# Evaluation of Marshall and Hveem Mix Design Procedures for Local Use

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Conventional methods of mix design can sometimes result in materials that do not perform satisfactorily. In countries that experience extremes of temperature such as Saudi Arabia, the resultant failures can be severe, often occurring soon after the road is opened to traffic. A laboratory evaluation of Marshall and Hveem mix designs was undertaken with an objective of minimizing permanent deformation in asphaltic layers. Five different gradations were selected based on Ministry of Communications specifications. The design procedures were examined, and the mixes were subjected to dynamic and static testing to evaluate resilient modulus, split tensile strength, stiffness, and creep compliance characteristics. The test results indicated that Hveem mixes possessed better engineering properties than those designed by the Marshall method because the Hveem method can better identify mixes with high rutting susceptibility. Recommendations for additional testing techniques could be used for both mix design and quality control purposes.

Over the past two decades, Saudi Arabia has initiated massive construction programs to modernize and improve its highway network. In the short span of 20 years, Saudi Arabia has built an impressive highway network comparable to that of many developed countries. This network—which includes more than 3,600 km (2,200 mi) of divided highways, more than 30,000 km (18,600 mi) of paved roads, and thousands of bridges, some of which are marvels of engineering achievement—was built at a cost of more than 100 billion Saudi riyals ($27 billion) (*1*). Most of these roads have served for more than a decade, and a number of them have started to fall apart. The rate of deterioration of pavements has been augmented by increasing traffic and axle loads and a lack of good-quality materials. Roads are designed for lives of 15 to 20 years before they need any major maintenance. However, during the past few years these roads have experienced excessive failure (rutting) at an early stage of pavement life.

The rutting problem, because of its extent and importance, has attracted the attention and care of many highway authorities. Khan et al. (*2*) pointed out that the requirements and specifications used in Saudi Arabia allow construction with mixtures susceptible to rutting because of the following factors:

1. Unlimited amount of natural sand,
2. Low voids in mineral aggregate (VMA),
3. High asphalt content, and
4. No measure of shear strength.

Most asphaltic paving technologists and literature on the subject agree that for good performance asphaltic concrete must have high stability and durability values. For asphaltic concrete to have good stability (i.e., resistance to stress), it must have adequate strength in tension to prevent cracking and adequate strength in shear to prevent deformation or rutting. The literature has indicated that Hveem stability yields a measure of the angle $\varphi$ (angle of internal friction in the Coulomb-Mohr equation), which furnishes resistance to rutting, and that the Marshall stability is a measure of $c$ (cohesion in the Coulomb-Mohr equation) of tensile strength to resist cracking in pavement (*3*).

Because the mix design procedure currently used in Saudi Arabia—the Marshall mix design—does not measure shear strength of the paving mixture, an attempt was made to explore and evaluate other design procedures, such as the Hveem mix design method, and to compare their abilities to predict the strength properties of designed mixes (especially rutting resistance) and in-service performance using laboratory tests. Additional laboratory tests, such as static creep and resilient modulus, were used to characterize the mechanical properties of asphalt mix in order to predict the permanent deformation (rutting) that will occur when the mix is used in a pavement of given construction and subjected to the unique traffic loading and climatic conditions in Saudi Arabia.

## STUDY APPROACH

A systematic study approach was important in order to achieve the study objectives. The study included three main interconnected tasks. The first task was material collection and mix design. The second task involved laboratory testing and evaluation. The third task involved analyzing data and making conclusions, and recommendations. A schematic for the study approach is shown in Figure 1.

The first task involved material characterization and the design of five mixes for five gradations according to the Ministry of Communications (MOC) specification using the Marshall mix design method (ASTM D1159) and the Hveem mix design method (ASTM D1560 and ASTM D1561). These mixes were subjected to further characterization tests, such as the resilient modulus, split tensile, and static creep tests, in order to provide a better evaluation and basis for comparing the two mix design methods, to develop recommendations to improve local mix design, and to minimize the rutting problem on local roads.

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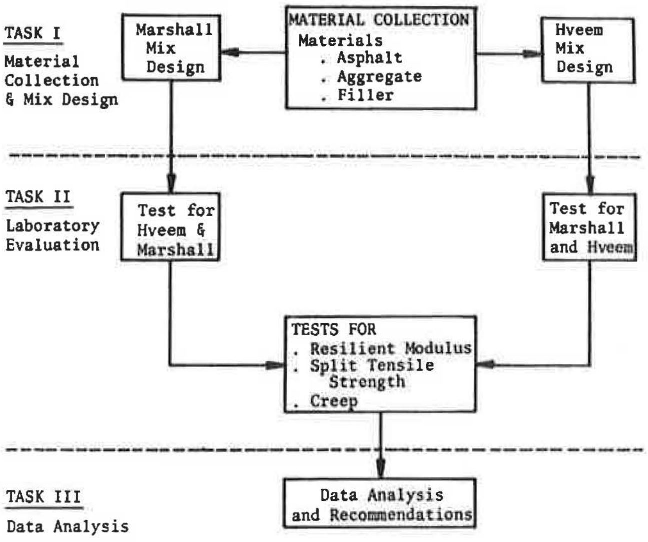

**FIGURE 1 Study approach.**

## MATERIAL CHARACTERIZATION AND MIX DESIGN

Material characterization included evaluation of engineering properties of pavement component materials (asphalt and aggregate); the laboratory mix design included determination of optimum asphalt content for different gradations by two mix design procedures. Asphalt cement with 60/70 penetration was used in this study. A series of tests, including penetration, flash point, softening point, specific gravity, and solubility in trichloroethylene, was conducted to identify the basic physical properties of the asphalt.

