Dune Sand-Aggregate Mixes and Dune Sand-Sulfur Mixes for Asphalt Concrete Pavements

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Results are presented of a study to determine the feasibility of using dune sand in asphalt concrete pavement in hot, desertlike climates through the use of one-size crushed aggregates, dense-graded aggregates, and powdered sulfur in the sand-asphalt mixes. Engineering properties, including Marshall design parameters, compressive strength, tensile strength, modulus of rupture, and dynamic modulus of elasticity, of the various mixes are given and discussed. Results indicate that a mixture of dune sand and asphalt is weak, unstable. easily deformed under light loads, and therefore unacceptable for pavement construction in a desertlike environment. Introducing a one-size crushed gravel at various ratios improved the mix but not sufficiently for it to pass the required standards. Introducing a dense-graded aggregate to the mix raised its properties to the required standards; however, such improvement was only achieved when the ratio of dense aggregate to dune sand was at least 60 percent to 40 percent. The results also demonstrate that the use of powdered sulfur in the sand-asphalt mixes reduces the optimum asphalt content, considerably increases the qualities of the mix even under severe environmental conditions, and reduces the pavement thickness required to protect the subgrade from deflections and the surface layer from fatigue cracking. A tentative thickness design chart of a pavement for typical traffic and environmental conditions found in desertlike areas is also presented.

In Saudi Arabia an extensive road-building program is currently under way. During the second five-year plan (which ended in 1980), about 7460 miles of asphalt roads and 6200 miles of rural roads were completed (1). Although a good percentage of these roads and of others currently planned go through sand-dune areas, dune sand had not been used as a pavement material. Instead, good-quality aggregates, which are in scarce supply, are being imported from other localities at a considerably high cost. Therefore, it seems appropriate to consider the potential of large-scale use of dune sand as a pavement material to reduce cost and save the goodquality aggregates for other construction uses.

Dune sand is a natural material that exists in abundant quantities on every continent and under almost every climatic condition. Although the existence of dune sand is characteristic of desert areas, sand is also commonly found along the shores of seas, lakes, and large streams ($\underline{2}$).

This paper presents some data from a comprehensive investigation aimed at determining the feasibility of using dune sand in asphalt concrete pavement through the use of one-size crushed aggregates, a dense-graded aggregate, and powdered sulfur in the sand-asphalt mixes $(\underline{3})$.

MATERIALS USED

Dune Sand

The dune sand selected was obtained from the dunes area west of Yuma, Arizona. The sand is composed of subrounded to subangular grains with very fine texture. It is essentially a one-size material with a uniformity coefficient of about 2 and a specific gravity of 2.65. The grain-size distribution for this sand is included in Figure 1. Quartz is the major constituent of this material. Other minerals such as plagioclase feldspars, orthoclase feldspars, and micas are also present. It is classified as an A-3(o) material.

One-Size Crushed Gravel

This aggregate is primarily a mixture of crushed gravel and limestone and was obtained from the

Tanner Pit southeast of Tucson, Arizona. The maximum particle size is 3/4 in, with only 2 percent retained on a 3/8-in sieve, as shown in Figure 1. The specific gravity is 2.65, the Los Angeles abrasion loss (AASHTO T96-65) is 20 percent, and the sodium sulfate soundness test (AASHTO T104-65) gave a loss of 6 percent. More than 90 percent of this gravel had at least one mechanically fractured face.

Dense-Graded Aggregate

The dense-graded aggregate is a mixture of four materials: 15 percent 3/4-in crushed gravel, 25 percent 3/8-in crushed gravel, 53 percent Pantano Wash sand, and 7 percent fly ash.

1. Crushed gravel, 3/4-in: This is the one-size crushed gravel discussed above.

2. Crushed gravel, 3/8-in: This material, as shown in Figure 1, has a maximum size of 3/8 in with about 20 percent retained on a No. 4 sieve. The specific gravity is 2.63, the Los Angeles abrasion loss is 20 percent, and the sodium sulfate soundness test loss is 6 percent. More than 90 percent of this gravel had at least one mechanically fractured face.

3. Pantano Wash sand: This sand was obtained from the Pantano Wash, a dry river in the Tucson area. The unwashed sand had a sand equivalent (AASHTO T176-6) of about 31 and 8 percent passing a No. 200 sieve. The sand used in this investigation was washed thoroughly until all the fines were washed out. The clean sand gave a sand equivalent of 83. The grain-size distribution for the washed sand is given in Figure 1.

