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Title:

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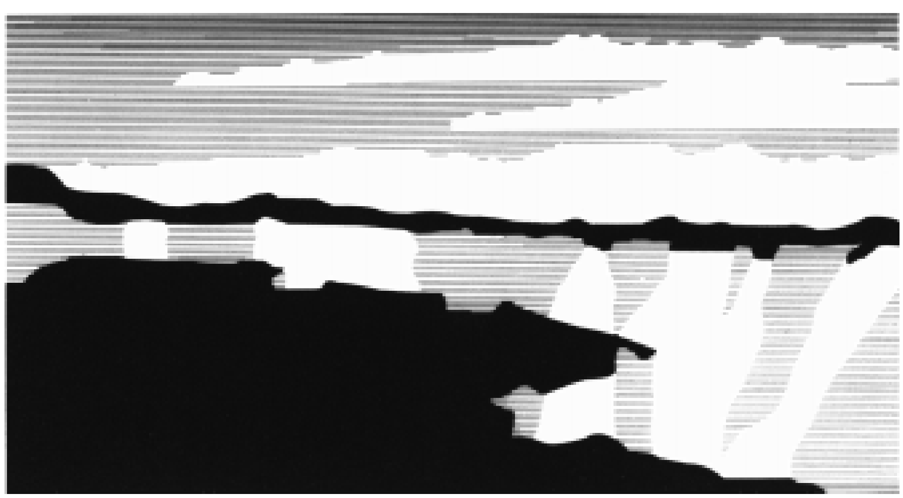

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Title: ***MECHANICAL RESPONSE OF SHOCK CONDITIONED HPNS-5 (R-1) GROUT***

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## ABSTRACT

HPNS-5 (R-1) grout is a portland cement formulated mix designed for use as a rigid containment plug in vertical boreholes at the Nevada Test Site. Coincident with field testing of this grout in 1991 and 1992 , two drums of the grout mix were collected and positioned in the by pass drift of the DISTANT ZENITH event to expose the grout to passage of a nuclear driven stress wave. The drums were later retrieved to determine the mechanical behavior of the shock conditioned grout. Sealed hollow tubes positioned within the grout-filled drums to detect ductile flow on passage of the stress wave were found partially to completely filled with HPNS-5 grout following the experiment. Static mechanical tests support the evidence for ductile flow and place the transition from brittle fracture failure to ductile behavior in the shock conditioned grout at a confining stress between ambient and 5 MPa (725 psi). Uniaxial and triaxial tests delineated a stress - strain field for interstice collapse that interposes between the mechanics of linear elastic deformation and dilatancy. Hydrostatic stress loading between 25 MPa (3.6 ksi) and 60 MPa (8.7 ksi) results in a significant change of permanent set from 1% to greater than 15% volume strain.

## INTRODUCTION

In September 1990 the Department of Energy (DOE) Nevada Operations Office undertook a review of nuclear test operations and related support functions, including practices ensuring the containment of radioactive materials produced by test explosions. The review was ordered to consolidate, standardize and optimize the practices and procedures among the testing and operational support organizations, with the intent to create cost savings, enhanced productivity, efficiency, and quality of operations. It was forced upon the nuclear weapons test community by increased fiscal pressures, requirements to comply with environmental, health and safety regulations, and DOE Orders and Directives. This program review was the impetus for several design changes in the Los Alamos National Laboratory (LANL) stemming plan.

Stemming backfill following emplacement of a nuclear device in a vertical borehole prevents the borehole from being the path of least resistance for the flow of radioactive material. For LANL, this objective was achieved with an alternating sequence of fines and coarse aggregate, obtained from primarily volcanic source material, in an uncased borehole. This sequence was interrupted with placement of rigid plugs used to encapsulate cable gas blocks and cable bundle fan-outs. Prior to the review, two rigid plugs, one either within or below a surface conductor pipe, and one of intermediate depth, consisted of two-part epoxy (TPE) mixed with aggregate and sand. A third rigid plug, closest in proximity to the device, consisted of Husky Pup Neat Slurry (HPNS-3) grout, as it was operationally not possible to place TPE deep in the borehole by gravity feed from the surface portal.

