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Mechanical Properties of Cores Obtained From the Unleached Saline Zone, Piceance Creek Basin, Rio Blanco County, Colo.

By Frank G. Horino and Verne E. Hooker

UNITED STATES DEPARTMENT OF THE INTERIOR
Cecil D. Andrus, Secretary

BUREAU OF MINES

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MECHANICAL PROPERTIES OF CORES OBTAINED FROM THE UNLEACHED SALINE ZONE, PICEANCE CREEK BASIN, RIO BLANCO COUNTY, COLO.

by

Frank G. Horino[1] and Verne E. Hooker[2]

ABSTRACT

Drill cores from 18 exploratory holes that were drilled into the unleached saline beds were tested for mechanical properties by the Bureau of Mines. Test cores were primarily selected from zones L4B, R4B, L3, and R3A in the Piceance Creek Basin, Rio Blanco County, Colo. Regression analysis techniques were tried in an attempt to relate kerogen yield or apparent specific gravity to the parameters compressive strength, Young's modulus, and Poisson's ratio. Correlation coefficients were very poor, indicating that this type of analysis was not amenable to these data. Analysis of variance techniques were tried using a division of either greater than or less than 10% nahcolite together with the requirement of less than 3% dawsonite. Results showed that a larger percentage of nahcolite tended to lower the compressive strength and to increase Young's modulus. A second analysis was made using a division of less than 3% dawsonite and greater than 3% dawsonite together with the requirement of less than 1% nahcolite. For this analysis, a larger percentage of dawsonite tended to increase compressive strength, Young's modulus, and Poisson's ratio. Mean compressive strength values were determined for the mining horizons of interest. Average physical properties for design purposes were also determined for the horizons of interest and for a proposed adit based only on logged geologic depths to these horizons. No consideration was given to percentages of nahcolite and dawsonite. Creep data obtained from nahcolite- and dawsonite-rich oil shales provides a best fit to a modified power equation.

INTRODUCTION

The evaluation of resources and development of satisfactory mining systems require knowledge and information on critical rock mechanics parameters. One of these is physical properties of the materials in the proposed mining zones.

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Since very little is known at this time about the properties of the materials in the saline-rich zones of the Piceance Basin, the Bureau of Mines entered into a cooperative agreement with The Superior Oil Company to obtain this information relative to their proposed development and mining location. Rock properties were determined on drill cores obtained from 18 exploratory holes to assist in the development of preliminary mine design criteria. The selection of test cores included dawsonite- and nahcolite-rich oil shale rock materials. The physical properties that were determined and analyzed, and that are presented in this report, include uniaxial compressive strength, triaxial strength, Young's modulus (E), Poisson's ratio, apparent specific gravity, indirect tensile strength, and creep characteristics.

LOCATION

Surface locations of the 18 exploratory holes from which drill core was tested are shown in figure 1. All of these holes lie in T 1 N, R 96 W, and R 97 W, Rio Blanco County, Colo. The approximate area of study lies in the north-central edge of the Piceance Creek Basin as shown in figure 2.

PHYSIOGRAPHY AND STRATIGRAPHY

The Piceance Creek Basin lies in the northwestern part of Colorado in Rio Blanco and Garfield Counties. It covers an area of approximately 1,600 sq mi with the axis of the basin trending northwest-southeast. The plateaus are as much as 1,000 to 4,000 ft above the lowlands. Elevations range from about 6,000 to 9,400 ft above sea level with the greatest relief being shown in the south margin of the area which the Roan Cliffs tower above the valley of the Colorado River (3).[5]

Late Cretaceous to Tertiary beds are exposed in the area. The Mesaverde Group of Late Cretaceous Age is represented by sandstones, shales, and coalbeds. The Mesaverde Group forms prominent benches, ridges, and cliffs. Overlying the Mesaverde Group is the Ohio Creek conglomerate of Paleocene Age and the Fort Union Formation of late Paleocene and early Eocene Age. The Fort Union Formation is composed primarily of a sequence of massive brown and gray, poorly consolidated sandstone beds; gray and brown clay and shale beds; and a few thin coal lenses. Above the Fort Union Formation is the Wasatch Formation of Eocene Age. The Wasatch Formation is composed of bright-colored clays and shales with some sandstones and coalbeds. Above the Wasatch Formation lies the Green River Formation of middle Eocene Age. The Green River Formation is composed largely of kerogen-rich magnesium marlstones, sandstones, siltstones, limestones, and oolite. It is divided into four members, with the Douglas Creek Member being the oldest, followed by the Anvil Points Member, Garden Gulch Member, and finally by the Parachute Creek Member. The Douglas Creek Member is made up of sandstone, limestone, and small amounts of gray shale. This member has only been found in the southern, western, and central parts of the basin. The Douglas Creek Member attains a maximum thickness of 800 ft in the southwestern part of the basin.

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[5] Underlined numbers in parentheses refer to the items in the list of references at the end of this report.

