Creep Properties of Saskatchewan Potash as a Function of Changes in Temperature and Stress

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ABSTRACT

Creep tests have been performed on sets of identical model pillars made from Saskatchewan potash ore. The pillars were subjected to constant vertical stresses in the range 5000 to 7000 psi, at constant temperatures of 80°F and 110°F, for a period of time of 1000 hours. These test conditions represent those existing at depths of between 3400 and 4500 feet in Saskatchewan, for extraction ratios at depths of and 36 percent respectively.

For times greater than 200 hours after the test had started, the vertical natural strain on the pillars, $\overline{\epsilon}$, could be related to the time, t, by a simple power law of the form: $\bar{\epsilon} = at^{b}$. The coefficient, a, and exponent, b, were found to be constant for a particular temperature and vertical stress on the pillar. Whereas the value of a was increased by an increase in temperature or vertical stress on the pillar, the value of b tended to decrease.

The rate of vertical creep of the model pillars was found in all cases to decrease with an increase in time. It was concluded that, for pillars having a width-to-height ratio of 4 or more, brittle failure of the pillars would not occur at the test temperatures and stresses, provided there were no discontinuities in the roof and floor.

INTRODUCTION

Potash companies in Saskatchewan have been reluctant to increase the extraction ratio in room-and-pillar mining much above 30 percent because of a lack of knowledge of the creep properties of evaporites. They have also been deterred from conventional mining at depths greater than about 3400 feet for the same reason. The problem is aggravated in Saskatchewan by the presence of water bearing formations immediately above the evaporites. Mine pillars must therefore be designed to preclude the possibility of fracture of the overlying strata.

There are two methods in which the stability of mine openings in evaporites can be investigated. The first is based on the experimental determination of mechanical properties of evaporites, as Serata (1964, 1966, 1968) has done with halite. These properties can then be used in an analysis of the time dependency of stress and deformation around mine openings: either theoretically by employing the finite-element method with a digital computer, or experimentally by employing dimensional analysis and suitable materials to model the evaporites (Thompson and Ripperger, 1964). The second method involves studying the deformation of model evaporite pillars as a function of changes in stress and temperature. In this way the empirical laws governing creep in evaporites can be obtained (Obert, 1965 and Lomenick, 1968).

Because of difficulties associated with determining the mechanical properties of materials behaving in as complex a manner as evaporites, it was decided to employ the second method in the research reported here. The creep properties of Saskatchewan potash have been obtained from tests on model pillars held at different temperature and stress levels for periods of 1000 hours. The temperatures and stresses at which the tests have been conducted were chosen to be representative of those existing in Saskatchewan at depths between 3400 and 4500 feet for extraction ratios up to 50 percent. In Figure 1, extraction ratio is plotted as a function of depth for constant axial

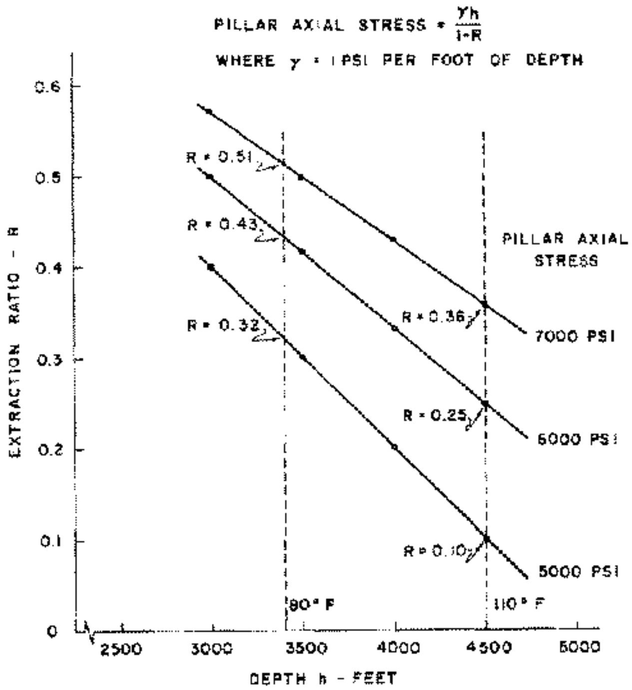

Figure 1. Extraction ratio versus depth for different axial stresses.

stresses of 5000, 6000 and 7000 psi. The temperatures of 80°F and 110°F corresponding to depths of 3400 feet and 4500 feet, respectively, are typical of those occurring towards the top of the Prairie Evaporite in Saskatchewan (Holter, 1969).

Obert (1965) has investigated the creep of model pillars made from rock-salt, trona and potash. The first phase of his investigation was to design a model pillar realistically related to its prototype in the mine, so that the actual deformation in the mine could be approximated by testing scaled model specimens uniaxially in the laboratory. His test specimens were cylindrical in shape, with the central peripheral parts ground out to form the rooms. The projecting upper and lower portions of the specimen represented the roof and floor. Steel rings were cemented around the top and bottom portions to provide the lateral confining pressure existing in the mine roof and floor. The steel rings also provided a method whereby the lateral stress in the model roof and floor could be calculated from the hoop strain measured in the rings.