As a result of the Test Operations Review, the two material LANL rigid plug system was scheduled to be replaced with a single material. Although judged the better material by its lower permeability and ability to bond to cables and surface conductor pipe, the cost of TPE epoxy-based materials and the labor costs for batching the mix were considered excessive. Confident that grout could perform in principle the gas impeding characteristics of TPE, LANL decided to field grout as its only rigid plug material. The choice to field a grout mix also avoided the expense of using a cementing contractor had a third candidate plug material, sanded gypsum concrete (SGC), been selected to replace TPE.

It was recognized that the LANL grout mix in use, HPNS-3, was not necessarily a suitable replacement for TPE mainly due to its high cure temperature. In July 1991 the U. S. Army Engineer Waterways Experiment Station (WES) was formally requested to develop a grout mix for containment plugs in vertical emplacement holes (Field Engineering, 1991). The criteria for the mix were that it be formulated with portland or "Chem Comp" cement; be pumpable through tubing or capable of gravity flow through a tremie pipe; be limited to a maximum temperature of 150°F and definitively no greater than 180°F during hydration assuming an initial batch temperature of 50°F; have an unconfined compressive strength of 5.2 MPa (750 psi) at 48 hours cure; be non-shrinking; have minimum density of 112 lbm / cu ft; have an initial set in less than 10 hours; and be capable of being batched and mixed in a concrete mixer truck. WES designed a grout mix that nominally satisfied these criteria and designated the formulation as HPNS-5 (R-1), Husky Pup Neat Slurry formula five, revision 1.

The mix formula for the grout (Table 1) consists of portland cement Type I or Type II, water, barite (or barytes), a gel for suspension purposes, a high-range water reducer to retain fluidity with less water, and gypsum cement. Previous HPNS mix formulae used by LANL (HPNS-2 and -3) did not use gypsum and had significantly less barite. Barite is used to increase the density of the grout, and according to Boa (1992), the gypsum cement is incorporated in the mix as an expansion producing admixture. The high-range water reducer (superplasticizer) is specified as PSP powder, which is a Protex Industries trade name for a modified naphthalene sulphonate. 'D-19,' which was specified in the previous mixes, is stated to be a different industrial trade name for the same or similar high-range water reducer (Boa, 1992). Use of portland cement Type II, which is normally used as a precaution against moderate sulfate attack, is preferred because it has the advantage of generating less heat of hydration at a slower rate than Type 1

Table 1. Portland cement formulated mixes.

| FORMULATION | HPNS-2 | NOTES | HPNS-3 | NOTES | HPNS-5 (R-1) | NOTES |
|---|---|---|---|---|---|---|
| CEMENT ( CLASS A ) | 40.00 PCF | (1,5) | 35.00 PCF | (1,6) | 35.00 PCF | (1,2,7) |
| GEL | 4.00 PCF | | 5.00 PCF | | 1.75 PCF | |
| BARITE | 33.28 PCF | | 38.53 PCF | | 53.88 PCF | |
| HIGH-RANGE WATER REDUCER | 0.12 PCF | (3) | 0.04 PCF | (3) | 0.08 PCF | (4) |
| GYPSUM CEMENT | 0.00 PCF | | 0.00 PCF | | 2.10 PCF | |
| WATER | 40.00 PCF | | 40.00 PCF | | 37.00 PCF | |
| | | | | | | |
| DESIGN STRENGTH | 1500 - 2000 psi at 28 days | (5) | 1460 psi at 8 days | (6) | 995 psi at 48 hours | (7) |
| THEORETICAL UNIT WEIGHT | 117.4 PCF | | 118.6 PCF | | 129.8 PCF | |
| ACTUAL UNIT WEIGHT | 117.4 PCF | (5) | | | | |

| FORMULATION | HSSL-50/50 (R-4) | NOTES |
|---|---|---|
| CEMENT ( CLASS A ) | 12.96 PCF | (1,8) |
| GEL | 2.48 PCF | |
| HIGH-RANGE WATER REDUCER | 0.74 PCF | (3) |
| CONCRETE SAND A-1 | 36.7 PCF | |
| DESERT FINES | 36.38 PCF | |
| WATER | 25.92 PCF | |
| | | |
| DESIGN STRENGTH | 200 - 300 psi at 7 days | (8) |
| THEORETICAL UNIT WEIGHT | 115.2 PCF | |
| ACTUAL UNIT WEIGHT | 114.5 PCF | (8) |

NOTES:

(1) PCF, pounds mass per cubic foot.
(2) Class A cement, Type I or II specified (Boa, 1992).
(3) High-range water reducer specified as 'D-19.'
(4) High-range water reducer specified as 'PSP Powder.'
(5) W. E. S. (1987)
(6) W. E. S. (1989)
(7) Green and Boa (1991)
(8) R. S. N. (1990)

cement particularly for large volume emplacements. The high water-cement ratio (1.06) by weight for HPNS-5 is consistent with a designed compressive strength of ≤2000 psi (≤13.8 MPa) at 28 days (Kosmatka and Panarese, 1992).

