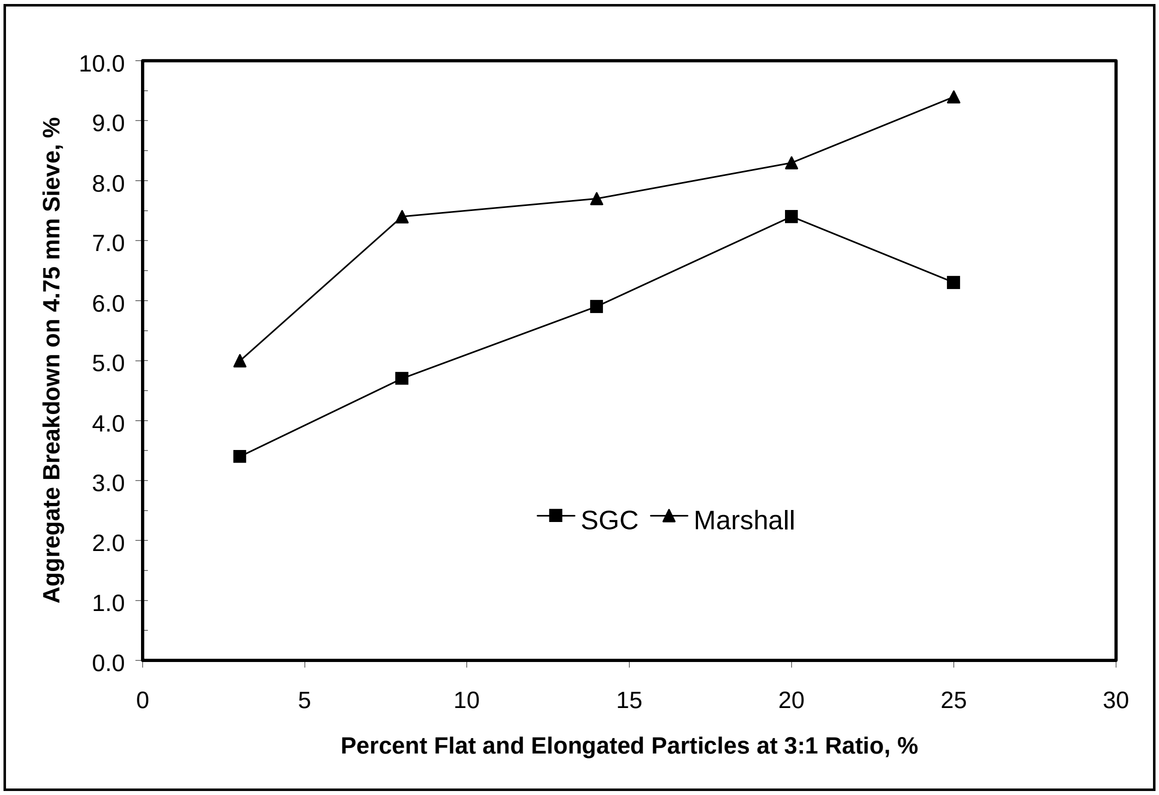

Figure 2.11: Effect of Flat and Elongated Particles on Aggregate Breakdown

It was thought that increasing percentages of flat and elongated particles would increase the moisture susceptibility of SMA mixes. Specimens were compacted with both compactors to evaluate the effect of flat and elongated particles on moisture susceptibility. Results of this analysis showed that flat and elongated particles had no effect on moisture susceptibility for either compactor.

Based on the flat and elongated particles work in both phases it was concluded that some amount of flat and elongated could be used without any detrimental effect on mixture properties. However, after some point was reached the effect becomes more severe. It appears that the current criteria of no more than 20 percent 3 to 1 and no more than 5 percent 5 to 1 flat and elongated particle is satisfactory. Values in excess of these criterion were shown to lead to excessive aggregate breakdown in compacted samples.

2.7 AGGREGATE BREAKDOWN ANALYSIS

Aggregate breakdown occurs when SMA mixtures are compacted in the laboratory and field. The amount of breakdown is a function of hardness and the method of compaction. It is important that the amount of breakdown occurring in the laboratory be approximately equal to that which occurs in the field. If there is a significant difference in the breakdown in the laboratory and in the field, the mix design method is suspect because the volumetrics in the laboratory compacted samples may have no relationship to the volumetrics in the field.

Aggregate breakdown was evaluated during both phases of the study. During Phase I, laboratory breakdown was evaluated using eight different aggregates. This laboratory evaluation showed that for most of the aggregates used, there was very little difference in the breakdown with 50-blows of the Marshall hammer and 100 gyrations of the SGC. For some of the aggregates, however, the difference was significant. The Marshall hammer always gave as much or more breakdown than the SGC.

During this Phase I investigation, a good correlation existed between the amount of aggregate breakdown on the 4.75 mm sieve and the LA Abrasion values for both the Marshall hammer and the SGC (Figures 2.12 and 2.13, respectively). For both compaction methods, higher abrasion values correlated to higher breakdown values. The data indicated that the expected breakdown on the 4.75 mm sieve at a LA Abrasion value of 30 is approximately 10 percent.

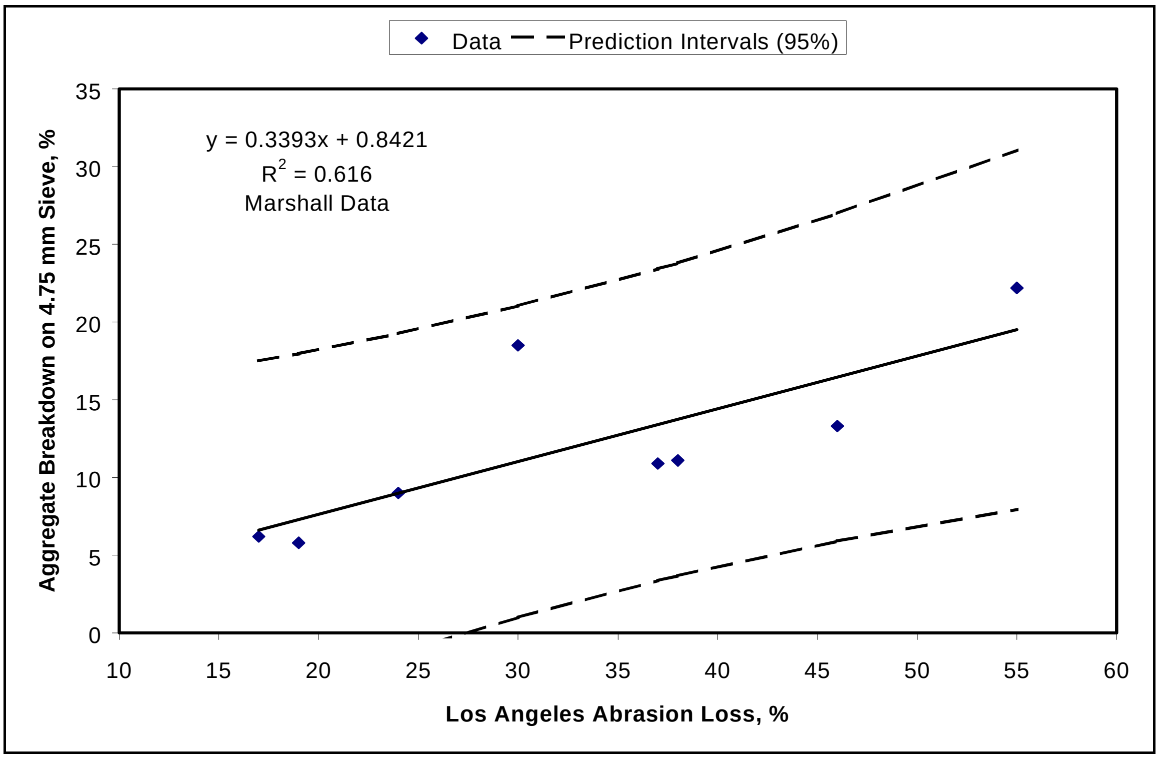

Figure 2.12: Aggregate Breakdown Caused By Marshall Hammer As A Function of Los Angeles Abrasion Loss

During Phase II of the project, field produced SMA mixtures from eleven projects were compacted with both 50-blows of the Marshall hammer and 100 gyrations of the

SGC. In addition to these laboratory compacted specimens, field compacted (rollers) samples were obtained for eight of the eleven projects visited. Analysis of the data showed that there was significant differences in mixture gradation before and after compaction. Analysis of this data also showed that the Marshall hammer consistently resulted in more breakdown than the SGC. However, the data also showed that the breakdown underneath rollers was approximately equal to that observed with both laboratory compactors (Table 2.3).

