Comparison of Mix Design Concepts

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Three mix design methods currently available to industry were used to select the asphalt content for a mix used on an overlay placed in November 1993 on Interstate 17 near Phoenix, Arizona. The methods used were Marshall, Superpave Level I, and a performance-based procedure developed during the SHRP-A003A research project using the results of the repetitive simple shear test at constant height and the flexural bending beam test. The mix, with the asphalt content selected based on the method derived in Project SHRP-A003A, was further evaluated by the Hamburg wheel tracking device. The results of a condition survey performed on the actual pavement several months after construction, are presented.

During the Strategic Highway Research Program (SHRP) several new concepts and test methods were developed to evaluate mix performance in the mix design stage. The Arizona Department of Transportation (ADOT) decided to evaluate some of these methods by placing two 1-mi test sections 6 mi north of Phoenix on Interstate 17 near the Pioneer Living Museum exit. Construction took place in November 1993. The primary purpose of the test sections was to evaluate new SHRP materials requirements and tests for mineral aggregate, asphalt, and hot-mix asphaltic concrete (HMAC) by designing and building a 75-mm (3-in.) HMAC inlay that could sustain 10 million design equivalent single axle loads (ESALs) in the 10-year design period. The major design criterion was to limit permanent deformation in the mix so that the rut depth over the life of the project would be less than 10 mm (0.4 in.). The asphalt content was selected using a performance-based mix design developed during Project SHRP-A003A. The field mix was then evaluated by the Marshall method as currently used by ADOT and by the Superpave Level I procedure (*1*). Further evaluation of the selected mix was made using the Hamburg wheel tracking device.

MIX DESIGN CONCEPTS

The goal of a mix design procedure is to combine aggregates and binder into a mix that is able to satisfy desired levels of performance. The definition of performance can be quite broad. With improvements in technology, the concept of mix design has changed. Current methods can be categorized on the basis level of complexity and ability to predict performance:

- **Level 1:** fabrication of specimens under a given set of conditions to determine their volumetric characteristics. Aggregate and binder characteristics are based on prior experience. Asphalt content is based on compactability data. This is basically the approach followed by Superpave Level I.
- **Level 2:** fabrication of specimens under a given set of conditions and execution of a test to measure a reduced set of specimen properties. Limits are set on those variables based on prior experience. Asphalt content is based on limits, ranges, or extreme values of the variables evaluated. This is basically the concept followed by the Marshall method.
- **Level 3:** determination of some fundamental properties using specimens that have undergone specific preconditioning. Performance is predicted on the basis of statistical correlations between laboratory results obtained under a given set of conditions and field observations. Asphalt content can be selected based on desired pavement performance in fatigue and permanent deformation. This is achievable with the current state of knowledge and is basically the approach proposed by some other reseachers (2–7) and used by Superpave Level III (*1*).
- **Level 4:** determination of fundamental properties of the mix (and/or components) and evolution of those properties with time, aging, strain and stress levels, and moisture. Prediction of behavior is made through an elaborate set of computer simulations. This approach is beyond the current state of knowledge. Asphalt content would be selected based on predicted pavement performance, which would be very close to actual performance.

Given that Level 4 is not readily applicable at this time, the other three concepts were addressed.

Volumetric Method—Superpave Level I Mix Design

The Superpave Level I volumetric design is similar in concept to historical volumetric mix design methods. No direct measurements are made of mixture mechanical properties and no prediction of performance is made (*8*). It differs from the Marshall method in that no test is performed on the mix at temperatures representative of those encountered in the field at which permanent deformation occurs. It also differs in that the design conditions vary with location and traffic. However, for a given set of conditions the compaction effort is the same for all mixes. Within Level I concepts the maximum number of gyrations is expected to be representative of compaction levels that lead to design life density. Given that all measurements are executed at the compaction temperature, this procedure could be used to evaluate compactability of the mix.

Volumetric mix design includes compaction using a gyratory compactor that monitors increase in density with increasing compactive effort. Compaction specimens are required to be mixed and compacted under equiviscous temperature conditions corresponding to 0.170 Pa·sec and 0.280 Pa·sec, respectively (*1*).

After short-term aging, the loose mix is ready for compaction with the Superpave gyratory compactor (SGC). The vertical pres-

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sure is set at 0.6 MPa and the angle of gyration is 1.25 degrees. The number of gyrations per minute is 30. Three gyration levels are of interest: design number (N_{des}), initial number (N_{ini}), and maximum number (N_{max}). Relationships were developed between those values. The design number of gyrations ranges from 68 to 172 as a function of climate and traffic level. The value 68 is used for selection with design levels of less than 300,000 and average design high air temperatures below 39°C, whereas 172 is used for traffic levels above 100 million ESALs and corresponding temperatures above 44°C.

The compaction data are analyzed by computing the estimated bulk specific gravity, corrected bulk specific gravity, and corrected percentage of maximum theoretical specific gravity ($\%G_{mm}$) for each desired gyration. The volumetric properties are calculated at the design number of gyrations for each trial asphalt binder content. From these data points, the designer can generate graphs of air void content, VMA (voids in mineral aggregate), and VFA voids filled with asphalt) versus asphalt binder content. Several criteria should be observed. The target air void content should be 4 percent, VMA values are a function of the nominal maximum particle size (for instance, for a 19-mm nominal size, VMA should be higher than 13 percent), and VFA values depend on traffic level (for instance, for a project with 10 million ESALs the range is 65 to 75 percent). Furthermore, the $\%G_{mm}$ at N_{ini} should be less than 89 percent and the $\%G_{mm}$ at N_{max} should be less than 98 percent.

