Effect of Inclusion of Oil Shale Ash on Behavior of Asphalt Concrete

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Because of a shortage of asphaltic material and the increasing price of asphalt, researchers are investigating different methods of using available materials, such as waste materials, and substitute binders or extenders in roadway construction. The Jordanian government is concerned with the exploration of every possible source of energy, especially oil shale. Oil shale ash is one of the few materials that is expected to be in vast oversupply in the future in Jordan. The purpose of this study is to investigate the effect of oil shale ash on properties of bituminous concrete. To achieve this objective, oil shale ash was added to bituminous mixtures in different ratios. Marshall stability, Marshall immersion, and resilient modulus tests were performed on the mixtures. Results indicate that oil shale ash produces paving mixtures that have higher Marshall stability and resilient modulus than do paving mixtures without ash. The experiments also indicated that oil shale ash reduces the potential of stripping in bituminous mixtures.

In view of the growing energy problem in Jordan, which is becoming a major threat to its national economy, the Jordanian government is concerned with the exploration and development of every possible domestic source of energy, especially oil shale. The oil shale reserves of the El-Lajjun area are estimated to be more than one billion metric tons. The El-Lajjun area is located in west central Jordan midway between Qatrana and Karak (see Figure 1 for location). Oil shale ash is one of the few materials that is expected to be in vast oversupply in the future.

To date, considerable use has been made of ash as a substitute for or supplement to asphalt cement. One of the successful uses of ash has been as a mineral filler in bituminous concrete mixes. Studies done on mineral fillers indicate that it is possible for a mineral filler such as fly ash to act as an inexpensive asphalt substitute in bituminous mixtures.

Because changes in mix composition usually influence mix properties, work is needed to determine how the addition of oil shale ash to bituminous paving mixes would alter Marshall stability, flow, unit weight, voids in mineral aggregate (VMA), air voids, and resilient modulus of a mix. Therefore the primary objective of this study was to investigate the feasibility of using oil shale ash as a substitute for part of the asphalt in bituminous paving mixtures in order to achieve economic advantage and good performance.

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The effects of mineral fillers on the behavior of asphalt concrete have been studied by many researchers for many years. Richardson (*1*) was one of the earliest to report on mineral fillers. He hypothesized that mineral filler not only filled voids but also caused a physicochemical interaction between the asphalt and the filler. From extensive studies on mineral fillers, Puzinauskas (*2*) also concluded that mineral fillers play dual roles in asphalt mixtures: (a) they are part of the mineral aggregate that fills the interstices and provides contact points between larger aggregate particles and (b) when mixed with asphalt they form a high-consistency binder or matrix that cements larger aggregate particles together.

Anderson and Goetz (*3*) found that the size and mineralogy of the filler affected rheological behavior. The temperature susceptibility of the asphalt was also increased with the addition of the mineral fillers. Baghouse fines have also been used as a mineral filler. The California Department of Transportation (*4*) was one of the first to report on baghouse fines in 1976. Their study indicated that using a maximum of 2 percent baghouse dust had very little effect on an asphaltic mixture, provided that the maximum amount passing the No. 200 sieve, including the added baghouse dust, did not exceed the limits established in their 1975 standard specification. Ishai and Craus (*5*) studied the effects of physicochemical properties of fillers on bituminous mixes. They found that, for most types of fillers tested, all physicochemical effects result in greater geometric irregularity correlated with greater intensity of absorption. They concluded that this combined effect causes a strengthening of the filler-bitumen bonds and a relative increase in the amount of fixed bitumen; the result is mastics with higher consistency or mixtures with higher strength. The West Virginia Department of Highways (*6*) conducted a study on baghouse fines, from different sources, that had different particle size distribution and physical properties. Their study showed that (a) baghouse fines when used in proper quantity can improve the stability and cohesion of the paving mix, (b) the finer sizes of dust act as an asphalt extender, and (c) changes in either the size or the amount of the dust added to the paving mix have about the same effect as changing the asphalt content.