4. Fly ash: The fly ash (Navajo fly ash) used in this investigation was obtained from the Western Ash Company. Its major constituents include 52.7 percent silicon dioxide, 20.5 percent aluminum oxide, and 4.9 percent ferric oxide ($\underline{4}$). The grainsize distribution is given in Figure 1.

These four materials were combined in the proportions indicated above to form a dense-graded aggregate that met the Asphalt Institute gradation limits ($\underline{5}$, Specification IVb).

Asphalt

The asphalt cement used throughout this investigation was an AR-4000 (6-70 penetration), which is widely used for hot mixes in road construction in Arizona. Its physical properties are given elsewhere $(\underline{1},\underline{3})$.

Sulfur

The sulfur used in preparing the sand-asphalt-sulfur mixes was a bright yellow elemental sulfur in a powdered form that had 99.5 percent purity. It is a commercial-grade sulfur known as Ortho Sulfur and manufactured by the Chevron Ortho-Division Company. Additional data on this sulfur are given elsewhere (3). Figure 1. Grain-size distribution curves for aggregates used.



SAMPLE PREPARATION

Mixes of Dune Sand, Aggregate, and Asphalt

The dune sand, one-size crushed gravel, and components of the dense-graded aggregate were dried to a constant weight at 230°F. The desired portions of these materials for each type of mix were combined, mixed dry, and then placed in a forced-draft oven at 300 + 5°F for at least 10 h. The asphalt was heated to $250 + 5^{\circ}F$ in an electric oven for not more than 1 h. The heated aggregate mix (sand and aggregate) was dumped into a preheated mixing bowl, a crater was formed in the aggregate, and the heated asphalt was weighed into the crater. Mixing was done with a Hobart C-10 mixer at medium speed for 90 s. This speed and mixing time produced a uniformly coated aggregate-asphalt mix. Next, the mix was placed in an oven at 250 + 5°F until it was ready for compaction.

The first combination of sand, aggregate, and asphalt (Test Series A) consisted of dune sand, 3/4-in one-size crushed gravel in various proportions, and asphalt. The proportions of sand to one-size crushed gravel were 100/0, 90/10, 80/20, 70/30, and 60/40.

The second combination (Test Series B) consisted of dune sand, the dense-graded aggregates in various proportions, and asphalt. The proportions of dune sand to dense-graded aggregates were 100/0, 80/20, 60/40, 50/50, 40/60, 20/80, and 0/100.

Mixes of Dune Sand, Asphalt, and Sulfur

Sufficient sand was weighed and placed in a forceddraft oven at $350 \pm 5^{\circ}F$ overnight. Asphalt was heated to $300 \pm 5^{\circ}F$. Sufficient powdered sulfur was weighed and maintained at a room temperature of $72 \pm 2^{\circ}F$. The order of mixing the three components resulted in either a sulfur-coated mix of dune sand and asphalt (S-A) or an asphalt-coated mix of dune sand and sulfur (A-S).

For the (S-A) mix, the preheated sand and the sulfur (at room temperature) were placed in a preheated mixing bowl and mixed at a medium speed in the Hobart C-10 mixer for about 60 s. The mixture was then hand mixed with a trowel four or five times, which took about 10 s. A crater was formed in the mix and the required amount of preheated asphalt was weighed into the sulfur-coated sand mix. Additional mixing at medium speed for about 60 s was required to coat the particles uniformly with the asphalt. This combination was designated Test Series C.

For the (A-S) mix, the heated asphalt was added to the preheated sand and the two components were mixed together in the preheated bowl of the Hobart C-10 mixer for 60 s. The sulfur (at room temperature) was then added and the entire batch was remixed for an additional 60 s. This combination was designated Test Series D.

After mixing, both mixtures were placed in an oven at 280 \pm 5°F until compaction.

TEST RESULTS AND DISCUSSION

Test Series A

The Marshall test procedure for evaluating the performance of hot asphalt concrete mixes (ASTM.D1559) was used to evaluate the properties of these mixes. The Marshall test was performed on specimens prepared for the medium-traffic category (50 blows per end). The Marshall design criteria ($\underline{6}$) were used to evaluate the results obtained.