Field testing of HPNS-5 for mixing, handling, and conveyance through a tremie pipe to a shallow down hole location began late August 1991 at the Nevada Test Site (NTS) Area 3 suspended borehole site U3-jz. Field testing of full-scale plugs, which were cured in surface conductor pipes and penetrated with cable bundles and wire rope harnesses, proceeded in early 1992 for bulk permeability measurement and for determining performance characteristics against pressurized gas flow in the stemming sequence (Engstrom, 1991; Trent, 1993). Concurrent with these studies time-temperature profiles of the heat of hydration and laboratory strength test data were collected.

In addition to these performance-based field test activities, two drums of the grout mix were collected during the late August 1991 mixing and handling exercise to examine the shock conditioned mechanical response of the grout. Included in the drums at the time of their preparation was a passive experiment, i.e. an experiment without real-time sensor measurement, designed to explore the possibility that any of the HPNS grout mixes might "flow" upon passage of an explosively driven stress wave. This report is specific to these latter tests and describes the mechanical response of HPNS-5 grout subjected to a stress wave of 55.2 - 74.8 MPa (8 - 10.85 ksi; thousand pounds per square inch) peak pressure. The results are interpreted from observations of the passive experiment placed inside the drums and from quasi-static uniaxial, triaxial and hydrostatic tests conducted on the bulk material from the recovered drums.

## SHOCK CONDITIONING EXPERIMENT

Defense Nuclear Agency's DISTANT ZENITH line-of-sight event, executed in the NTS U12p.04 drift on 19 September 1991 (U. S. G. S., 1991), presented the opportunity to subject containerized stemming materials to a nuclear-driven stress wave and to retrieve them for characterization. The grout for this experiment was batched 30 August 1991 for the U3-jz handling exercise, placed in two 55-gallon drums and allowed to establish initial set prior to transport to the Area 12 portal. The grout-filled drums were then positioned in pour 30 of the U12p.04 by pass drift with their sides resting on the invert and flat circular bases oriented toward the working point (Fig. 1). It was planned that one drum each would be placed at two locations within the pour selected for their significantly different stress levels. However, as built they