EXPERIMENTAL INVESTIGATIONS

The laboratory investigation undertaken in this study was intended to quantitatively evaluate the effect of ash on the behavior of bituminous concrete mixes. The tests used were

1. Marshall design method,

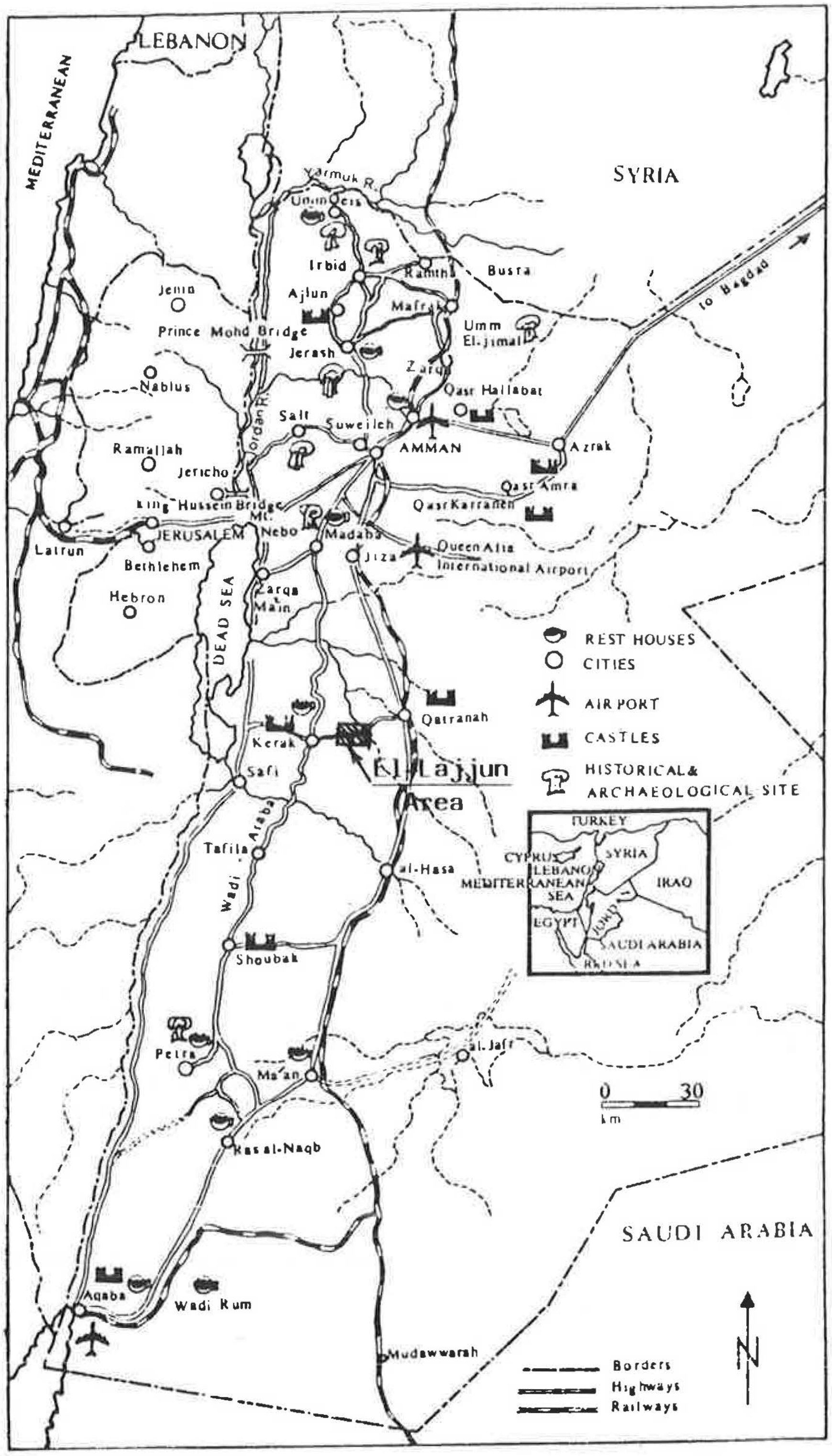

FIGURE 1 General map of Jordan.