The Marshall stability results for these mixes are given in Figure 2, and they indicate that with an asphalt content up to 7 percent by total weight, the Marshall stability generally increases as the ratio of dune sand to crushed gravel decreases. The highest stability value obtained was about 200 lbf for the 60/40 mix. This stability value is well below the minimum 500-lbf value required for roads in the medium-traffic category (6), and therefore no further testing was conducted on the Test Series A combinations. The test results also indicated that increasing the amount of crushed gravel increased the unit weight from 112 to 130 lb/ft3, reduced the Marshall flow from 25 to 6, reduced the percentage of air voids from 25 to 12, decreased the percentage of voids in mineral aggregate (VMA) from 37 to 26, and increased the percentage of filled voids (3).

Test Series B

The Marshall test procedures were also used to evaluate the properties of these mixes. Specimens were compacted with 50 blows per end (medium-traffic category).

The Marshall stability results for these mixes are given in Figure 3; they indicate that as the ratio of dune sand to dense-graded aggregate decreased (less sand and more aggregate), the Marshall stability increased slightly up to a ratio of 50/50 and then increased considerably as the amount of sand decreased further. The combination of dune sand and asphalt (100/0) gave a stability value of 82 lbf at an optimum asphalt content of 6.5 percent. The combination of dense-graded aggregate and asphalt with no dune sand (0/100) gave a maximum stability value of 1860 lbf at an optimum asphalt content of 5.4 percent.

To meet the stability requirement for mediumtraffic conditions (500 lbf minimum) the ratio of dune sand to dense-graded aggregate should not be lower than 40/60 (i.e., a minimum of 60 percent dense-graded aggregate) at the corresponding optimum asphalt content. Although a mix of this ratio met the minimum required stability and flow values, it failed to meet the durability requirements such as percentage of air voids and percentage of filled voids ($\underline{3}$). Furthermore, such a mix would not be economical due to the large percentage of imported dense-graded aggregates. Accordingly, no further testing was conducted on Test Series B.

Test Series C and D

All specimens used in these series were from mixes that had an asphalt content of 5 percent by total weight. This was based on various reported results on mixes of sand, asphalt, and sulfur (7-9). The sulfur content in the mixes varied from zero to 20 percent by total weight.

For the Marshall stability test on these mixes, each specimen was compacted by applying 10 blows to each end of the specimen. It was decided this would be the optimum compaction effort after a series of test specimens (80 percent sand, 5 percent asphalt,

Figure 2. Relation between Marshall stability and ratios of dune sand to one-size crushed gravel (Test Series A).



Figure 3. Relation between Marshall stability and ratios of dune sand to densegraded aggregate (Test Series B).



and 15 percent sulfur) had been compacted by using 2, 5, 10, 15, 25, and 50 blows per face $(\underline{3})$.

The Marshall stability results for the (S-A) mixes and the (A-S) mixes are given in Figure 4 with data for a similar mix that used a binder of molten sulfur and asphalt added to the same dune sand in a one-wet-mixing process (7). The results indicate that both the (S-A) and (A-S) mixes have their maximum Marshall stability values at 15 percent powdered sulfur. The maximum Marshall stability value for the (A-S) mix was 6500 lbf and that for the (S-A) mix was 5983 lbf. A sulfur content greater than 15 percent reduced the stability of both mixes.

The sharp increase in Marshall stability from a weak, unstable sand and asphalt mix (82 lbf) to a strong, stable mix of sand, asphalt, and sulfur is attributed to the filling of the voids by the recrystallized sulfur. The sulfur acts as a filler in addition to bonding the sand particles and thus increasing their interlocking. The (S-A) mix gave a slightly lower stability value because the particlet to-particle contact was asphalt, a viscous material, rather than sulfur, a solid material below 235°F.

Aboaziza (7) used a premixed blend of molten sulfur and asphalt mixed in a high-shear mixer at 300°F as the binder, and he mixed it with the dune sand in a one-wet cycle. Similar results to those shown in Figure 4 were reported but with slightly lower Marshall stability values.

Figure 5 presents the effect of increasing the percentage of sulfur in the mix on its unit weight. The increase of sulfur between 0 and 15 percent significantly increases the unit weight. Sulfur additions beyond 15 percent do not increase the unit weight very much, if at all. The main reason for the increase in unit weight is the high specific gravity of sulfur (about 2.0), which moves in to fill the voids between the sand particles. It appears that at sulfur additions above 15 percent the sulfur tends to start displacing equal volumes of sand, the specific gravity of which is 2.65.

The effect of sulfur addition on the Marshall flow is given in Figure 6, which indicates sharp reductions in the flow as the percentage of sulfur increases. This reduction in flow is attributed to



Figure 4. Relation between Marshall stability and sulfur content in mixtures of dune sand, asphalt, and sulfur.

the brittle nature of the recrystallized sulfur and the increased unit weight of the mix.