Obert (1965) found that the evaporite rocks which exhibited viscoelasticity and viscoplasticity, such as rock-salt and potash, would tend to flow rather than fail in a brittle fashion, provided the diameter-to-height ratio of the pillar was equal to or greater than 4. His tests were conducted on pillars with a diameter-to-height ratio of 4 at room temperature for a period of 1000 hours, under axial stresses in the range 2000 psi to 12,000 psi. His results indicated that the creep rate in model pillars made from rock-salt and potash became constant after a relatively short transient initial period. He found also that the creep rate varied as some power of the applied stress. There appeared to be qualitative agreement between the results of model pillar tests and in situ measurements. An attempt to fit the model pillar data for a given rock type to simple rheological models was not successful.

Obert's (1965) data was re-interpreted by Bradshaw et al., (1964). They found that the model pillar creep could be fitted by a power law of the form

$$\epsilon = a t^b \sigma^c, \qquad \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

where ϵ = axial strain, σ = axial stress, t = time,

a, b, c = constants, with $o < b < 1.0$.

Bradshaw et al., concluded that the results of this type of model pillar test could be used to predict the creep of pillars in salt mines up to 70 years old. Their data from a salt mine in Kansas indicated that the vertical creep rate of mine pillars continued to decrease with time up to 12 years.

Serata (1964) investigated the time dependent deformation of model pillars made from rock-salt in order to determine if their behavior agreed with a theory of his based on continuum mechanics. His specimens were 5-inch cubes containing semi-cylindrical openings along the center-lines of their four sides to represent the mine openings. The samples were loaded axially while the top and bottom portions of the model pillars were confined to prevent lateral movement. The lateral pressure was made equal to the natural lateral pressure expected in situ. Tests were conducted at room temperature on two models having width-to-height ratios of 10.0 and 16.6 at axial stresses of 5300 psi and 4300 psi respectively for a period of 130 days. The results showed reasonably good agreement with those predicted by theory. They indicated that the rate of creep decreased exponentially with time for both tests.

Lomenick (1968) studied the creep of model pillars made from rock-salt at elevated temperatures and pressures. His model pillars were similar to those of Obert (1965): cylindrical in shape with the central peripheral parts removed to form the pillar and surrounding rooms. The effect of different thicknesses of salt at the top and bottom parts of the models was also investigated. Lateral constraint was provided by steel rings cemented to the top and bottom of the pillar. The pillar dimensions were 4 inches diameter by 1 inch high. Tests were conducted at temperatures in the range 22.5°C to 200°C for axial stresses in the range 2000 psi to 10,000 psi for each temperature. These tests showed that there was a marked increase in the rate of deformation when either the axial stress or temperature was increased. The creep rate was found to decrease with time in all cases, even after more than three years of testing in one case. Lomenick found that the creep could be represented for all test conditions by a power law of the form

$$\epsilon = at^b \sigma^c T^d , \quad \ldots\ldots\ldots\ldots (2)$$

where ϵ = axial strain, σ = axial stress,

T = temperature, t = time,

a, b, c, d = constants, where $b = 0.3$.

Lomenick apparently preferred to use the percent shortening for his definition of axial strain rather than natural strain, despite the large strains encountered in his experimental work.

The only published quantitative information on in situ shaft and pillar creep in potash mines has been presented by Barron and Toews (1963) and by Coolbaugh (1967). Barron and Toews investigated the creep of an unlined vertical shaft in halite above the potash beds in Saskatchewan. Plotted on logarithmic coordinates their strain data was linear with time, indicating a simple power law of the form

$$\epsilon = at^b . \quad \ldots\ldots\ldots\ldots (3)$$

Coolbaugh showed that a simple power law also applied to the vertical creep of potash mine pillars in the same mine. He presented data for deformation of the pillars and shaft which could be fitted with the exponent, b, in Equation 3 equal to 0.15.

TEST PROCEDURE AND APPARATUS

In choosing the size, shape and loading of the model pillars used in these tests, the following simplifying assumptions have been made:

1. The evaporite formation being modelled is homogeneous; no discontinuities, such as clay partings, are present to complicate the analysis. In Saskatchewan this condition will only apply to certain areas.
2. The deadweight of the overlying strata is applied to the pillar immediately the surrounding openings are made. Because of elasticity of the overlying strata and the effect of arching, the deadweight is not usually transferred immediately to the mine pillar. This assumption is therefore on the conservative side.
3. The behavior of mine pillars of rectangular cross section can be represented by that of model pillars of circular cross section. Obert (1965) observed that this is a valid assumption provided the diameter-to-height ratio of the model pillar is equal to the width-to-height ratio of the mine pillar. Reanalysis of data presented by Lomenick (1968, p. 61) tends to confirm Obert's observation.
4. The behavior of mine pillars of large cross-sectional area can be represented by that of very much smaller model pillars. For representative results with crystalline materials such as halite, Lomenick (1968, p. 27) quotes the necessity for at least 500 grains within the pillar, and a pillar diameter of at least eight to ten grains.