2. Water sensitivity of bituminous mixtures, and
3. Resilient modulus test.

Material Used

Asphalt

One penetration grade asphalt cement (80-100) was used in this study. This asphalt was obtained from Jordan Refinery, Zerka, Jordan. This grade was chosen because it is widely used in pavement construction. Table 1 gives a summary of the results of some tests run on the asphalt.

Aggregate

One type of limestone aggregate was used in this study. This aggregate is the most commonly used in pavement construction

TABLE 1 PROPERTIES OF ASPHALT CEMENT

Property	ASTM Test Designation	Test Result
Specific gravity at 77°F	D 70	1.010
Penetration (0.1 mm) at 77°F, 100 g, 5 sec	D 5	81
Softening point (°F), ring and ball	D 36	122
Ductility (cm) at 77°F	D 113	130
Kinematic viscosity (cSt) at 275°F	D 2170	310

NOTE: 1 mm = 0.0394 in.

in Jordan. It was obtained from local quarries in the north of Jordan. The gradation used in this study conformed to the Jordanian Ministry of Public Works specification. This gradation is given in Table 2. Table 3 gives a summary of the properties of the aggregate.

Oil Shale Ash

The ash used in this study was obtained by burning oil shale at 600°C. The oil shale was supplied by the Department of Natural Resources of Jordan. The specific gravity of this ash is 2.47 (Table 3). Table 4 gives the results of a hydrometer analysis of a selected ash sample.

TABLE 2 AGGREGATE GRADATION

Sieve Size	Percentage Passing	Specification[a]
3/4 in.	100	100
1/2 in.	96	90–100
3/8 in.	85	75–90
No. 4	60	45–70
No. 8	45	33–53
No. 30	25	15–33
No. 50	14	10–20
No. 100	6.5	4–16
No. 200	5	2–9

NOTE: 1 in. = 2.54 cm.
[a]Jordanian specification limits.

TABLE 3 PROPERTIES OF AGGREGATE

Type of Aggregate	ASTM Test Designation	Bulk Specific Gravity	Apparent Specific Gravity	Absorption (%)
Limestone coarse aggregate	C 127	2.40	2.67	3.20
Limestone fine aggregate	C 128	2.43	2.70	3.70
Limestone mineral filler	C 128	2.53	2.78	4.20
Oil shale ash	C 188	–[a]	2.47	–[a]

[a]Data not applicable.

Marshall Test

A series of tests was performed on the bituminous mixtures using the Marshall method to find the optimum binder content for the mix. The variables involved were

TABLE 4 HYDROMETER ANALYSIS OF SELECTED ASH SAMPLE

Size (microns)	Percentage Finer
75	100
56	97
21	90
20	80
8	76
3	27
1	10

NOTE: 1 μm = 0.0394×10^{-3} in.

1. Percentage of ash by volume of binder (0, 5, 10, 15, and 20 percent) and
2. Binder content equivalent by weight of aggregate (5, 6, 7, and 8 percent).

The term "binder content equivalent" means that for a given experiment the volume of asphalt plus the volume of ash was kept constant.

Preparation of Ash-Asphalt Binders

The following steps were followed in preparing ash-asphalt binders:

1. Ash was heated in a stainless steel beaker and maintained at a temperature between 145°C and 150°C (293°F and 302°F).
2. Asphalt cement was heated in an oven at a temperature of about 145°C (293°F).
3. The stainless steel beaker used for mixing was cleaned and kept in the oven at a temperature of about 145°C.
4. The required amount of asphalt was weighed into the beaker; then, the amount of ash required to yield the desired ash-to-asphalt ratio was weighed.
5. The beaker was placed on a hot plate to maintain a constant mixing temperature. The mix temperature varied between 140°C and 145°C (284°F and 293°F).
6. The laboratory mixer used was then placed so that the propeller was about 1.5 cm above the bottom of the beaker.
7. The mixer was started, and mixing was continued for 5 min at 1,600 RPM. During mixing it was necessary to watch for any undesirable splashing, which might introduce small air bubbles into the mix. By changing the position of the mixer's propeller within the mixing beaker, it was possible to stop the splashing.
8. At the end of the mixing operation, the ash-asphalt binder was mixed with the heated aggregate to prepare ash-asphalt concrete specimens.