Figure 7 shows the effect of the sulfur addition on the percentage of air voids in the mix, which indicates sharp reductions of the air voids and results in more stable mixes. The mix of dune sand and asphalt without sulfur has a very high amount of air voids due to the uniformity of the sand-grain size. When sulfur is added to the mix, it fills the voids and results in a denser mix on recrystallization. It may be pointed out that although the percentage of air voids in the mixes exceeds the recommended range for the Marshall design criteria (6), it had been shown that the permeability of mixtures

Figure 5. Relation between unit weight and sulfur content of mixes of dune sand, asphalt, and sulfur.



Figure 6. Relation between Marshall flow and sulfur content of mixes of dune sand, asphalt, and sulfur.



of sand, asphalt, and sulfur is much lower than that of conventional asphalt concrete mixes for a given content of air voids (<u>10</u>). Burgess and Deme (<u>10</u>) reported that at 15 percent content of air voids, sand-asphalt-sulfur mixes were considered impervious with a permeability coefficient of about 1.0 x 10^{-6} cm². Conventional dense-graded asphalt concrete mixes reached similar permeability values at about 4-5 percent content of air voids (<u>10</u>).

Similar results were obtained by Aboaziza (7) by using molten sulfur. These results are also given in Figures 5 through 7 for purposes of comparison.

Based on the above test results, the (A-S) mixes in Test Series D appeared to give the overall best performance for the mixes of sand, asphalt, and sulfur. The (A-S) mix with dune sand, asphalt, and sulfur contents of 80, 5, and 15 percent, respectively, was therefore considered for further testing. Additional tests included tensile strength, compressive strength, soaked compressive strength, flexural strength, and dynamic modulus of elasticity.

Tensile-Strength Test

The static double-punch test (<u>11</u>) was proposed as a simple indirect tension test for determining the tensile strength of concrete. Fang and Chen (<u>12</u>) developed, both theoretically and experimentally, the applications of the double-punch test to cohesive soils. Jimenez (<u>13</u>) extended the use of the double-punch method to test asphaltic mixtures for tensile strength, indicating its better repeatability than the split-cylinder (Brazilian) test.

The static double-punch test is conducted by using two steel disks (punches) centered on both flat ends of a cylindrical specimen. The vertical load is then applied slowly on the punches until the specimen reaches failure. The tensile strength of the specimen is calculated from the maximum load by a simple equation based on the theory of perfect plasticity $(\underline{12})$.

In this investigation, specimens for the static double-punch test were 4 in in diameter and 2.5 in high. The mixes of sand, asphalt, and sulfur were compacted by the Marshall compactor (10 blows per

Figure 7. Relation between percentage of air voids and sulfur content of mixes of dune sand, asphalt, and sulfur.



Figure 8. Effect of temperature on tensile strength of various mixes.



Figure 9. Effect of temperature on compressive and immersion compressive strength of mixes of dune sand, asphalt, and sulfur.



end). Specimens were tested in an Instron Universal Testing Machine at a deformation rate of 0.05 in/min. After compaction, the specimens were cured at various temperatures for 24 h prior to being tested. The curing (and testing) temperatures of $40 \pm 5^{\circ}$ F, 77 $\pm 5^{\circ}$ F, and $140 \pm 5^{\circ}$ F were selected to represent the average low temperature, the average mean temperature, and the average high temperature in a desert environment, respectively (3, 14).

Tensile-strength data for these (A-S) mixes are given in Figure 8 along with strength data for a sand-asphalt mix without sulfur and data for a mix of sand, asphalt, and molten sulfur obtained by Aboaziza $(\underline{7})$. The results indicate significant improvement in the tensile strength of the sand-asphalt mix on addition of 15 percent sulfur in either molten or powdered form. The mix without sulfur had very low tensile-strength values at temperatures above 70°F. Similar tensile-strength values were obtained for the powdered-sulfur (A-S) mix and the molten-sulfur (one-wet-cycle) mix, with significant reductions in strength values as the curing (and testing) temperature increased from 40° F to 140° F. This reduction in tensile strength is attributed to the fact that the binder, and thus the mix, becomes softer and more flexible, which results in a progressive decrease in tensile strength as temperature increases.