The dimensions chosen for the model pillars are indicated in Figure 2. The potash used in these

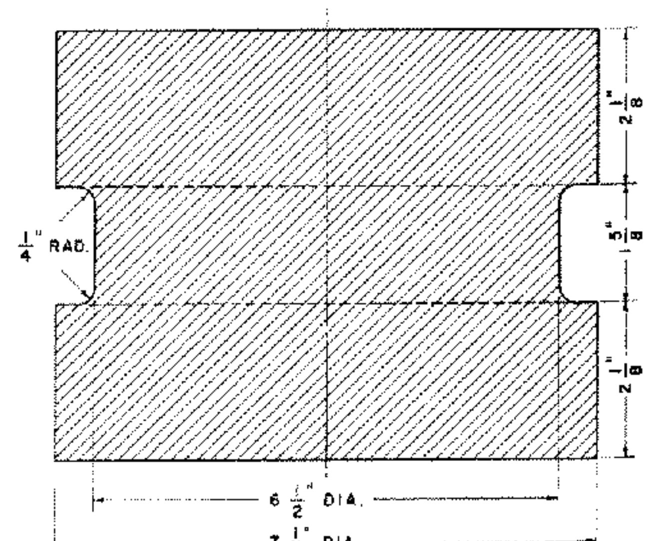

Figure 2. Section through model pillar with diameter-to-height ratio 4:1.

tests has a mean grain size of approximately 0.3 inches, with very few grains exceeding one inch in size. The model pillars, with dimensions of 6 1/2 inches diameter and 1 5/8 inches height, therefore include approximately 2000 grains. The diameter-to-height ratio of 4 is the minimum suggested by Obert (1965) for model pillars of potash and halite. The dimensions of the roof and floor portions were chosen to be sufficiently large to simulate actual conditions underground.

The model pillars were all obtained from a single block of potash ore, by first cutting them roughly to shape with a chain saw. The oversize blocks obtained in this way were then trimmed to shape on a band saw. Finally, the blocks were ground to shape on the multi-purpose grinding machine shown illustrated in Figure 3. The cylindrical and plane surfaces of the sample were finished on the grinding machine to a tolerance of ±0.001 inches. The axes of the pillars were all oriented perpendicular to the bedding plane, which was marked on the original block of ore.

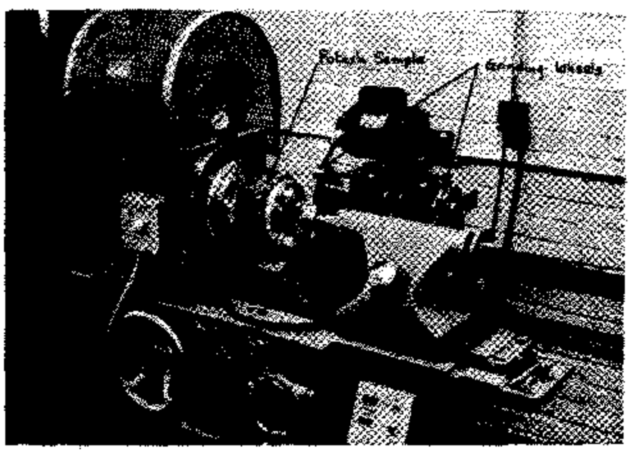

Figure 3. Multi-purpose grinder.

Steel rings provided lateral constraint on the roof and floor portions of the model. The rings were machined with an inside diameter 0.008 inches greater than the outside diameter of the roof and floor. After heating the rings to 120°F they were epoxy-cemented in place, as shown illustrated in Figure 4. The rings always cooled down to room temperature before the epoxy cement hardened. A clearance of 1/8 inches potash was left above the top ring and below the bottom ring to

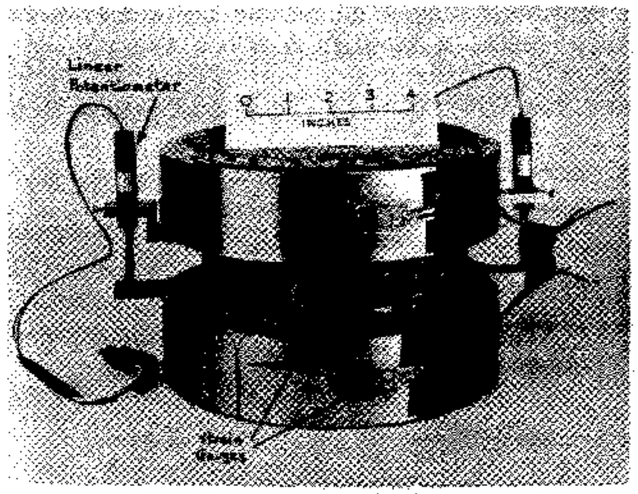

Figure 4. Model pillar with steel rings.

ensure the rings were not subjected to an axial stress during loading. The axial deformation of the pillar was sensed by a pair of linear potentiometers attached 180° apart on the upper steel ring. The hoop strain in the steel rings was sensed by two strain gauges attached to the center-line of each ring. The lateral stress in the roof and floor was then calculated from the hoop strain, using the formula relating the lateral stress to hoop strain for thick cylinders (Timoshenko and Goodier, 1951).

A constant axial load was applied to the specimen in the manner indicated in Figure 5. Nitrogen gas under closely-controlled pressure is supplied to the low-pressure side of the pressure

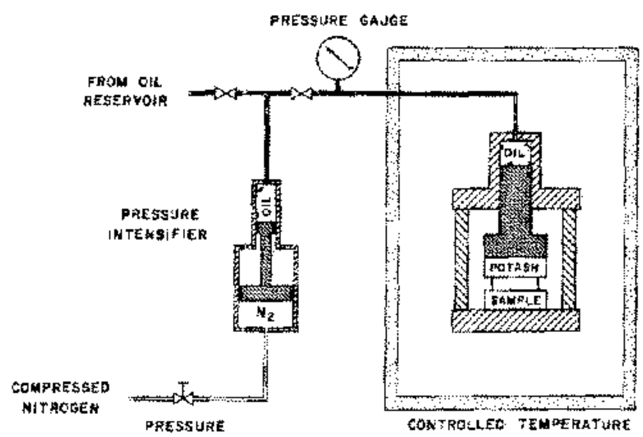

Figure 5. Hydraulic pressure system.

