DOE/MC/11076--2992

DE91 002073

**Soil Stabilization Using Oil Shale Solid Wastes:
Laboratory Evaluation of Engineering Properties**

NOV 04 1991

Topical Report

J.P. Turner

January 1991

Work Performed Under Cooperative Agreement No.: DE-FC21-86MC11076

For
U.S. Department of Energy
Office of Fossil Energy
Morgantown Energy Technology Center
Morgantown, West Virginia

By
University of Wyoming
Department of Civil Engineering
Laramie, Wyoming

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SUMMARY

Oil shale solid wastes were evaluated for possible use as soil stabilizers. A laboratory study was conducted and consisted of the following tests on compacted samples of soil treated with water and spent oil shale: unconfined compressive strength, moisture-density relationships, wet-dry and freeze-thaw durability, and resilient modulus. Significant increases in strength, durability, and resilient modulus were obtained by treating a silty sand with combusted western oil shale. Moderate increases in strength, durability, and resilient modulus were obtained by treating a highly plastic clay with combusted western oil shale. Solid waste from eastern oil shale can be used for soil stabilization if limestone is added during combustion. Without limestone, eastern oil shale solid waste exhibits little or no cementation. The testing methods, results, and recommendations for mix design of spent shale-stabilized pavement subgrades are presented.

INTRODUCTION AND BACKGROUND

Some solid wastes produced as a result of oil shale retorting and combustion contain pozzolanic silica and alumina that react in the presence of water to form hydrous cements consisting of calcium silicates and aluminates. The pozzolanic silica and alumina begin to form at process temperatures above about 1100°F (593°C). At process temperatures above approximately 2000°F (1093°C), the cementitious components are diminished, possibly through the sintering of the pozzolanic silica and alumina (Culbertson et al. 1970).

It may be possible to produce materials with improved engineering properties, by mixing cementitious oil shale solid wastes with water and soil. For example, subgrade soils or base-course aggregates that are marginal or unsuitable for pavement construction may be strengthened by the addition of cementitious oil shale solid wastes. Portland cement, lime, and fly ash presently are used widely for this purpose. Based on the chemical reactions that occur when spent shale is used for soil stabilization, oil shale solid waste can be categorized as an active soil stabilizing agent (Terrel et al. 1979). The use of oil shale solid waste for soil stabilization can improve the economics of shale oil production while mitigating one of the environmental liabilities (disposal of solid wastes).

Previous research at the University of Wyoming suggested that solid waste derived from the combustion of oil shale mined from the Green River Formation in the Piceance Basin, Colorado, could improve the engineering properties of subgrade soils (Turner and Suryavanshi 1988). Two subgrade soils were evaluated, a silty sand and a sandy clay. Further work by Suryavanshi (1989) and Suryavanshi and Turner (1989) on a variety of spent shales showed that Green River Formation spent shales are cementitious if the retorting process involves combustion temperatures over about 1100°F (593°C). Eastern spent Chattanooga Shale and New Albany Shale are cementitious and have excellent stabilizing properties if the retorting process involves combustion temperatures exceeding 1100°F plus the addition of limestone to reduce sulfur emissions (Suryavanshi and Turner 1989). Addition of limestone during combustion of the oil shale provides calcium carbonate needed to react with pozzolanic silica and alumina to produce cementation. Without the addition of limestone, eastern spent shale exhibited little or no cementing characteristics.

OBJECTIVES

This study was undertaken to evaluate the technical feasibility of using oil shale solid waste for subgrade soil stabilization. The specific objectives were to (1) evaluate the influence of process temperature on the cementing properties of oil shale solid wastes and (2) further develop the existing data base on the engineering properties of soils stabilized with spent shale for use in highway pavement construction.