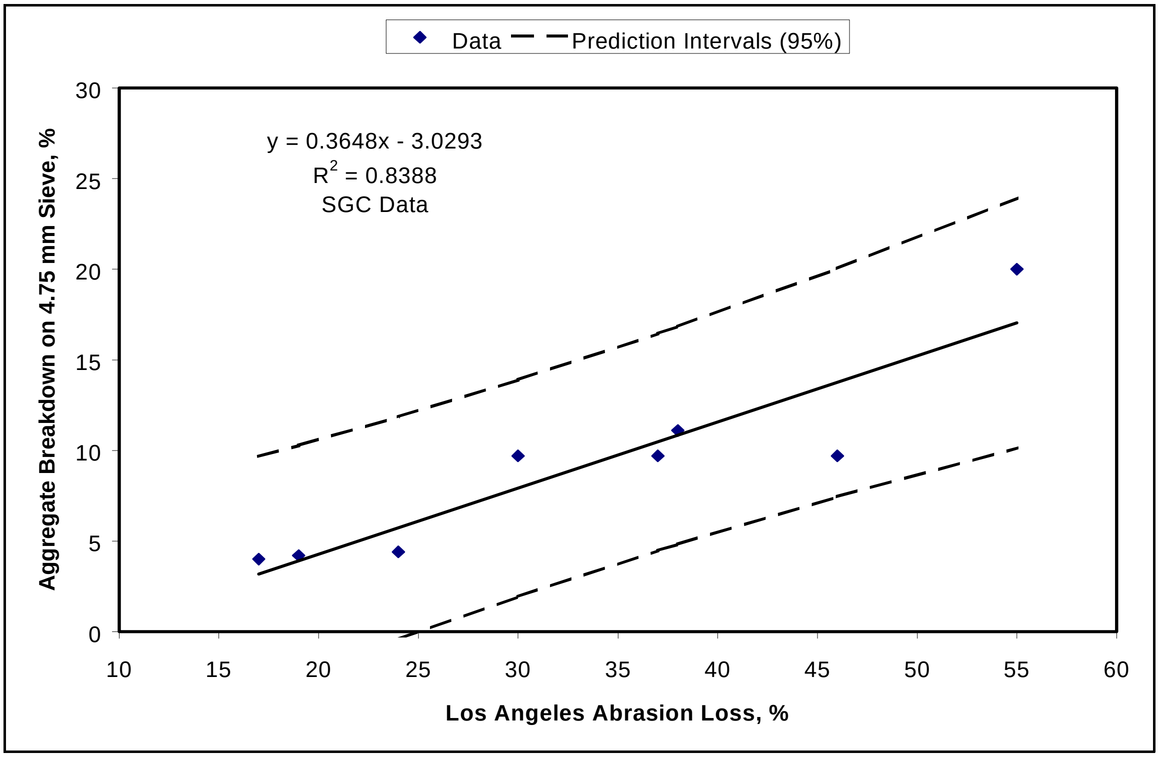

Figure 2.13: Aggregate Breakdown Caused By SGC As A Function of Los Angeles Abrasion Loss

2.8 MIXING AND COMPACTION TEMPERATURES

The mixture design procedure developed during Phase I specified that mixing and compaction temperatures be determined in accordance with AASHTO T245. This method is a temperature-viscosity relationship in which the mixing and compaction temperatures are selected based on viscosity ranges. Because of the high filler contents and the frequent use of polymer modified asphalt cements, it was thought that this method of determining mixing and compaction may not be the best.

Table 2.3: Results of ANOVA Performed To Compare Aggregate Breakdown						
Site No.	Mean Percent Passing 4.75 mm Sieve			F-stat	Probability > F	Significant Difference?
	SGC	Marshall	Field Cores			
2	32.5	35.4	36.0	4.57	0.030	Yes
3	35.5	36.3	40.6	20.98	0.000	Yes
4	33.9	36.2	33.0	2.87	0.084	No
5	37.3	37.9	36.5	1.35	0.286	No
6	31.6	33.5	33.9	3.96	0.051	No
9	34.2	38.4	33.5	16.19	0.000	Yes
10	31.5	34.0	33.4	1.19	0.328	No
11	32.7	35.1	33.4	7.97	0.004	Yes

Therefore, two different methods were evaluated to determine if they provided more reasonable results. The first method entailed combining the material finer than 0.075 mm from the design gradation and the asphalt binders (no fibers were included) for each of the eleven projects visited under Task 8. These mortars were then tested in the Brookfield viscometer. The second method was a workability device that was developed to measure the stiffness of SMA mixtures. Using this device at different temperatures allowed the stiffness of the mixture in relation to the temperature to be determined.

The data indicated that both tests do a good job of measuring the stiffness of the mortar (Brookfield viscometer) and the mix (workability). However, neither test appeared to provide a method of determining the mixing and compaction temperature. Therefore it was concluded that the best approach for determining the mixing and compaction temperatures was AASHTO T245.

2.9 PERMEABILITY EVALUATION

Evaluation of the permeability characteristics of SMA was undertaken in an effort to establish whether SMA mixtures are more or less permeable to water than are conventional dense-graded mixtures. Using four aggregates, specimens were prepared at optimum asphalt content by varying the compactive efforts (both Marshall and SGC). These specimens were then tested in a laboratory falling head permeameter to determine how the permeability varies within a SMA as a function of air voids.

This data generally suggested that the permeability began to increase rapidly as the air voids increased from 6 to 7 percent. Therefore, ideally SMA mixtures should be compacted to around 94 percent of theoretical maximum density. Field permeability work during Phase II was in agreement that 6 percent air voids are needed.

2.10 EVALUATION OF NOMINAL MAXIMUM AGGREGATE SIZE

Most SMA mixtures that have been placed in the US have been 12.5 or 19.0 mm nominal maximum size gradations. There is often a need to use a smaller or larger nominal maximum aggregate size. This part of the study evaluated the effect of nominal maximum aggregate size.

SMA mixtures typically have a large percentage of aggregate down to a certain sieve size after which the percentage of aggregate is small. The sieve size that separates the sieve containing large percentages from the sieves with small percentages is considered the break point sieve.

This part of the study looked at 11 SMA mixes ranging in nominal maximum size from 4.75 mm up to 25 mm. A number of breakpoint sieves were also evaluated. For comparison purposes, four Superpave mixes were designed and tested (two above the restricted zone and two below the restricted zone).

All of the 11 proposed SMA mixes were successfully designed using the proposed mix design method. Both of the 4.75 mm nominal maximum aggregate size mixtures evaluated had to be designed based on the limiting VCA ratio of 1.0 minimum. The remaining mixtures which included two 9.5 mm, two 12.5 mm, two 19.0 mm, and three 25.0 mm nominal maximum aggregate size were all designed successfully using the proposed mix design method. Stone-on-stone contact along with the desired air void level was achieved for all mixture designs.

Wheel tracking tests were conducted on the SMA mixes and the Superpave mixes. All mixes met the typical requirements. Generally speaking, the finer mixes had higher VMA, higher asphalt contents, and higher rutting.

As stated earlier, another concern that has been expressed about some SMAs is permeability. Coarse graded mixes are more prone to being permeable than fine graded mixes. The mixes with 4.75 mm nominal maximum aggregate size had insignificant permeability until the air voids reached 8 to 10 percent. However, all the other SMA mixes had significant permeability even with less than 7 percent air voids. The mix permeability increased as the nominal maximum aggregate size of the mix increased. However, the coarse graded Superpave mixes at the same nominal maximum size were less permeable than the SMA mixes for the same void level. The fine graded Superpave mixes were even much less permeable.