It can be observed from this procedure that binder type should have no effect on the development of gyratory compaction data because the compaction procedure is based on equiviscous temperature conditions. As such, selection of binder content should become independent of binder type. Conceptually, a standard binder could be specified to execute the compaction curves. Within Superpave Level I methodology, binder grade selection is independent of compaction curve data, and there is absolutely no need to execute the compaction curves with the same binder that will eventually be used in the field. It can also be observed that compaction data (air void content as a function of the number of gyrations) are a function of the angle of gyration, number of gyrations per minute, and axial pressure for the gyratory compactor. Small changes in any of these parameters can have a significant impact on the compaction data and criteria.

In addition to these mix criteria, Superpave Level I has asphalt binder criteria (from AASHTO MP-1, performance-graded specifications), aggregate quality criteria (coarse aggregate angularity, fine aggregate angularity, flat/elongated particles, and sand equivalent), combined aggregate gradation requirements (based on the nominal maximum particle size of the mixture), and moisture sensitivity criteria. Within Superpave concepts this mix design is intended to perform as a system, and subtracting any of these components could result in mixtures designed with unacceptable performance properties. On the other hand, it is possible that mixes that do not satisfy all these criteria may perform very well.

Marshall Mix Design Method

The basic concept of the Marshall mix design method is the selection of asphalt content based on optimization or limits for several variables that are not direct measures of performance. On the one hand, there is a volumetric evaluation based on specimens fabricated under a given set of conditions with a given level of compaction energy. The preset compaction energy is expected to produce density levels similar to those imposed by trafficking. After compaction, specimen VMA, VFA, and air void content measurements are reported and evaluated against a given set of allowable values. On the other hand, a test is executed at 60°C (140°F), which is assumed to be a temperature representative of that typically encountered in the pavement at which permanent deformation is likely to occur. From the test, specific parameters are measured (e.g., Marshall stability and flow). For instance, minimum Marshall values are set in the specification criteria. It should be noted that in this approach changing binder type can result in the selection of a different asphalt content as long as the viscosity of the binder at 60°C.

Performance-Based Mix Design Method

The objective of the performance-based mix design method is to establish the appropriate amount of asphalt content in a mix that will simulataneously satisfy the rut resistance and fatigue cracking requirements for a given set of conditions (e.g., traffic and environment). Figure 1 shows the process in which two mixes, A and B, are evaluated and compared with the design requirements. Mix A would satisfy the requirements, whereas Mix B would not. To evaluate rut and fatigue cracking resistance of the mixes, tests developed during Project SHRP-A003A were used. These tests are executed in conditions most critical for the distress mechanism being evaluated. For instance, the repetitive simple shear test at constant height (RSST-CH), developed to evaluate permanent deformation of the mix, should be executed at high temperatures representative of those encountered in the top 5 cm (2 in.) of the pavement during the warmest days of the year (*2*). The four-point flexural bending beam fatigue test should be executed at temperatures around 20°C, where the conditions that cause fatigue cracking are generally most severe (*7*). The effects of aging and moisture on the mix are addressed as they affect performance. Furthermore, it is recognized that air void content changes according to traffic densification, and tests are executed accordingly. For instance, for dense-graded mixes, the RSST-CH should be executed at air void contents of approximately 3 to 4 percent, where the mix is most resistant to accumulation of permanent deformation due to shear stresses. It is assumed that rutting is only likely to occur when the mix drops below that air void content range. However, successful performance-based approaches to mix design require that compaction in the laboratory yield specimens with performance properties identical to those obtained from field cores (*9*).

Using this performance-based approach, there is no need to set explicit limits on volumetric characteristics. If a mix does not meet a particular value of VMA or VFA, but still has the desired performance at the expected in situ volumetric characteristics, it would be

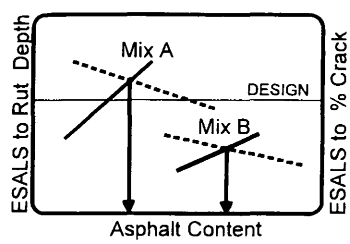

FIGURE 1 Performance-based mix design concept.

acceptable. The selection of asphalt content is based on the desired level of performance for each mode of distress. For instance, in this framework a change of asphalt type, even within the same binder grade, can affect the predictions of fatigue life.

MATERIALS

A modified binder was used for this project (*10*) to satisfy the PG70-10 grade recommended for the location. The aggregate used in the mix design stage was a crushed river gravel, and contained larger fractions with rounded faces, whereas the smaller fractions exhibited all crushed faces. Portland cement (1.0 percent by dry weight of aggregate) was used to reduce moisture sensitivity in the mix. Aggregate fractions were combined in order to meet the ADOT standard gradation.

This mix design gradation conforms with the Superpave guidelines as shown in Figure 2. It also satisfied all binder and aggregate recommendations of Superpave. However, during construction the gradation was changed and a larger percentage of crushed material was used, with 95 percent crushed on one face and 90 percent on two faces. The fine aggregate was 100 percent mechanically crushed. It can be seen in Figure 2 that the field gradation passes through the Superpave restricted zone.

PERFORMANCE-BASED LABORATORY MIX DESIGN

Permanent Deformation Evaluation

Selection of Test Temperature

It has been ADOT's experience that most rutting develops when summer temperatures are above normal. To minimize the possibility of this occurrence, the RSST-CH temperature was carefully selected. The average 7-day maximum surface pavement temperature at the site is 68.1°C (154.6°F) with a standard deviation, based on records for 42 years, of 1.7°C (3.0°F) (obtained from the SHRP project data base). From these values the temperature at the critical depth for shear deformation, 50 mm (2 in.), was computed to be 61.3°C (142.3°F). Considering that a high reliability is desired, so that this temperature is not exceeded, two standard deviations were added (approximately 0.98 percent reliability) to that value, resulting in a test temperature of 65°C (149°F).