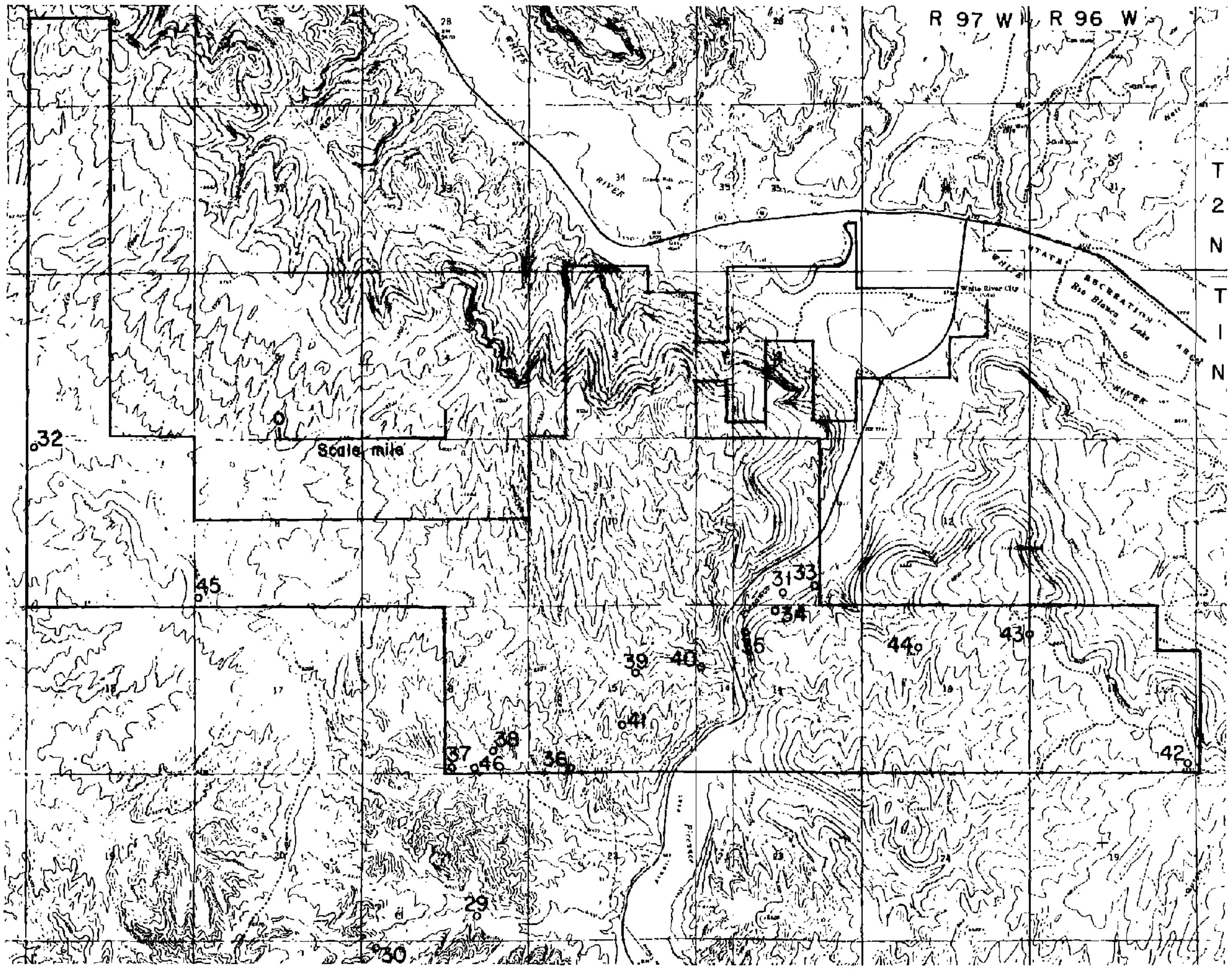

FIGURE 1. - Topographic location of exploratory holes.

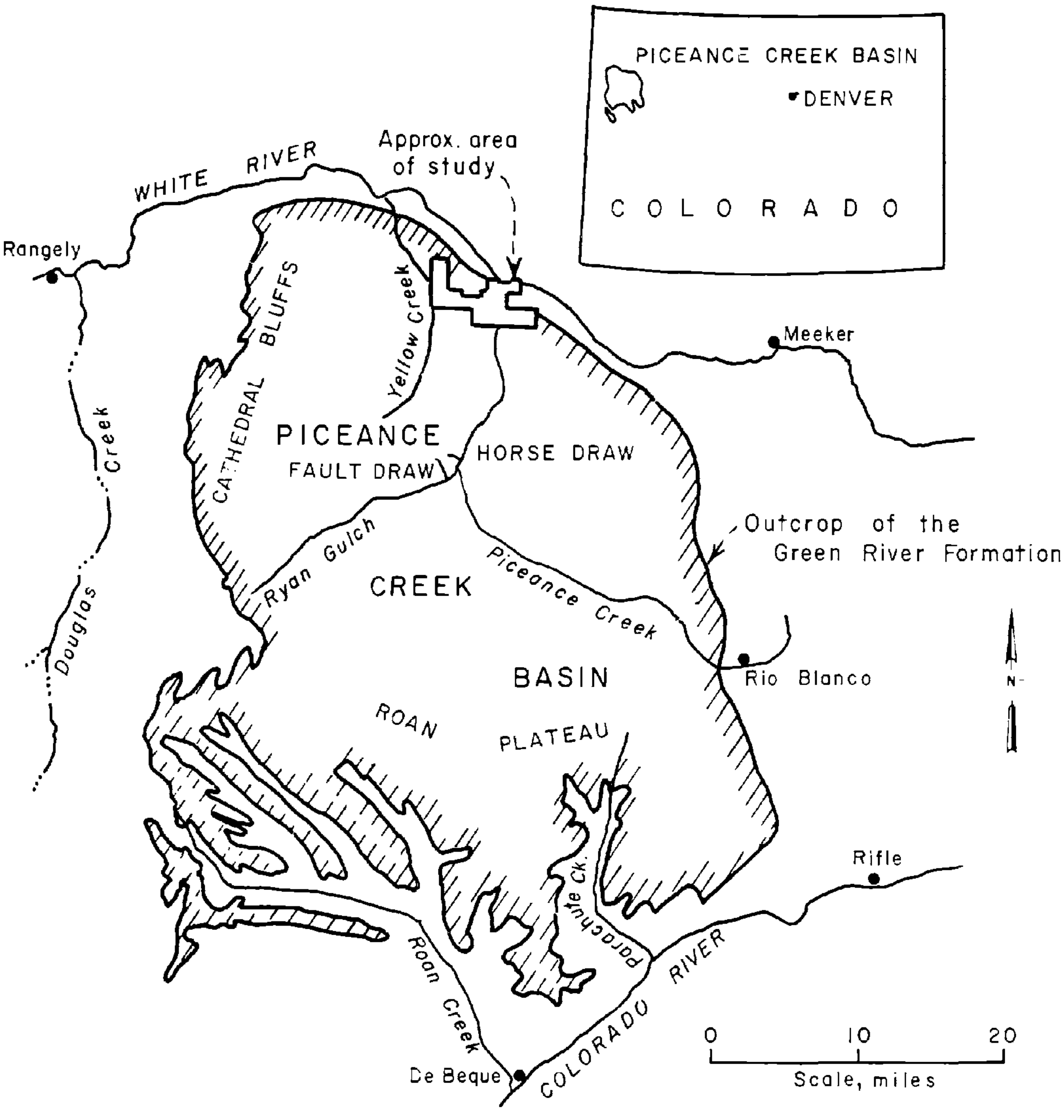

FIGURE 2. - Approximate area of study in the Piceance Creek Basin—northwestern Colorado.

The clastic facies of the Douglas Creek, Garden Gulch, and lower Parachute Creek Members are designated as the Anvil Points Member. It is very heterogeneous and is composed of gray shale, gray shale interbedded with brown and gray sandstones, marlstone, siltstone, and limestone. It ranges from 0 to 1,870 ft thick and it is found only in the eastern and southern part of the basin.

The Garden Gulch Member is predominantly made up of shales and marlstones; the marlstones are generally barren of oil. The Garden Gulch Member attains a thickness of 900 ft in the northwestern part of the basin. The lower and upper contacts of the Garden Gulch Member are well-defined on resistivity logs and are known as the Orange and Blue markers. Resistivity logs show these two contacts as low resistivity zones. The Blue marker marks the contact between the Garden Gulch Member and the overlying Parachute Creek Member.

The Parachute Creek Member is the most important member of the Green River Formation as it contains the richest and thickest beds of oil shale. The thickness ranges from over 2,000 ft in the north-central part of the basin to 500 ft around the margins. The Parachute Creek Member also contains numerous thin, analcime-rich tuff beds, finely disseminated dawsonite, nodular nahcolite, and beds of halite and nahcolite (4). The Parachute Creek Member can be divided into zones, ledges, beds, and groups of beds on the basis of yield or weathering characteristics. The Mahogany zone is the richest in kerogen content, and it is the most widespread. The upper boundary of the Mahogany zone is marked by the "A" groove, a 10- to 15-ft-thick sequence of marlstone and lean oil shale. This "A" groove sequence is less resistant to erosion than the kerogen-rich beds below, and it will form slopes on outcrops which resemble grooves. The thickness of the Mahogany zone will range from 100 to 215 ft depending upon whether the section measured is near the margin or in the north-central part of the basin. The lower limit of the Mahogany zone is defined by the "B" groove, a lean oil shale zone. Below the "B" groove, a series of rich zones (R zones) and lean zones (L zones) have been identified by Donnell and Blair. These zones can also be divided into the leached and unleached zones on the basis of whether nahcolite and/or halite have been removed by dissolution or leaching by ground water. The unleached zone or saline zone contains very probable economic deposits of nahcolite and dawsonite (6). The unleached zone ranges from 500 to 1,100 ft thick in the central part of the basin.