2.11 MIXTURE PERFORMANCE EVALUATION TESTING

Dynamic creep tests, resilient modulus, indirect tensile strength, and Marshall stability were all conducted on SMA mixtures. Of these four tests, the dynamic creep test showed the most promise to predict the rutting performance of SMA.

A comparison of the results of the SMA mixtures and the dense-graded mixtures showed that the magnitude of the dynamic modulus at low voids is greater for the dense-graded mixtures than for the SMA mixtures. This was contrary to what was expected. Previous work performed at NCAT had shown that dense-graded mixtures were more sensitive to change in air voids than SMA mixtures (69). One intent of the dynamic creep testing was to show this sensitivity. The testing showed that SMA and dense-graded mixtures had about the same sensitivity to changes in voids but the dense-graded mixtures always had less permanent deformation. It should be noted though that the dense-graded mixtures were designed below the maximum density line and therefore were coarse and similar to SMA mixtures. The percent passing the 4.75-mm sieve for these dense-graded mixtures was 41.0 percent which is only about 10 percent finer than that for the SMA mixes. Even though the results of dynamic creep testing showed that the SMA did not perform (within the test) as well as dense-graded mixtures, the dynamic creep test was able to rank the SMA mixtures and thus showed the most promise. However, later work during Phase II indicated that the loaded wheel tester also had potential for evaluating SMA mixtures.

2.12 FIELD EVALUATION OF MIXTURE DESIGN PROCEDURE

It was important to verify that the proposed mix design procedure developed under Phase I work could be verified on a number of projects. For most of the eleven projects visited, the SMA mixtures were not designed using the recommended design procedure, specifically the existence of stone-on-stone contact was not evaluated. However, they were typically designed using an approach similar to the recommended procedure so the job mix formula was not that different from what would have been obtained using the proposed procedure. Most of the designs were performed using 50-blows of the Marshall hammer. Another goal of the field evaluation was to verify that the procedure developed for the SGC was applicable. Based on the following discussion, it was concluded that the proposed mix design method for SMA would produce acceptable SMA mixtures.

2.12.1 Comparison of Field Data To Mixture Design Procedure

The locations of the eleven projects were selected to include all regions of the country. This was done to include a wide variation in materials and mixture design procedures. The mixtures encountered should be representative of mixtures currently utilized for SMA. Some projects used fibers (both mineral and cellulose), some used polymers, and some used both. Some projects used pelletized fibers while others used loose fibers. A wide range of mineral filler types was used and included limestone dust, marble dust, dolomite dust, fly ash, and agricultural lime. Eight of the projects used anti-stripping agents with some using lime and others using liquid anti-strip agents. Different asphalt binders encountered at these projects included PG 76-22, PG 76-28, PG 70-22, PG 64-28, PG 64-22, PG 58-28, AC-20, and 20-40 multi-grade binders. Aggregate types encountered included crushed gravels, granite, limestone, traprock, and rhyolite.

Tables 2.4 through 2.8 present comparisons of the different mixtures encountered to the requirements in the proposed mixture design procedure. Table 2.4 shows how the different gradations compared to the gradation band recommended in the proposed mix design procedure. The sieve that had the most projects not meeting the criteria was the 4.75 mm sieve. Four projects did not meet the criteria. All of the mixtures that did not meet the criteria were above the recommended upper limit of 28 percent passing and ranged from 29 to 33 percent passing. Tables 2.5 and 2.6 show that most of the coarse and fine aggregate requirements were met. Based on these tables, it appears that the aggregate quality test that most often failed to meet the requirements was the flat and elongated requirement for the coarse aggregate (Table 2.5). All of the other aggregate quality requirements were met most of the time. Table 2.7 presents the comparison of mixture properties to the recommended criteria.

Two of the projects had asphalt contents below 6 percent but the combined bulk specific gravities of the aggregates were greater than 2.75; therefore, the minimum asphalt content could be lowered slightly. Five of the mixtures were constructed with laboratory air voids below 3.5 percent while three were constructed with laboratory voids above the 4.0 percent air void level. All of the mixtures met the recommended minimum VMA of 17 percent. Six of the mixtures did not meet the VCA requirements; however, by reducing the percentage passing 4.75 mm sieve the VCA requirements could have been met.

Table 2.8 presents the comparisons for the fine mortars test results for each of the projects. Based on this table, only one project did not meet the high temperature requirements for unaged mortars and two did not meet for RTFO aged mortars. All of the projects met the low temperature stiffness requirements.

The field work accomplished during the design procedure evaluation did indicate that the recommended mix design does develop mixes that can be produced and placed in the field. The draindown test developed as part of the mix design procedure can be used as part of quality control testing during construction.

Based on the field projects, the draindown test was easy to conduct and seemed to be a good indicator of mix changes. When the filler content was low or the asphalt content was high, the amount of draindown observed in the laboratory tended to increase. This occurred for most of the projects.

Table 2.4: Comparison of Gradations From Field Projects To SMA Gradation Specification Band

Sieve Size, mm	% Passing*	Meet Specification (Yes/No)?											
		Site 1		Site 2	Site 3	Site 4	Site 5	Site 6	Site 7	Site 8	Site 9	Site 10	Site 11
		JMF-01-1	JMF-01-2										
19.0	100	Yes	Yes	Yes	Yes	Yes	Yes	**	Yes	Yes	Yes	Yes	Yes
12.7	85-95	No	Yes	No	Yes	Yes	No	**	Yes	Yes	No	Yes	Yes
9.5	75 max.	Yes	Yes	No	Yes	Yes	No	Yes	Yes	Yes	No	Yes	Yes
4.75	20-28	Yes	No	No	Yes	No	No	Yes	Yes	Yes	Yes	Yes	Yes
2.36	16-24	Yes	Yes	Yes	Yes	Yes	Yes	**	Yes	Yes	Yes	Yes	Yes
0.60	12-16	Yes	Yes	Yes	Yes	Yes	Yes	**	Yes	Yes	Yes	Yes	Yes
0.30	12-15	Yes	Yes	No	Yes	Yes	Yes	**	Yes	Yes	Yes	**	No
0.075	8-10	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	No

* SMA Specification Band From Phase I Mixture Design Procedure.

** These sieves were not used on the JMF and therefore it is unclear whether the criteria would meet.

Table 2.5: Comparison of Coarse Aggregate Quality From Field Projects To SMA Mixture Design Criteria

Test	Method	Criteria	Meet Specification (Yes/No)?											
			Site 1		Site 2	Site 3	Site 4	Site 5	Site 6	Site 7	Site 8	Site 9	Site 10	Site 11
			JMF-01-1	JMF-01-2										
LA Abrasion	AASHTO T 96	30 max.	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	No
Flat or Elongated 3:1 5:1	ASTM D 4791 Section 8.4	 20 max. 5 max.	 Yes **	 ** **	 No Yes	 Yes **	 Yes **	 ** Yes	 Yes	 No No	 No No	 ** **	 No Yes	 ** **
Absorption	AASHTO T 85	2 max.	Yes	Yes	**	**	Yes	**	**	Yes	Yes	Yes	Yes	No
Soundness (5 cycles) Sodium Sulfate Magnesium Sulfate	AASHTO T 104	 15 max. 20 max.	Yes	Yes	Yes	**	Yes	**	Yes	Yes	Yes[2]	Yes[2]	**	**
Crushed Content One Face Two Faces	[1]	 100 min. 90 min.	 Yes Yes	 Yes Yes	 Yes Yes	 Yes Yes	 Yes Yes	 Yes Yes	 Yes Yes	 Yes Yes	 Yes Yes	 Yes Yes	 Yes Yes	 Yes Yes

[1] Most State DOTs have their own method for calculating crushed content. If no method currently exists for the agency, Pennsylvania DOT Test Method No. 621 can be used.
[2] This state used a modified version of AASHTO T 103 to determine soundness. Test results showed loss values below 6 percent. These results were interpreted as acceptable.
** Data Not Available.