intensifier. Mineral oil on the high-pressure side then applies a constant load on the ram of a 250,000 lb compression loading machine, shown illustrated in Figure 6. The system proved to be

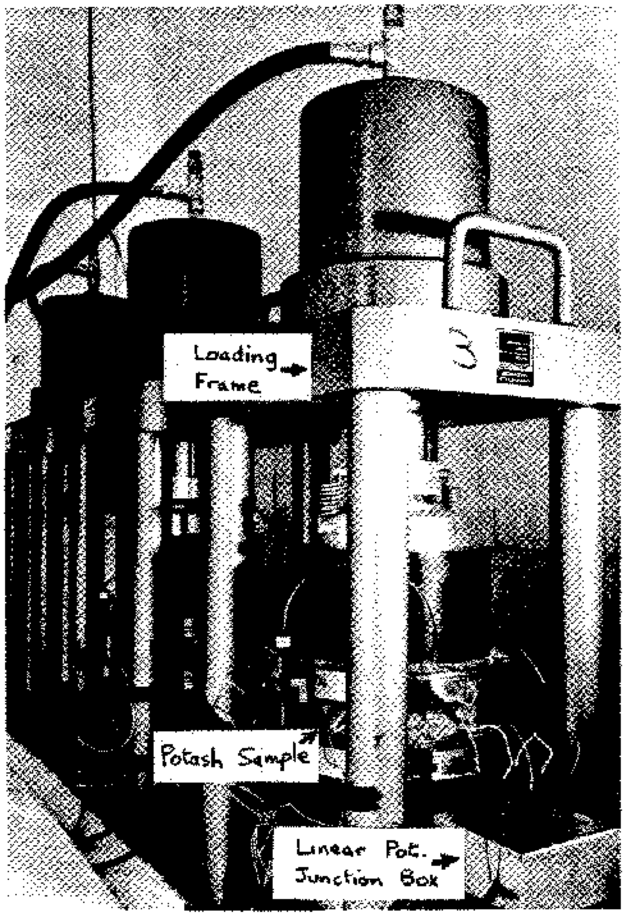

Figure 6. Hydraulic loading frame.

stable, and the axial stress on the model pillars was in all cases maintained to within ±1/2 percent over a complete test. A pair of polythene sheets, greased in between, provided friction reducers between the specimens and the loading platens.

Three model pillars could be tested concurrently in the temperature-controlled chamber shown illustrated in Figure 7. The temperature in the chamber could be controlled at any value in the range 80°F to 130°F. The temperatures of all three specimens were monitored and they were controlled to within ±0.2°F of the desired temperature throughout all test runs. The relative humidity in the chamber was

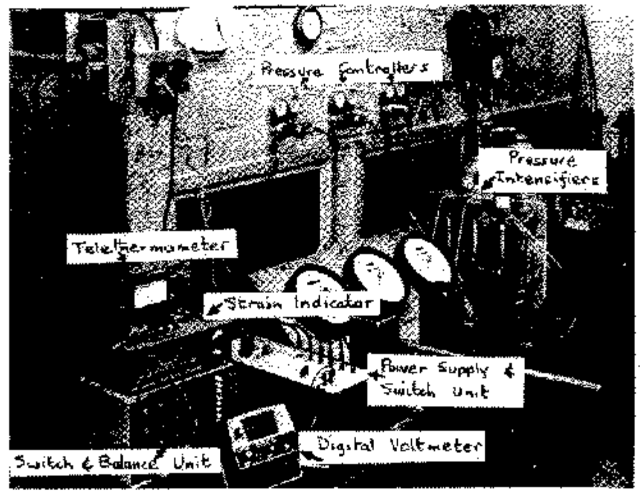

Figure 7. General view of equipment.

also monitored; at no time did it exceed 20 percent during the tests.

A 10-volt d.c. precision power supply provided a constant potential across the linear potentiometers. The potentiometer wiper voltages, which are linearly related to the axial deformations of the model pillars, were read on a digital voltmeter. The six linear potentiometers were checked against a dial guage at intervals between tests. No change in calibration was noted for any of them over the period of the tests. The strain gauges attached to the steel rings on the specimens were excited by and read on a strain indicator in conjunction with a 12-channel switch and balance unit. The electronic equipment is shown illustrated in Figure 7.

DISCUSSION OF RESULTS

The results of two sets of tests, each lasting 1000 hours, are reported here. The first set was performed at 80°F, with constant axial stresses on the three pillars of 5000, 6000 and 7000 psi. The second set was performed at 110°F, with the same axial stresses as at 80°F. Before applying the actual test loads on the specimens, an axial stress of 750 psi was applied for 24 hours to seat the loading platens on the samples. This stress was then removed for several hours and the base readings for the linear potentiometers and strain gauges were recorded immediately before applying the test loads.