A testing program was conducted in three phases: (1) a screening phase, (2) a developmental phase, and (3) tests to determine design parameters. In the screening phase, unconfined compression tests were used to determine whether or not samples of compacted and hydrated spent shale could develop compressive strengths that would make them potentially useful materials for stabilized highway construction. If a spent shale failed the screening tests, no further tests were conducted using that spent shale. In the developmental phase, the strength and durability of soil-spent shale mixtures were measured to provide a basis for evaluating the effects of combustion temperature on the strength of cementation. In the final phase, determination of design parameters, the spent shales exhibiting the best performance as soil stabilizers were further evaluated to determine the resilient modulus.

LABORATORY TESTING PROGRAM

Materials

Spent Shales

Western Research Institute (WRI) provided seven different samples of spent shale for use in this study. One was obtained by processing oil shale from the New Albany Shale in Kentucky (eastern shale), and the other six samples were derived from the Green River Formation (western shale). The combustion temperature of the western spent shales ranged from 1130 to 2050°F (638 to 1121°C). Table 1 summarizes the source and combustion temperature of each spent shale used in this study.

Table 1. Spent Shale Sources and Combustion Temperatures

Spent Shale	Source	Combustion Temperature, °F
A	New Albany Shale	1180
B	Green River Formation	1130
C	Green River Formation	1550
D	Green River Formation	1620
E	Green River Formation	1800
F	Green River Formation	1905
G	Green River Formation	2050

Soils

Three soils were tested, including two coarse-grained (soils A and B) and one fine-grained (soil C) soils. Soil A, a reddish-brown silty sand, is classified as A-2-4 in the AASHTO Soil Classification System (AASHTO 1986a). Soil A was obtained near Laramie, Wyoming, from an alluvial deposit in the bed of Spring Creek. Soil B was obtained from the same location as soil A, but it has slightly different properties than Soil A. Soil B is also classified A-2-4 but has a higher

percentage of fines than soil A. Soil C is classified as A-7-6, highly plastic clay, and it was provided by the Wyoming Highway Department from a road construction project near Sheridan, Wyoming. Soils A and B were chosen to represent coarse-grained soils for stabilization evaluations. Soil C was chosen because it is a highly plastic clay, a soil type that commonly exhibits poor subgrade characteristics; therefore, it is a good candidate for soil improvement.

Each soil was characterized and classified by the following tests: particle size analysis, specific gravity of soil solids, liquid limit, plastic limit, plasticity index, moisture-density relationships, and unconfined compressive strength. The results of these tests are summarized in Tables 2 and 3.

Table 2. Particle Size Distribution of Soils

Particle Diameter, mm	Percentage Passing, by weight		
	Soil A	Soil B	Soil C
4.75	95	100	100
2.00	84	98	100
0.85	72	82	100
0.425	56	58	100
0.150	40	46	99
0.075	25	34	98

Table 3. Index Properties and Soil Classification

	Soil A	Soil B	Soil C
Plastic Limit, %	nonplastic	nonplastic	26.2
Liquid Limit, %	26.3		75.2
Plasticity Index	nonplastic	nonplastic	49.0
AASHTO Classification	A-2-4	A-2-4	A-7-6
Maximum Dry Density, pcf	118.4	122.6	98.2
Optimum Water Content, %	13.0	12.0	26.0
Unc. Comp. Strength, psi	75.0	8.4	33.9

Methods

Moisture-Density Relationships (Compaction Test)

The purpose of the moisture-density test, commonly called the compaction test, is to determine the moisture content at which the maximum dry density of the soil can be achieved. Increasing the density of a stabilized soil is desirable for engineering purposes for increased shear strength, decreased compressibility, and decreased

permeability. The moisture content corresponding to the maximum dry density of a soil is called the optimum moisture content. Specifications for field compaction of highway subgrades are commonly based upon the contractor obtaining 90 to 95% of the maximum dry density. All tests were conducted in accordance with ASTM D 558-82, Test Methods for Moisture-Density Relations of Soil-Cement Mixtures (ASTM 1985).