Table 2.6: Comparison of Fine Aggregate Quality From Field Projects To SMA Mixture Design Criteria

Test	Method	Criteria	Meet Specification (Yes/No)?										
			Site 1		Site 2	Site 3	Site 4	Site 5	Site 7	Site 8	Site 9	Site 10	Site 11
			JMF-01-1	JMF-01-2									
Soundness (5 cycles) Sodium Sulfate Magnesium Sulfate	AASHTO T 104	15 max. 20 max.	**	**	Yes	**	**	**	Yes[2]	Yes[2]	**	**	**
Angularity	AASHTO TP 33	45 min.	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	No
Liquid Limit	AASHTO T 89	25 max.	**	**	Yes	**	**	**	**	**	**	**	**
Plasticity Index	AASHTO T 90	NP[1]	**	**	Yes	**	**	**	Yes	Yes	**	**	**

[1] Non-Plastic

[2] This state used a modified version of AASHTO T 103 to determine soundness. Test results showed loss values below 1 percent. These results were interpreted as acceptable.

** Data Not Available.

NOTE: Site 6 did not use a fine aggregate.

Table 2.7: Comparison of Volumetric Data From Field Projects To SMA Mixture Specification													
Property	Requirement	Meet Specification (Yes/No)?											
		Site 1		Site 2	Site 3	Site 4	Site 5	Site 6	Site 7	Site 8	Site 9	Site 10	Site 11
		JMF-01-1	JMF-01-2										
Asphalt Content	6 min	Yes	No[1]	Yes	Yes	No[1]	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Air Voids	3.0 - 4.0	Yes	No	Yes	No	No	No	Yes	No	No	Yes	No	No
VMA	17 min.	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
VCA	Less than VCA_{DRC}	No	No	No	Yes	No	No	Yes	Yes	Yes	Yes	No	Yes

[1] Using the stipulation that the asphalt content can be slightly lower if the combined bulk specific gravity exceeds 2.75, this property meets the requirement.

Table 2.8: Comparison of Fine Mortar Properties From Field Projects To SMA Mixture Specification												
Property	Requirement	Meet Specification (Yes/No)?										
		Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	Site 7	Site 8	Site 9	Site 10	Site 11
Unaged DSR, G*/Sinδ (kPa)	5 min.	Yes	No	Yes[1]	Yes	Yes	Yes[1]	Yes	Yes	Yes	Yes	Yes
RTFO Aged DSR, G*/Sinδ (kPa)	11 min.	Yes	No	Yes[1]	Yes	No	Yes[1]	Yes	Yes	Yes	Yes	Yes
PAV BBR, Stiffness (MPa)	1500 max.	Yes	Yes	Yes[1]	Yes	Yes	Yes[1]	Yes	Yes	Yes	Yes	Yes

[1] Results of this test passed the criteria but the test results were suspect.

2.12.2 Comparison of Marshall Hammer and Superpave Gyratory Compactor

Work in Phase I of this project indicated that 100 gyrations of the SGC would provide about the same density as 50-blows with the Marshall hammer. Since past experience with SMA has been good and since most SMA mixtures in the past were designed using 50-blows of the Marshall hammer, it was determined in this study that the compaction effort with the SGC should be set to provide a density approximately equal to that with the Marshall hammer. Comparisons were made on the field projects to verify that 100 gyrations with the SGC was equal to 50-blows of the Marshall hammer (Figure 2.14). Based on Figure 2.14, there was a lot of scatter in the data when comparing the 50-blow Marshall density with 100 gyrations of the SGC. Some projects needed more than 100 gyrations to produce density equal to that produced by 50-blows of the Marshall hammer. On other projects less than 60 gyrations of the SGC were needed to provide equal density. However, based on the data it appears that approximately 80 gyrations of the SGC are required to provide equal density to that of 50-blows with the Marshall hammer.

Part of the variation shown in Figure 2.14 could be caused by errors inherent in the back calculation of bulk specific gravities when using the SGC. Another possible source of variation in the data was the differences in aggregate Los Angeles Abrasion loss values from the different field projects. SMA mixtures that contain softer aggregates will tend to compact faster than mixtures with harder aggregates. To determine if the hardness of the different aggregates affected the compaction characteristics of the different mixtures, a multiple linear regression analysis was performed. For this analysis, the G_{mb} ratio was the dependant variable while the gyration levels and Los Angeles Abrasion loss values were designated the independent variables.

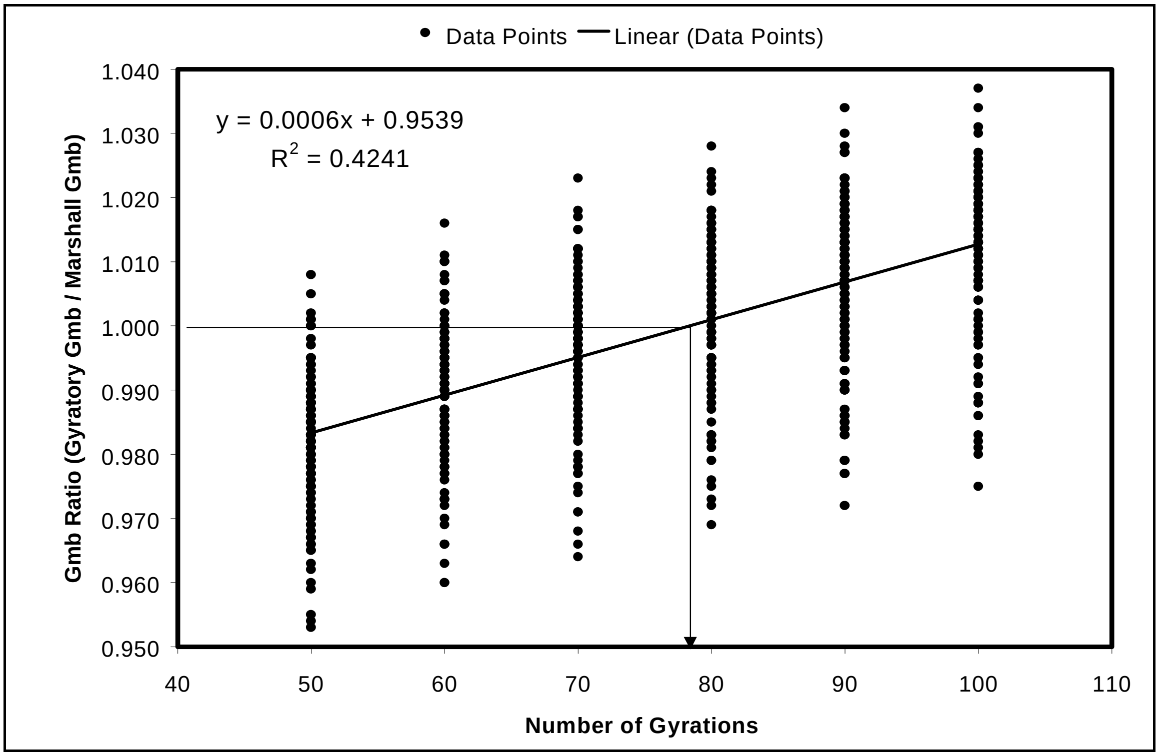

Figure 2.14: Comparison of Densities of Samples Compacted With 50-Blow Marshall and 100 Gyrations of SGC

Based on the analysis, 47 percent of the variation in Figure 2.14 could be attributed to the two independent variables. Therefore a chart showing the effects of both gyration levels and Los Angeles Abrasion loss values was developed (Figure 2.15). Instead of showing a regression line for all of the projects evaluated, this figure shows the results for Los Angeles Abrasion loss values of 20, 30, and 40 percent with the same gyration levels as Figure 2.14.

Based on Figure 2.15, the number of gyrations needed to produce a similar density as 50-blows of the Marshall hammer ranges from 68 to 82 for aggregates with 20 to 40 percent loss. Therefore, it was recommended that for SMA mixtures utilizing aggregates with LA Abrasion loss values of more than 30 percent, a design number of gyrations of 70 be used. For harder aggregates (loss values less than 30 percent), a design number of gyrations of 100 should be used. The difference in these two gyration levels will result in a difference in optimum asphalt content of approximately 0.4 percent. The 70 and 100 gyrations were selected to compare to the recommended gyration levels from NCHRP contract 9-9.