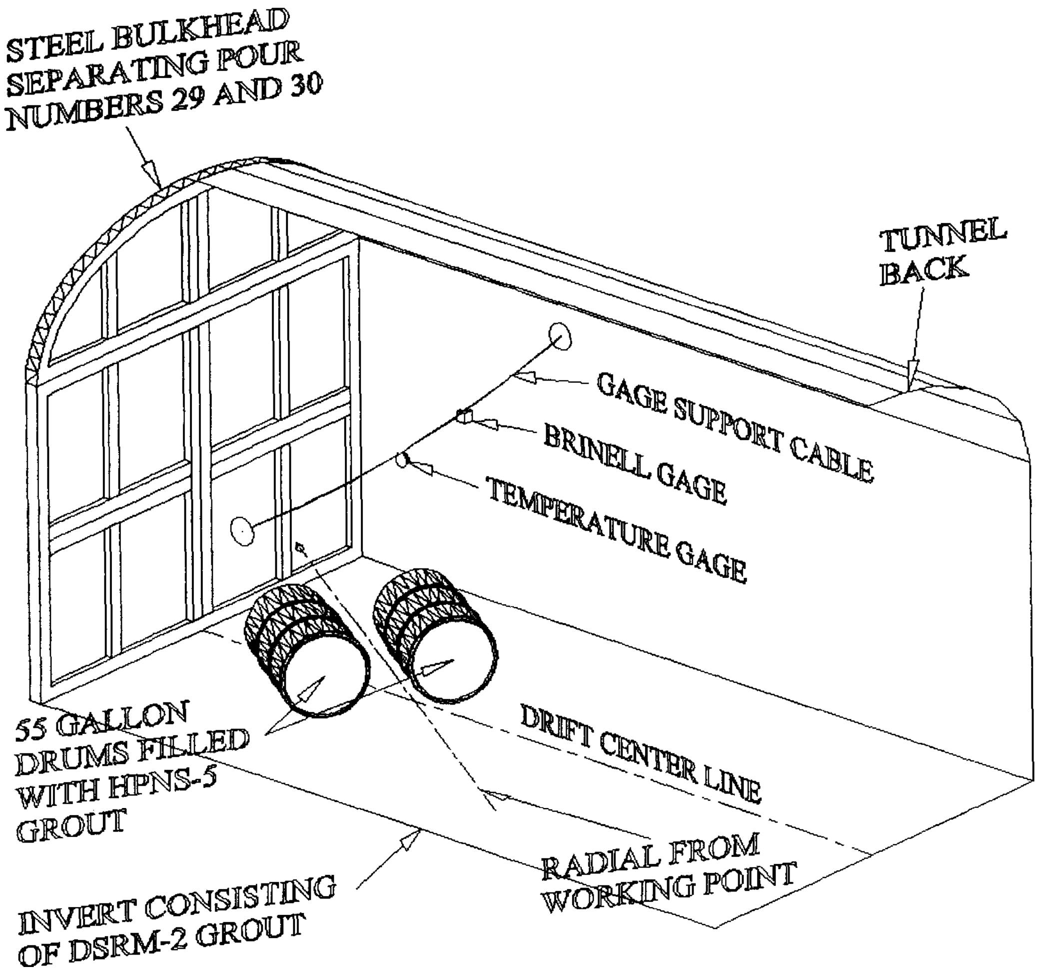


Fig. 1. Sketch portraying the configuration of grout-filled drums as emplaced in pour 30 of the U12p.04 by pass drift. The base of the drums (not visible in this perspective) were oriented toward the working point. The drift at pour 30 was 11 feet wide and 11 feet from invert to back.

were both placed side by side at the greater stress level location. The drums were enveloped in HSSL-50/50 (R-4) superlean grout (Table 1) during the button-up stemming operation of pour 30 on 03-04 September 1991. The HPNS-5 grout had cured 20 days at the time of the DISTANT ZENITH device detonation.

A passive experimental package was placed in each grout drum center base during their preparation. Each package consisted of a sealed tube and two anvil pressure gages. The sealed tube was constructed to capture grout should it exhibit flow-like characteristics on passage of the stress wave. It consisted of a cylindrical tube of A2 tool steel 2 inches OD, 3/8 inch wall and 2 inches long that was heat treated to Rockwell 57/59. Estimated tensile yield strength for A2 tool steel heat treated to Rockwell 60 is 1.5 GPa (220 ksi). The outside diameter at each end of the open tube was fitted with a viton o-ring. The o-ring and tube end were covered with 1 mil thick aluminum foil which was pulled back and held against the body of the tube adjacent to the o-ring with wire tie. The assembly was then coated with a solvent resistant RTV sealant. The interior of the tube retained air at atmospheric pressure. Strapped against the side of the tube were two anvil peak pressure gages supplied by Sandia National Laboratories Albuquerque (Sandia) to make passive measurement of the stress wave intensity. In addition to the anvil gages placed within the grout drums, Sandia placed six anvil gages, one Brinell composite directional pressure gage and a peak temperature gage in pour 30 of the by pass drift in the vicinity of the drums.

## OBSERVATIONS FROM THE PASSIVE EXPERIMENT

The grout drums were retrieved from the by pass drift in late March 1992 and returned to LANL for characterization. Pressure and temperature gages were also retrieved at this time and sent to Sandia for analysis. The average peak stress recorded with the Brinell composite directional pressure gage was 74.8 MPa (10.85 ksi). The stress component directed radial from the nuclear device measured 76.2 MPa (11.05 ksi) average peak stress, the transverse or horizontal component was 80.3 MPa (11.65 ksi), and the vertical component was 67.9 MPa (9.85 ksi) (Staller, 1992; 1993). These values suggest that transmission of the nuclear driven stress wave through the superlean grout may have had a slight anisotropic characteristic. The average peak stress from 6 anvil gages placed in the superlean grout (orientations not reported) was 74.5 MPa (10.8 ksi). The best determination of peak stress within the containerized HPNS-5 grout as provided by one of two analyzed gages was 55.2 MPa (8.0 ksi).