Unconfined Compression

The unconfined compressive strength (q_u) following a 7-day curing period was used to evaluate potential increases in strength for soils treated with spent shale, compared with untreated samples. The unconfined compression test was used to determine the percentage of spent shale in the soil-spent shale mixture that would yield the greatest strength increase. The results of the compression tests also were used to compare the stabilizing potentials of the different spent shales.

Samples of soil and soil stabilized with spent shale were prepared by mixing the desired proportions of water, soil, and spent shale. Percentages of spent shale ranged from 0 to 30%, by weight, and water contents ranged from 8 to 35%. Samples were prepared by compacting the mixture using the Harvard miniature apparatus (Soiltest 1964). This apparatus consists of a cylindrical mold 1.3 inches in diameter and 2.8 inches high and a 20-lb, spring-loaded compaction hammer. Each sample was compacted in five lifts using 10 blows per lift. Following compaction, excess soil was trimmed from the top of the mold, and the weight of the mold and soil was recorded. The density of each sample was computed by dividing the weight of the soil by the known volume of the mold. The sample was then extracted from the mold, wrapped in saran wrap, and allowed to cure for 7 days at 70°F (21°C) and at a relative humidity of 100% before being tested in unconfined compression.

The testing procedure consists of compressing a cylindrical sample of soil (Harvard miniature sample) at a loading rate corresponding to 0.5 to 2% strain per minute. The sample deformation and load are monitored at specified time intervals. Loading is continued until a visible failure plane is observed or until a maximum of 20% strain is reached. The unconfined compressive strength is defined as the vertical stress corresponding to failure or 20% axial strain. All tests were conducted in accordance with ASTM D 2166, Standard Test Method for Unconfined Compressive Strength of Cohesive Soils (ASTM 1985).

Durability Tests

Wet-dry and freeze-thaw durability tests were used to determine soil-cement losses, moisture changes, and volume changes produced by repeated wetting and drying or freezing and thawing of hardened soil-spent shale samples. Samples were compacted to maximum density at optimum moisture content in special soil-cement molds (ASTM 1985) and were 2.8 inches in diameter and 5.6 inches high. Two samples were

prepared for each test and then cured for 7 days at 70°F (21°C) and 100% relative humidity.

In the wet-dry test, the two samples are submerged in a water bath for five hours. One of the specimens is weighed and measured. The second sample is given two firm strokes on all surface areas with a wire scratch brush and then is weighed and measured. Both samples then are placed in an oven at 160°F (71°C) for 42 hours. Twelve such cycles are applied, in accordance with ASTM D 559-82, Standard Method for Wetting-Drying Tests of Compacted Soil-Cement Mixtures (ASTM 1985). In the freeze-thaw test, the two samples are maintained at -10°F (-23°C) for 24 hours. One sample is brushed, and then both samples are weighed, measured, and placed in a moist room at 70°F (21°C) and 100% relative humidity for 23 hours. Twelve cycles of freezing and thawing are required in accordance with ASTM D 560-82, Standard Method for Freezing-and-Thawing Tests of Compacted Soil-Cement Mixtures (ASTM 1985). To satisfy the durability requirements for pavement construction, soil-cement mixtures must withstand 12 wet-dry or freeze-thaw cycles, and the scratch samples must exhibit less than 14% weight loss (referred to as cement loss).

Resilient Modulus Test

The resilient modulus is a measure of the stiffness of a subgrade soil for conditions that represent the stresses in pavements subjected to moving wheel loads. The results of the test describe the resilient, or elastic, response of the soil when a repeated axial deviator stress of fixed magnitude, frequency, and load duration is applied while the specimen, in a triaxial chamber, is surrounded by pressure that acts as a static, all-around stress. Resilient modulus has been selected by AASHTO (1986b) as the definitive material property to characterize roadbed soils for pavement design.

