EXPANSIVE STRESSES OF A GROUT PLUG ON THE WALLS OF BOREHOLE

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ABSTRACT

The primary function of a concrete plug in a repository seal system is to provide a viable seal at the interface with the host rock by developing and maintaining a positive normal stress across the interface. While standards do exist for unrestrained and restrained expansion of mortar and concrete there are few systems that permit calculation of stress for a simulated borehole geometry.

A system was designed to determine the radial stresses introduced by expansive, cementitious grout on the borehole. It consists of a strain gage instrumented cell and its associated signal conditioner/amplifier. Cell material and thickness can be varied to simulate restraining conditions at given depths. Prior to sample emplacement the cell/system is calibrated by fluid pressurization. Special cell design eliminates the effects of longitudinal stresses during calibration. An analog output as a function of time is recorded, in conjunction with surface temperature of the cylinder.

The cell containing grout is maintained under controlled temperature conditions which can be varied from 25°C to 90°C. Pressure can be applied to the grout column to simulate hydrostatic/geostatic load conditions.

Using the equipment described, several expansive grout formulations were studied at 38°C. Results obtained for expansive stresses as a function of time are presented together with implications on repository-seal durability.

INTRODUCTION

Cement-based plugs/seals have been designed to isolate access shafts and boreholes in radioactive-waste repositories. Their primary function is to provide a tight seal at the interface with the host rock by developing and maintianing a positive normal stress across the interface. Successful performance, in this respect, could be dependent almost entirely on expansivity of the plug relative to the restraining forces of the surrounding host rock.

In cementitious formulations, where ettringite is the principal expansive component, the degree of restraint offered by the surrounding rock mass is of importance to the development of interfacial stress. Information exists on restrained and standard restrained expansion for mortars and concrete, however, most do not permit calculation of actual interface stresses under the existing restraining forces of actual borehole geometry.

A system to determine the radial stresses of the grout/concrete on the host rock which permits simulation of rock mechanical properties was designed. A brief description of the system is presented together with typical data, and their implications on repository-seal durability.

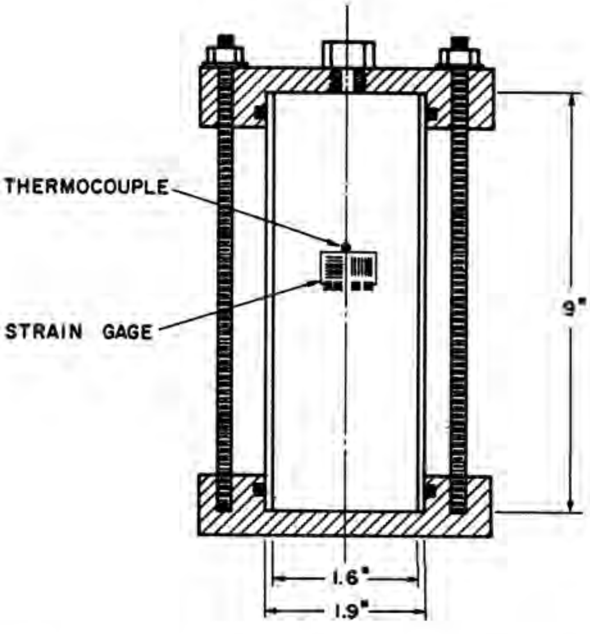

Fig. 1. Test cell for determination of expansive force.

DESIGN

The apparatus used for expansive force determinations consists of a steel cylinder capped with base and top plates, as shown in Fig. 1. Both bottom and top plates are provided with 'O' rings to ensure effective sealing of the steel cylinder during calibration. This design eliminates the effect of hydrostatic load in the vertical direction on the steel cylinder, i.e., any internal pressure on the top and bottom plates is transferred to the external clamping bolts. The physical and mechanical characteristics of the steel cylinder are shown in Table I.

A 90° rossette strain gage is attached to the central part of the outer surface of the cylinder. The gage is connected to a signal conditioner and recorder. Both radial and longitudinal strains are recorded continuously. The physical characteristics of the strain gage are shown in Table II.

TABLE I

Physical and Mechanical Characteristics of the Test Cell Used in Stress Measurement.