Five gradations were selected for this study: three gradations for wearing course (W-1, W-2, and W-3) and two gradations for base course (B-1 and B-2) as defined by MOC specifications (*4*), which are shown in Table 1. The adopted gradation for the W-1, W-2, W-3, B-1, and B-2 mixes are shown in Figure 2. The aggregates were subjected to further testing to evaluate other physical properties that are significant in hot-mix asphalt surfaces. These tests included Los Angeles abrasion, soundness, water absorption, and specific gravity tests. Material properties are shown in Table 2. Properties were within the limits specified by MOC.

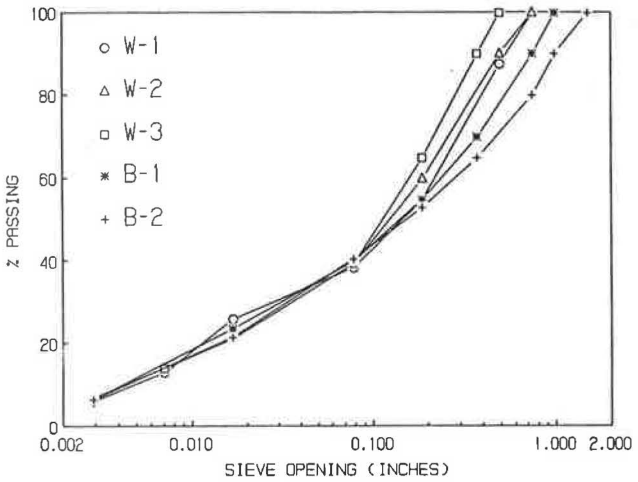

**FIGURE 2 Grading curves of aggregates used in mix design.**

### Marshall Mix Design

The five selected gradations were designed by using the Marshall method and the Hveem method of mix design. To determine the optimum asphalt content for each mix, Marshall testing was conducted at 60°C (140°F). The percentages of air voids in the specimens were determined from the bulk specific gravity of the specimens (ASTM D2726-82) and the maximum theoretical specific gravity of voidless mix (ASTM D2041-82). Stability loss, after immersion in water at 60°C (140°F) for 24 hr, was also determined to check resistance to stripping, which was estimated on the basis of strength index. The optimum asphalt content of the mix was then calculated in accordance with the recommendation of the Asphalt Institute (1981). Marshall properties are shown in Figure 3; optimum

TABLE 1 DESIGN GRADING OBTAINED FOR MIX DESIGN

| Sieve Size | Wearing Course (W) Gradation Designation | | | Base Course (B) Gradation Designation | |
|---|---|---|---|---|---|
| | W-1 | W-2 | W-3 | B-1 | B-2 |
| 1½ inch | - | - | - | 100 | 100 |
| 1 inch | - | - | - | 100 | 90 |
| 3/4 inch | 100 | 100 | - | 90 | 80 |
| 1/2 inch | 87.5 | 90 | 100 | - | - |
| 3/8 inch | - | - | 90 | 70 | 65 |
| No.4 | 55 | 60 | 65 | 55 | 53 |
| No.10 | 38.5 | 39.5 | 39.5 | 40 | 40.5 |
| No.40 | 26 | 21 | 21 | 23.5 | 21.5 |
| No.80 | 13 | 14 | 14 | - | - |
| No.200 | 6 | 7 | 7 | 6.5 | 6.5 |

Saudi Arabian Ministry of Communications Specification

TABLE 2 MATERIAL PROPERTIES

| Material | Physical Properties | Mix Designation | | | | | Saudi Arabian Ministry of Communications Specification Limits |
|---|---|---|---|---|---|---|---|
| | | W1 | W2 | W3 | B1 | B2 | |
| Aggregate | • L.A. Abrasion | 22 | 22 | 22 | 23 | 23 | 30 |
| | • Soundness<br>5 cycles | | | | | | |
| | - Coarse aggregate | 2.86 | 2.86 | 2.63 | 3.2 | 3.4 | 10 max |
| | - Fine aggregate | 1.96 | 1.96 | 1.95 | 2.2 | 2.3 | 10 max |
| | • Bulk Specific Gravity (Sat. surface dry) | 2.597 | 2.611 | 2.592 | 2.598 | 2.60 | |
| | • Water Absorption | | | | | | |
| | - Coarse aggregate | 2.625 | 2.63 | 2.64 | 2.6 | 2.56 | 4 max |
| | - Fine aggregate | 3.83 | 3.82 | 3.83 | 3.62 | 3.61 | |
| Asphalt | • Flash Point, Cleveland open cup | 628°F | | | | | 450 minimum |
| | • Penetration, 77°F, 100 gm, 5 sec. | 61 | | | | | 60-70 |
| | • Specific Gravity, 25°C | 1.043 | | | | | |
| | • Solubility in Trichloro-ethylene | 99.9 | | | | | 99.9 min |