Resilient modulus samples were prepared at optimum moisture content using a California kneading compactor in accordance with AASHTO T190 (AASHTO 1986a). Samples were 4 inches in diameter and 8 inches high. Each sample was cured for 7 days in the moist room at 70°F (21°C) and 100% relative humidity. A sample was placed in the triaxial cell (Figure 1), and the cell pressure was increased to the desired confining stress. A repeated vertical load was applied for 200 cycles, in accordance with AASHTO T274 (AASHTO 1986a). The load was measured by an electronic load cell and the vertical deformation of the sample was measured by two displacement transducers mounted as shown in Figure 1. A detailed description of the device, including instrumentation and data acquisition, is given by Farrar and Turner (1991). The deviator stress divided by the vertical resilient strain on the 200th cycle is the resilient modulus, M_r . The resilient modulus of each specimen was determined for the seven combinations of confining and deviator stresses given in Table 4.

Figure 1. Resilient Modulus Test Device (Asphalt Institute 1988)

Table 4. Confining and Deviator Stress Combinations for Resilient Modulus Test

Test Sequence	Confining Stress, psi	Deviator Stress, psi
1	0	5
2	0	10
3	0	15
4	2	6
5	15	20
6	0	20
7	2	6

RESULTS

Eastern Spent Shale

Unconfined compression tests on the eastern spent shale (spent shale A) yielded strengths that are not adequate for soil stabilization. Of six samples fabricated for the unconfined compression testing, three samples fell apart during the curing process. The remaining three samples achieved unconfined compressive strengths of 42, 23, and 13 psi. Anything less than 100 psi is unsuitable for soil stabilization. Based upon these screening tests and previous tests on eastern spent shale reported by Turner and Suryavanshi (1989), no further tests were conducted using eastern spent shale.

Western Spent Shales

Screening Tests

Western spent shales used for screening tests included spent shale samples B through F. Unconfined compression tests were conducted in accordance with the methods described previously on Harvard miniature samples of each spent shale prepared at a moisture content of 30% by weight. This amount of moisture is just sufficient to create a cement paste that can be compacted in the Harvard miniature molds. All samples were cured for 7 days in the moist room before testing. The results are summarized in Table 5. The highest measured value of unconfined compressive strength, q_u , was 395.7 psi for a sample of spent shale D. This value is much higher than the average q_u for spent shale D, and the next highest value was 146.6 psi. Apparently, the high q_u value was anomalous for spent shale D. Spent shale F, combusted at 1905°F (1041°C), exhibited the highest average q_u of 314.3 psi.

Attempts to fabricate Harvard miniature samples of spent shale G (combusted at 2050°F/1121°C) for screening tests were unsuccessful. Spent shale G consisted of very coarse-grained angular particles, including several particles greater than 3 inches. This observation is consistent with the fact that the high temperature conditions fused the oil shale. No further tests were conducted on spent shale G.

The results in Table 5 show a general trend of increasing cementation and strength with increasing combustion temperature for western spent shale. Based on the highest average q_u of 314.3 psi, spent shale F was chosen for further developmental tests.

Developmental Tests

Spent shale B was evaluated with soil A (silty sand) by conducting moisture-density relationships and 7-day unconfined compression tests on samples of soil A with 10, 20, and 30% spent shale B. A total of 16 samples were fabricated, cured for 7 days, and tested using the methods described previously. The results are summarized in Table 6. These data show that a mixture of at least 30% spent shale B is required to obtain a significant increase in the strength of soil A. The q_u of the 30% mixture approaches 200 psi, which is suitable for subgrade stabilization (Terrel 1979).

Spent shale F (combusted at 1905°F/1041°C) was evaluated in mixtures with soils B and C. With soil B, moisture-density relationships and unconfined compression tests were conducted on samples mixed with 10, 15, 20, and 25% spent shale. All samples were prepared with the Harvard

Table 5. Unconfined Compressive Strengths of Western Spent Shales

Spent Shale	Number of Samples	Combustion Temperature, °F	Unconfined Compressive Strength q_u , psi	
			Range	Average q_u
B	3	1130	34.7-54.3	49.3
C	9	1550	31.9-90.8	64.3
D	9	1620	113.0-395.7	156.8
E	9	1800	93.9-297.2	175.4
F	3	1905	303.5-326.3	314.3