Unconfined-Compression Test

The compressive strength of the (A-S) mix was determined according to the ASTM.DL074 (AASHTO T167) test procedure. The specimens were compacted statically to their respective unit weights obtained in the Marshall test. The specimens were 4 in in diameter and 4 in in height. After compaction, the specimens were cured at various temperatures for 24 h prior to testing. After being cured, the specimens were immediately tested in compression at a deformation rate of 0.05 in/min.

Figure 9 shows the compressive-strength results for the (A-S) mix as a function of curing (and testing) temperatures, which indicates that the compressive-strength values decreased as the temperature increased due to the softening effects of the binder. It may also be pointed out that the addition of sulfur to the sand-asphalt mix significantly increased the compressive strength (<u>1</u>). The compressive-strength values for the sand-asphalt mix were 950, 180, and 5 psi at temperatures of 40, 77, and 140°F, respectively (<u>1</u>); these values are compared with values of 940, 370, and 235 psi, respectively; for the (A-S) mix.

Immersion Compressive Strength

The immersion compressive strength of specimens similar to those tested for the standard compressive strength was tested after an additional 24-h immersion in water at the same temperatures at which they were cured. The immersion compression test results at the three temperature levels, shown in Figure 9, are lower than the respective standard compressivestrength values.

If we take the ratio of the immersed compressive strength to the respective standard compressive strength as an index for retained strength, the results indicate a minimum retained strength of about 73 percent for the temperature range tested. The highest index of retained strength for the sand-asphalt mix (without sulfur) was reported by Aboaziza $(\underline{7})$ to be only 45 percent. This demonstrates that the addition of sulfur in sand-asphalt mixes significantly increases their strength and durability and hence their resistance to stripping or debonding.

Flexural Strength Test

The modulus of rupture, which measures the flexural strength of the (A-S) mixes, was determined by using simple beams with third-point loading tests. These tests were conducted according to the ASTM C78 (AASHTO T97) test procedure. The beam specimens, $3 \times 3 \times 11.25$ in, were statically compacted to the corresponding unit weights obtained in the Marshall test. After compaction, the beams were cured at the various temperatures for 24 h. After being cured, the beams were tested at a deformation rate of 0.05 in/min.

Flexural strength data for these (A-S) mixes are

Figure 10. Effect of temperature on flexural strength of various mixes.



Figure 11. Effect of temperature on dynamic modulus of elasticity of various mixes.



Table 1. Comparison of dynamic moduli of elasticity obtained by different methods.

given in Figure 10 along with strength data for a sand-asphalt mix without sulfur and data for a mix of sand, asphalt, and molten sulfur obtained by Aboaziza (7). The results indicate significant improvement in the flexural strength on addition of sulfur, in either powdered or molten form, to the sand-asphalt mix. It may be pointed out that at 77°F, the mix without sulfur had no flexural strength and could not support its own weight, whereas with 15 percent sulfur, the mixes of sand, asphalt, and sulfur had a flexural strength of about 200 psi at that temperature.

Dynamic Modulus of Elasticity

The dynamic or resilient modulus of elasticity is considered one of the most important characteristics of a pavement material. Use of the elastic theory (multilayered systems) is essentially dependent on application of this modulus. The dynamic modulus of elasticity is defined as the ratio of applied stress to the recoverable strain as obtained by dynamic measurements. In this investigation, the dynamic modulus of elasticity for the (A-S) mixes was obtained by using the dynamic double-punch test (15).

Jimenez (<u>15</u>) extended the use of the double-punch test to determine the dynamic modulus E_D of asphaltic concrete. Fatani (<u>3</u>), Aboaziza (<u>7</u>), and Jimenez (<u>15</u>) have discussed this procedure and the theory used to formulate the equation for calculating E_D in more detail.

The test data for dynamic modulus E_D -values for the (A-S) mixes are given in Figure 11 along with data for a sand-asphalt mix without sulfur and data for a mix of sand, asphalt, and molten sulfur obtained by Aboaziza (7). The data indicate the superiority of the mixes of asphalt, sand, and sulfur over the sand-asphalt mixes (without sulfur), particularly at high temperatures. All mixes indicate a reduction in E_D -values with increases in temperature.

Table 1 shows a comparison between the values of the dynamic modulus of elasticity at the three temperature ranges reported here and those from other investigations $(\underline{7}, \underline{16-18})$ by using different techniques with or without sulfur. It can be noted that the dynamic modulus results from the double-punch test are in general agreement with those obtained by using the Schmidt method (<u>16</u>), especially at the low testing temperature. The weak, unstable sand-asphalt mix gave E_D -values either below or at the lower range of the typical values of dynamic modulus obtained for a dense-graded aggregate-asphalt mix along the entire temperature range under consideration (<u>18</u>).