Preparation and Testing of Marshall Specimens

The procedure used in preparing and testing the bituminous concrete Marshall specimens was that outlined in the Asphalt Institute Manual Series (*7*, pp. 17–32). Table 5 gives the Marshall properties of mixtures without ash. An example of the calculation of asphalt and ash weights for one specimen follows: Assume that a given mix will be used. This mix had a binder content equivalent of 5.0 percent by total weight of

TABLE 5 MARSHALL PROPERTIES OF MIXTURES WITHOUT ASH

Asphalt Cement (%)	Marshall Stability (lb)	Flow (0.01 in.)	Unit Weight (lb/ft^3)	VMA (%)	Air Voids (%)
5	2216.6	13.4	133.2	16.9	8.7
6	1908.6	14.6	135.4	16.4	5.6
7	1541.4	17.4	136.4	16.7	3.7
8	1410.4	18.2	134.9	18.5	3.5

NOTE: 1 lb = 0.454 kg; 1 in. = 2.54 cm; 1 lb/ft^3 = 16.019 kg/m^3.

aggregate. Assume that an ash-asphalt binder with 10 percent ash (by volume of binder) is to be used instead of the original asphalt. This asphalt cement has a specific gravity of 1.01, and the ash has a specific gravity of 2.47. All mixes were prepared from a batch of which the weight of the aggregate was 1200.0 g. The weight of the asphalt cement (AC) for this mix without ash was calculated as follows:

$1200 \times 5/100 = 60.0$ g

Therefore

Volume of AC = $60.0/1.01 = 59.4$ cm^3

This means that the volume of asphalt plus the volume of ash should be 59.4 cm^3 for this mix.

The volume of ash for this mix was calculated as follows:

$59.4 \times 10/100 = 5.94$ cm^3

Volume of asphalt for this mix = $59.4 \times 90/100 = 53.46$ cm^3. Weight of ash for this mix = $5.94 \times 2.47 = 14.67$ g. Weight of asphalt for this mix = $53.46 \times 1.01 = 54.0$ g. Therefore weight of binder = $14.67 + 54.0 = 68.67$ g.

Table 6 gives a summary of the weights of asphalt and ash calculated using this procedure for each Marshall specimen. The freshly prepared ash-asphalt binder was added, in the desired proportion, to 1200 g of the hot aggregate, and the combination was mixed until all aggregate was covered completely with binder.

TABLE 6 WEIGHTS OF ASPHALT AND OIL SHALE ASH FOR MARSHALL SPECIMENS

BCE[a] (% by weight of aggregate)	Ash by Volume of Binder (%) 0	5	10	15	20
5	60.0[b]	57.0	54.0	51.0	48.0
	0.0[c]	7.3	14.7	22.0	29.3
6	72.0	68.4	64.8	61.2	57.6
	0.0	8.8	17.6	26.4	35.2
7	84.0	79.8	75.6	71.4	67.2
	0.0	10.3	20.5	30.8	41.1
8	96.0	91.2	86.5	81.6	76.8
	0.0	11.7	23.5	35.2	46.9

NOTE: Units are grams; 1 g = 2.2×10^{-3} lb; weight of aggregate for each specimen = 1200 g.
[a]BCE = binder content equivalent.
[b]Weight of asphalt.
[c]Weight of ash.

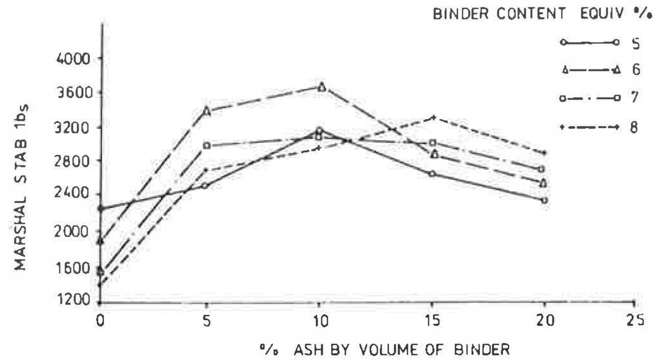

FIGURE 2 Effect of replacing asphalt with oil shale ash on Marshall stability of bituminous mix (1 lb = 0.454 kg); each point is an average of three values.