Table 6. Summary of Results of Moisture-Density and Unconfined Compression Tests on Soil A with Spent Shale B

% Spent Shale	w^a	$\gamma_{d,max}^b$, pcf	$q_{u,max}^c$, psi
0	13.0	118.4	75.0
10	18.3	116.3	25.1
20	17.9	115.8	35.4
30	9.9	99.7	197.6

^a w = optimum water content, %

^b $\gamma_{d,max}$ = maximum dry density

^c $q_{u,max}$ = maximum unconfined compressive strength

miniature device and cured for 7 days before being tested using the ASTM methods described previously. A total of 46 samples were prepared and tested. The results are summarized in Table 7 and show that the highest strength increase occurred when soil B was mixed with 25% spent shale.

Stabilized soil consisting of 25% spent shale F with soil B was chosen for the durability testing. Wet-dry and freeze-thaw tests were conducted. A mix consisting of 20% spent shale F with soil B also was tested for wet-dry durability. The results are listed in Table 8. For wet-dry durability, both mixes withstood 12 cycles with acceptable levels of volume change and cement loss. The 25% mix yielded slightly lower cement loss than the 20% mix. The freeze-thaw test is more severe than wet-dry test because the soil water increases in volume when it changes from liquid to ice. The 25% mix withstood 12 freeze-thaw cycles, but did not pass the criteria for maximum cement loss (14%), as specified by ASTM (1985).

Spent shale F was evaluated using soil C, a highly plastic clay. Moisture-density relationships and unconfined compressive strengths were determined for mixes consisting of 10, 15, 18, 20, and 25% spent shale, using the ASTM method described previously. The results are summarized in Table 9 and show that mixtures consisting of 15 to 20% spent shale yield the highest strength increase.

Table 7. Summary of Results of Moisture-Density and Unconfined Compression Tests on Soil B with Spent Shale F

% Spent Shale	w ^a	$\gamma_{d,max}^b$, pcf	$q_{u,max}^c$, psi
0	12.0	122.6	8.4
10	13.3	118.4	50.5
15	16.0	113.6	66.8
20	16.0	109.0	59.7
25	17.0	106.0	89.0

a w = optimum water content, %

b $\gamma_{d,max}$ = maximum dry density

c $q_{u,max}$ = maximum unconfined compressive strength

Table 8. Results of Durability Tests, Soil B with Spent Shale F

% Spent Shale	Test Type	Dry Density, pcf	Molded Water Content, %	Max Vol. Change, %	Cement Loss, %
20	W-D	110.9	17.0	-2.8	7.5
25	W-D	107.0	18.0	+0.5	6.4
25	F-T	106.5	18.0	+0.9	23.9

Wet-dry durability tests were conducted on soil C with 15 and 20% spent shale (Table 10). Both mixes failed to last through 12 cycles. Soil C was treated with 5% lime, which reduced the plasticity index from 49.0 to 27.2. Samples of the lime-treated soil were prepared with 18% spent shale. These samples also failed to last 12 cycles, but they withstood more cycles than the mixes prepared without lime. Freeze-thaw tests were conducted on two sets of samples with 18% spent shale, one set was lime-treated and one set was not. The set without lime failed in 9 cycles, whereas the lime-treated samples withstood 12 cycles with 40.6% cement loss.