The Uinta Formation, which was formerly the Evacuation Creek Member, is composed of marlstones, shales, siltstones, and sandstones which overlie most of the basin. The Uinta Formation, for the most part, rests, conformably on the Parachute Creek Member (3).

EXPERIMENTAL PROCEDURE

Cores were selected by Federal Bureau of Mines personnel and W. I. Duvall, consultant to The Superior Oil Company. Core selection was based primarily on the stratigraphic locations of potential roof rock, pillar rock, and floor rock of the nahcolite- and dawsonite-rich beds in the unleached saline zone. Primary emphasis was placed upon the L4B, R4B, L3, and R3A beds because these were deemed the prospective horizons of interest. Core samples were also obtained in the zone of a proposed pilot adit incline.

In general, specific strength tests were determined from zones relevant to their potential application. For instance, indirect tensile strengths were obtained by the Brazilian technique from roof rock and, where possible, triaxial data were obtained for rock located in potential pillar zones. Apparent specific gravity or weight-volume relationship was determined for each test

FIGURE 3. - NX cores of solid oil shale and nodular nahcolite.

piece of core. Fischer assays to determine kerogen content and percentages of nahcolite and dawsonite were determined by The Superior Oil Company on all tested cores, and these were provided to the Bureau for use in data analyses. Fischer assay and mineral analyses were made on the actual sample tested and not on a split sample taken over a 1-ft interval.

Sample Preparation

Samples were cut to the desired lengths and the ends were surface finished with a grinder. End planes were made parallel within a 0.001-in tolerance. Lengths of the cores were kept within a length tolerance of 0.1 in for the length-to-diameter (L:D) ratio specified. Perpendicular tolerance of the end planes to the axis of the specimen was less than 1°. Figure 3 shows NX cores of solid oil shale and nodular nahcolite.

Equipment Used

A materials test system (MTS)[4] stiff testing machine was used for the testing of the cores. This is a closed loop, servocontrolled hydraulic system with a rated capacity of 600,000 lb. This machine can be programed for a constant load rate or constant strain rate.

Linear variable differential transformers (LVDT) were used as the readout device to measure axial as well as lateral deformation under uniaxial tests as shown in figure 4. This physical arrangement allows a determination of Young's modulus (E) and Poisson's ratio (ν).

Triaxial tests were completed using a triaxial cell originally designed by Obert (12), but modified so that LVDT's could be used as the axial deformation readout device.

[4]Reference to specific brands is made for identification only and does not imply endorsement by the Bureau of Mines.

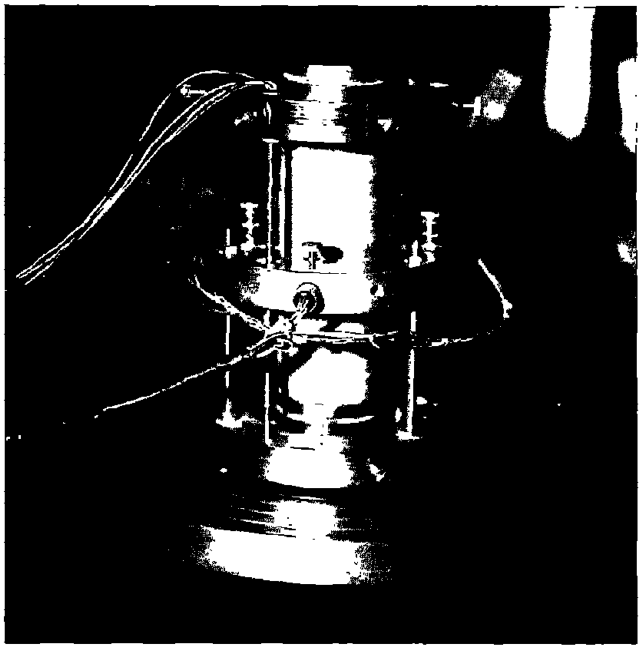

FIGURE 4. - Instrumented NX-size oil shale core (2.125 in diameter X 5.313 in length) with LVDT's to measure both axial and lateral displacements.

TESTS CONDUCTED

Uniaxial Tests

Samples with L:D values of 1:1, 2:1, and 2.5:1 were selected as desirable for these tests. The 2.5:1 samples were tested to reduce the end constraint effects from steel platens. Thus, it was on these specimens that Young's modulus and Poisson's ratio values were determined under uniaxial conditions. L:D ratios of 2:1 and 1:1 were tested to evaluate whether the following formula (13) was applicable:

$$C_o = \frac{C_p}{0.778 + 0.222\left(\frac{D}{L}\right)},$$

where C_o = compressive strength of sample with L:D = 1:1

and C_p = compressive strength of sample with 2 > L:D > 1/3.

The results indicate that the strength results are valid only if the kerogen yield is the same for samples with different L:D ratios. This would also have to be true for samples containing nahcolite and dawsonite, because the testing indicated that the mechanical properties are dependent upon the percentages of these two minerals. Thus, the effect of the difference in L:D ratio cannot be measured unless a very large number of samples are tested.

The value of Young's modulus and Poisson's ratio were determined between an overburden stress level and a selected stress value of approximately 7,500 psi. This stress value was found to be within the linear portion of the stress-strain curve for the specimen tested. Thus, those elastic parameters are secant values up to approximately 7,500 psi for this rock material.

Triaxial Tests

Triaxial testing was conducted using lateral pressures of 250, 500, 750, 1,000, and 2,000 psi. Values of shear strength (S_o) and the coefficient of internal friction (μ_m) were determined by obtaining a Mohr's envelope using the maximum shear stress (τ_t) and mean normal stress (σ_m) technique that has been described elsewhere (7). It is important to note that the validity of the Mohr's envelope generated and the resulting shear strength and coefficient of internal friction values are dependent upon tests being performed on samples with the same or nearly the same kerogen yield or apparent specific gravity.

Brazilian Tests

Cylindrical specimens were loaded across the diameter with the axis of the core horizontal between the platens of the compression machine. A minimum L:D ratio of 1:2 was used with the ends of the specimen cut perpendicular to the axis; the ends were not finished by grinding. A small 3- by 5-in cardboard was inserted between the specimen and upper platen which contained a spherical seat, and another was placed between the bottom platen and the specimen (11).

This tensile strength, calculated by the following equation gives a value which is usually greater than the direct tensile strength and less than the flexural strength:

$$T_o = \frac{2\ F_c}{\pi DL},$$

where F_c = the failure load,

and D and L are the diameter and length of the specimen.