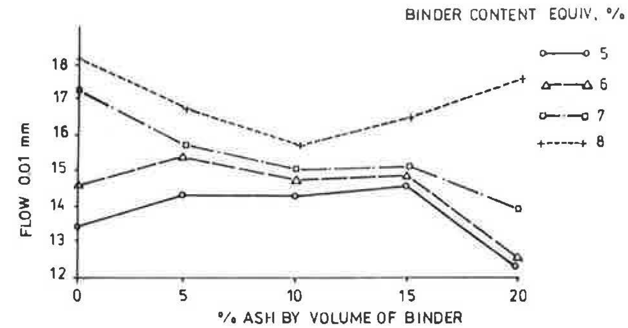

FIGURE 3 Effect of replacing asphalt with oil shale ash on Marshall flow of bituminous mix (1 in. = 2.54 cm); each point is an average of three values.

TABLE 7 OPTIMUM BINDER CONTENT EQUIVALENT FOR ASH-ASPHALT CONCRETE MIXES

Ash by Volume of Binder (%)	Specific Gravity of Binder	Optimum Binder Content (% by weight of mix)	Asphalt Content (% by weight of mix)	Ash Content (% by weight of mix)
0	1.01	5.89	5.89	0.00
5	1.083	6.29	5.57	0.72
10	1.156	6.69	5.26	1.43
15	1.229	7.08	4.95	2.13
20	1.302	7.47	4.64	2.83

Three specimens were prepared for each mix. One day after the specimens were prepared, their bulk specific gravities were measured. Then the specimens were subjected to Marshall tests. Figures 2–6 show the results of these tests. Table 7 gives a summary of the optimum binder content equivalent for ash-asphalt concrete mixes.

Water Sensitivity of Ash-Asphalt Concrete Mixes

The susceptibility of asphalt concrete mixes to attack by water is considered a primary design criterion. This is especially true in areas in which the pavement is in contact with water. Water can get between the binder and the surface of the aggregate. If this happens, the pavement starts to break up as the result of loss of cohesion in the mix. Before ash-asphalt concrete mixes can be used for highway construction, their susceptibility to loss of cohesion in the presence of water must be evaluated.

The Marshall immersion test was used to evaluate the influence of ash on the moisture resistance of ash-asphalt concrete mixes. This test was developed by Taylor and Khosla (*8*). In this test, Marshall stability is measured for wet and dry specimens. The optimum binder contents given in Table 8 were used to design the Marshall specimens. Prepared specimens were divided into two groups. One group of specimens was cured in air at room temperature for 24 hr (unconditioned) and then put in a water bath at 60°C for 30 min. The other group of specimens was immersed in a water bath at 60°C for 24 hr (conditioned).

Conditioning of specimens was performed to investigate the effect of hot water on the cohesion of compacted mixtures. Both groups of specimens were tested using the Marshall apparatus to determine their stability and binder flow values after conditioning. Moisture damage is evaluated on the basis of the ratio of Marshall stability for conditioned and unconditioned specimens. Figures 7 and 8 show the results of these tests.

Resilient Modulus

The resilient modulus test was used to determine the effect of ash on the resilient modulus of ash-asphalt paving mixes. Marshall size specimens were prepared as outlined previously.