Figures 8 and 9 show the creep curves for model pillars tested at 80°F and 110°F. For each sample

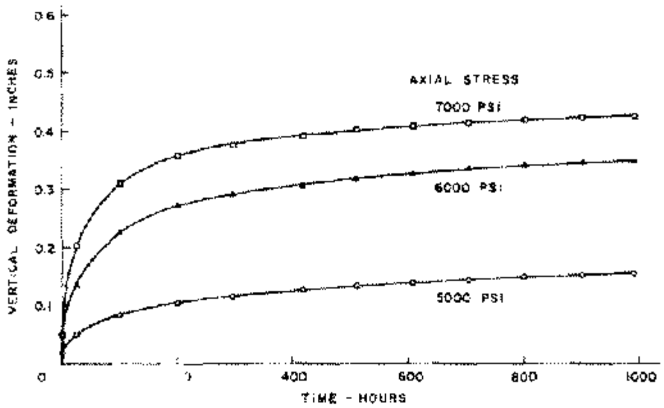

Figure 8. Pillar deformation versus time, temperature 80°F.

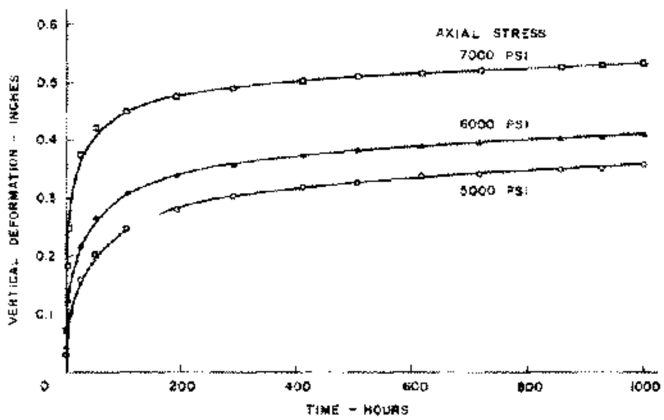

Figure 9. Pillar deformation versus time, temperature 110°F.

there is initially a high rate of convergence which decreases with time. The degree of convergence is seen to increase with higher stresses and temperature. In Figure 8, the creep curve for 7000 psi reflects a lower absolute convergence than expected. The reason for this is attributed to the degree of confinement afforded by the steel rings, which was greater for this sample than for the others. The creep curves for model pillars tested at 80°F with axial stresses of 6000 psi and 7000 psi lie very close to those for pillars tested at 110°F with axial stresses of 5000 psi and 6000 psi, respectively. It appears, therefore, that an increase in temperature of 30°F is approximately equivalent to an increase in axial stress of 1000 psi in the creep behavior of the model pillars.

Figures 10 and 11 show the lateral stresses in model pillars tested at 80°F and 110°F as a function

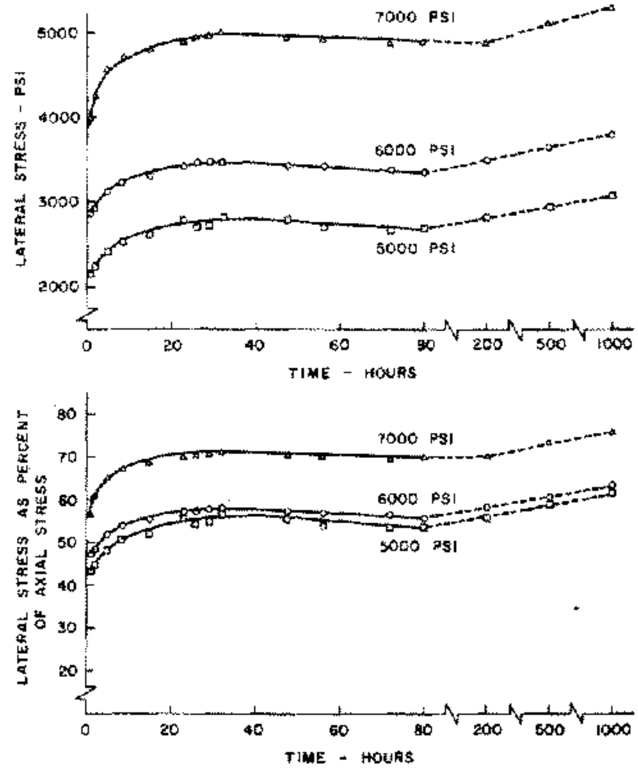

Figure 10. Lateral stress in pillar roof and floor at 80°F.

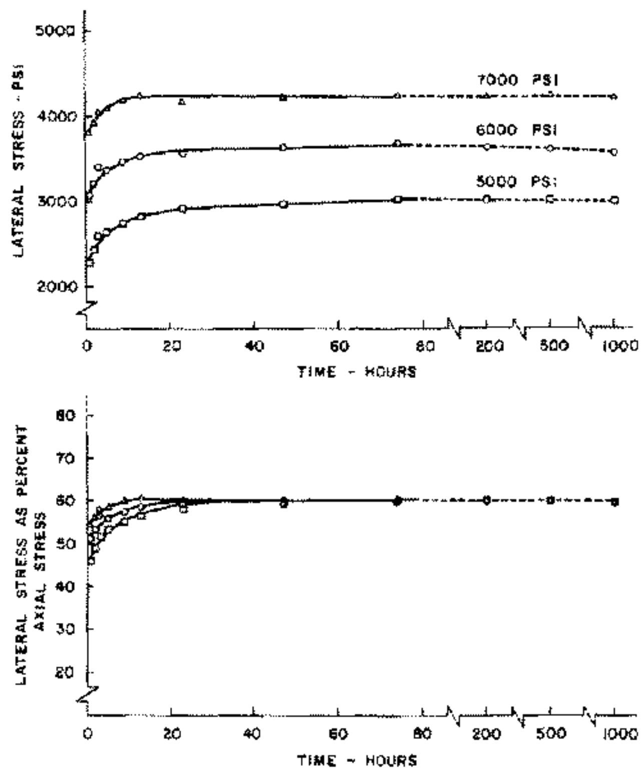

Figure 11. Lateral stress in pillar roof and floor at 110°F.