At low temperatures, the addition of sulfur to sand-asphalt mixes improved the E_D -values to the middle ranges of E_D for the dense-graded aggregate-asphalt mix. The improvement approached the

F Reference
(16)
(16)
(17)
$(\overline{7})$
$(\overline{7})$
(3)
(18)
1
.2

^aMolten sulfur. ^bPowdered sulfur.

higher ranges of E_D at intermediate temperatures, and it exceeded the given ranges at the high temperatures (which are critical for arid and semiarid climates).

Figure 12. Design chart (18 000-lbf single-axle load) for mix of dune sand, asphalt, and sulfur.



Figure 13. Design chart (18 000-lbf single-axle load) for mix of dune sand and asphalt.



PRELIMINARY THICKNESS DESIGN

A preliminary theoretical analysis by using the elastic-layered system was conducted to determine the thickness requirements for selected mixes of asphalt, sand, and sulfur under typical loading and subgrade conditions (3). The thickness design requirements were evaluated for a 9000-lbf wheel load (18-kip axle load); this load was applied by dual wheels (each 4500 lbf). The contact pressure was assumed to be 80 psi acting on a circular area of 4.23-in radius. The center-to-center spacing of the wheels in the dual axle was also assumed to be three times the radius of the loaded area, i.e., 12.69 in. The Chevron Computer Program (19) with a slight modification that permits the use of dual-wheel loading (17) was used to calculate the developed stresses and strains at various strategic locations in the pavement section. The computer program listing and description are given elsewhere (3,17).

Based on data reported by others $(\underline{17},\underline{20})$, an average dynamic modulus for dune-sand subgrades is about 3 x 10⁴ psi. The E_D-values used for the mixes of sand, asphalt, and sulfur in this analysis at 40, 77, and 140°F are 1.11 x 10⁶, 6.3 x 10⁵, and 2.4 x 10⁵ psi, respectively.

Based on the above design criteria and the elastic properties of the dune sand and (A-S) mixes, a set of thickness design charts was developed $(\underline{3})$. The outline of the development procedure for the charts is detailed elsewhere $(\underline{3})$. Figure 12 presents a thickness design chart for the (A-S) mixes at these three effective temperatures with a subgrade modulus of 3×10^4 psi [California bearing ratio (CBR) of 20]. As shown, the design curves are steep and closely spaced, which indicates that a great increase in the expected number of load applications requires only a small increase in pavement thickness and that this type of pavement can withstand a great number of load repetitions with reasonable thickness requirements, even at high temperatures.

AlSalloum $(\underline{17})$ presented a similar design chart for sand-asphalt mixes (without sulfur), which is reproduced here as Figure 13. If we compare Figures 12 and 13, there is an indication that significant reductions in pavement thickness required to withstand the same conditions are achieved with additions of sulfur.

It may be pointed out that the above analysis and chart are of a preliminary nature and were based on the assumed design criteria. Therefore, they should be used as guidelines for preliminary thickness design only until more detailed and inclusive design charts are developed.

CONCLUSIONS

A mix of dune sand and asphalt is weak, unstable, easily deformed under light loads, and nondurable. It is not acceptable for pavement construction in a desertlike environment. The introduction of a crushed gravel at different ratios improved the mix but not to the required level. The introduction of a dense-graded aggregate resulted in some improvement, but the quantity of costly high-quality mineral aggregate required to meet specifications made the mix uneconomical.

The introduction of 15 percent sulfur to a mix of dune sand and asphalt gives the following beneficial results:

 Reduces the optimum asphalt content of the mix from 6.4 to 5.0 percent, a reduction of 22 percent;

2. Considerably increases the engineering quali-

ties of the mix even under severe environmental conditions (such improvements are evident in the Marshall criteria, tensile strength, compressive strength, modulus of rupture, and dynamic modulus of elasticity values);

3. Significantly reduces the pavement thickness required under similar loading and environmental conditions; and

4. Removes the need to import dense-graded aggregate to the site because the engineering qualities of the mix of dune sand, asphalt, and sulfur are equal to or better than those of conventional dense-graded aggregate-asphalt mixes. Not having to use dense-graded aggregate in the mix further reduces construction costs, especially if the aggregate has to be hauled a considerable distance. An additional benefit is that high-quality mineral aggregate may be saved for other purposes and/or for reducing the ecological damage caused by excavating borrow areas and hillsides.

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