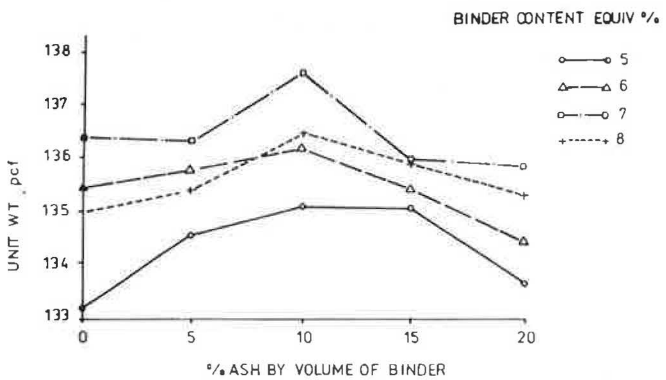

FIGURE 4 Effect of replacing asphalt with oil shale ash on unit weight of bituminous mix (1 lb/ft^3 = 16.019 kg/m^3).

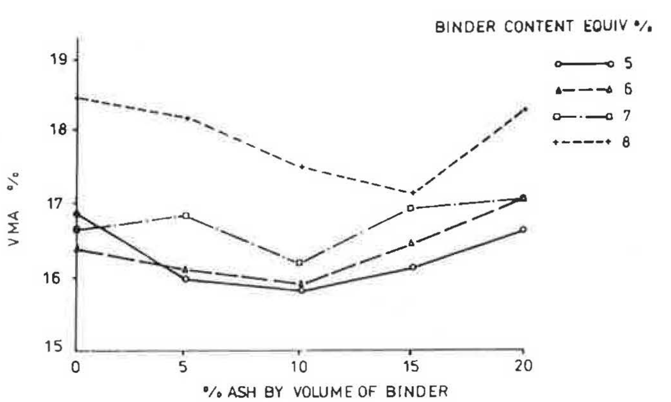

FIGURE 5 Effect of replacing asphalt with oil shale ash on voids in mineral aggregate of bituminous mix.

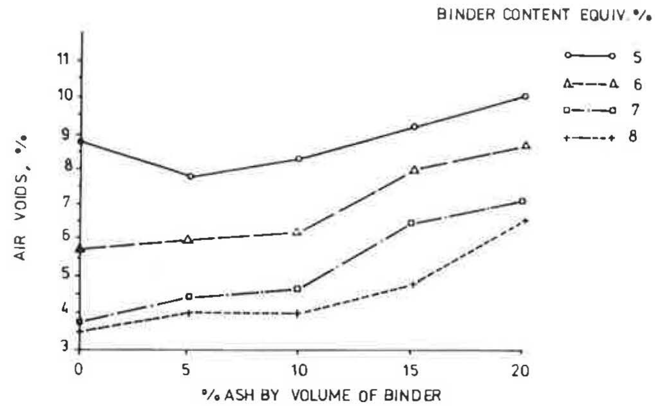

FIGURE 6 Effect of replacing asphalt with oil shale ash on air voids of bituminous mix.

TABLE 8 BINDER, ASPHALT, AND ASH CONTENT FOR DURABILITY AND RESILIENT MODULUS TESTS

Ash by Volume of Binder (%)	Optimum Binder Content (% by weight of mix)	Asphalt Content (% by weight of mix)	Ash Content (% by weight of mix)	Weight of Binder (g)	Weight of Asphalt (g)	Weight of Ash (g)
0	5.89	5.89	0.00	75.10	75.10	00.00
5	6.29	5.57	0.72	80.55	71.33	09.22
10	6.69	5.26	1.43	86.04	67.65	18.39
15	7.08	4.95	2.13	91.43	63.93	27.51
20	7.47	4.64	2.83	96.88	60.18	36.70

NOTE: 1 g = 2.2 × 10^{-3} lb.

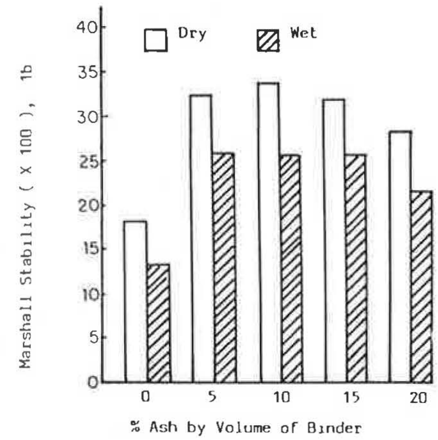

FIGURE 7 Effect of oil shale ash on dry and wet stability of bituminous mixtures (1 lb = 4.448 N).