of time. Except for the specimen tested at 80°F and 7000 psi, the lateral stresses all approach approximately 60 percent of the axial stress on the pillars after 20 to 40 hours. The lateral stress on the specimen tested at 80°F and 7000 psi approaches a value some 10 percent higher than the remainder, due probably to the steel rings having less clearance when mounted. The lateral stresses on pillars tested at 110°F reach their asymptotic values more quickly than those tested at 80°F. There appears to be a tendency for the lateral stresses on pillars tested at 80°F to drop slightly after 40 hours and then to rise to a maximum at 1000 hours.

In Figures 12 and 13 the natural strain $\bar{\epsilon}$ ($\bar{\epsilon}$ = ln $\frac{\iota_0}{\iota}$, where ι = current height and ι_0 = original height of pillars [12]) is plotted as a function of time on logarithmic coordinates, for pillars tested at 80°F and 110°F. Natural strain was used instead of normal strain, because the latter is not suitable for representing the large strains encountered in creep tests. At both temperatures a straight-line relationship exists between log $\bar{\epsilon}$ and log t after 200 hours testing.

The straight-line portions of Figures 12 and 13 can be expressed by

$$\epsilon = at,^b, \qquad \ldots\ldots\ldots\ldots (4)$$

where $\bar{\epsilon}$ = natural strain,
t = time,
b = slope of linear portion,
a = constant.

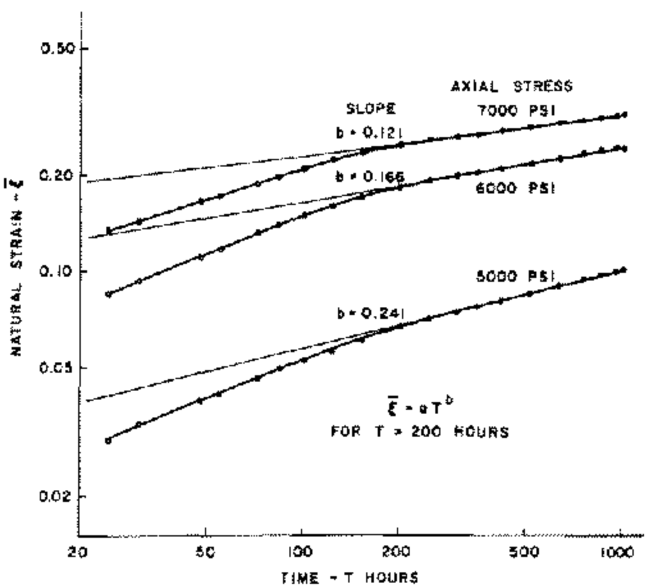

Figure 12. Natural strain versus time; temperature 80°F.

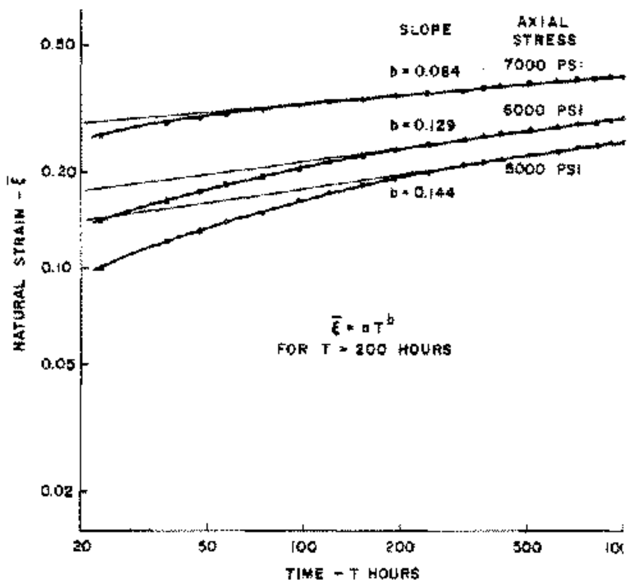

Figure 13. Natural strain versus time; temperature 110°F.

Both a and b are functions of the axial stress ar temperature. Values of a and b are given in Table and plotted in Figures 14 and 15 as a function ‹ the strain at 200 hours. It can be seen that tl exponent, b, decreases as the strain on a pillar . 200 hours is increased. Changes in temperatu alone appear to have a minor effect on this vari tion in b. The coefficient, a, increases in value . the strain on the pillar at 200 hours is increased.