ANALYSIS OF DATA

Statistical Analyses

Earlier studies of the mechanical properties of oil shale by authors such as East and Gardner (5), Sellers, Haworth, and Zambas (14) at the Anvil Points mine, Garfield County, Colo.; Agapito (1), Horino and Hooker (8) at the Colony mine, Garfield County, Colo.; Horino and Hooker (9) on the Union Oil Co.'s property, Garfield County, Colo.; and Horino and Hooker (10) on White River Oil Shale Corp.'s property in Uintah County, Utah; all clearly indicate a dependence of mechanical properties on the yield in gallons per ton (gpt) for Mahogany zone rock materials. There is an apparent one-to-one correspondence between kerogen yield and apparent specific gravity. The mechanical properties can also be predicted by knowing the apparent specific gravity. Therefore, statistical treatment of the Mahogany zone data can produce predictive equations relating kerogen yield or apparent specific gravity to compressive strength, Young's modulus, and Poisson's ratio.

Selection of The Superior Oil Company's samples was primarily based on the determination of physical properties on the nahcolite and dawsonite zones. Regression analyses were run, but the correlation coefficients were very poor for the saline zone tests as shown in table 1. No acceptable relationships between the control parameters can be concluded.

TABLE 1. - Correlation coefficient, R, of regression analyses

Control parameters	Number of data points	Correlation coefficient, R
Density versus yield...........................	439	0.66
Compressive strength versus density............	184	.39
Compressive strength versus yield..............	173	.21
Compressive strength versus percent-nahcolite...	185	.37
Compressive strength versus percent-dawsonite...	185	.49

An assumption was made that high percentages of nahcolite or dawsonite in the samples may affect the density subsequently giving poor correlation coefficients. Therefore, all samples containing a nahcolite percentage greater than 1% were then excluded and the regression analyses were rerun on data from holes 29, 36, 38, 39, and 45. T-tests performed on the two regressions for each of the five holes showed that there was not a significant difference in the correlation coefficients with nahcolite and without nahcolite; the results are shown in table 2.

TABLE 2. - Correlation coefficients for density versus yield with and without 1% nahcolite

Hole	Sample size	Correlation coefficient with nahcolite	Sample size	Correlation coefficient without nahcolite
29..........	32	0.778	27	0.784
36..........	15	.682	10	.784
38..........	40	.253	31	.274
39..........	41	.712	35	.691
45..........	41	.917	36	.931

Analysis of variance techniques (2) were used to determine if yield, percent-nahcolite, and percent-dawsonite had any effect on the compressive strength, Young's modulus, and Poisson's ratio for the saline zone materials.

The following tabulation shows the format used to show the F-statistics with a high significance level by asterisks.

	Indicated by:[1]
$0.01 <$ significance level ≤ 0.05	*
$.001 <$ significance level $\leq .01$	**
significance level $\leq .001$	***

[1] No asterisks are printed for significance levels > 0.05.

The higher the "F" ratio, the lower the probability that an error will be made in accepting the hypothesis that the two variances came from the same population. Thus, three asterisks would indicate that the two variances came from different populations.

For the effect of kerogen yield, the samples were grouped as indicated in table 3. Only samples with less than 3% dawsonite and less than 10% nahcolite were used. The values of these percentages were determined by trial and error until it became apparent that these percentages represented significant changes for the parameters sought. The results of table 3 with an F ratio of only 1.92 would indicate no significant difference with the yield divided as given. However, if the yield is divided into only two divisions, less than 25 gpt and greater than 25 gpt, a significant difference is obtained as shown in table 4.

TABLE 3. - Variation of compressive strength with yield variation of 5 gpt

Yield, gpt	Average compressive strength, psi	Standard deviation, psi	Number of samples
Less than 15.............	13,202	3,814	14
15 to 20.................	14,871	4,476	11
20 to 25.................	13,472	2,955	15
25 to 30.................	12,942	3,022	17
30 to 35.................	10,885	2,167	11
35 to 40.................	11,458	2,394	10
Greater than 40..........	12,989	1,155	6

NOTE.--F ratio for one-way analysis of variance = 1.92 and significance level = 0.09.

TABLE 4. - Variation of compressive strength with yield divided into two groups--less than 25 gpt and greater than 25 gpt

Yield	Average compressive strength, psi	Standard deviation, psi	Number of samples
Less than 25 gpt.........	13,762	3,690	40
Greater than 25 gpt......	12,097	2,590	44

NOTE.--F ratio for one-way analysis of variance = 5.82 and significance level = 0.018*.

Nahcolite was grouped as indicated in table 5 for samples with less than 3% dawsonite and regardless of kerogen yield. There is a significant difference in the means of the two groups for the compressive strengths and Young's modulus, but not for Poisson's ratio. A greater percentage of nahcolite in the sample tended to give a lower compressive strength and a larger Young's modulus.

TABLE 5. - Variation of elastic parameters for samples with less than 10% nahcolite and greater than 10% nahcolite

Elastic parameter	Less than 3% dawsonite		Analysis of variance	
	Less than 10% nahcolite	Greater than 10% nahcolite	F ratio	Significance level
Average compressive strength...psi..	12,702	9,379	21.80	0.00001 ***
Standard deviation.............psi..	3,164	1,599		
Number of samples..................	94	21		
Average Young's modulus x 10^6..psi..	1.06	2.38	67.77	0.00000 ***
Standard deviation.............psi..	0.52	1.03		
Number of samples..................	87	20		
Average Poisson's ratio............	0.33	0.32	0.08	1.00000
Standard deviation.................	0.14	0.10		
Number of samples..................	87	19		

Dawsonite was grouped as indicated in table 6. The nahcolite content for all data values was less than 1%. Analysis of variance indicated a significant difference in the means of the two groups for all three elastic parameters. A higher dawsonite content in the sample tended to give a greater compressive strength, greater Young's modulus, and a greater Poisson's ratio.

TABLE 6. - Variation of elastic parameters for samples with less than 3% dawsonite and greater than 3% dawsonite

Elastic parameter	Less than 1% nahcolite		Analysis of variance	
	Less than 3% dawsonite	Greater than 3% dawsonite	F ratio	Significance level
Average compressive strength...psi..	12,821	15,398	18.75	0.0000 ***
Standard deviation.............psi..	3,245	3,819		
Number of samples..................	86	57		
Average Young's modulus x 10^6..psi..	1.10	1.47	11.99	0.00072 ***
Standard deviation.............psi..	0.54	0.69		
Number of samples..................	79	57		
Average Poisson's ratio............	0.33	0.37	5.0	0.02700 *
Standard deviation.................	0.13	0.14		
Number of samples..................	79	57		

Further refinement of the data using various restrictions on the percent of nahcolite and dawsonite have been tabulated and these values are shown in table 7 for the horizons of interest.