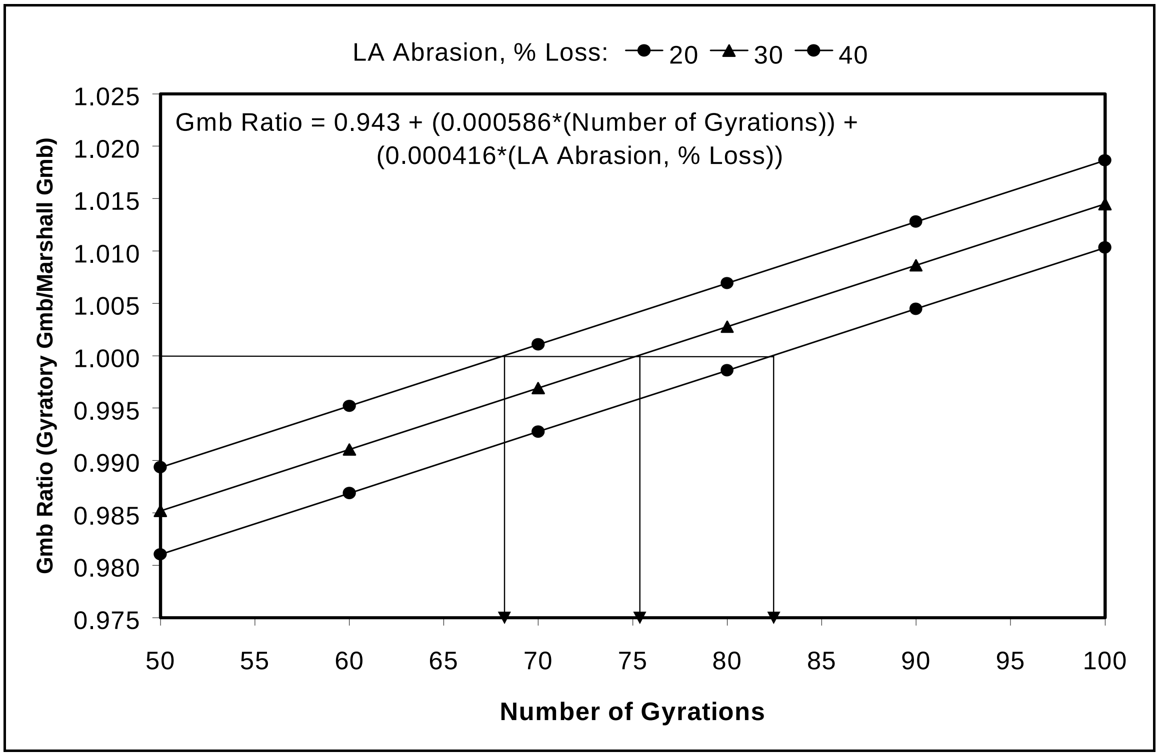

Figure 2.15: Gmb Ratio As A Function of Gyration Level and Los Angeles Abrasion

2.13 FIELD DENSITY REQUIREMENTS

At the present time most SMA projects are required to be compacted to an in-place air void content of 5 to 6 percent. This appears to be acceptable, but there is some evidence that indicates that SMA mixtures could be more permeable to water at a lower air void content than are dense-graded mixtures. Work in Phase I showed that SMA mixtures become permeable at approximately 6 percent air voids. This work was accomplished to determine at what density SMA becomes permeable based on field measurements.

In-situ permeability measurements were made at eight of the field projects visited under Task 8. The in-situ permeability was determined using a falling head method that consisted of sealing a plastic cylinder to the pavement. At each location that in-situ permeability measurements were made, cores were obtained. These cores were brought back to the NCAT laboratory to evaluate the laboratory permeability.

Based on these two methods of evaluating permeability, increasing air voids generally resulted in increasing permeability. Based on all of the data collected from the eight projects, it appeared that SMA mixtures become permeable to water at air void contents between 5.0 and 6.5 percent. This confirmed that SMA mixtures should be compacted in the field to air void contents of between 5 and 6 percent.

2.14 ACCURACY AND PRECISION OF NUCLEAR GAUGE

In order to evaluate the accuracy and precision of nuclear gauges for measuring the density of SMA pavements, cores were obtained from eight of the eleven projects visited under Task 8. At each location that cores were obtained, density measurements were made with a nuclear density gauge with and without Ottawa sand. Two different methods were used to analyze the data accumulated. Both methods consisted of determining a correction factor to correct the nuclear density gauge measurements, the primary difference being how the correction factors were determined. The two methods were investigated to determine which method was more accurate and precise.

The first method consisted of determining an average bias based on the average difference between the cores and the nuclear density measurements. The premise of this type of correction factor was that the final corrected nuclear gauge density would be equal to the core density.

The second method of evaluating the data consisted of determining a sliding (dynamic) correction factor based on measured nuclear density gauge readings. For a given project's data, the core densities were divided by the nuclear density gauge measurements to yield individual density ratios. This was done for both the with and without leveling sand data. Next, the individual density ratios were plotted as a function of nuclear density gauge measurements and a simple linear regression performed (separate regression analysis were performed for the with and without sand data). Based on the regression line, the correction factor was obtained for each individual nuclear gauge measurement. This correction factor was then multiplied by the nuclear density gauge reading for the corrected nuclear gauge density. Unlike the average bias correction factors, the premise of this analysis was that a strong relationship existed between the corrected nuclear density gauge readings and the core densities.

To compare which method of reducing the data provided a more accurate estimation of true density, the standard error of the estimate was used and was determined for both the sand and without sand readings. Using the method of static correction factors, the standard error of the estimate was based on the line of equality since the premise of that analysis was that the corrected nuclear density gauge readings would be equal to the core density. For the dynamic correction factor measurements, the standard error of the estimate was based on the linear regression line between the corrected densities and the core densities.

Results of these analyses showed that the dynamic correction factors provided a better estimate of true densities (Table 2.9). Standard error of the estimates ranged from 0.61 to 2.75 lbs per cu ft for the dynamic correction factors. Using the static correction factors, the standard error of the estimates ranged from 1.02 to 5.19 lbs per cu ft. Additionally, it appeared that the nuclear density gauge readings made with a leveling sand gave a better estimate of true densities than did the measurements without sand (Table 2.9). For the dynamic correction factors, the with sand readings had lower standard errors of the estimate for six of the eight sites.

Table 2.9: Standard Error of the Estimates for Nuclear Density Gauge Measurements				
Site	Static Correction Factors		Dynamic Correction Factors	
	With Sand	Without Sand	With Sand	Without Sand
2	2.53	3.73	2.44	2.85
3	1.98	1.65	0.83	1.31
4	1.32	1.55	1.28	1.52
5	1.76	2.08	1.15	1.73
6	2.29	2.68	1.56	1.17
9	2.29	1.02	0.61	0.96
10	5.19	4.45	2.57	2.75
11	2.28	2.20	1.82	1.78
Avg.	2.46	2.42	1.53	1.76

Based on this discussion, it was concluded that the nuclear density gauges could be used to estimate the density of SMA pavements in the field. A dynamic correction factor should be employed to correct the nuclear density gauge measurements and Ottawa sand should be placed on the pavement surface when performing nuclear density tests for best accuracy. Tests can be conducted without sand but more readings would be necessary to develop the same accuracy as that obtained when sand is used.

CHAPTER 3 - CONCLUSIONS AND RECOMMENDATIONS

The conclusions provided below are based on the research results obtained during both Phase I and Phase II along with available literature.