Modulus of elasticity (10^6 psi):
  tension: 26.0
  compression: 26.0
  torsion: 9.5
Poisson's ratio: 0.32
Coefficient of linear expansion (in/in/°Fx10^{-6}) [at 70-200°F]: 7.7
Thermal conductivity (BTU/in/hr/sq.ft/°F); 151.0; at 200°F; 167.0
Specific heat (BTU/lb/°F). at 70°F; 0.102; at 200°F; 0.105
Physical dimensions:
  length: 9.0 in.
  internal diameter: 1.60 in.
  external diameter: 1.90 in.

TABLE II

Physical Characteristics of the 90° Rossette Strain Gage.

Type: CEA-06-125UT-120

Micro-measurements Group, Raleigh, NC

Resistance (OHM): 120.00 ± 0.4%
Gage Factor (75°F): 2.025 ± 0.5%
Transverse sensitivity (X_t %)[a]: Radial + 1.4%; Longitudinal +0.6%

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[a] The values of transverse sensitivities gave very minute correction factors to the recorded strains, which are considered the true values of strains in both directions.

A chromel-alumel thermocouple is attached to the outer surface of the cylinder, in close proximity to the strain gage, to record any temperature variations and supply the necessary corrective factors for the temperature-induced strains. The entire cell is placed in a chamber, adjusted to the desired experimental temperature. The chamber is surrounded by a heated water jacket to ensure constant temperature, and to minimize the effects of thermal pulses of the heating elements on the strain gage output. The temperature control accuracy is ±0.5°C, over extended periods of time.

The current design of the stress-measurement system permits using cells having different mechanical properties (different material or thicknesses) to simulate the insitu deformational characteristics of the candidate host rock. The following relationship was developed to calculate the ratio of outside radius to the inside radius from the knowledge of the host rock mechanical properties (1):

$$r_o/r_i = \left(\frac{1/2G_R + (1-v_s)E_S}{1/2G_R - 1/2G_S}\right)^{1/2} \qquad (1)$$

where r_o = outer radius of the cylinder, r_i = internal radius of the cylinder, G_R = modulus of rigidity of the rock (GPa), G_S = modulus of rigidity of the cylinder (GPa), E_S = Young's modulus of the cylinder (GPa), and v_S = Poisson's ratio of the cylinder. For a given material, e.g., steel, it is possible to construct a *plot representing variation* of r_o/r_i versus modulus of rigidity of the rock (Fig. 2).

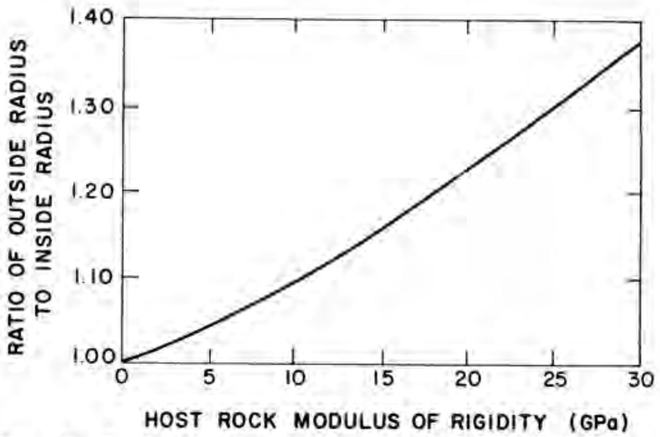

Fig. 2. Ratio of outer to inner radii of test cell related to modulus of rigidity of host rock.

Knowing the modulus of rigidity of the host rock, and using either Eq. (1) or Fig. 2, it is possible to determine the outer to internal radius of the cylinder as required to simulate the mechanical properties of the host rock at a given depth. In the present investigation, a tuff was simulated. Its modulus of rigidity was found to be 16.5 GPa (2). This value corresponds to a steel cylinder of $r_o/r_i = 1.2$. The length of the cylinder was 9 inches, a sufficient length to reduce longitudinal end effects.

EXPERIMENTAL PROCEDURE

Calibration

Prior to each experiment, the steel cylinder-strain gage combination is calibrated. These procedures permit precise measurement of the actual stresses exerted by the grout inside the steel cylinder. They also allow applying corrective terms for different conditions to the recorded strains, in order to obtain the true stresses applied by the grout on the cylinder.