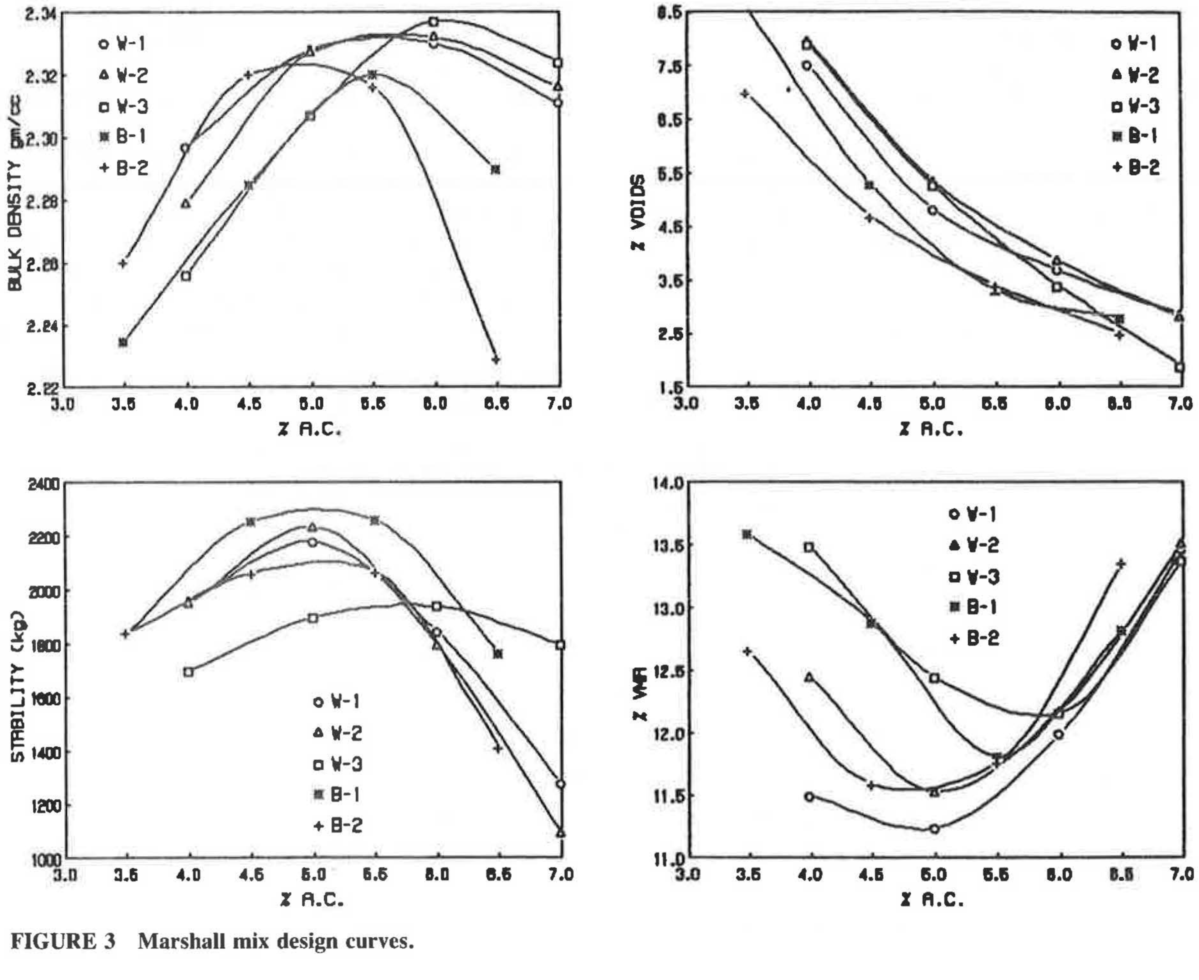

FIGURE 3 Marshall mix design curves.

asphalt content and Marshall properties at these asphalt contents for each mix series are shown in Table 3. The optimum asphalt content for all mixes seems to be affected by the gradation: the finer the gradation, the higher the optimum asphalt content.

### Hveem Mix Design

The Hveem mix design procedure used in this study was carried out in the following steps:

1. Centrifuge kerosene equivalent test,
2. Preparation of test specimen (by California kneading compactor), and
3. Hveem stability test.

The specimens prepared by the kneading compactor were tested for Hveem stability. The bulk density test was performed as described in ASTM D2726; the percentage of air voids was determined from bulk specific gravity and maximum theoretical specific gravity of voidless mix. The optimum asphalt content was determined based on stabilometer values, air voids, and surface flushing and bleeding. The pyramid technique (*5*) was used to determine the optimum asphalt content for each mix. The Hveem properties at optimum asphalt (designed by Hveem mix design) are summarized in Table 4 and shown in Figure 4. The Hveem stability for the W-3 mix is 37, which just satisfies the minimum requirement of the Asphalt Institute but does not satisfy the Saudi minimum specification of 40. This low stability value may be attributed to the high percentage of the sand in the mix, which is about 65 percent since the percentages of air voids are above 4 percent in all five mixes.