- The dry-rodded test for coarse aggregates is acceptable for measuring the voids in coarse aggregate (VCA) that can define when stone-on-stone contact is achieved in the mixture. (Phase I)
- Excessive aggregate breakdown in aggregates may make it difficult to meet VMA requirements. This often becomes a problem when the L.A. Abrasion is over 30. (Phase I)
- Superpave binder tests can be used to evaluate the quality of SMA mortars. The DSR minimum requirement for $G^*/\sin\delta$ on unaged mortars should be set at 5.0 kPa. The minimum requirement for $G^*/\sin\delta$ for RTFO aged mortars should be set at 11.0 kPa. The maximum stiffness in the BBR test should be set at 1500 Mpa. These suggested requirements are optional and should be used with care until experience is obtained with these procedures. (Phase I and Phase II)
- No test was identified that clearly showed promise in predicting performance of the SMA mixture during Phase I; however, loaded wheel testing during Phase II showed promise. Tests during Phase I included dynamic creep tests, indirect tensile strength, resilient modulus, and Marshall stability. A major effort to develop a performance test is on-going as part of Superpave. Results of this effort should be applicable to SMA. (Phase I and Phase II)
- The coarse and fine aggregates used in SMA mixtures should be 100 percent crushed. The fine aggregate angularity should equal or exceed 45. (Phase I)
- The L.A. Abrasion of the coarse aggregate should be a maximum of 30, however, experience has shown that good SMA mixes have been constructed with L.A. Abrasion values above 30. (Phase I and Phase II)
- Flat and elongated particles should be measured on a 3 to 1 and 5 to 1 ratio. The requirement for 3 to 1 should be set at 20 percent maximum. However, some locations may have problems meeting this requirement. The requirement for 5 to 1 should be set at 5 percent maximum. (Phase I)
- A good screening test for fillers is the modified Rigden voids. Fillers that exceed 50 cause the mortar to be excessively stiff and difficult to work. (Phase I)
- There should be no specification requirement for SMA that sets a limit on the percentage of material passing the 0.02 mm size. (Phase I)
- When SMA is used, it is normally better to increase the PG grade by one or two grades above that recommended based on the climate. AASHTO MP2, “Standard Specification for SUPERPAVE Volumetric Mix Design,” should be consulted for guidance to change the performance grade of the asphalt binder for traffic speed or traffic level. (Phase I and Phase II)
- The minimum VMA requirement should be set at 17 percent. (Phase I)

- The 50-blow compactive effort with the Marshall hammer appears to be reasonable. The compactive effort with the Superpave Gyratory Compactor should be 100 gyrations for mixtures having aggregates with Los Angeles Abrasion loss values of less than 30 percent. However, if the L.A. Abrasion is above 30 then consideration should be given to lowering the compactive effort to 70 gyrations. These gyration levels are the design number of gyrations. For both gyration levels, VMA requirements should be met as well as in-place density requirements. (Phase I and Phase II)
- The tensile strength ratio (TSR) of SMA mixtures is typically lower than for dense-graded mixes. This does not indicate that SMAs are more susceptible to moisture but does indicate that the acceptance limit for TSR should be lower for SMA than for dense-graded mixtures when tested in accordance with AASHTO T283. The TSR requirement should be set at 70 percent. The TSR should be conducted at an average air void level of 6.0 percent. For SGC designed SMA, the samples should be compacted in accordance with AASHTO MP2, Section 7.6, which states the samples should be compacted to a height of 95 mm for 150 mm diameter specimens. (Phase I)
- The use of fibers tend to do a better job than polymers in reducing draindown. Polymers seem to do a good job of decreasing temperature susceptibility of a mixture. So there are advantages for both additives and in certain cases both may be used. (Phase I)
- Breakdown in the laboratory tends to be 5 to 10 percent on the 4.75 mm sieve for harder aggregates (L.A. Abrasion loss value of 30 percent or less) and more for softer aggregates (L.A. Abrasion loss value of more than 30 percent). The Marshall hammer tends to breakdown the aggregate more than the gyratory compactor (at 100 gyrations). Both laboratory compactors provide breakdown approximately equal to in-place compaction. (Phase I and Phase II)
- Mixes designed using the method provided within this report can be produced and placed in the field. There are no specific areas of difficulty in meeting specifications. (Phase II)
- SMA mixtures prepared in the laboratory perform well when tested under laboratory wheel tracking tests. (Phase II)
- Increasing the maximum aggregate size and/or the percentage of coarse aggregate produces a mix that is more susceptible to permeability. When a mix with a smaller nominal maximum aggregate size is used, such as 4.75 mm, the optimum asphalt content will tend to be very high. The in-place voids must be approximately 6 percent or lower to insure that it is not permeable. Compaction requirements should be set at a minimum of 94 percent of theoretical maximum density for SMA mixtures. (Phase II)
- SMA mixes are more permeable than coarse graded Superpave mixes and even more permeable than fine graded Superpave mixes for similar void contents and

similar nominal maximum size aggregates. Thus SMA should be compacted in-place to a void content of approximately 6 percent or less. (Phase I and Phase II)

- For the construction projects evaluated in this study there was no significant difference in aggregate breakdown for static and vibratory rollers. The L.A. Abrasion appeared to have little effect on the in-place breakdown of aggregate. (Phase II)
- Asphalt binders undergo significant physical changes when heated above 180°C. SMA mixes often use modified binders which require higher temperatures but be cautioned when approaching temperatures of 180°C. (Phase II)
- The Brookfield viscometer and a workability test were used successfully to measure the mixture stiffness, however, these tests could not be successfully used to determine mixing and compaction temperatures. (Phase II)
- A laboratory test was used successfully to measure the permeability of SMA mixtures. However, a field test for permeability was not successful. (Phase II)
- A nuclear gauge can be used to measure the in-place density of SMA mixtures. However, the error can be significant. The correction factor for nuclear gauges should be based on cores and should be a function of measured in-place density. The use of a leveling sand, such as Ottowa sand, was shown to provide better accuracy than not using leveling sand. When measuring the density of SMA pavements, if leveling sand is not used, more nuclear gauge tests should be performed to provide a similar accuracy. (Phase II)
- Too many projects are being constructed with incorrect laboratory voids and high in-place voids. For best performance, these properties must be controlled. SMA volumetrics are extremely sensitive to gradation changes, especially on the 4.75 mm sieve and on the 0.075 mm sieve. (Phase II)

BIBLIOGRAPHY

Bibliography of Stone Matrix Asphalt

	Date	Paper/Publication Title	Author(s)	Publication
1.	1985	Long-term Experience with Splittmastxasphalt in the Federal Republik of Germany	Kast, O. E.	Eurobitume Symposium 1985
2.	1988	Slitlager av HABS	Translation by Kjell Sardal, Ballast Vast AB, Gothenburg	Publication 1988:42 HABS (The Swedish Construction Specification), NCC, 19
3.	1989	Report of the AASHTO Joint Task Force on Rutting		American Association of State Highway and Transportation Officials, Feb 1989
4.	1989	Untersuchungen an einer Splittmastixasphaltdeckschict- Follgerungen fur die Praxis	Tappert, A.	Bitumen 2/89, p 53
5.	1989	EAPA Investigates Porous Asphalt and Stone-Mastic Surface Layers in the EAPA Countries		INF. European Asphalt Pavement Association, May 1989
6.	1989	Steenmastiekasfalt op Plaatsen met Zware Belastingen	Rinckes, G.	Asphalt No. 2, VBW-Asfalt, 1989, p 16
7.	1990	Stone-Mastic and Porous Asphalt Experiences from the City of Gothenburg	Ohlsson, S., and Sandin, A.	The Street and Highway Department of the City of Gothenburg
8.	1990	Heavy Duty Asphalt Pavements-How Do they Look?	Liljedhal, B.	Asphalt Study Tour, Sweden, The Swedish Ashpalt Pavement Association 1990
9.	1990	Splittmastixasphalt	Tappeneir, W.J.	Novophalt America Inc., 1990
10.	1990	Zusazliche Technische Vertragsedingungen und Richtlinien fur den Bau von Farahndeckenaus Asphalt (in German-Section 4 Splittmastixasphalt)		Der Bundeminster fur Verkehr 1984, (Revised edition 1990)
11.	1990	Drainage Asphalt Concrete (HABD) and Splimastic Asphalt Concrete (HABS)- History, Technical Descriptions, Experiences and Future in Sweden	Johansson, J.	Swedish National Road Administration, 1990
12.	1990	General Specifications for Stone Mastic Asphalt		Udbuds-og anlaegsforskrifter, Almindelig arbejdsbeskrivelse Varmblandet asfalt. Nov 1990 (Draft translation of Danish Specification, Apr 1991)
13.	1991	An Introduction to Stone Matrix Asphalt (SMA)		ScanRoad, Sweden, Jan 1991
14.	1991	Stone Mastic Asphalt Reduces Rutting	Scherocman, J.A.	Better Roads Vol 61, No 11, Nov 1991, P 26