TABLE 7. - Average compressive strengths for the horizons of interest using the indicated percentages of nahcolite and dawsonite

Horizon	Less than 1% nahcolite		Less than 3% dawsonite	
	Less than 3% dawsonite	Greater than 3% dawsonite	Less than 10% nahcolite	Greater than 10% nahcolite
R4B:				
Average compressive strength..psi..	12,065	12,975	11,764	NCT
Standard deviation............psi..	1,216	2,157	1,169	-
Number of samples..................	6	23	8	-
L3:				
Average compressive strength..psi..	13,185	18,517	13,185	NCT
Standard deviation............psi..	2,768	4,849	2,768	-
Number of samples..................	11	13	11	-
R3A:				
Average compressive strength..psi..	12,207	14,012	11,805	9,671
Standard deviation............psi..	2,767	2,126	3,411	1,508
Number of samples..................	19	4	21	11

NCT No core tested.

To establish the average values of compressive strength, Young's modulus (E), apparent specific gravity, indirect tensile strength (T_o), and Poisson's ratio (ν) for design purposes for the horizons of interest, test values were grouped on the basis of logged geologic depths alone and table 8 was determined. It is to be noted that large standard deviations are evident. This is to be expected in the light of the previous conclusion that physical property values are dependent on percentages of nahcolite and dawsonite. Table 9 is included here to verify that, based on logged geologic depths alone, large differences in compressive strengths for a given horizon do exist and consequently, large standard deviations can be expected. Therefore, design values in table 8 are to be taken as good first approximations only.

The average physical properties of a proposed adit were also determined based only on depth of intersection in certain holes and these results are given in table 10.

TABLE 8. - Average physical properties for design purposes for horizons of interest

Horizon	Roof					Pillar				
	σ_c, psi	E x 10^6, psi	S.G.	T_o, psi	Poisson's ratio	σ_c, psi	E x 10^6, psi	S.G.	T_o, psi	Poisson's ratio
R4B:										
Average..........................	11,921	0.88	2.020	1,230	0.29	12,107	0.93	2.068	1,191	0.38
Number of samples..............	17	14	15	12	14	61	61	61	33	59
Standard deviation.............	±2,574	±0.36	±0.10	±294	±0.09	±2,167	±0.34	±0.09	±356	±0.11
L4B:										
Average..........................	21,798	2.38	2.220	655	0.37	10,056	1.17	2.220	NCT	0.37
Number of samples..............	1	1	1	1	1	2	2	2	-	2
Standard deviation.............	-	-	-	-	-	±556	±0.13	±0.02	-	±0.0
R3A:										
Average..........................	15,177	1.67	2.247	1,098	0.26	11,059	1.47	2.134	1,084	0.33
Number of samples..............	32	32	32	30	33	86	80	84	29	79
Standard deviation.............	±3,573	±0.71	±0.13	±330	±0.10	±2,886	±0.81	±0.09	±341	±0.13
L3:										
Average..........................	11,214	0.60	2.080	1,061	0.16	15,895	1.44	2.168	1,241	0.32
Number of samples..............	2	2	2	3	2	28	28	28	25	26
Standard deviation.............	±492	±0.09	±0.05	±463	±0.12	±4,508	±0.69	±0.15	±244	±0.09

NCT No core tested.

TABLE 9. - Average compressive strengths for the horizons of interest at the various holes based on geologic depths

Hole	R3A	R4B	L4B	L3
29.....	NCT	NCT	$\overline{x}$ = 13,970, s = 6,791, n = 3	NCT
30.....	$\overline{x}$ = 7,287, s = 992, n = 4	NCT		NCT
33.....	$\overline{x}$ = 11,608, s = 513, n = 4	$\overline{x}$ = 9,878, s = 1,000, n = 4	NCT	NCT
34.....	$\overline{x}$ = 14,410, s = 2,188, n = 7	$\overline{x}$ = 12,566, s = 238, n = 2	NCT	NCT
35.....	NCT	$\overline{x}$ = 12,237, s = 751, n = 9	NCT	$\overline{x}$ = 14,829, s = 2,260, n = 4
36.....	$\overline{x}$ = 9,631, s = 3,944, n = 2	$\overline{x}$ = 12,738, s = 1,451, n = 8	NCT	NCT
37A....	$\overline{x}$ = 11,290, s = 1,291, n = 7	$\overline{x}$ = 13,105, s = 1,141, n = 6	NCT	NCT
38.....	$\overline{x}$ = 9,667, s = 1,746, n = 8	$\overline{x}$ = 12,993, s = 1,844, n 4	NCT	NCT
39.....	NCT	$\overline{x}$ = 11,351, s = 846, n = 7	NCT	$\overline{x}$ = 16,220, s = 2,959, n = 6
40.....	$\overline{x}$ = 15,123, s = 1,093, n = 3	NCT	NCT	$\overline{x}$ = 18,584, s = 4,721, n = 12
41.....	$\overline{x}$ = 13,134, s = 2,979, n = 9	$\overline{x}$ = 13,181, s = 922, n = 6	NCT	NCT
42.....	$\overline{x}$ = 11,200, s = 2,911, n = 5	NCT	NCT	NCT
43.....	$\overline{x}$ = 10,510, s = 889, n = 3	NCT	NCT	NCT
44.....	NCT	NCT	NCT	$\overline{x}$ = 10,904, s = 783, n = 6
45.....	$\overline{x}$ = 11,443, s = 2,337, n = 13	$\overline{x}$ = 12,822, s = 3,105, n = 6	NCT	NCT
46.....	$\overline{x}$ = 9,391, s = 1,178, n = 11	$\overline{x}$ = 12,383, s = 4,210, n = 3	NCT	NCT

Where $\overline{x}$ = average compressive strength in psi; s = standard deviation in psi; n = number of samples; NCT - no core tested.

TABLE 10. - Average physical properties of proposed adit based on geologic depths

	Compressive strength, psi	Young's modulus $\times 10^6$, psi	Apparent specific gravity	Indirect tensile strength, psi	Poisson's ratio
Adit roof:					
Average..................	17,497	1.95	2.328	1,239	0.33
Number of samples........	10	10	10	11	10
Standard deviation.......	3,220	0.29	0.04	306	0.09
Adit walls:					
Average..................	13,357	1.46	2.155	1,188	0.35
Number of samples........	18	18	18	8	16
Standard deviation.......	2,538	0.79	0.12	273	0.13

The average shear strength values and coefficient of internal friction values are given in table 11 for the horizons of interest from a limited number of tests.

TABLE 11. - Average shear strength and coefficient of internal friction for horizons of interest

Horizon	Shear strength, psi	Coefficient of internal friction
R4B:		
Average........................	3,620	0.420
Number of samples..............	11	11
Standard deviation.............	1,234	0.201
L3:		
Average........................	3,350	0.660
Number of samples..............	7	7
Standard deviation.............	601	0.303
R3A:		
Average........................	3,138	0.406
Number of samples..............	8	8
Standard deviation.............	748	0.123

Creep Data

A series of tests was conducted on core samples from the saline zone with L:D ratios of either 1:1 or 0.5:1 at several stress levels that may be anticipated in the prototype structures.