TABLE 4 HVEEM PROPERTIES OF VARIOUS MIX SERIES AT OPTIMUM ASPHALT CONTENT

| Mix Designation | Optimum Asphalt | Hveem Stability | Air Voids % |
|---|---|---|---|
| W-1 | 5.0 | 47 | 4.3 |
| W-2 | 5.0 | 52 | 4.2 |
| W-3 | 5.5 | 37 | 4.0 |
| B-1 | 4.5 | 49 | 4.4 |
| B-2 | 4.5 | 45 | 4.6 |
| MOC Specifications | | 40 | 4-7% |

### Comparative Study

The optimum asphalt content predicted by Marshall mix design is about 0.5 percent (0.4 to 0.66 percent) more than the optimum asphalt content predicted by Hveem mix design. A relative comparison of optimum asphalt content determined by both mix design procedures is shown in Figure 5. Further, the Hveem specimens have higher bulk density and lower air void contents than Marshall specimens, indicating that a different orientation of particles is obtained and that more aggregate interlock is achieved. Hveem stability at optimum asphalt content of Marshall mix design, in Hveem mix design curves, showed a very low stability value and was below the specified minimum value of 40 for all five mixes (Figure 6), indicating that the increase in asphalt content from optimum of Hveem mix design affects Hveem stability drastically. For example, the Hveem stability in the W-2 mix dropped from 52 to 38 by increasing asphalt content by only 0.5 percent. Hence, it can be said that Marshall mix design predicts more asphalt content than the Hveem method, which may lead to rutting in the field, especially in hot climates.

## RESILIENT MODULUS TEST

The resilient modulus ($M_R$) test provides an important input for structural design of pavement systems using multilayer elastic theory. This test is basically a repetitive load test using the stress distribution principle of indirect tensile test. The horizontal deformation of a cylindrical specimen subjected to dynamic vertical loading was measured by two transducers; the load applied was measured by using a flat load cell. In each test, a static load of 10 lb was applied to hold the sample in place. The dynamic load duration was fixed at 0.1 sec, and the load frequency at 60 cycles was fixed at 50°C (122°F) to represent in-service condition. The maximum load applied and the horizontal elastic tensile deformation were recorded to determine the $M_R$ value using the following equation (*6*):

$$M_R(\mathrm{MPa}) = 10^3 P(0.9974\mu + 0.2692)/h \cdot \Delta \quad (1)$$

TABLE 3 MARSHALL PROPERTIES OF VARIOUS MIX SERIES AT OPTIMUM ASPHALT CONTENT

| Mix Designation | Optimum Asphalt Content | 1/2 hr Stability kgs | Flow 0.25 mm | Air Voids % | VMA % | 24 hrs Stability kgs | Strength Index % |
|---|---|---|---|---|---|---|---|
| W-1 | 5.5 | 2090 | 15.3 | 4.2 | 11.5 | 2060 | 98.6 |
| W-2 | 5.6 | 2060 | 14.5 | 4.3 | 11.8 | 1953 | 94.8 |
| W-3 | 5.9 | 1940 | 16.9 | 3.5 | 12.1 | 1832 | 94.4 |
| B-1 | 5.2 | 2307 | 17.5 | 3.9 | 12.3 | 1960 | 85.0 |
| B-2 | 4.9 | 2120 | 14.8 | 4.1 | 11.5 | 2040 | 96.2 |
| MOC Specification | | Minimum 700 | 10-16 | 4-7 | | | Minimum 80 |