The cell is filled with water, the upper cap is placed and the four restraining bolts are tightened to a given torque. The upper cap is connected to a water pump that provides controlled pressurization of the cell. The entire assembly is placed inside the thermal chamber, adjusted to the temperature at which the stress is to be determined with the strain gage output and temperature of the surface of the restraining steel cylinder being recorded. When thermal equilibrium is obtained calibration is initiated by pressurizing the cell with water at successively increasing pressure increments and recording the corresponding outputs of the strain gage. Calibration curves were constructed as shown in Figs. 3 and 4. The radial strain is recorded as positive output indicating tension, whereas the longitudinal strain is negative. The ratio of longitudinal strain to radial strain is equal to 0.327, which equals the Poisson's ratio of the steel material of the cylinder. The results of the calibration of several cylinder-strain gage combinations are shown in Table III.

To separate actual strains exerted by the grout from temperature-induced strains, the steel cylinder-strain gage combinations were also calibrated for thermal effects. The steel cylinder is filled with water and a heating element is inserted. Heat is applied in successive increments with constant slow rate of heating. The output is recorded after a period of time adequate to ensure the attainment of thermal equilibrium. The resultant temperature coefficient of induced strain is calculated (Table III). Thus, it is possible to apply

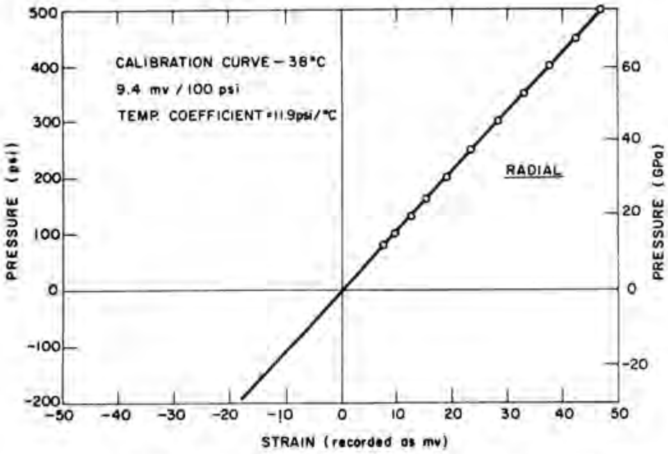

Fig. 3. Sample calibration curve for radial expansion.

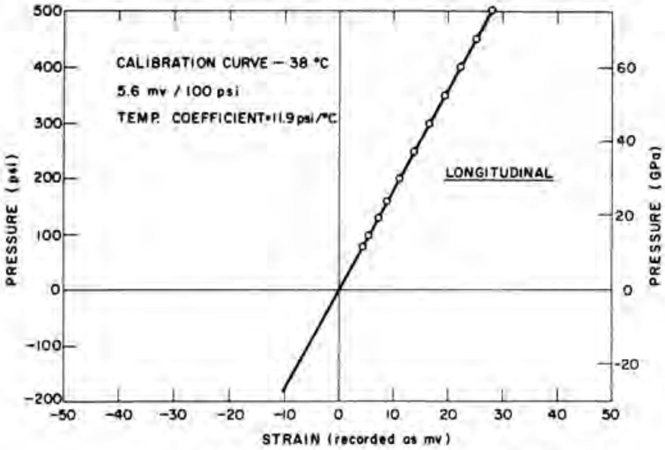

Fig. 4. Sample calibration curve for longitudinal expansion.

TABLE III

Results of Calibration for Steel-Strain Gage Combinations.

	strain (mvolts/psi x 10^{-2})	coefficient of temperature induced strains (psi/°C)
Cell I:		
(38°C)		
Radial	+8.88	11.50
Longitudinal	-5.32	14.34
Cell II:		
(38°C)		
Radial	+9.40	11.90
Longitudinal	-5.60	11.90

corrective terms for temperature-induced strains.

After calibration of the steel cylinder/strain gage combination for stress and temperature, the complete assembly is placed in the thermally controlled chamber until the cell is loaded with the material to be tested.

Formulations and Mixing Procedures

Two formulations have been chosen for the present study. Formulation I (F-I) a mortar based on type K expansive cement and Formulation II (F-II), a grout based on Class H cement with added calcium sulphate hemihydrate. The compositions of these two formulations are shown in Table IV. Standard ASTM procedures as applicable were used throughout the present study. The mixing water was preheated to 38°C prior to mixing. This procedure is adapted to avoid severe temperature fluctuations during the initial stages of hydration. The temperature of the mixes prior to placement in the steel cylinder was to be 34°C. The mix is quickly cast into the test cell, equilibrated to the experimental conditions, tamped and the test cell reassembled. The complete assembly loaded with cement grout is placed in the curing chamber adjusted to 38°C. The radial and longitudinal strains as well as the temperature of the steel cylinder are continuously monitored.