Bibliography of Stone Matrix Asphalt

	Date	Paper/Publication Title	Author(s)	Publication
15.	1991	A Preliminary Evaluation of Selected Factors Influencing the Performance of Stone Mastic Asphalt Mixtures (SMA)	Little, D.N., Dutt, P., and Syed, A.	Interim Report, TexasTransporation Institute, 1991
16.	1991	Evaluation of Selected SMA Mixtures with emphisis on Materials Used in the I-85, Georiga SMA Project	Little, D.N.	Draft Final Report, Texas Transportation Institute, 1991
17.	1991	Fiber and Fill: A Key to Super Asphalt Success		Asphalt Contractor, Nov-Dec 1991, p 52
18.	1991	Der Splittmastixasphalt-eine Bauweise mit vielen Anwendungen	Hoppe, W.	Bitumen 1/91 p 2
19.	1991	Verleichende Untersuchungen an stabilisierenden Zusatzen fur Splittmastixasphalt	Richter, E.	Bitumen 2/91 p 69
20.	1991	Stone Mastic Asphalt Test and Evaluation Project No 18	Bukowski, J	Office of Technology Applications Federal Highway Administration, Dec 1991
21.	1991	Stone Mastic Asphalt: A Potential Rutting Solution	Pryor, C.	Stone Review Oct 1991
22.	1991	Asphalt Mix Technology Puts Emphasis on Aggregate	Drake, R.	Pit & Quarry, September 1991
23.	1991	Wisconsin tests New Stone Mastic Asphalt Technique	Eaton, M.	Roads & Bridges Vol 29, No 9, 1991, p45
24.	1991	Development of Stone Mastic Asphalt for Ontario Use	Carrick, J., Macinnes, K., Davidson, K.., Schenk, W., and Emery, J.	Asphalt Review, Vol.10, No 4, Dec 1991, Australian Asphalt Pavement Association
25.	1991	SMA Comes to the USA	Warren, J.M.	Hot Mix Asphalt Technology, Fall 1991, National Asphalt Pavement Association
26.	1991	Report on the 1990 European Asphalt Study Tour		American Association of State Highway and Transportation Officials, 1991
27.	1991	Split Mastic Asphalt-Next Overseas Import?	Kuennen,T.	Roads and Bridges Vol 29, No 1, Jan 1991, p 48
28.	1991	Over 300 Gather for European SMA FHWA/ Michigan Demo Project	Eaton, M	Roads and Bridges Vol 29, No 10, Sep 1991, p 98
29.	1991	European Paving Technology Spurs American Thought	Parson, R.H.	AASHTO Vol 70, No 4, American Association of State Highway and Transportation Officials, Oct 1991
30.	1991	Dunne Deklagen van Steenmastiekasfalt	Rinckes, G.	Asfalt 4/1991, VBW-Asfalt, 1991, p 5

Bibliography of Stone Matrix Asphalt

	Date	Paper/Publication Title	Author(s)	Publication
31.	1992	Stone Mastic Asphalt		Georgia Department of Transportation, Sep 1992/July 1993
32.	1992	Supplemental Specifications		Georgia Department of Transportation, Sep 1992/July 1993
33.	1992	Stone Mastic Asphalt for Very Thin Wearing Courses	Serfass, J.P., and Samanos,J.	Transportation Research Board, 1992
34.	1992	Stone Mastic Asphalt	McDaniel, P.	Experimental Project No. Mo91-05 Initial Report, Missouri Highway and Transportation Department, 1992
35.	1992	Stone Mastic Asphalt (SMA) Mixture Design	Stuart, K.D.	FHWA-RD-92-006 Federal Highway Administration, Mar 1992
36.	1992	Splittmastixasphalt		Deutscher Aphaltverband
37.	1992	European Road Comes to the U.S.	Prendergast, J.	Civil Engineering, May 1992
38.	1992	Did Pheonix Originate SMA Mix Design?	Matteson, J.H./ Kuennen, T.	Roads & Bridges, Vol 30, No 1, Jan 1992, p 58
39.	1992	New Mixes, Modifiers Put to Test on I-94	Milo, A.C.	Centerline, Michigan Asphalt Pavement Association, Fall 1992
40	1992	Experience with Stone Matrix Asphalt in the United States	Brown, E.R.	National Center for Asphalt Technology, March 1992
41.	1992	Use of Stone Mastic Asphalt in Germany State of the Art	Bellin, P.	Paper subitted to Transportation Research Board Committee A2RO2, 1992
42.	1992	The Future of SMA in America	Bukowski, J.R.	Asphalt, Asphalt Institute, Winter 1992-1993
43.	1992	Construction Procedures for Asphalt Concrete Pavements in Europe	Schultz, O.W.	Association of Asphalt Paving Technologists Vol 61, 1992, Symposium: Application of European Technology for Improved Pavement Performance, p 612
44.	1992	Materials and Mix Design	Van Der Heide, J.P.H.	Association of Asphalt Paving Technologists, Vol. 61, 1992, Symposium: Application of European Technology for Improved Pavement Performance, p 584
45.	1992	Transfer of Technology from Europe to the USA	Harrigan, E.T.	Association of Asphalt Paving Technologists Vol. 61,1992, Symposium: Application of European Technology for Improved Pavement Performance, p 638

Bibliography of Stone Matrix Asphalt

	Date	Paper/Publication Title	Author(s)	Publication
46.	1992	Construction of Stone Mastic Asphalt Test Sections in the U.S.	Scherocman, J.A.	Association of Asphalt Paving Technologists Vol. 61, 1992, Symposium: Application of European Technology for Improved Pavement Performance, p 642
47.	1992	Introduction of Stone Mastic Asphalts (SMA) in Ontario	Kennepohl, G.J., and Davidson, J.K.	Association of Asphalt Paving Technologists Vol. 61, 1992, p 517
48.	1992	Evaluation of SMA used in Michigan (1991)	Brown, E.R.	National Center for Asphalt Technology, Report No. 93-3, 1993
49.	1992	The Construction and Performance of Polymer Modified Asphalt Concrete Pavements	Scherocman, J.A., and Schutz, O.W.	7^{th} International Conference on Asphalt Pavements
50.	1992	The Design and Construction of Stone Mastic Asphalt Pavements	Scherocman, J.A.	American Association of State Highway and Transportation Officials, Annual Meeting, 1992
51.	1992	Experiences with SMA	Schroder, I., and Kluge, H-J	Bitumen 4/92
52.	1992	The Design, Construction and Performance of Stone Mastic Asphalt Pavement Layers	Scherocman, J.A.	Proceedings of the Canadian Technical Asphalt Association, Nov 1992, p132
53.	1993	Herstellen und von Splittmastixasphalt-ein Erfahrungbericht	Milster, R.	Bitumen, ARBIT, Jan 1993
54.	1993	Stone Matrix Asphalt: Introduction of Loose Cellulose Fibers into Drum Mix Plants	Karnemaat, R.J., Vreibel, D.J., and Van Deusen, C.H.	Transportation Research Board 1993
55.	1993	SMA, Arizona Link no Exaggeration	Morris, G.R.	Roads and Bridges Vol 31, No 6, Jun 1993
56.	1993	Multigrade Asphalt Multi-Contender for Large Aggregate, Surface Course and SMA Mixes		Asphalt Contractor, Jan 1993, p 22
57.	1993	Stone Matrix Pavements Require Special Technique	Kriech, A.J.	Asphalt Contractor, Feb 1993, p 8
58.	1993	Pre-Mix SMA Fibers with Asphalt Cement	Kuennen, T.	Roads and Bridges Vol 31, No 9, Sep 1993, p 38 (Adapted form Karnemaat et al Transportation Research Board 1993)
59.	1993	Laboratory Investigation into the Impact of Polymer Type, Polymer Concentration, and Aggregate Gradation on the Properties of Stone Matrix Mixes	Reinke, G.	Association of Asphalt Paving Technologists Vol. 62, 1993, p 314
60.	1993	Evaluatin of a Stone Matrix Asphalt Overlay over PCC	Campbell, B.E.	Research Report No. 9202, Georgia Department of Transportation, 1993
61.	1993	Stone Martix Asphalt in Indiana	Haddock, J.E., Liljedahl, B., and Kriech, A.J.	Transportation Research Board 1993