TABLE 1. Values of coefficient, a, and exponent, b, in expression for natural strain

Temperature °F	Axial Stress psi	a	b	Natural Strai at 200 hrs, ϵ_{2c}
80	5000	0.019	0.241	0.068
80	6000	0.077	0.166	0.186
80	7000	0.131	0.121	0.250
110	5000	0.091	0.144	0.195
110	6000	0.119	0.129	0.236
110	7000	0.222	0.084	0.347

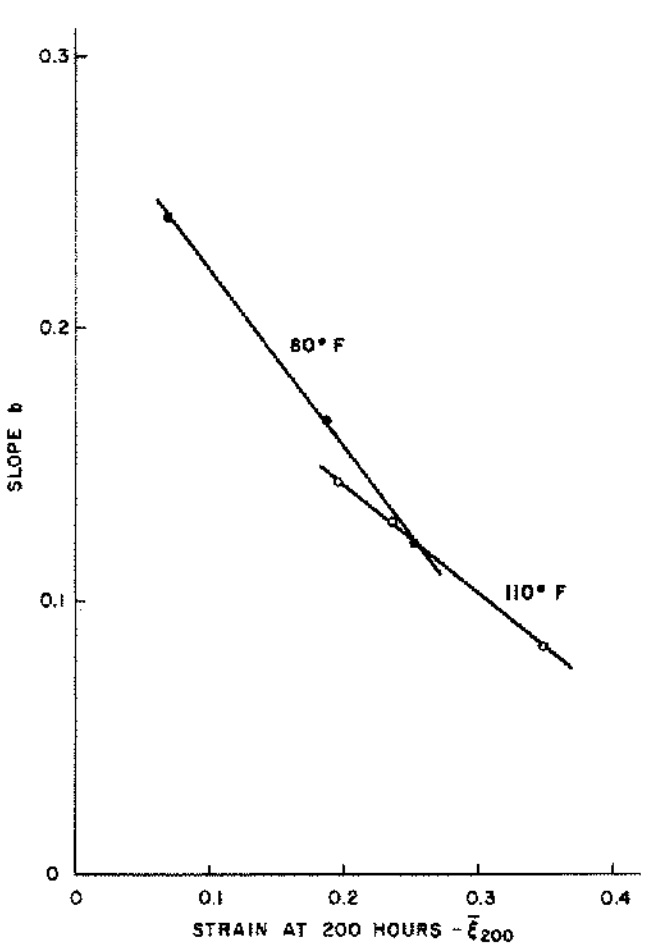

Figure 14. Slope of log $\bar{\epsilon}$–log T plot versus strain at 200 hours.

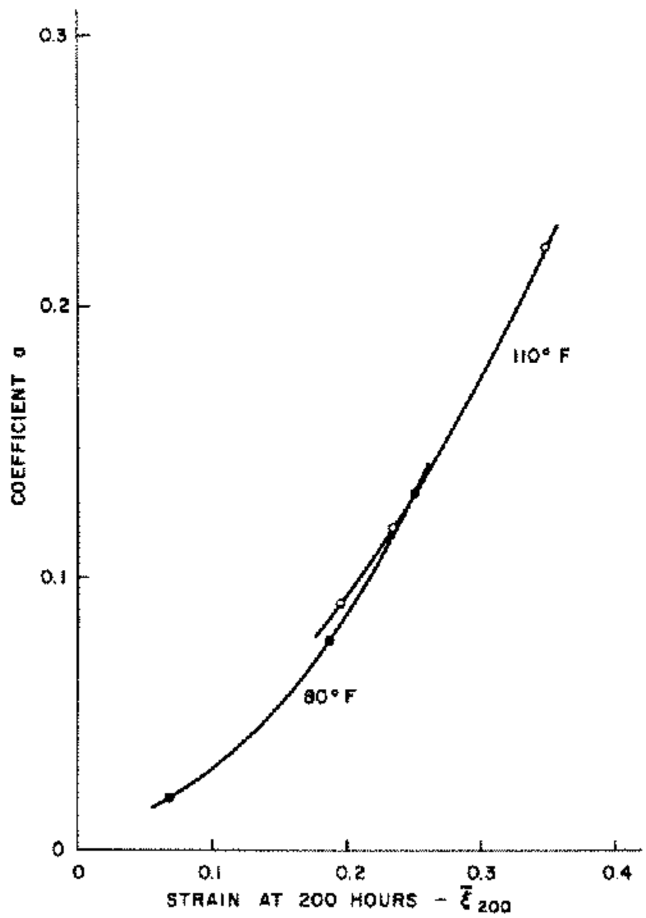

Figure 15. Coefficient of log $\bar{\epsilon}$–log 7 plot versus strain at 200 hours.

Differentiation of the expression for natural strain in Equation (4) with respect to time yields the creep rate

$$\dot{\bar{\epsilon}} = a\,b\,t^{\,b-1} \qquad \ldots\ldots\ldots\ldots\ldots (5)$$

It can be seen that since b is a positive constant always less than unity, the creep rate, $\dot{\bar{\epsilon}}$, will decrease continually with time. This continuous decrease in creep rate with time is in agreement with the results of model tests by Obert (1965) re-interpreted by Bradshaw et al., (1964), Serata (1964) and Lomenick (1968), and with in situ tests on mine pillars by Bradshaw et al., (1964), Barron and Toews (1963) and Coolbaugh (1967).

Figures 16 and 17 show the model pillars after completion of the creep tests. It can be seen that spalling had occurred on the surfaces of all pillars except that tested at 80°F and 5000 psi, with the effect more pronounced at higher axial stresses and temperatures. Cross sections from the model pillars

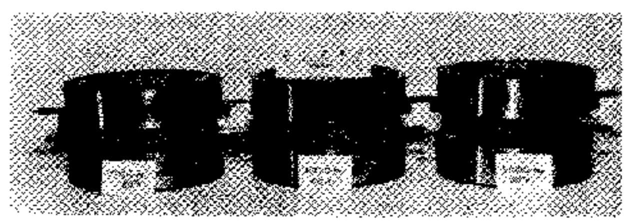

Figure 16. Samples after testing at 80°F.