Two specimens were used to determine the resilient modulus for each mix considered. The binder, asphalt, and ash content (percentage by weight of total mix) given in Table 8 were used. One day after the specimens were prepared, the resilient modulus (M_r) of the specimens was measured in dry condition at 77°F (*9*).

A nondestructive resilient modulus test reported by Schmidt (*9*) was used to determine the resilient modulus of the specimens. In this test a light 0.1-sec-duration pulsating load is applied across one diameter of a cylindrical specimen while the

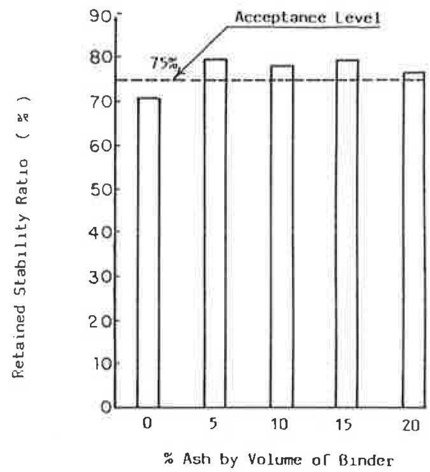

FIGURE 8 Relationship between percentage of ash and retained stability ratio.

resultant elastic deformation across the opposite diameter is measured. A pulsating load of 50 lb was used, and two measurements were taken on each specimen. The resilient modulus was then calculated using the following equation:

$$M_r = [P(\nu + 0.2734)]/t\Delta$$

where

P = applied load (50 lb),
ν = Poisson's ratio (assumed to be 0.35),
t = thickness of specimen (in.), and
Δ = elastic deformation measured (in.).

Figure 9 shows the results of this test.

TEST RESULTS AND DISCUSSION

Marshall Stability of Bituminous Mixtures

Figure 2 shows the effect of oil shale ash on Marshall stability of bituminous mixes for each binder content equivalent. From the results obtained, it was found that stability increases and then decreases with increasing percentages of ash in the binder. It was also found that for a particular binder content equivalent there is an optimum ash content that gives maximum stability. For the ash used in this study, the optimum ash content was around 10 percent for 5, 6, and 7 percent binder content equivalent and 15 percent for 8 percent binder content equivalent.

Marshall Flow of Bituminous Mixes

Figure 3 shows the effect of oil shale ash on Marshall flow of bituminous mixes for each binder content equivalent. At 5 and 6 percent binder content equivalent, the flow increases then decreases with increasing percentages of ash by volume of binder. At 7 percent binder content equivalent, flow decreases with increasing ash concentration in the binder. At 8 percent binder content equivalent, flow decreases and then increases with increasing percentages of ash by volume of binder.

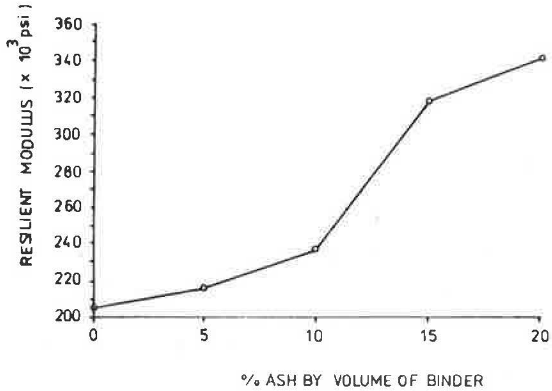

FIGURE 9 Effect of replacing asphalt with oil shale ash on resilient modulus of bituminous mix (1 psi = 6.89 kPa); each point is an average of two values.

Unit Weight of Bituminous Mixtures

Figure 4 shows the effect of oil shale ash on the unit weight of bituminous mixes for each binder content equivalent. The unit weight increases then decreases with increasing ash concentration in the binder for all curves of binder content equivalent.

Voids in Mineral Aggregate

Figure 5 shows the effect of oil shale ash on VMA in bituminous mixtures. VMA decreases then increases with increasing ash concentration in the binder. This increase in VMA can be due to the rough surface texture of aggregate particles that was developed after addition of ash to the bituminous mixtures.