Test Results

The RSST-CH testing was performed at the University of California, Berkeley (UC-Berkeley) Soils and Bituminous Materials Laboratory. The results were analyzed following concepts presented previously (*2,3*). Essentially, a correlation was made between the number of cycles in the RSST-CH to reach a given permanent shear strain and the number of ESALs that cause the equivalent rut depth. The relationship between permanent shear strain and rut depth is given by

$$\text{Rut depth (mm)} = 279 \times \text{maximum permanent shear strain} \qquad (1)$$

The relationship between the number of cycles in the RSST-CH and ESALs in the field is given by

$$\text{Log (cycles)} = -4.36 + 1.24 \log \text{(ESAL)} \qquad (2)$$

A summary of the actual results is shown in Figure 2. Air void contents were measured with parafilm (wp) and unsealed (np) (*11–13*) based on the Rice maximum specific density (ASTM D2041).

Asphalt contents used were 4.0, 4.5, and 5.0 percent by weight of aggregate. Rolling-wheel-compacted specimens were fabricated to air void contents of approximately 3.2 and 6.6 percent. All specimens were subjected to short-term oven aging (STOA) to simulate

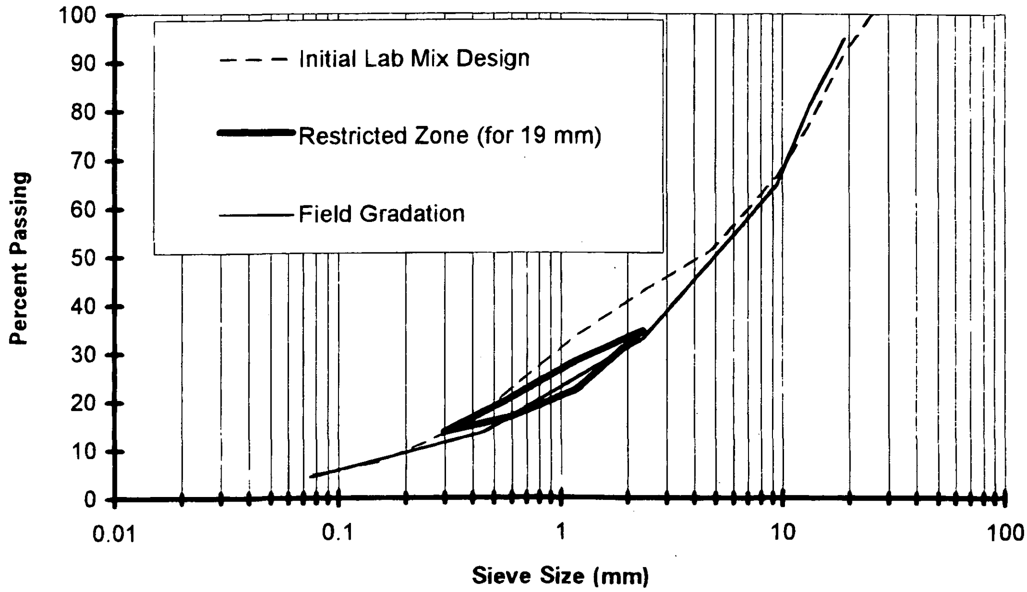

FIGURE 2 Initial laboratory mix design gradation and Superpave guidelines.

plant aging (*14*). Some of the specimens were also subjected to long-term oven aging (LTOA) to simulate long-term aging in the field (*14*). In addition, a few specimens subjected to STOA were conditioned in a moisture conditioning system (MCS) (*3*), which is an adaptation from the ECS concept (*15*).

The test results and corresponding analysis are presented in Figure 3. In general, it can be observed that low air void content specimens exhibit significantly higher resistance to permanent deformation because they can sustain higher number of ESALs before reaching the design rut depth. It can also be observed that shear resistance in low air void content specimens increases with decreasing asphalt content. The results also indicate that the mixture is not very sensitive to moisture damage, although some shear strength is lost during the moisture-conditioning process. As expected, the mix exhibits increased shear resistance with aging. The effects of the aging conditioning seem more pronounced on specimens with higher air void contents.

A multiplier of 8.97, used with the RSST-CH results here, will result in a design with a 95 percent reliability level (*3–5*). This multiplier accounts for variability in test results. Consequently, to ensure with 95 percent reliability that the RSST-CH permanent shear strain will not exceed 3.6 percent [equivalent to a 10-mm (0.4-in.) rut depth] before the expected 10 million-ESALs design criterion, a design criterion of 89.7 million ESALs should be used. Therefore, all considerations regarding asphalt concrete selection should be made at this level of traffic. This level is indicated by the 95 percent reliability design level (see Figure 5).