Peak temperature of the superlean-filled pour 30 was determined to be 60 °C (140 °F). It is assumed by the magnitude of thermal rise that the reported temperature was caused by exothermic hydration of the portland cement during cure. It is unlikely that this peak temperature reflects a transient thermal event resulting from the nuclear detonation at the site of the experiment.

The sealed tube experimental packages in the two 55-gallon drums of HPNS-5 were placed such that the cylindrical axis of one package was parallel with the flat circular base of the drum while the other was oriented with its axis perpendicular to the base of that drum (Fig. 2). After the test, two depressions along the base of one drum separated with a 2 inch gap marked the location of the first package (axis of sealed tube parallel with flat base). With steel drum base removed (Fig. 3), each depression measured 2.5 to 2.75 inch (6.4 - 7.0 cm) diameter and was truncated at its juncture with the A2 tool steel cylinder. Portions of the steel cylinder were exposed along the surface. The two depressions were about 0.4 inch (1.0 cm) deep.

With the package removed from the grout filled drum and sectioned along its cylindrical axis, HPNS-5 was found completely filling the center of the cylinder (Fig. 4). The aluminum foil and RTV sealant originally capping the ends of the cylinder were not ruptured, but rather were pushed from both ends to meet and form a nearly flat contact half way down the inside of the cylinder. No grout was found between the transported foil layers of aluminum. The foil and sealant were also found along the inside cylinder wall separating grout from the A2 tool steel. The grout, with its fine microscopic grain size, has nearly homogeneous texture and color. Several round-edged light colored inclusions similar to those found in unshocked material lie along the sectioned plane. These revealed no evidence of being fractured or distorted. Macroscopically, there was no appearance of shear banding or slip lines. There was also no evidence of turbulence along interfaces. These characteristics suggest that the grout was extruded into the air-filled space as a ductile material. Jagged hair-line tensile failure cracks perpendicular to the cylinder axis suggest a linear volume reduction parallel to the axis following full or partial extrusion into the original air-filled space.

Subtle features in a thin-section of the extruded grout provide evidence that the ductile flow is a microscopically brittle mechanism known as cataclastic flow (Paterson, 1978). Two features, noted in Fig. 5, are consistent with this mechanism. Their interrelationship, however, could not be deciphered from optical examination. The first feature consists of oval shaped structures with boundaries defined by slight grain size variations. These oval shaped structures appear to be fragments of grout that were available for rearrangement and relative transport past similar material. The second feature consists of curved lines suggestive of shear or sliding surfaces. These possible slip lines are not regularly spaced. Their curvature appears to be concave toward the extruding surface front which would be expected with