Bibliography of Stone Matrix Asphalt

	Date	Paper/Publication Title	Author(s)	Publication
62.	1993	SMA in America	Bukowski, J.R.	Transportation Research Board 1993
63.	1993	Evaluation of Stone Mastic Asphalt in Missouri Route I-70, Boone County	McDaniel, P.	Experimental Project No. Mo 92-07, Initial Report, Missouri Highway and Transportation Department, 1993
64.	1993	New Coarse Matrix High Binder Mixtures	Tahmoressi, M.	Asphalt, Asphalt Institute, Winter 1993-1994
65.	1993	New Developments in Analytical Asphalt Mix Design	Francken, L., and Vanelstraete, A.	5th Eurobitume Congress, Volume 1B, 1993, p 502
66.	1993	First Attempts in the Appliance of Splittmastix Asphalt in Bulgaria	Grosshans, D., Shivarov, I.I., and Nikolova, Sv.K.	5th Eurobitume Congress, Volume 1B, 1993, p 508
67.	1993	Effect of Mortar Stabilizers in Split-Mastic-Asphalts	Harders,O.	5th Eurobitume Congress, Volume, 1B, 1993, p 606
68.	1993	The Design, Construction and Performance of Stone Mastic Pavement Layers: the Continuing Story	Scherocman, J.A.	Proceedings of the Canadian Technical Asphalt Association, Nov 1993, p 333
69.	1993	Evaluation of Laboratory Properties of SMA Mixtures	Brown, E.R. and Manglorkar,H.	National Center for Asphalt Technology, Report No. 93-5, 1993
70.	1993	Stone Mastic Asphalt Wearing Course	Walsh, I.D.	Clause 995 AK, Kent County Council Specification, Nov 1993
71.	1993	Aggregate Production Requirements for Stone Matrix Asphalt	Marek, C.R. and Dukatz, E.L.	United States Hot Mix Asphalt Conference, Atlanta, Nov 1993
72.	1994	Dense Graded Mixtures Getting Industry Out of a Rut with Stone Matrix Asphalt Mix	Avera, L.T.	Asphalt Contractor, Jan 1994
73.	1994	U.S. Embraces Concept of Stone Matrix Asphalt	Flynn,L.	Roads and Bridges Vol 32, No 1. Jan 1994, p 44
74.	1994	Fibers Add Muscle To Asphalt Mix Operations		Asphalt Contractor, Feb 1994, p 66
75.	1994	Stone Mastic Asphalt Pavement and its Effect on Highway Traffic Noise Levels	Polcak, K.D.	Transportation Research Board 1994
76.	1994	Evaluation of Using Different Stabilizers in the U.S. Route 15 (Maryland) Stone Matrix Asphalt (SMA)	Stuart, K.D. and Malmquist, P.	Transporation Research Board 1994
77.	1994	Mix Design Considerations for SMA Mixes	Carpenter, S.H.	Transportation Research Board 1994
78.	1994	Evaluation of Stone Matrix Asphalt Versus Dense-Graded Mixtures	Mogawer, W.S., and Stuart, K.D.	Transportation Research Board 1994
79.	1994	Structural Strength of Asphalt Rubber Concrete Developed Through Stone Mastic Asphalt Concept	Svec, O.J., and Veizer, R.	Transportation Research Board 1994

Bibliography of Stone Matrix Asphalt

	Date	Paper/Publication Title	Author(s)	Publication
80.	1994	Stone Mastic Asphalt, Route I-70, Callaway County, Construction Phase Report		Report No. Mo 93-01, Missouri Highway and Transportation Department, 1994
81.	1994	Guidelines for Materials, Production, and Placement of Stone Matrix Asphalt		National Asphalt Pavement Association, Information Series 118, 8/94, 1994
82.	1994	A Comparison of Field and Laboratory Compacted Asphalt - Rubber, SMA Recycled and Conventional Asphalt - Concrete Mixes Using SHRP A-003A Equipment	Harvey, J., and Monismith, C.L.	Association of Asphalt Paving Technologists, Vol. 63, 1994
83.	1994	SMA--Innovation in Asphalt Pavement	Bukowski, J.R.	TR News 171, March --April 1994
84.	1994	Stone Matrix Asphalt — Properties Related to Mixture Design	Brown, E.R., and Mallick, R.B.	National Center for Asphalt Technology, Report No. 94-2, 1994
85.	1994	Stone Matrix Asphalt Construction Procedures (Draft)		SMA Technical Working Group, Sponsored by the FHWA, May 1994
86.	1994	Untitled	Fujita, D	Unpublished Report, Watanbe-Gumi Co. Ltd. 1994
87.	1995	Analysis of Mineral Fillers and Mastics used in Stone Matrix Asphalt	Harris, B.M., and Stuart, K.D.	Journal of the Association of Asphalt Paving Technologists, Vol. 64, 1995
88.	1995	Performance-Related Testing of Stone Mastic Asphalt	Partl, M.N. Vinison, T.S., Hicks. R.G., and Younger, K.	Journal of the Association of Asphalt Paving Technologists, Volume 64, 1995
89.	1995	Minimum Aggregate Quality Levels For Stone Mastic Asphalt Mixtures	Ruth, B.E., West, R.C, Huang, S. and Moroni, I.E.	Report No. FL/DOT/RMC/648-4483 Florida Department of Transportation, 1995
90.	1996	An Investigation of Stone Matrix Asphalt Mortars	Brown, E.R. Haddock, J.E. , and Crawford, C.	Transportation Research Board, 1996
91.	1996	Design and Construction of SMA Pavements in Wisconsin	Reinke, G. and Jensen, G.	Transportation Research Board, 1996
92.	1996	Summary of Georgia's Experience with Stone Matrix Asphalt Mixes	Watson, D. and Jared, D.	Transportation Research Board, 1996
93.	1996	Contruction of SMA section at Edwards AFB	Shoenberger, J.E.	Transportation Research Board, 1996
94.	1997	The Construction and Performance of Stone Matrix Asphalt Pavements In the United States	Scherocman, J.A.	Eighth International Conference on Asphalt Pavements, August 10-14, 1997, Seattle Washington, Vol. I Proceedings
95.	1997	Characterization of Stone Matrix Asphalt Mortars	Brown, E.R. and Haddock, J.E.	Eighth International Conference on Asphalt Pavements, August 10-14, 1997, Seattle Washington, Vol. I Proceedings

Bibliography of Stone Matrix Asphalt

	Date	Paper/Publication Title	Author(s)	Publication
96.	1997	Development of a Stone Mastic Asphalt Design Method for South African Conditions	Louw, L., Semmelink, C.J. and Verhaeghe, BMJA	Eighth International Conference on Asphalt Pavements, August 10-14, 1997, Seattle Washington, Vol. I Proceedings
97.	1997	Performance of Stone Matrix Asphalt (SMA) Mixtures in the United States	Brown, E.R., Mallick, R.B., Haddock, J.E. and Bukowski, J.	Journal of the Association of Asphalt Paving Technologists, Vol. 66, 1997
98.	1997	Development of a Mixture Design Procedure for Stone Matrix Asphalt (SMA)	Brown, E.R., Haddock, J.E., Mallick, R.B. and Lynn, T.A.	Journal of the Association of Asphalt Paving Technologists, Vol. 66, 1997
99.	1997	Method to Ensure Stone-on-Stone Contact in Stone Matrix Asphalt Paving Mixtures	Brown, E.R. and Haddock, J.E.	Transportation Research Board, 1997
100.	1998	Stone Matrix Asphalt: The Wisconsin Experience	Schmiedlin, R.B.	Preprint prepared for Presentation at the 1998 Annual Meeting of the Transportation Research Board, National Research Council, Washington, D.C. 1998
101.	1998	Evaluation of Permanent Deformation of Stone Matrix Asphalt Mixtures	Tung-Wen, H. and Jeng-Thoa, L.	Preprint prepared for Presentation at the 1998 Annual Meeting of the Transportation Research Board, National Research Council, Washington, D.C. 1998