Air Voids in Bituminous Mixes

Figure 6 shows the effect of oil shale ash on air voids in bituminous mixtures. Air voids increase with increasing ash content in the binder.

Optimum Binder Content

The optimum binder content was determined on the basis of the Marshall method of mix design (ASTM D 1559). The compactive effort was 50 blows on each face of the specimen. These values of binder contents were used in preparing Marshall immersion test and resilient modulus test specimens. Table 6 gives the effect of oil shale ash on optimum asphalt content of the bituminous mixtures.

Stability Test on Dry and Wet Specimens

Dry stability is the value after the specimen has been immersed in hot water at 60°C for 30 min (unconditioned) when tested by the Marshall test apparatus (*7*). Wet stability is the reading measured with the Marshall test apparatus after immersing the specimen in a water bath at 60°C for 24 hr (conditioned).

Figure 7 shows the effect of oil shale ash on dry and wet stability of bituminous mixes. Figure 7 shows that the stability of conditioned specimens was less than that of unconditioned specimens because hot water had softened the mixture, especially when it had been exposed to hot water for 24 hr. Using oil shale ash in bituminous mixes reduced the percentage difference in stability between dry and wet specimens. This is an indication that durability was improved.

Retained Stability Ratio

Evaluation of stripping is mainly based on the retained stability ratio (RSR), which is the ratio between wet and dry stabilities. Most researchers indicate that this ratio should not be less than 75 percent. Therefore 75 percent RSR was used as the acceptance/rejection criterion. Results are summarized in Figure 8. Figure 8 indicates that the RSR-value has been increased by adding oil shale ash to the normal mix (untreated). This increase indicates a reduced potential for stripping in bituminous mixtures. The retained stability of mixtures without ash was not acceptable.

Resilient Modulus of Bituminous Mixes

Figure 9 shows the effect of oil shale ash on the resilient modulus of bituminous mixes. Resilient modulus increases with increasing ash concentration in the binder. This is because the adhesive forces between asphalt and aggregate and the mechanical interlock between aggregate particles have been improved as the result of treatment.

Stiffness Ratio

Table 9 gives the stiffness ratio (SR) for ash-asphalt concrete. SR is defined here as the resilient modulus of the ash-asphalt concrete mix at 1 day divided by the resilient modulus of a similar mix with no ash (control mix) at 1 day. It was found that the SR increases as the percentage of ash in the binder is increased. In other words, the more ash used, the higher the resilient modulus of the mix. This is because the addition of ash enhances the adhesive forces between asphalt and aggregate.

TABLE 9 EFFECT OF REPLACING ASPHALT WITH OIL SHALE ASH ON STIFFNESS RATIOS

Ash in Binder (%)	Stiffness Ratio[a]
5	1.06
10	1.16
15	1.56
20	1.66
25	1.73

[a]Stiffness ratio = (Resilient modulus of ash-asphalt concrete mix)/(Resilient modulus of control mix with no ash).

CONCLUSIONS

From the results obtained in this study, the following conclusions were drawn:

1. Oil shale ash significantly increases the stability and cohesion of bituminous mixtures. The use of 10 percent ash by volume of asphalt could be considered optimum.
2. The unit weight of bituminous mix increases then decreases with increasing ash concentration in the binder.
3. Voids in mineral aggregate decrease then increase with increasing ash concentration in the binder.
4. Air voids increase with increasing percentages of ash in the binder.
5. Use of oil shale ash reduces the potential for stripping in bituminous mixtures because this additive converts the aggregate surface to one that is more easily wetted with asphalt than with water.
6. Oil shale ash improves the stiffness of bituminous mixtures because the adhesive forces between asphalt and aggregate and the mechanical interlock between aggregate particles are improved by treatment.
7. Ash as an additive to asphalt cement plays a dual role in paving mixtures. First, it and asphalt form a high-consistency binder that cements the aggregate. Second, it acts as a part of the mineral aggregate, fills the interstices, and provides contact points between particles, thereby strengthening bituminous mixtures.

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