TABLE IV

Compositions of Cementitious Mixtures.

	Formulation I	Formulation II
Type K cement	33.8%	---
Class H cement	---	47.3%
Deionized water	15.9	20.3
Silica fume	7.3	4.8
Low-Ca fly ash	8.2	---
High-Ca fly ash	---	15.20
Silica flour	---	4.8
ASTM C109 sand	33.8	---
Hemihydrate	---	6.5
Dispersant	0.5	1.1
Defoamer	0.005	0.02
Total	99.51	100.02

TEST RESULTS AND DISCUSSION

The two mixtures are contrasted in Fig. 5, which shows much greater stress being generated by the F-II grout relative to the F-I mortar, in which the sand in the mixture may mitigate stress generation.

All stress curves were corrected for temperature effects, and normalized to the experimental conditions. These curves reveal several stages of expansion, as anticipated for expansive cementitious mixtures. The initial stresses represent a thermal phase, occurring

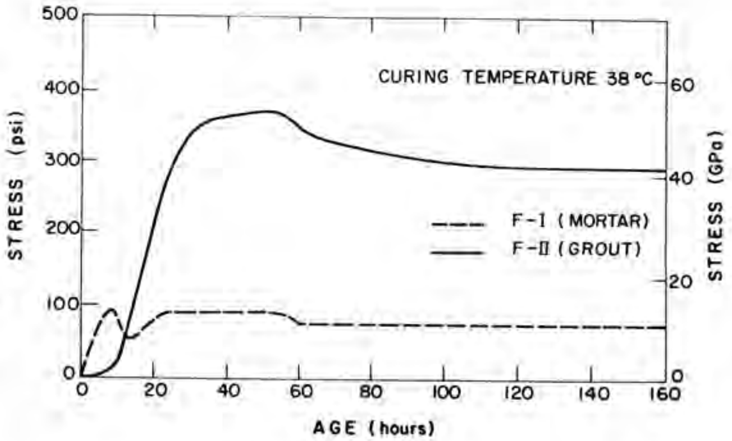

Fig. 5. Comparison of radial stresses of two mixtures.

with early heat liberation. Although the curves were corrected for temperature variation, this correction was accomplished only for the apparatus (especially the strain gage). Thus variations in the grout itself still play a role in early stages of hydration.

These initial thermal stresses are of short-term duration and have little effect on the ultimate strength of the cementitious material, because the latter is still in a plastic state. However, in scaling up to mass curing, heat dissipation may be much slower, and thermal stress may outlive the plastic state of the concrete or mortar.

The second phase of expansion occurs after the cement reaches its thermal maximum, and cooling is initiated. At least two simultaneous processes occur during this phase of the hydration. The grout begins to harden, fixing to a certain extent its physical integrity and porosity. Simultaneously, crystallization of the expansive component takes place.

For mixtures in which initial porosity is low, chemical expansion can become quite large even before the thermal stresses are relieved. This can be seen on the curve for mixture F-II in Fig. 5, wherein the initial thermal expansion is totally masked by expansion. It is difficult to compare the performances of the two mixtures based on the data in this figure, however, due to the fact that only one of them (F-I) contains sand.

A third phase in the expansion process is characterized by total relief of thermal stress. At this stage, controlled by the combination of cooling and of formation of the expansive component(s), the measured stress may show a slight decrease. This phase appears on Fig. 5 at about 60 hours after initiation of the experiment.

SUMMARY AND CONCLUSIONS

A system was developed to determine the radial stresses imposed by a grout under confinement. The test cell used in the system is unique in that it provides for direct calibration of the complete system including signal conditioners and output recording. The system is versatile in that cell material and dimensions can be selected to simulate restraint of a given host material under a geostatic load reflecting depth. Samples can be run under a range of temperature and pressure conditions, with the latter simulating either injection pressure or hydrostatic load conditions existing in a borehole.

Two cement-based formulations were evaluated, the first contained type K expansive cement with sand and the second contained Class H cement with hemihydrate. The second formulation was found to give higher stresses.

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