Table 9. Summary of Results of Moisture-Density and Unconfined Compression Tests on Soil C with Spent Shale F

% Spent Shale	w ^a	$\gamma_{d,max}^b$, pcf	$q_{u,max}^c$, psi
0	26.0	98.2	33.9
10	26.1	96.9	64.7
15	25.7	96.3	81.5
18	28.2	93.3	81.2
20	25.0	94.0	90.8
25	24.8	91.9	49.0

^a w = optimum water content, %

^b $\gamma_{d,max}$ = maximum dry density

^c $q_{u,max}$ = maximum unconfined compressive strength

Table 10. Results of Durability Tests, Soil C with Spent Shale F

% Spent Shale	Lime Treated	Test Type	No. of Cycles	Cement Loss, %
15	no	W-D	2	--
20	no	W-D	1	--
18	yes	W-D	5	--
18	no	F-T	9	--
18	yes	F-T	12	40.6

Tests for Design Parameters

Resilient modulus is the subgrade soil property recommended by AASHTO (1986b) for pavement design. Resilient modulus tests were conducted on soils B and C with no spent shale treatment, soil B with 25% spent shale F, and soil C with 18% spent shale F. All tests were conducted in accordance with AASHTO T274, as described previously. The results in Figures 2 and 3 show the resilient modulus as a function of deviator stress for zero confining stress. Stabilization of soil B with spent shale at 25% by weight increases the resilient modulus

significantly, but the increase is very sensitive to the water content of the mix. At a water content of 12.9%, the resilient modulus ranges from 200 to 400 ksi, which provides a subgrade of exceptional stiffness. The increase in resilient modulus of soil C due to spent shale stabilization is shown in Figure 3. The increase is not as dramatic as the results on soil B and may not be significant when considering pavement design.

CONCLUSIONS

Oil shale solid waste has the potential to be used as a low-cost construction material. This potential is a result of the cementing properties of spent shale when it is mixed with water to form hydrous cements. The work described in this report evaluates the technical feasibility of using oil shale solid waste for soil stabilization. The feasibility is based primarily upon increases in unconfined compressive strength, durability, and resilient modulus of spent shale-stabilized soils. The important findings of this study are:

- Eastern oil shale solid wastes are not suitable for soil stabilization unless limestone is added during combustion. The addition of limestone apparently results in the formation of quick lime in the solid waste, which increases the cementation of the hydrated spent shale.
- The optimum combustion temperature required for western spent shale to achieve maximum cementation properties is in the range of 1850 to 1950°F (1010 to 1066°C). This is based upon unconfined compressive strengths of compacted spent shale mixed to a water content of 30%. Compressive strengths of spent shale up to 300 psi were obtained.
- The use of 25%, by weight, western oil shale solid waste increased the unconfined compressive strength of a silty sand (A-2-4 in the AASHTO System) from 8 to 89 psi. This mix yields a resilient modulus of 200 to 400 ksi and exhibits excellent durability against wet-dry and freeze-thaw conditions. These results show that combusted western spent shale is an excellent material for the stabilization of granular soils.
- The use of 20%, by weight, western spent shale increased the unconfined compressive strength of a highly plastic clay (A-7-6 in the AASHTO System) from 34 to 91 psi. The resilient modulus of the stabilized clay was increased 20% over that of the unstabilized clay. To achieve adequate durability, it was necessary to treat the soil with lime before adding spent shale. These results suggest that western spent shale may be a marginal material for stabilization of highly plastic soils. Further research is recommended before using spent shale to treat subgrade soils with high plasticity indexes ($PI > 20$).

Figure 2. Resilient Modulus Values for Spent Shale Mixtures Using Soil B

Figure 3. Resilient Modulus Values for Spent Shale Mixtures Using Soil C

ACKNOWLEDGMENTS

Funding for this study was provided by the U.S. Department of Energy through the Western Research Institute under cooperative agreement number DE-FC-86MC11076. Mr. Richard McQuisten and Mr. Carl Roosmagi were the DOE project managers. The author is grateful to these individuals for their support.

Several graduate and undergraduate research assistants at the University of Wyoming participated in this study, primarily by conducting the laboratory tests. These include Kunal Suryavanshi, Robert Rothwell, Vicki Bonds, Robert Bonds, Andrew Beamer, Ken Muller, and Pemzang Tenzing. The author could not have asked for a more energetic and hard-working group of assistants, and expresses his thanks to each one.

DISCLAIMER

Mention of specific brand names or models of equipment is for information only and does not imply endorsement of any particular brand.

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