Selection of AC Content

Selection of the binder content of a mix depends on many factors, including resistance to permanent deformation, fatigue, raveling, and aging. It will be presented later that fatigue life was not the critical criterion for this pavement section. One of the major concerns in the design of this section was to limit permanent deformation by proper selection of aggregate, gradation, asphalt type, and content. Figure 3 shows the variation of the number of ESALs to reach a 10-mm (0.4-in.) rut depth as a function of the asphalt content for different air void contents and conditioning processes. It can be observed that depending on the conditioning process, at a 95 percent reliability level, one could select an asphalt content in a range between 4.1 and 4.6 percent. To be on the conservative side, and considering that rutting is likely to occur in the first or second summer, aging of the mix to resist permanent deformation was used. Therefore, the acceptable asphalt content range (at the 95 percent level) drops to 4.1 to 4.3 percent. Taking into consideration that asphalt content control in the field varies within ± 0.2 percent, an asphalt content of 4.2 percent was selected. In the worst scenario where 4.4 percent was placed, the mix would still be able to perform (especially if one takes aging into consideration).

Fatigue Evaluation

To evaluate the change in fatigue resistance with asphalt content, the four-point bending fatigue test (SHRP-M009 protocol) was selected. Beams were fabricated and tested using the new equipment (*7,16*), developed by SHRP-A003A. Two asphalt contents were selected for this analysis, 4.0 and 5.0 percent, to bracket the range of possible asphalt contents. The target air void content was 4.0 percent. Tests were executed under strain control at 20°C (68°F) and at 10-Hz sinusoidal loading. Failure is defined as the number of cycles at which the stiffness has fallen to 50 percent of its initial value. Fatigue results can be related to field performance by means of appropriate shift factors. For design, a multiplier of 10 was based on cracks in 10 percent of the wheelpaths. The corresponding fatigue curves are presented in Figure 4.

It can be seen that asphalt content affects fatigue performance considerably. As expected, fatigue resistance is improved with

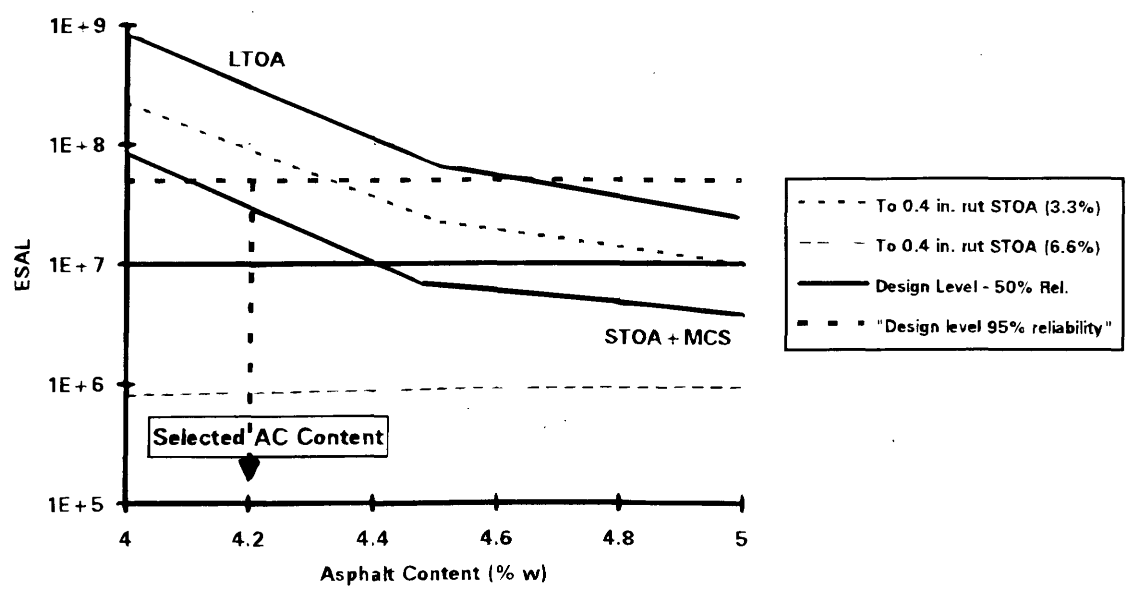

FIGURE 3 Variation of number of ESALs to reach 0.4-in. (10-mm) rut depth with asphalt content for mix used in Arizona Deer Valley: mix design RSST-CH at 65°C and 32 percent void content.

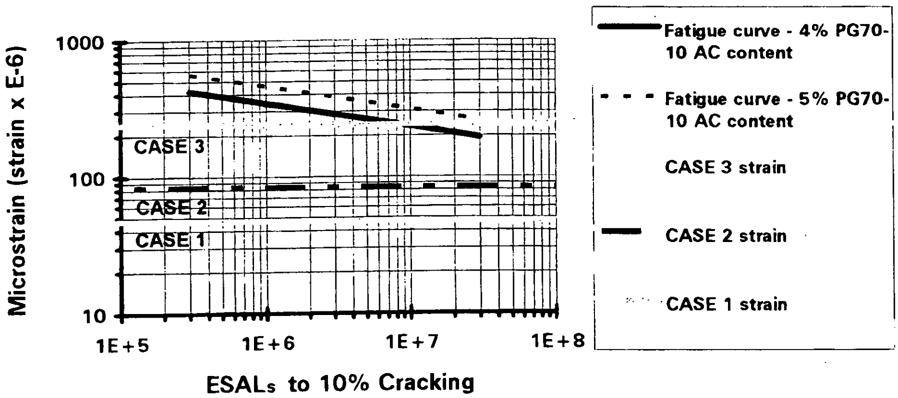

FIGURE 4 Fatigue curves for 4 and 5 percent asphalt contents.

increased asphalt content. However, to select an asphalt content that would insure adequate fatigue life, the strain level in the field must be determined. This evaluation is detailed elsewhere (*10*).