Because it was recognized that the strain rate is stress-dependent, the same sample was tested at various stress levels. The same sample had to be used to obtain meaningful results because of the ever-changing nature of the bedded materials in a vertical direction. Samples were loaded to a selected load level to simulate the in situ field condition. Deformation of samples was monitored mechanically by three precision dial gages, and an average of the three readings was then used. The testing equipment was kept in an air-conditioned room in which the temperature was kept constant at 74° F. Humidity controls were not available. The gages were read daily and the load was adjusted to offset the creep and the resulting load decrease of approximately 100 to 200 lb daily.

At the outset of the creep testing program, tests were run for only 7 days under a constant load. It appeared as though the sample had reached the secondary creep rate stage. This was later shown to be wrong when a long-term, 90-day test was run on nodular nahcolite. Thus, all subsequent tests were at least 45 days long, or until it was quite apparent that the creep rate was constant. A typical plot is shown in figure 5. Similar curves will be generated if this same sample is retested at different load levels. The only difference will be that the creep rate will be larger as the stress is increased. The results of the testing of some samples are shown in table 12. If the final steady-state creep rate of table 12 is plotted against the stress level for the two L:D ratios of 1:1 and 0.5:1, as shown by figure 6, the larger creep rate with the larger stress level becomes evident. The five samples tested in table 12 (45-178-4, 45-177-5, 45-177-2, 38-120, and 38-121) at three different load levels were analyzed to see if the data would fit the Burger's equation as follows:

$$\varepsilon = \frac{\sigma_o}{E} + B\,\sigma_o^{\alpha}\,t + C\,\sigma_o(1 - e^{-\beta t}),$$

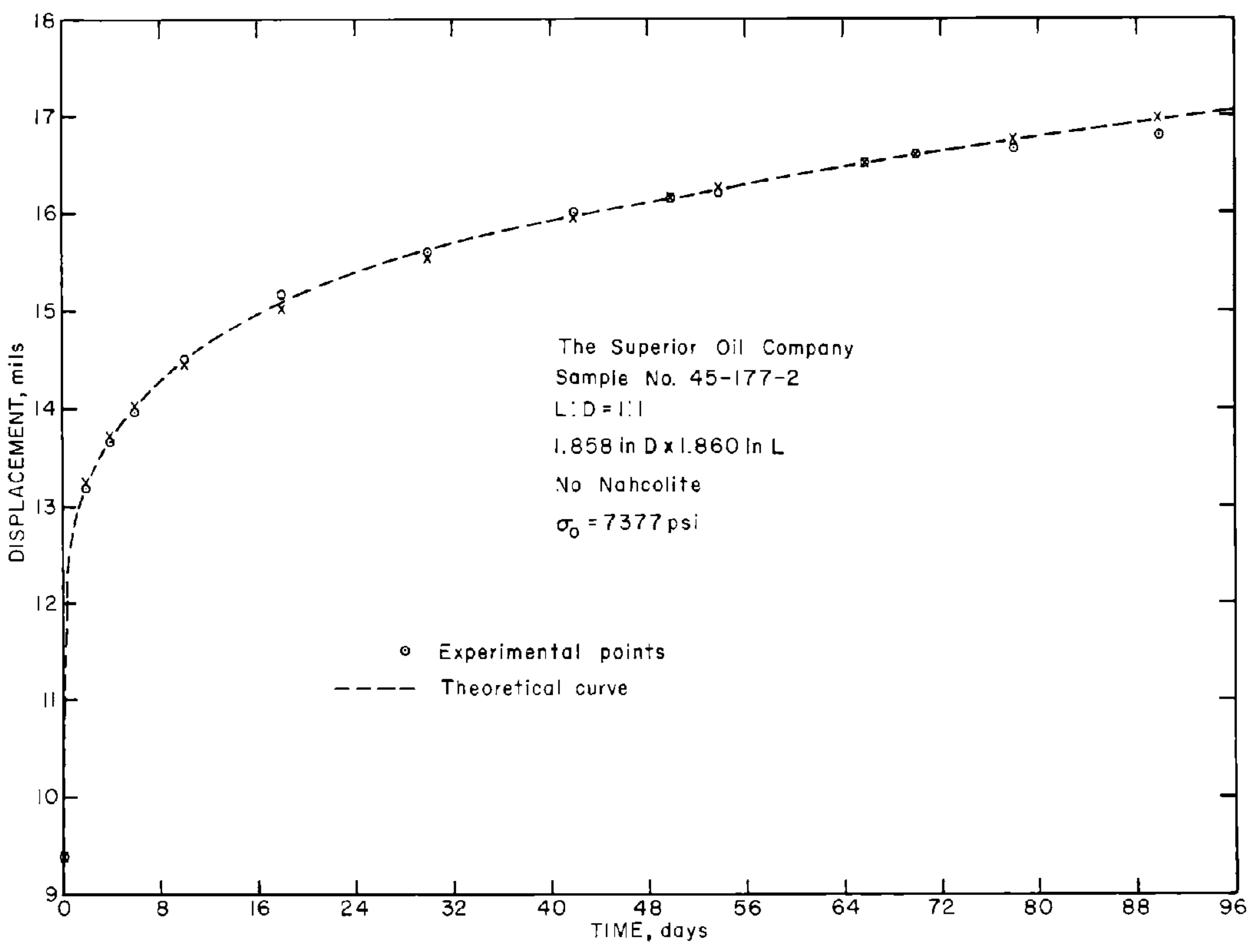

FIGURE 5. - Typical time-dependent curve for oil shale.