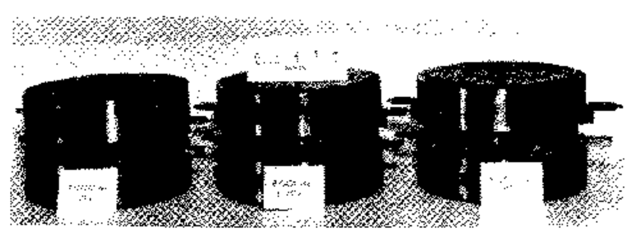

Figure 17. Samples after testing at 110°F.

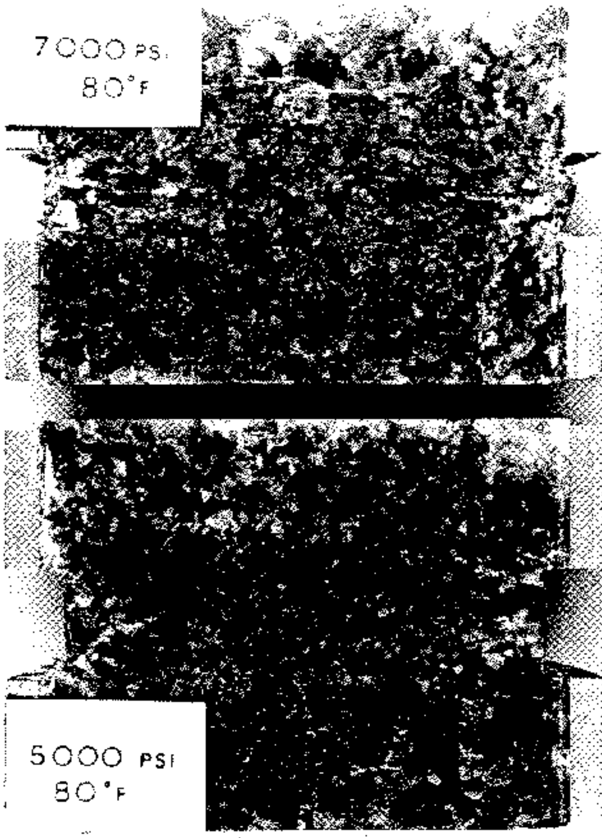

Figure 18. Cross sections of samples tested at 80°F.

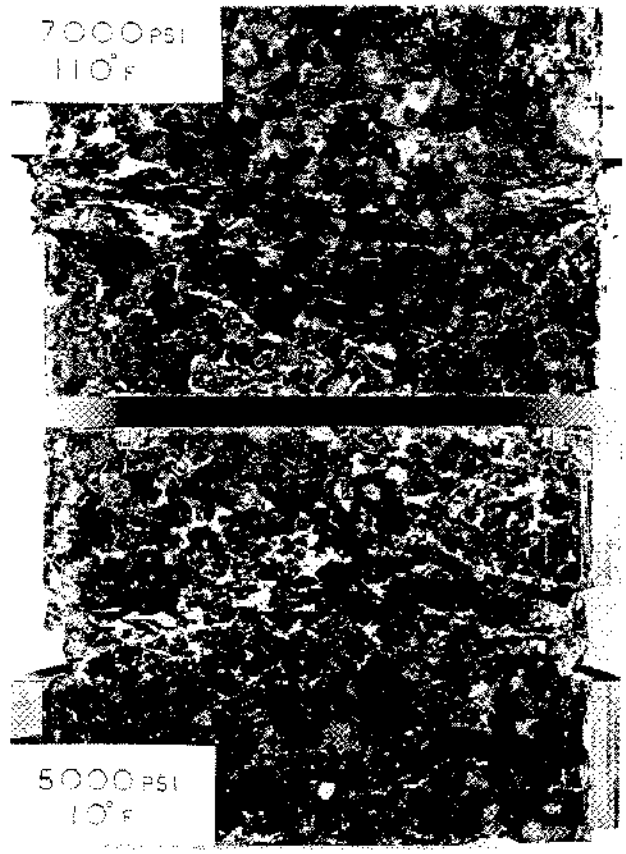

Figure 19. Cross sections of samples tested at 110°F.

are illustrated in Figures 18 and 19 for those tested at 80°F and 110°F and at axial stresses of 5000 psi and 7000 psi. Although the exact mode of deformation was not studied, it was observed that there had been flow of material into the opening from the pillar and by vertical flow from the roof and floor adjacent to the steel rings. The central part of the pillar resisted deformation because it has been subjected to a greater degree of confinement than the remainder of the pillar.

CONCLUSIONS

Tests on model potash pillars at stresses and temperatures typical of those occurring near the top of the Prairie Evaporite in Saskatchewan at depths of 3400 feet and 4500 feet, for extraction ratios of 51 percent and 36 percent respectively, indicate the following.

1. For pillars having a width-to-height ratio of 4 or more there will be no brittle failure, provided no clay partings occur in the roof or floor.
2. The rate of vertical creep of the pillar decreases continually with time.
3. A simple power law, $\overline{\epsilon} = at^b$, relates vertical strain, $\overline{\epsilon}$ and time, t. The coefficient, a, increases in magnitude as the temperature or vertical stress is increased. The exponent, b, tends to decrease as the temperature or vertical stress is increased.
4. The increase in temperature associated with an increase in depth of mining from 3400 feet to 4500 feet has approximately the same effect on creep behavior as an additional 1000 psi vertical stress on the pillar.

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