Before investigating the fatigue life of the overlay being placed, it was necessary to determine the structural characteristics of the existing pavement. This is traditionally done using back-calculation methods and falling weight deflectometer (FWD) data (*17*). Layer thickness and FWD data used in this study were provided by the ADOT. The purpose of this analysis was to have an indication of the expected fatigue life of the overlay.

From the back-calculation analysis, layer moduli were determined for a representative pavement section. Three scenarios were considered, Case 1, Case 2, and Case 3, and computations were made using elastic layer theory (ELSYM) to evaluate the magnitude of the strain level due to future pavement degradation caused by moisture effects and fatigue cracking. In Case 3 the moduli of the existing AC layer would be reduced by a factor of 10. This was considered the worst possible scenario. Cases 1 and 2 were considered more realistic with less severe material degradation (i.e., higher moduli for the existing layer and for the future condition of the new layer). It can be observed that the 10 million-ESAL design life is not reached, even in the worst-case scenario. Therefore, project fatigue life would not constrain the selection of asphalt content for this project.

It is recognized that in some cases fatigue cracks in the overlay might be due to shear fatigue instead of flexural fatigue. However, criteria have not yet been developed for shear fatigue of asphalt concrete, and it is reasonable to assume that improvements in flexural fatigue performance may be directly correlated with shear fatigue performance.

EVALUATION OF FIELD MIX WITH RSST-CH

Field cores were taken to the laboratory and tested under the same conditions as specimens cored from the rolling wheel slabs during the mix design stage. The results are presented in Figure 5. It can be observed that the cores from the field exhibit better performance than expected. The improved performance has been attributed (*10*) to gradation change (see Figure 2), better aggregate crushing, and also to more binder aging in the field than was simulated by the STOA procedure used in the laboratory mix design. It has been demonstrated (*9,10*) that the results obtained from this field mix when compacted with the rolling wheel compactor match the results obtained from the field cores, thus eliminating the possibility of differences due to compaction method (Figure 6). Although the laboratory mix was not prepared at the 4.2 percent asphalt content (by weight of aggregate) with the initial gradation, it is reasonable to expect that the behavior of such a mix would be between that of the mixes with 4.0 and 4.5 percent binder contents.

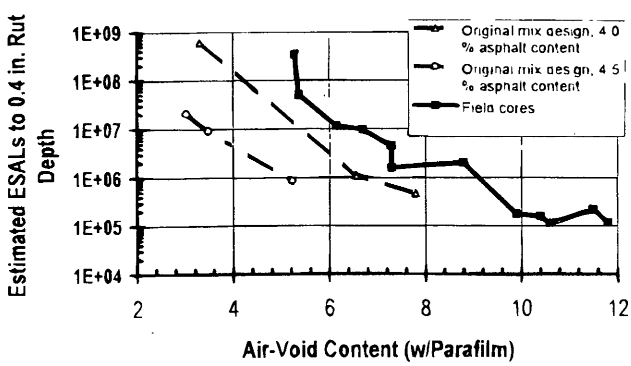

FIGURE 5 Comparison between predictions obtained from laboratory mix and those from field cores.

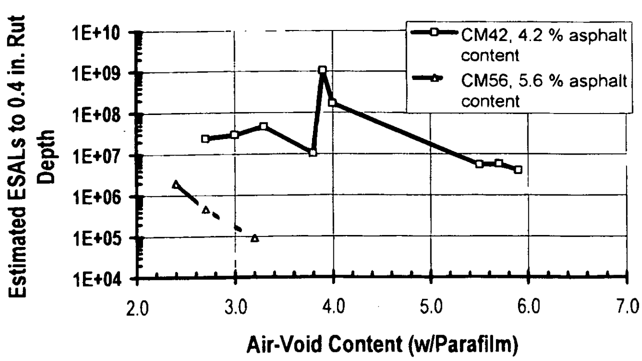

FIGURE 6 Comparison of performance of RSST-CH between mix with 5.6 percent asphalt content and another with 4.2 percent (by weight of aggregate).

EVALUATION USING SUPERPAVE LEVEL I MIX ANALYSIS

The Superpave Level I mix design was executed at the Asphalt Institute (AI), initially using the field mix (*18*). The samples were heated to 146°C for compaction in the SGC. Two samples were compacted to the maximum number of gyrations suggested by Superpave for the traffic and paving location. For I-17 in Phoenix, that corresponded to 220 gyrations (N_{max}), with 9 and 135 gyrations being the respective values for initial (N_{ini}) and design (N_{des}) compaction levels. After compaction, the two specimens were tested to determine the bulk specific gravity of the compacted mixture. From these data, the properties of the mix were determined on the basis of air void contents measured with parafilm and unsealed. The average air void content at 135 gyrations was 7.6 and 6.3 percent with and without parafilm, respectively.

The combined aggregate specific gravity was calculated as 2.655. This specific gravity would yield an average VMA of 13.5 percent at N_{des}. The mix design criteria for a 19.0-mm nominal mixture with an expected design traffic of 10 million ESALs, as well as the average mixture properties, are indicated in Table 1.

As can be seen from Table 1, the field mixture would not meet the requirements for a Superpave Level I mixture. In particular, the air void contents are too high at 4.0 percent asphalt binder content (by weight of mix), and the percent VFA is too low. As part of the Level I mix design procedure, this mixture normally would be evaluated against other aggregate gradations by mathematically adjusting the asphalt binder content to an amount that would result in 4 percent air voids. The air void criterion is the most critical. In the Superpave Level I mix design system, all mixtures are designed to achieve 4 percent air voids.