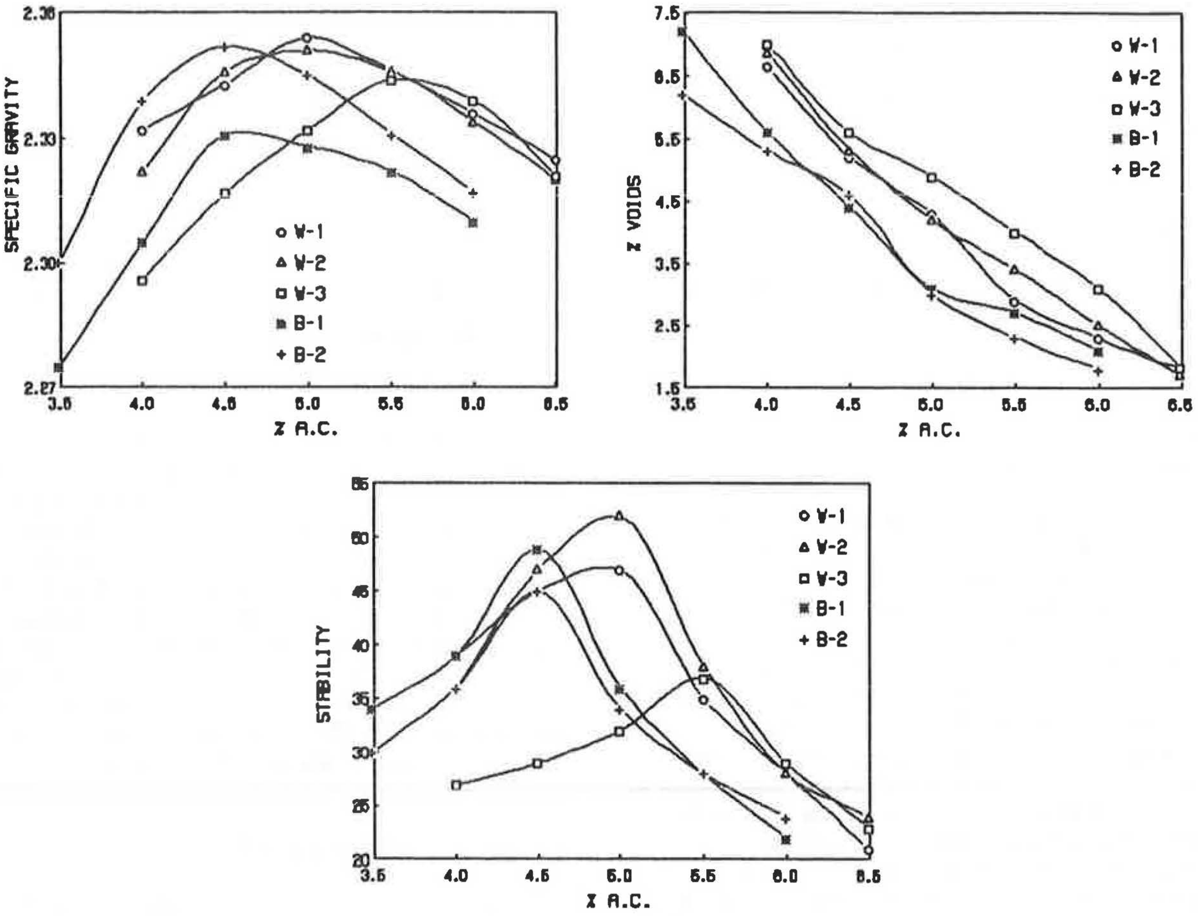

**FIGURE 4 Hveem mix design curves.**

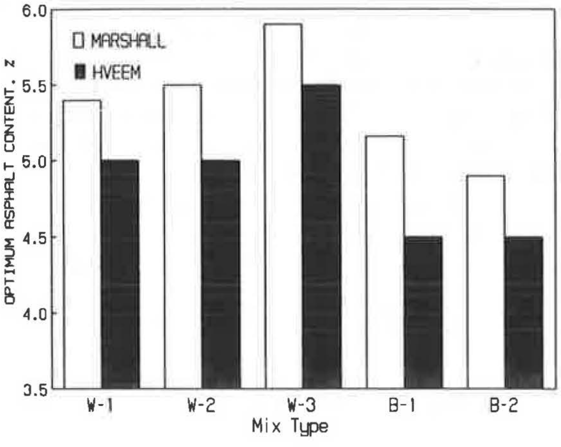

**FIGURE 5 Optimum asphalt contents determined by Marshall and Hveem mix design procedures.**

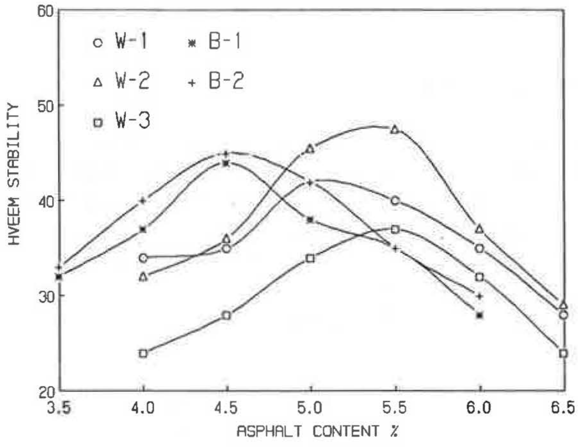

**FIGURE 6 Relationship between asphalt content and Hveem stability for Marshall-prepared samples.**

where

$P$ = applied load (kN),
$h$ = thickness of specimen (mm),
$\Delta$ = recoverable horizontal deformation across sample (mm), and
$\mu$ = Poisson's ratio.

The effect of asphalt content on the resilient modulus was studied for mixes compacted by the Marshall hammer and kneading compactor. Table 5 shows asphalt contents at maximum modulus values for all mixes prepared by Hveem and Marshall methods. These asphalt values are about 0.5 percent less than optimum values predicted by both mix design methods. Also, the optimum asphalt contents predicted by the modulus test for samples prepared by Marshall compaction for all five mixes are similar to the optimum asphalt contents predicted by Hveem mix design. The results of resilient modulus at optimum asphalt content of mixes designed by the

TABLE 5 PERCENTAGE OF OPTIMUM ASPHALT CONTENT ESTABLISHED BY RESILIENT MODULUS AND TENSILE STRENGTH TEST FOR MARSHALL AND HVEEM COMPACTIONS

| Compaction | Marshall | | Hveem | |
|---|---|---|---|---|
| Test / Mix Type | Resilient Modulus | Tensile Strength | Resilient Modulus | Tensile Strength |
| W1 | 5.0 | 5.3 | 4.5 | 5.1 |
| W2 | 5.0 | 5.4 | 4.5 | 5.3 |
| W3 | 5.5 | 5.8 | 5.0 | 5.5 |
| B1 | 4.5 | 5.0 | 4.0 | 4.8 |
| B2 | 4.5 | 4.8 | 4.0 | 4.7 |

Marshall or Hveem methods are summarized in Figure 7. The values of resilient modulus at optimum asphalt contents of Hveem mix design are consistently higher than the values of $M_R$ at optimum asphalt contents of Marshall mix design. The higher modulus for mixes designed by the Hveem method can be considered favorable because the mixtures may be less susceptible to cracking and permanent deformation.