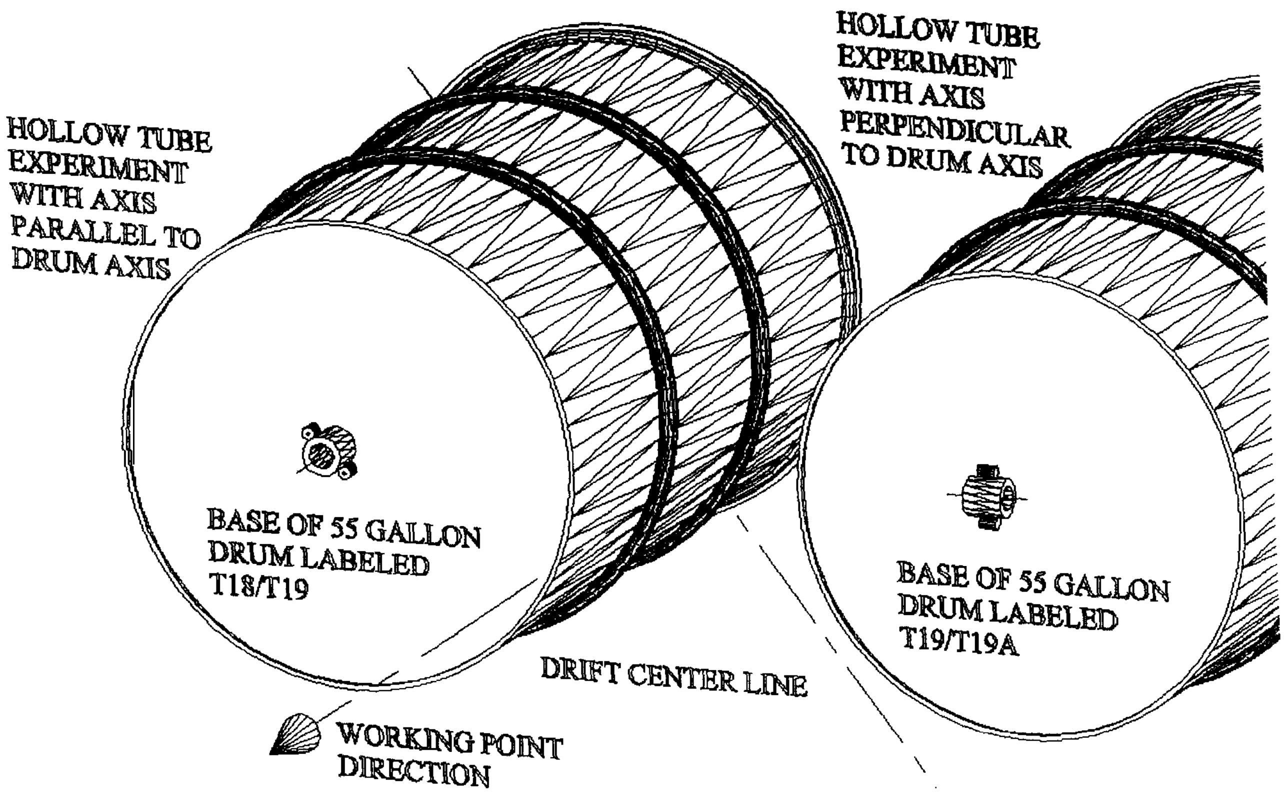


Fig. 2. Sketch portraying the orientation of the hollow tube experiments relative to the base of each grout-filled drum and to a radial from the working point.