As a first approximation, the 4.0 percent air void content requirement (without parafilm) could be satisfied by a mix with about 1.0 percent more asphalt content. Once mixtures are normalized to the same air void level, the aggregate structures can be properly com-

TABLE 1 Compacted Mixture Properties from Actual Field Mix Results at 4.2 Percent Asphalt Binder and Estimates from Mix with 5.2 Percent and Actual Specimen with 5.1 Percent Asphalt Binder

Property	Results Field Mix	Estimated Mix Properties from Field Mix.	Actual Mix Properties from lab SGC specimen	Criteria
%Asphalt Binder (by wt. of aggregate)	4.2%	5.2%	5.1%	n/a
%Air Voids @ N_{design} = 135 gyrations	6.3% (without parafilm) 7.6% (with parafilm)	4.0% (no parafilm)	3.7% (no parafilm)	4.0% (no parafilm)
%VMA @ N_{design} = 135 gyrations	13.5%(without parafilm)	13.0%	12.9%	≥13.0% min.
%VFA @ N_{design} = 135 gyrations	53.3%(without parafilm)	69.2%	71.3%	65-75%
Dust-Asphalt Ratio	not available	not available	not available	0.6-1.2
%G_{mm} @ $N_{initial}$ = 9 gyrations	85.4%(without parafilm)	87.7%	89.0%	<89%
%G_{mm} @ $N_{maximum}$ = 220 gyrations	94.8%(without parafilm)	97.1%	97.3%	<98%

pared. Table 1 indicates the mixture properties at the estimated design asphalt binder content.

It can be observed that on the basis of these estimated properties, the compacted mix with the higher asphalt content would meet all Level I criteria; however, it would be considered marginally failing on both percent VMA and percentG_{mm} at N_{ini}. If this mixture had been part of a Superpave Level I trial blend analysis, an alternative aggregate structure (different combination or source of aggregates) could have been considered to improve the VMA requirements. A mix was fabricated in the laboratory with a 5.1 percent asphalt content using the field mix gradation. The mix was aged and compacted following Superpave Level I procedures. The results are also presented in Table 1 and corroborate the expected results.

A 7.6 percent air void content (with parafilm) was obtained at the design number of gyrations for the actual field mix. If, instead of using the air void content unsealed, one would consider air void content measurements with parafilm as being more representative (11–13), then the mixture would require approximately 1.4 percent more asphalt binder or a change in aggregate or aggregate gradation. Although this is not a direct application of Superpave Level I, this was the first criterion used to estimate the asphalt content of a mix with the given gradation that would satisfy Superpave Level I requirements. If time had permitted, specimens would have also been compacted with an asphalt content of 5.1 or 5.2 percent.

Specimens were fabricated at UC-Berkeley with the rolling wheel compactor at 5.6 percent (4.2 + 1.4 percent) asphalt content. The purpose of this exercise was to evaluate the mix performance with the RSST-CH at this asphalt content, representative of an asphalt content required to achieve 4 percent air voids (with parafilm) by the Superpave Level I procedure. Specimens were fabricated in the laboratory with the field gradation at 5.6 percent asphalt content (specimens labelled as CM56) and 4.2 percent asphalt content (specimens labeled as CM42) with the rolling wheel compactor. The results of the RSST-CH are presented in Figure 6. It can be observed that asphalt content has a strong effect on mix performance. At 5.6 percent it is very unlikely, within the performance-based procedure concepts, that the CM56 mix would satisfy the design requirements (i.e., it would be likely that a rut depth higher than 10 mm would develop before the 10 million design ESALs). Although not as dramatic, it is also likely that a mix with a 5.2 percent asphalt content (by weight of aggregate) would not satisfy the design requirements.

These results indicate that within Superpave Level I procedures, volumetric and densification properties obtained from the field mix are identical to those obtained from laboratory-prepared mix. They also indicate that the criteria used by Superpave to estimate Level I properties at different asphalt contents based on results at one asphalt content are quite accurate.

It can then be concluded that the 4.2 percent asphalt content used for the I-17 project does not satisfy Superpave Level I requirements. Those requirements would be marginally satisfied with an asphalt content of 5.1 to 5.2 percent (by weight of aggregate): however, the field mix gradation crosses the restricted zone suggested in the Superpave guidelines and as such would not be recommended as part of a Superpave Level I design. Nevertheless, if this mix were used with an asphalt content of 5.1 percent, the RSST-CH results indicate that it would likely exhibit unacceptable premature permanent deformation.

EVALUATION USING MARSHALL MIX DESIGN

From 1969 to 1983, the 75-blow Marshall test was used to monitor construction of HMAC by ADOT. In 1983 the Marshall test was adopted as the HMAC mix design test by ADOT. Currently, the Marshall test criteria include a minimum Marshall stability of 3,000 lb for Interstate highways. Marshall flow must be between 8 and 16. The VMA range is 14.5 to 17 percent, and the HMAC air void range is 5.8 to 6.2 percent. Marshall design criteria are monitored and controlled during construction by taking four samples per lot. For each sample, three Marshall specimens are compacted and tested. In addition, a Rice test (ASTM D2041) is performed to determine the maximum theoretical density (MTD) for each of the four Marshall samples. Marshall stability and flow, as well as Marshall bulk density and air void content, are also determined for each specimen.

The results of the Marshall analysis for the field mix and cores indicated Marshall stabilities of 5,044 and 3,760 lb and air voids of 6.2 percent and 6.9 percent, respectively. The ADOT field cores had 8.5 percent air void content on average. The VMA was 13.8 percent with a VFA value of 71.6 percent. As can be seen, the design Marshall stabilities were quite high and the field stabilities were also very high, which is indicative of a very stable mix.