## SPLIT TENSILE STRENGTH

Specimens prepared by Marshall and Hveem methods for optimum asphalt content and range of asphalt content failed an indirect tensile test at a loading rate of 2 in. (50.8 mm)/min. The test was conducted at 50°C. The specimens failed along the vertical diameter. Split tensile strength was determined by the following equation (*7*):

$$S_T = \frac{2P_{\max}}{\pi h D} \qquad (2)$$

where

$S_T$ = split tensile strength (psi);
$P_{\max}$ = load at failure (lb);
$D$ = diameter of sample (4 in.); and
$h$ = sample thickness (in.).

The split tensile strength at optimum asphalt contents of Marshall and Hveem design are shown in Figure 8. Mixes designed by the Hveem method are about 4 percent higher in strength than those designed by the Marshall method, indicating no significant difference in split tensile strength between both methods. Maximum values of split tensile strength were observed at optimum asphalt contents of Marshall and Hveem mixes, as shown in Table 5.

## STATIC CREEP TEST

Present design methods suffer the limitation of accuracy in determining the full effects of variation in environmental and loading conditions and material properties on pavement performance. The major improvement in hot-mix design is the ability to analyze test results quantitatively as well as qualitatively. Qualitatively, the relative improvements between mixes can be evaluated based on creep modulus at the specified temperature.

The permanent deformation of asphalt mixes depends on a number of external and inherent variables in the mix: the main external variables are overall stress condition and the temperature; the inherent variables are the mix composition. In 1973, Hills (*8*) presented a physical deformation model for asphalt mixes using static creep testing as a key tool for predicting pavement rutting.

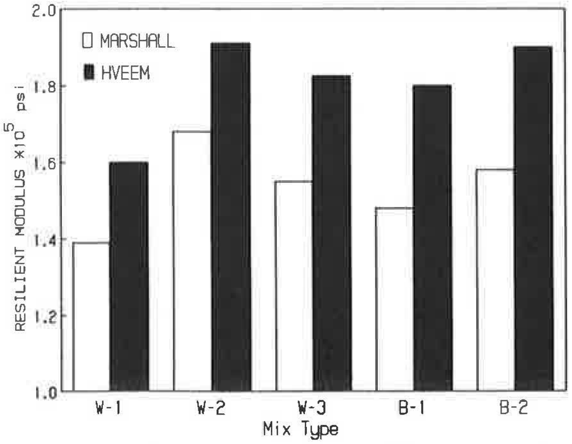

**FIGURE 7 Resilient modulus (50°C) at optimum asphalt content of Marshall and Hveem mix design.**

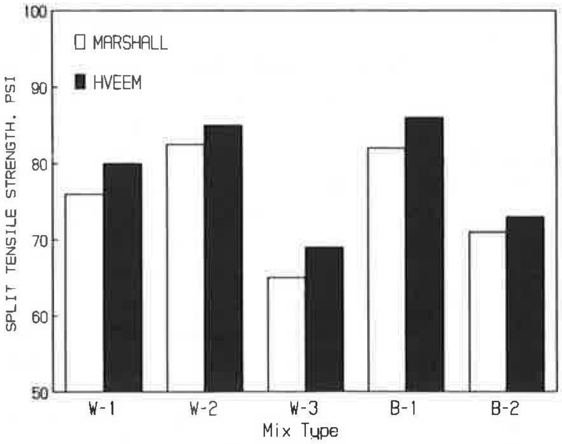

**FIGURE 8 Split tensile strength (50°C) at optimum asphalt content of Marshall and Hveem mix design.**

Creep test as described in the Shell Pavement Design Manual (*9*) was performed by applying a static load of 14.5 psi. The temperature of test specimens was kept constant as desired by means of an environmental control cabinet. Vertical deformation (displacement) was measured by dial gauges accurate to 0.0001 in.

In this study, the creep test was performed on specimens prepared by the Marhsall and Hveem methods for a range of asphalt contents, including optimum asphalt content at temperature of 50°C. The sample size recommended by Shell investigators (*9*) was governed by maximum aggregate size. For mixes W-1, W-2, and W-3, the sample size was 4 in. (10 cm) in diameter by 2.5 in. (6 cm) high; the sample size for mixes B-1 and B-2 was 6 in. (15 cm) in diameter by 4 in. (10 cm) high. Each specimen was tested at a stress level of 14.5 psi maintained for 3 hr. Before the test, a preconditioning stress of the same magnitude as the test stress was applied for at least 2 min (*10*).

Recorded deformation and applied stress were used to calculate the creep modulus (mix stiffness, $S_{mix}$) as a function of time of loading using the following equation (*11*):

$$S_{mix}(T,t) = \frac{\sigma}{\varepsilon_t} \qquad (3)$$

where

$S_{mix}(T,t)$ = mix stiffness at a specified temperature ($T$) and time of loading ($t$);
$\sigma$ = applied stress (psi); and
$\varepsilon_t$ = axial strain at $t = \Delta h/h_o$ where $\Delta h$ is change in height of specimen, and $h_o$ is original height of specimen.

Further, these results (i.e., $\varepsilon_t$ and $\sigma$) were used to calculate creep compliance ($J_t$) in order to study the viscoelastic characteristics of the mixes. Creep compliance ($J_t$), was calculated by dividing the strain by applied stress as follows:

$$J_t = \frac{\varepsilon_t}{\sigma} \text{ at any test temperature } T \qquad (4)$$

where $\varepsilon_t$ is strain at time $t$, and $\sigma$ is applied stress (psi).