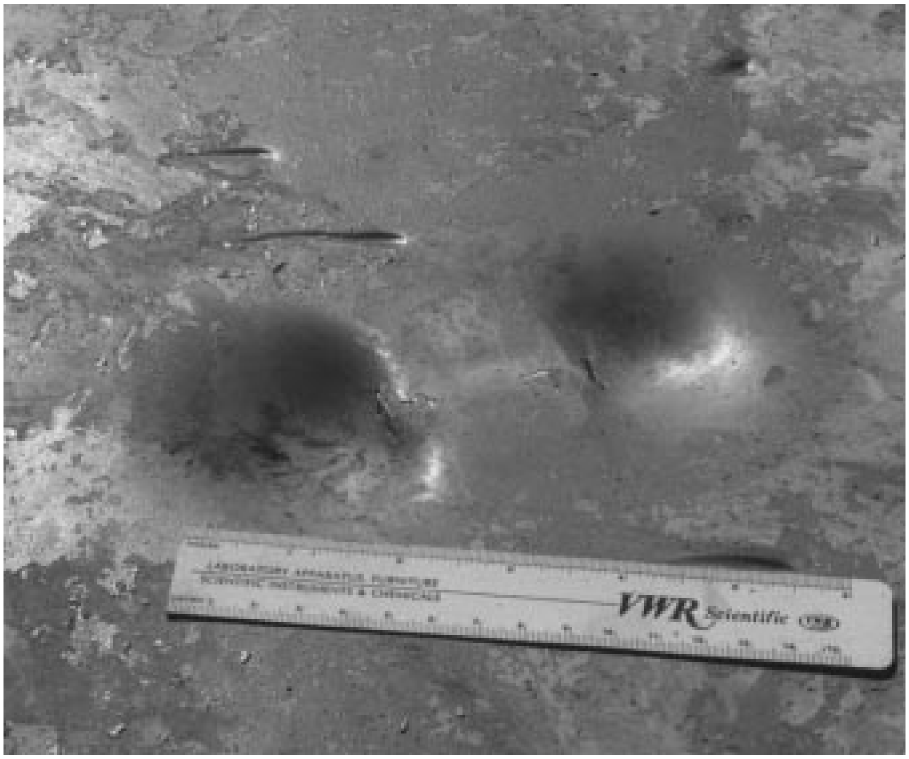


Fig. 3. View of sealed tube experiment exposed along the base of a grout-filled drum after shock conditioning. The axis of the tool steel cylinder is parallel with the flat circular base of the 55 gallon drum, and is aligned such that the extension of the axis passes through the two depressions visible in the figure. This view is shown with metal drum base removed. The two depressions, each measuring 2.5 inch to 2.75 inch diameter and 0.4 inch deep, were created when the differential stress between bulk grout and the interior of the steel cylinder was sufficient to favor ductile flow in the grout surrounding the cylinder end caps. The ductile behavior of the grout allowed its extrusion into the unoccupied volume (except for air) of the cylinder interior. Ductile flow ceased when the advancing extrusion front was confined by a similar front advancing from the opposite end of the cylinder (Fig. 4). Discoloration of the grout surface was caused by a coating on the interior of the 55 gallon steel drum. Top of scale is in inches, the bottom in centimeters.

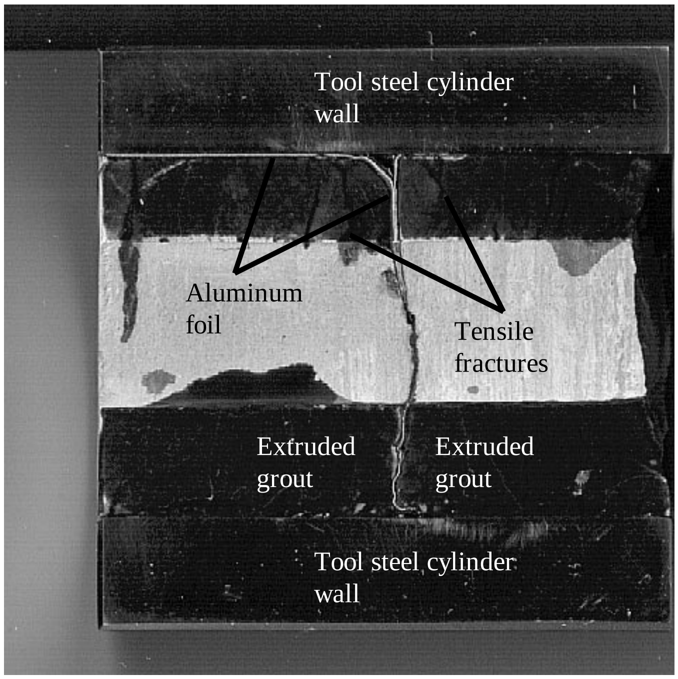


Fig. 4. Section along axis of tool steel cylinder extracted from one of two grout-filled drums which were subjected to a stress wave with average peak magnitude between 55.2 MPa and 74.8 MPa. The cylinder was originally void of material, sealed at both ends and placed in freshly poured HPNS-5 (R-1) grout at the base of a 55 gallon drum. The axis of the tool steel cylinder was oriented parallel with the flat circular base of the drum. Dark coloration of grout and adjacent tool steel in this figure is due to a stain. The light grey coloration is that of the grout exposed by extraction of a small diameter core along the axis of the experiment. In section, grout is observed to have extruded into the cylinder from both ends, pushing the aluminum foil end covers ahead of the advancing grout. A continuous, nearly planar aluminum foil - aluminum foil contact marks the meeting of advancing fronts. Aluminum foil is also observed between grout and the steel cylinder wall. The cylinder wall length is 2 inches.