EVALUATION OF FIELD MIX USING HAMBURG WHEEL TEST TRACK

Field cores 400 mm (12 in.) in diameter were taken from the pavement overlay, shipped to the Terre Haute Koch laboratory, mounted in the Hamburg wheel tracking device, and tested at 50°C (122°F) under water. One core was tested at 55°C (131°F) following Colorado Department of Transportation recommendations for PG 70 binders (*19*). The Koch laboratory has tested cores from all over the nation in the Hamburg wheel tracking device. Figure 7 shows the range of results of all 157 cores tested in the equipment as well as the results from the cores from I-17. The percentile rankings for the cores were 94 to 95 percent. The Colorado DOT's Eurolab has correlated results from the Hamburg wheel tracking test to the known performance of 20 asphalt pavements (*19*). Based on their experience, the 50th-percentile curve represents a "high maintenance" pavement, and the curve at the 90th percentile would be considered "good," corresponding to a pavement lasting 10 to 15 years. These results indicate that the mix as evaluated by this method is very resistant to ruts and stripping.

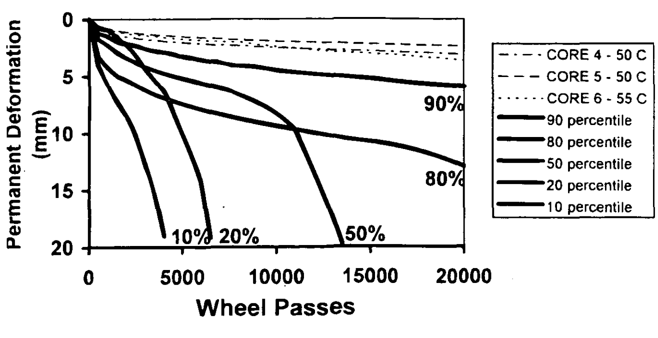

FIGURE 7 Hamburg wheel test track results compared with percentile ratings from other mixes from the United States.

EVALUATION OF FIELD PERFORMANCE

In July 1994, rut depths were measured by a K. J. Lan 690 DNC electronic profilometer at 33.3-m (100-ft) intervals. Rut depth measurements with this device are representative of a 1.5-m (5-ft) straightedge placed across each wheel path, with the recorded value being approximately equal to the average of the two wheel path ruts.

The average 7-day maximum air temperature reached 46°C (116.6°F) previous to the rut depth measurements, which would correspond to a temperature of 61.2°C (142.1°F) at 50-mm (2-in.) depth. This temperature is identical to the average [61.3°C(142.3°F)] obtained from 42 years of temperature records. The average rut depth measured in the section where field quality control took place was 1.5 mm (0.06 in.). This is indicative of good performance based on ADOT experience, where most of the mixes that fail do so in the first summer.

COMPARISON BETWEEN FIELD AND LABORATORY COMPACTION METHODS

The differences in mix design methods are not only a result of the evaluation method used but also of the compaction method employed in specimen fabrication. To identify which laboratory compaction method creates an aggregate structure most similar to that obtained in the field, specimens were prepared by compacting field mix with the following compaction methods: UC-Berkeley rolling wheel, California kneading, Texas gyratory, SHRP gyratory Reinhart (Asphalt Institute), SHRP gyratory Reinhart (FHWA field trailer), and Marshall hammer (Arizona DOT). These specimens were tested using the RSST-CH at UC-Berkeley with the prototype of the SHRP shear machine (also known as the universal testing machine), along with field cores from the section where the field mix was taken.

Using a SHRP gyratory compactor by another manufacturer additional specimens were prepared by the Asphalt Institute using a laboratory mix with the same gradation and asphalt content as the field mix. These specimens were then tested at the Asphalt Institute using the commercial version of the SHRP shear tester manufactured by Cox and Sons.

The rolling wheel, kneading, and Texas gyratory specimens were all cored and cut to their final dimensions from larger compacted masses. The SHRP gyratory and Marshall hammer specimens were cut to their final heights but had as-compacted diametral perimeters. The results of testing to a 2 percent permanent shear strain using the RSST-CH are plotted in Figure 7.

The data indicate that the rolling wheel compactor best duplicated the permanent shear deformation resistance of the field cores. The Texas gyratory specimens had somewhat less resistance than the field cores, whereas the kneading specimens had somewhat more resistance. Note that if the kneading-compacted specimens had lower air void content, higher shear resistance would be expected. The SHRP gyratory and Marshall specimens had much more resistance than the field cores. In addition, the Marshall specimens could not be compacted to the same low air void contents as the other specimens.

Three different SHRP gyratory compactors were used in this study. The specimens fabricated by those compactors were tested using two different shear machines. It must be noted (see Figure 7) that the results are quite similar, indicating good reproducibility of the compaction equipment and of the testing equipment.

It is important to note that differences were found between the results obtained from field mix with laboratory compaction and laboratory mix compacted with the rolling wheel compactor (see Figure 5). Those results suggested that the STOA aging procedures used in this project [4 hr at 135°C (275°F)] might not be representative of the aging occurring in the mix conditions in Arizona. However, the test results obtained from specimens compacted using the SHRP gyratory prepared with field mix and laboratory mix did not show any differences (see Figure 8). The most likely reason for this is the fact that the aggregate structure created by the SHRP gyratory overwhelms all other effects.