Stiffness results for mix W-1 designed by the Marshall and Hveem methods as a function of loading time at different asphalt contents, including optimum asphalt content, are shown in Figures 9 and 10. Stiffness decreased with loading time. Further, mixes designed by the Hveem method gave relatively higher stiffness values than those obtained from Marshall specimens at loading times greater than 1 hr. Stiffness moduli decrease as the asphalt content increases. The stiffness moduli at optimum asphalt content of both Hveem and Marshall mix design methods (200,000 and 400,000 psi) are comparable with values reported by Finn et al. (150,000 and 550,000 psi) (*12*) in a performance study for Middle East airport pavements.

Creep compliance, which is used to determine viscoelastic properties of pavement materials, was plotted as a function of loading time at different asphalt contents, including optimum asphalt content, for mix W-1 designed by both methods, as shown in Figures 11 and 12. Creep compliance increases with time. Furthermore, mixes designed by the Hveem method

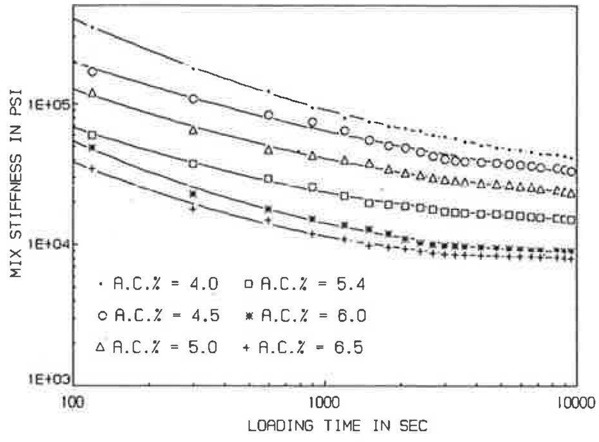

**FIGURE 9 Effect of asphalt content on mix stiffness for Marshall specimens, Mix W-1 at 50°C.**

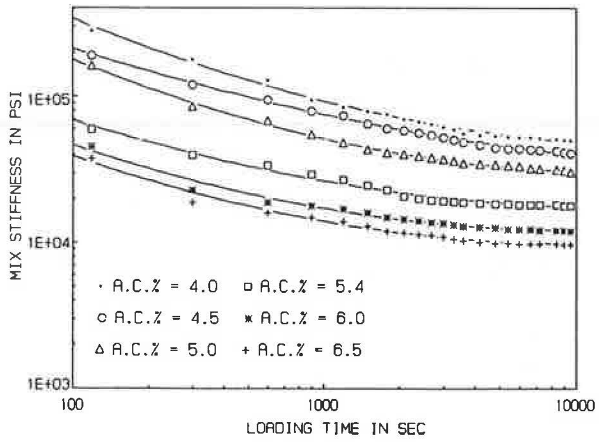

**FIGURE 10 Effect of asphalt content on mix stiffness for Hveem specimens, Mix W-1 at 50°C.**

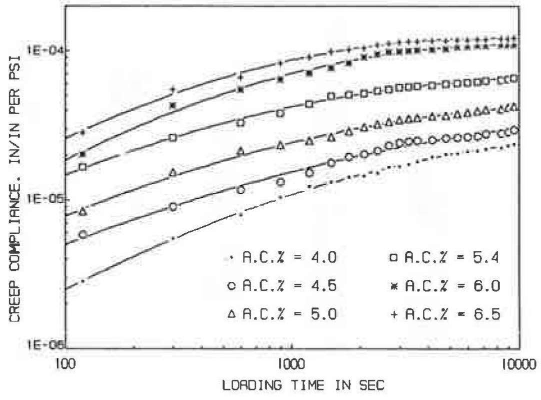

**FIGURE 11 Effect of asphalt content on creep compliance for Marshall specimens, Mix W-1 at 50°C.**

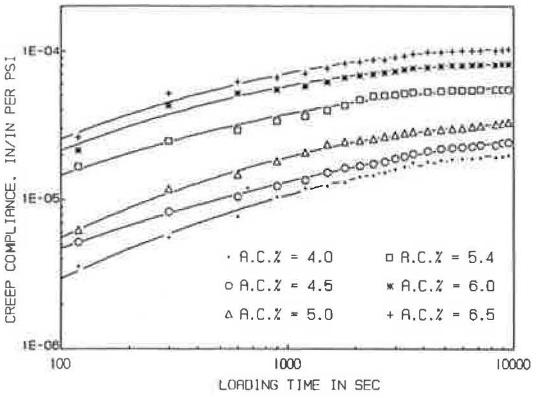

**FIGURE 12 Effect of asphalt content on creep compliance for Hveem specimens, Mix W-1 at 50°C.**

gave lower values of creep compliance than did mixes designed by the Marshall method at specified asphalt content and loading time.