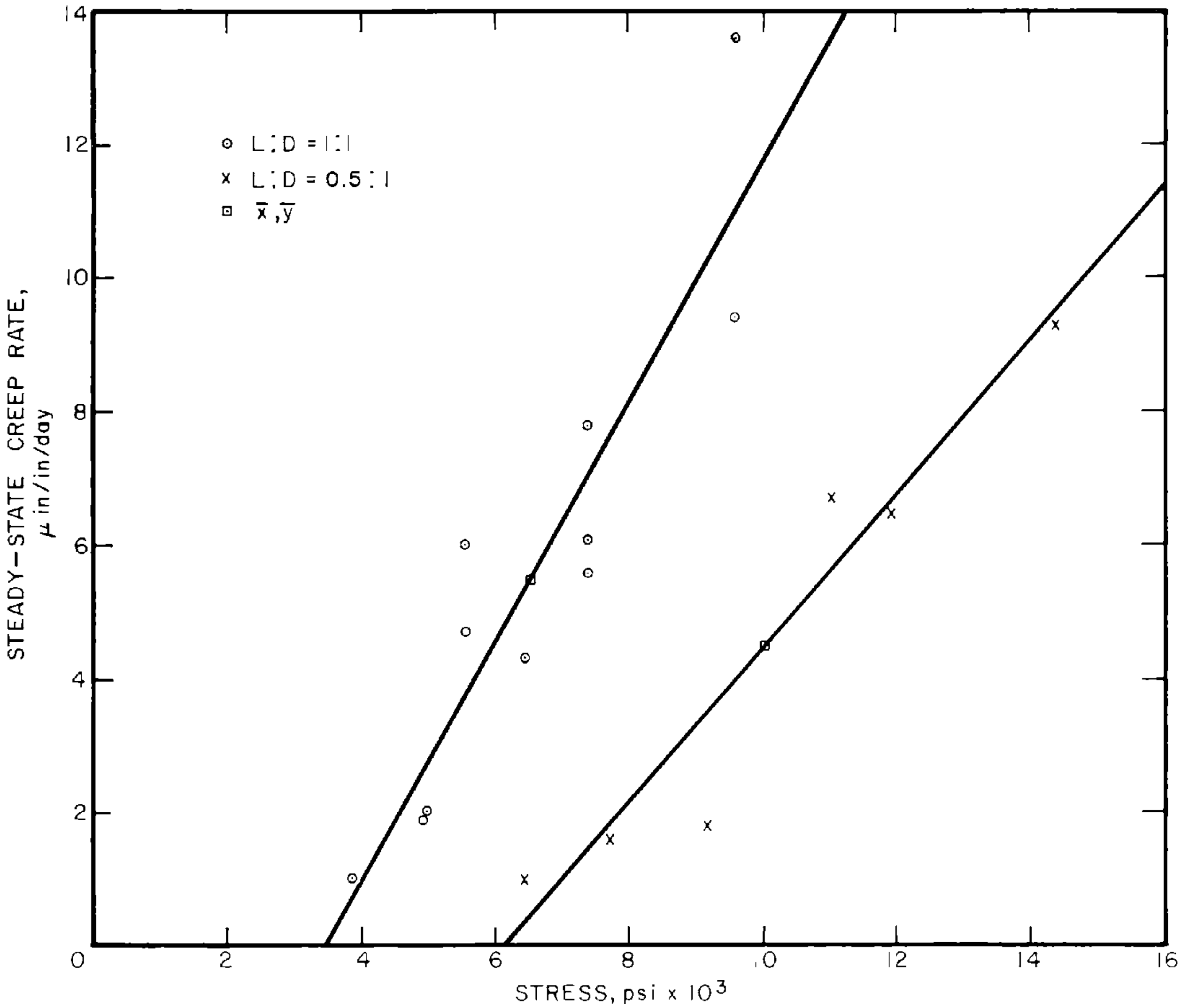

FIGURE 6. - Dependence of final steady-state creep rate on stress level for L:D ratios of 1:1 and 0.5:1.

where ϵ = strain,

σ_o = constant stress,

t = time of stress application,

$\frac{\sigma_o}{E}$ = instantaneous elastic strain,

$B \sigma_o^{\alpha} t$ = steady-state creep,

and $C \sigma_o (1 - e^{-\beta t})$ = initial or transient creep.

The initial or transient creep term did not conform too well to the curves.

TABLE 12. - Creep rates for samples tested

Sample	Depth, ft	Length of test, days	L:D ratio	Stress, psi	Ultimate stress, percent	Nahcolite, percent	Dawsonite, percent	Final steady-state creep rate, µin/in/day
45-176-2.....	2,408.3 to 2,408.5	90	1:1	5,543	50.8	27.19	2.37	3.5
45-176-4.....	2,408.5 to 2,409.1	90	1:1	6,467	46.4	9.10	1.91	4.3
45-178-2.....	2,412.0 to 2,412.2	90	1:1	5,543	51.2	12.93	2.48	4.7
45-175-2.....	2,405.8 to 2,406.0	90	1:1	7,399	46.5	.38	3.86	7.8
45-178-4.....	2,412.4 to 2,412.65	45	1:1	4,985	29.9	26.34	2.51	2.0
45-178-4.....	2,412.4 to 2,412.65	90	1:1	7,386	44.2	26.34	2.51	5.6
45-178-4.....	2,412.4 to 2,412.65	45	1:1	9,601	57.5	26.34	2.51	9.4
45-177-5.....	2,410.1 to 2,410.3	45	1:1	3,880	33.5	12.53	2.56	1.0
45-177-5.....	2,410.1 to 2,410.3	90	1:1	5,543	47.9	12.53	2.56	6.0
45-177-5.....	2,410.1 to 2,410.3	45	1:1	7,021	60.7	12.53	2.56	13.9
45-177-2.....	2,409.5 to 2,409.7	45	1:1	4,980	31.7	3.51	3.49	1.9
45-177-2.....	2,409.5 to 2,409.7	90	1:1	7,377	46.9	3.51	3.49	6.1
45-177-2.....	2,409.5 to 2,409.7	45	1:1	9,591	61.0	3.51	3.49	13.6
38-120.......	2,000.5 to 2,000.6	45	0.5:1	7,729	30.8	.88	3.22	1.6
38-120.......	2,000.5 to 2,000.6	45	0.5:1	11,042	44.1	.88	3.22	6.7
38-120.......	2,000.5 to 2,000.6	45	0.5:1	14,354	57.3	.88	3.22	9.3
38-121.......	1,002.4 to 1,002.5	32	0.5:1	6,441	25.2	33.37	2.88	1.0
38-121.......	1,002.4 to 1,002.5	45	0.5:1	9,201	36.0	33.37	2.88	1.8
38-121.......	1,002.4 to 1,002.5	45	0.5:1	11,962	46.8	33.37	2.88	6.5

A simple power law decay with time equation $\epsilon = B\sigma^{m} t^{n}$ was tried, but this also did not fit the data too well. Therefore, a modified power equation was then tried as follows:

$$\epsilon = \frac{\sigma_o}{E} + B\,\sigma_o^{\alpha}\,t + C\,\sigma_o^{\gamma}\,t^{\beta}.$$

The first term is the instantaneous elastic strain, the second term is the steady-state creep, and the third term is the initial or transient creep; σ_o and E must be in kip per square inch, t must be in days, and ϵ must be in inches per inch. These components of the final strain are shown in figure 7.

The proper analytical treatment of the equation and subsequent log-log plots will determine the constants of the equation. Pooling techniques were tried, and division had to be made for samples loaded at greater than 35% anticipated ultimate stress and less than 35% anticipated ultimate stress. The results are given in tables 13-14.

To test the validity of the equations generated, the values of the constants of sample 45-177-2, table 13, with the stress value of 7.377 kip/in^2, were used to calculate the resulting strains and are shown as the theoretical curve in figure 5. Thus, using the following formula, table 15 was generated:

$$\epsilon = \frac{7.377}{1.40 \times 10^{3}} + (2.6 \times 10^{-9})(7.377)^{3.17}t + (24.69 \times 10^{-5})(7.377)^{1}\ t^{0.171}.$$

The curve fit of the theoretical to the experimental as shown by figure 5 is excellent. A very cursory examination of the data of table 12 would indicate that the higher the percentage of nahcolite, the less will be the strain rate for like stress levels.