SUMMARY AND RECOMMENDATIONS

This paper presents a case study where performance-related tests developed by Project SHRP-A003A were used in the mix design process. The performance-based mix design system used is derived from SHRP-A003A findings and uses the RSST-CH to evaluate the rutting propensity of the mix. It uses the results of flexural bending beam tests in an analysis system to evaluate site-specific structural pavement fatigue life. Based on these concepts, an asphalt content of 4.2 percent by weight of aggregate was selected, and two test sections 1.6-km (1 mi) long were constructed in Phoenix, Arizona, in November 1993. The field mix and cores were then subjected to a Marshall mix design evaluation. The results indicated that according to that methodology, the mix would be very stable.

The mix was also evaluated based on Superpave Level I design concepts. The mix would not be acceptable within the Superpave framework because the field mix gradation crosses the restricted zone for a 19-mm nominal size. Furthermore, results from the gyratory compactor indicated that the mix would require about 1.0 percent more asphalt content to satisfy the 4.0 percent air void requirement. Tests were executed with 5.6 percent asphalt content (by weight of aggregate) with the RSST-CH, and based on the performance-based mix design system, the mix with higher asphalt would likely exhibit premature rutting.

Cores from the field were also subjected to the Hamburg wheel test track; the results showed that the mix satisfies the requirements associated with that equipment, indicating a mix with high resistance to rutting and to stripping. Preliminary field observation over one summer, with temperatures above normal, indicated that the mix is performing well, with virtually no rutting.

Comparisons of performance between several laboratory compaction methods and field cores over a wide range of air void contents revealed that the rolling wheel compactor produces specimens that have permanent deformation performance properties similar to those of field cores.

It appears that the mix selected will be able to satisfy the design requirements. It should therefore be asked why Superpave Level I is not capturing the good performance of this mix. Initially, Level I mix designs were proposed for traffic levels lower than 1 million ESALs (*10*); however, the Superpave manual now recommends Superpave Level I for traffic levels higher than 100 million ESALs.

One could consider that Superpave Level I might be more conservative because it would have rejected this mix. However, the

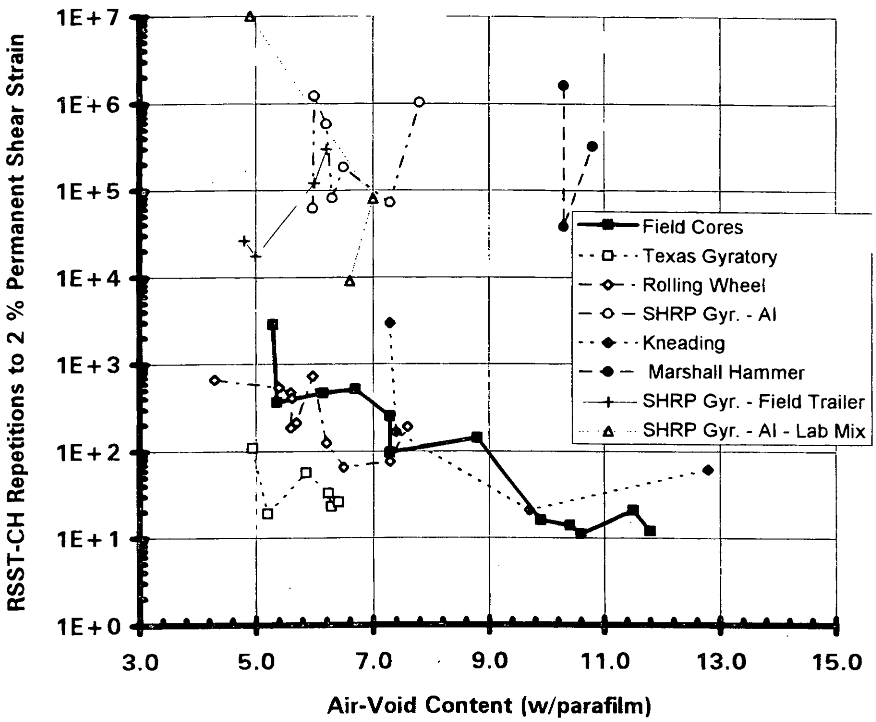

FIGURE 8 Comparison of results of RSST-CH tests for different compaction methods.

main criterion for rejection was the gradation crossing the gradation-restricted zone. Except for that reason, the mix could be considered marginally acceptable with a 5.1 to 5.2 percent asphalt content (by weight of aggregate). At those asphalt contents the predictions from the performance-based mix design system suggest that the mix would likely exhibit permanent deformation. Furthermore, ADOT experience would avoid using such high asphalt contents in that pavement section.

It is therefore recommended that performance-based mix design concepts be evaluated for implementation and that further evaluation be made in conditions similar to those presented in this paper before the Superpave Level I mix design is implemented for high-volume roads without the corresponding performance-related tests proposed in Superpave Level III. With this consideration, ADOT now has two projects under contract to further evaluate SHRP aggregate asphalt and mix design recommendations, and another project is planned for 1995.

ACKNOWLEDGMENT

The authors express their appreciation for the collaboration and efforts of the following: Mark Bouldin of Applied Paving Technology; Carl Monismith, Tom Mills, and Clark Scheffy from the University of California at Berkeley; Douglas Forstie, Larry Scofield, and Julio Alvarado from the Arizona Department of Transportation; Robert McGennis and Mike Anderson of the Asphalt Institute; FNF Construction Company and its construction crew; and Bernard A. Vallerga from B. A. Vallerga. Inc. Mike Anderson's critical review of the draft of this paper is acknowledged, recognized, and appreciated.

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Publication of this paper sponsored by Committee on Characteristics of Bituminous Paving Mixtures To Meet Structural Requirements.