In order to explore the role of asphalt content on stiffness and creep modulus, bar charts were prepared for a range of asphalt contents in the vicinity of optimum asphalt content predicted by both mix design procedures, as shown in Figures 13–16. The value of stiffness and creep compliance was chosen at the 60-min loading time. Optimum mixes prepared by Hveem had stiffness values twice those of optimum Marshall for wearing course mixes and three times those for base mixes. Moreover, the W-3 mix, which follows the gradation of MOC Type C of wearing course, had very low stiffness values (10,000 and 13,000 psi) and high creep compliance (1,050 and 800 · $10^{-7}$/psi) for mixtures designed by the Marshall and Hveem methods, respectively, indicating its high susceptibility to rutting.

## CONCLUSIONS

Based on a literature search and experiments conducted in this study, the following conclusions are drawn:

1. Marshall mix design tends to predict optimum asphalt contents that are higher than those predicted by the Hveem

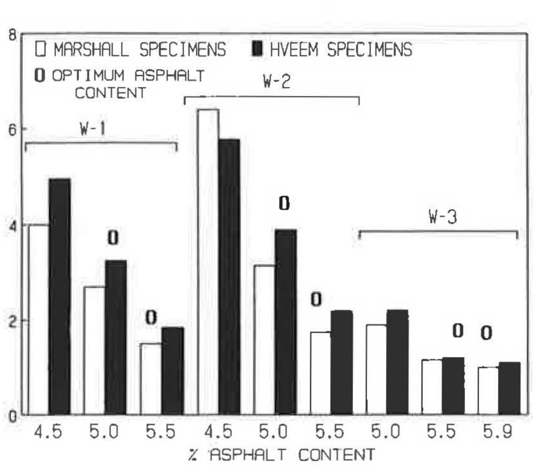

**FIGURE 13 Comparison between mix stiffness of Marshall and Hveem specimens for wearing course.**

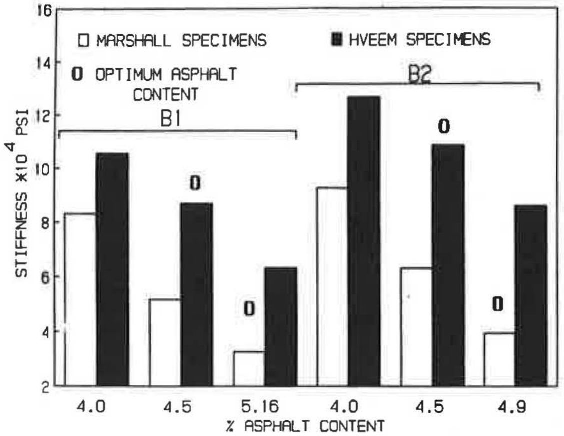

**FIGURE 14 Comparison between mix stiffness of Marshall and Hveem specimens for base course.**

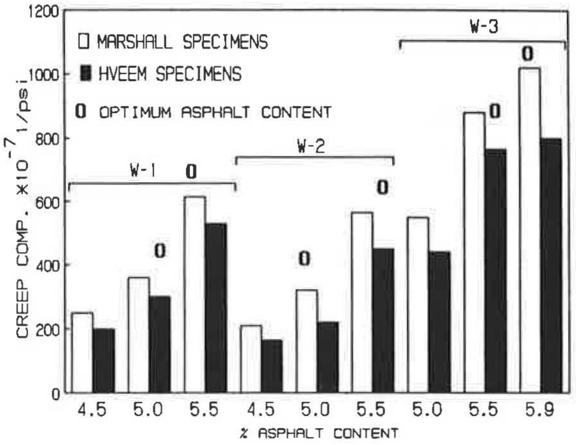

**FIGURE 15 Comparison between creep compliance of Marshall and Hveem specimens for wearing course.**

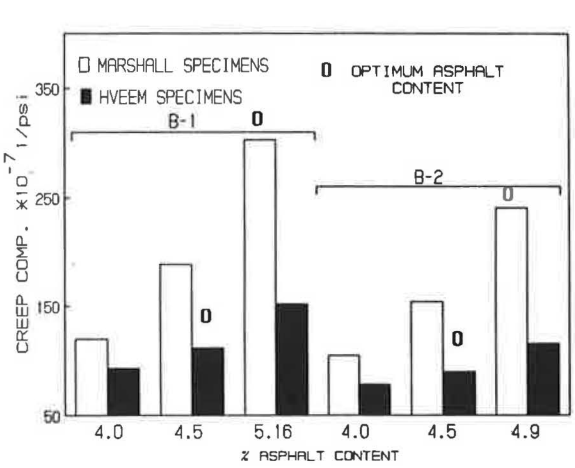

**FIGURE 16 Comparison between creep compliance of Marshall and Hveem specimens for base course.**

mix design method. In this study, the optimum asphalt contents predicted by the Marshall mix design were about 0.5 percent higher than those predicted by the Hveem mix design method.

2. Hveem specimens have a higher bulk density and a lower air void content than Marshall specimens, indicating that a different orientation of particles is obtained and that more aggregate interlock is achieved by kneading compaction.

3. Mixes designed by the Hveem method gave higher resilient modulus values, higher stiffness values, and lower creep compliance values than those obtained from mixes designed by the Marshall method.

4. Resilient modulus tests on Marshall samples predicted optimum asphalt contents that were similar to those predicted for Hveem samples. The deficiency of the Marshall mix design could be improved by using the resilient modulus test.

5. Hveem mix design seems to have a potential application for Saudi Arabia's roads because it more closely simulates field conditions and can better identify mixes with high rutting susceptibility than does the Marshall method.

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