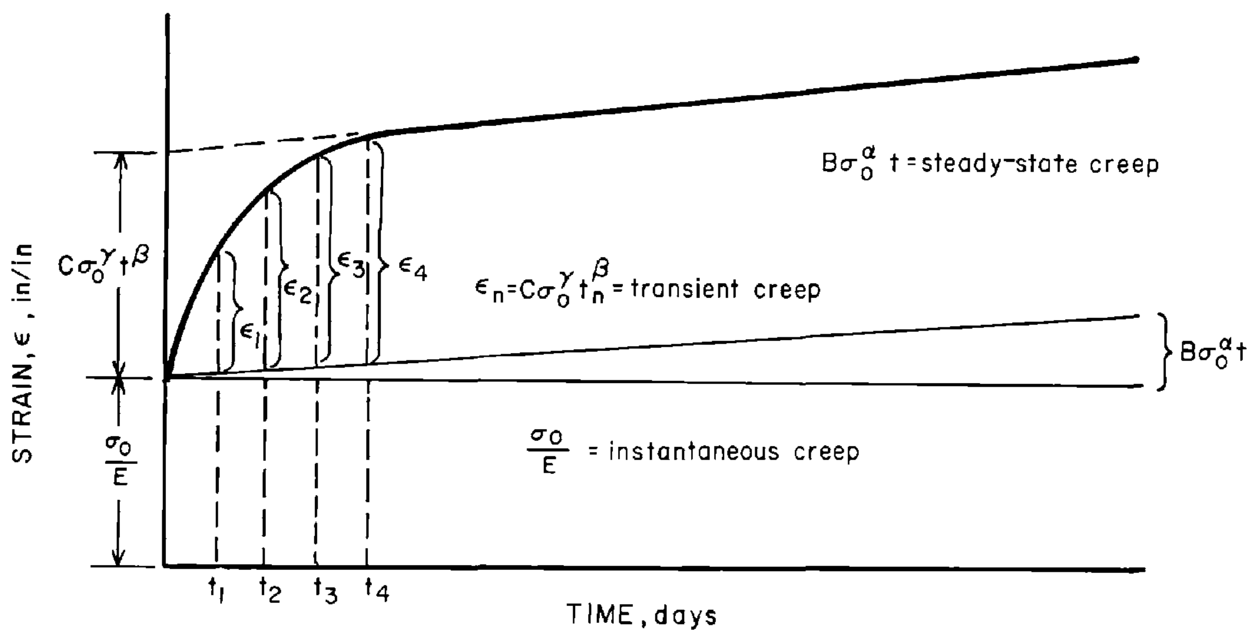

FIGURE 7. - Elements of creep equation.

TABLE 13. - Constants for creep equation for samples loaded greater than 35% anticipated ultimate stress

Sample	E, kip/in^2	B, in^3/in kip day	α	C, in^3/in kip day	γ	δ
38-120............	2.08×10^3	2.5×10^{-9}	3.17	8.69×10^{-6}	1.0	0.171
38-121............	2.03×10^3	9.7×10^{-9}	3.17	7.89×10^{-6}	1.0	.171
45-177-2..........	1.40×10^3	2.6×10^{-9}	3.17	24.69×10^{-6}	1.0	.171
45-177-5..........	1.32×10^3	21.4×10^{-9}	3.17	19.42×10^{-6}	1.0	.171
45-178-4..........	1.44×10^3	11.1×10^{-9}	3.17	20.19×10^{-6}	1.0	.171

TABLE 14. - Constants for creep equation for samples loaded less than or equal to 35% anticipated ultimate stress

Sample	E, kip/in^2	B, in^3/in kip day	α	C, in^3/in kip day	γ	δ
38-120............	2.08×10^3	2.5×10^{-9}	3.17	7.76×10^{-6}	1.0	0.09
38-121............	2.03×10^3	9.7×10^{-9}	3.17	3.98×10^{-6}	1.0	.09
45-177-2..........	1.40×10^3	2.6×10^{-9}	3.17	10.70×10^{-6}	1.0	.09
45-177-5..........	1.32×10^3	21.4×10^{-9}	3.17	2.43×10^{-6}	1.0	.09
45-178-4..........	1.44×10^3	11.1×10^{-9}	3.17	$13.7\ \times10^{-6}$	1.0	.09

TABLE 15. - Theoretical strain values for sample 45-177-2

t, days	B, $\sigma_o^{3.17}t$ in/in $\times10^{-6}$	C, $\sigma_o t^{0.171}$ in/in $\times10^{-6}$	E, σ_o in/in $\times10^{-6}$	ϵ, in/in $\times10^{-6}$	Displacement, mils	Experimental curve value, mils
0....	0	0	5,053	5,053	9.40	9.40
2....	3	2,051	5,053	7,107	13.22	13.17
4....	6	2,309	5,053	7,368	13.70	13.66
6....	9	2,474	5,053	7,536	14.02	13.95
10....	15	2,700	5,053	7,768	14.45	14.48
18....	26	2,986	5,053	8,068	15.01	15.15
30....	44	3,258	5,053	8,355	15.54	15.58
42....	62	3,451	5,053	8,566	15.93	16.01
50....	73	3,556	5,053	8,682	16.15	16.15
54....	79	3,603	5,053	8,735	16.25	16.20
66....	97	3,729	5,053	8,879	16.51	16.49
70....	103	3,766	5,053	8,922	16.59	16.57
78....	114	3,837	5,053	9,004	16.75	16.67
90....	132	3,932	5,053	9,117	16.96	16.81

Using the highest load level and the largest creep rate of 14.0 μin/in/day from table 12, a 1:1 pillar 20 ft high, loaded at 60% of breaking strength, would have a total displacement of 24.5 in in a time span of 20 years as shown in the following:

$$\text{displacement} = 14.0 \times 10^{-6} \times (20 \times 12) \times (20 \times 365) = 24.5 \text{ in.}$$

SUMMARY

In an effort to predict behavioral characteristics of new potential mining materials, static and time-dependent property tests were conducted on NX-size drill cores from 18 exploratory holes located in the northern portion of the Piceance Creek Basin, Colo.

Emphasis during the core sampling and testing was on the saline-rich beds of the Green River Formation, namely R4B and R3A and the accompanying roof horizons L4B and L3. Regression analyses techniques were used in an attempt to relate gpt or apparent specific gravity to compressive strength, Young's modulus, and Poisson's ratio; these correlation coefficients were very poor.

Statistical treatment of the data for samples with less than 3% dawsonite and with a division of less than 10% nahcolite and greater than 10% nahcolite showed that there is a significant difference in the means of the two groups for the compressive strengths and Young's modulus. A greater percentage of nahcolite tends to lower the compressive strength and to increase Young's modulus.

Analysis of data using less than 1% nahcolite and with a division of less than 3% dawsonite and greater than 3% dawsonite showed a significant difference in the means of two groups for all three elastic parameters. A higher percentage of dawsonite tends to increase compressive strength, Young's modulus, and Poisson's ratio.

Average physical properties for design purposes for the horizons of interest and for the proposed adit are given based only on the logged geologic depths. No consideration is given for the percentages of nahcolite and dawsonite and thus, large standard deviations are the result. However, the values should be useful for first approximations for preliminary mine design.

Creep tests indicated that the amount of creep is stress-dependent and that the larger stress levels produce the greater creep rate. Attempts were made to fit the data to both the Burger's equation and the simple power law equation. The data did not fit these models; therefore, a modified power equation was used and constants of this equation were determined. These data should be useful in preliminary mine design criteria and in the evaluation of rock structure problems.

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