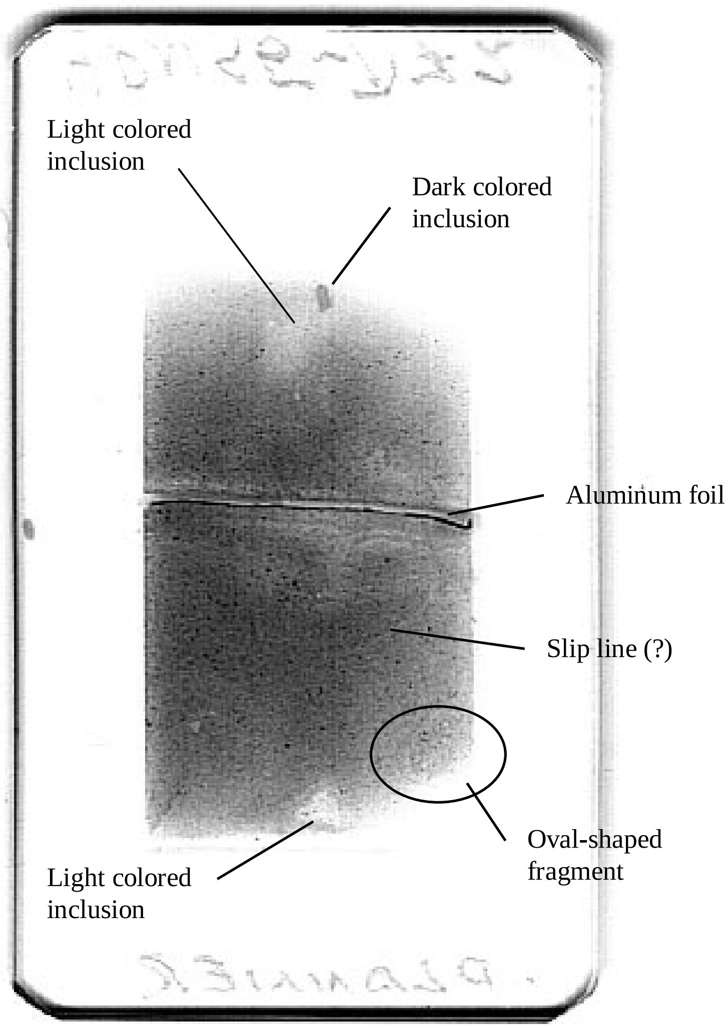


Fig. 5. Thin section view of grout - grout interface from sealed tube experiment shown in Fig. 4. The interface is marked by the thin dark line representing aluminum foil. Except for light and dark colored inclusions, the HPNS-5 grout appears largely homogeneous and featureless. Oval shaped fragments appear along the thinnest portions of the thin section. Slip lines appear as curved lines concave toward the interface. Width of glass plate outline (horizontal) is 1 inch.

ductile flow. Both features are distinguishable from the ghostly angular inclusions present in the pristine grout, which have no obvious distortions following shock conditioning.

For the sealed tube package oriented with cylindrical axis perpendicular to the base of the 55-gallon drum, the experiment was locatable post-test along the base of the drum by a circular puncture through the steel drum wall. Exposed in the center of the puncture was HSSL-50/50 superlean grout, the material that originally encapsulated the drums in pour 30. Figure 6 shows the superlean incursion into the A2 tool steel cylinder as viewed following removal of the steel drum base.

Sectioned along its axis, the A2 tool steel cylinder was also found filled with grout (Fig. 7). From one end of the cylinder came HSSL-50/50 superlean grout and from the other came HPNS-5 grout. At the conclusion of the flow processes, HSSL-50/50 occupied most of the tube volume. The HPNS-5 grout extruded 0.5 inch (1.25 cm) at most, and the extruding process pushed the original aluminum foil end cap ahead of it. The boundary between the two grouts is undulatory, evidently owing to the fluid-like mechanics of HSSL-50/50. The superlean grout was found to have encapsulated the circular piece of steel punched from the base of the drum, and transported it along the side of the tube's inner wall.

One additional visual observation of bulk shock conditioned HPNS-5 grout is that air bubbles retained in the grout after batching and cure, which were typically circular to elliptical in form with 0.29 inch (0.74 cm) maximum length, are not observed in specimens of shock conditioned grout. The bubbles collapsed, and the bubble surfaces eliminated on passage of the stress wave. No evidence was found for migration of the bubble volume. The gas which filled that volume appears to have been taken into the pore and/or fracture volume of the HPNS-5 grout.

## MECHANICAL TESTING

After the passive experiments were removed from the grout-filled drums, the drums were cored to retrieve specimens for mechanical test. Cylindrical core and prepared test specimens were stored by immersing the stock in sealed 5-gallon containers of water maintained at room temperature. Specimens, which were prepared for testing by WES, were individually wrapped in water-saturated wipes, and placed in sealable plastic bags for shipment.

Fifteen mechanical tests were conducted on shock conditioned grout. The tests consisted of six uniaxial compression tests, six triaxial tests, two tensile tests and one test dedicated to hydrostatic compression to 400 MPa (58.0 ksi).

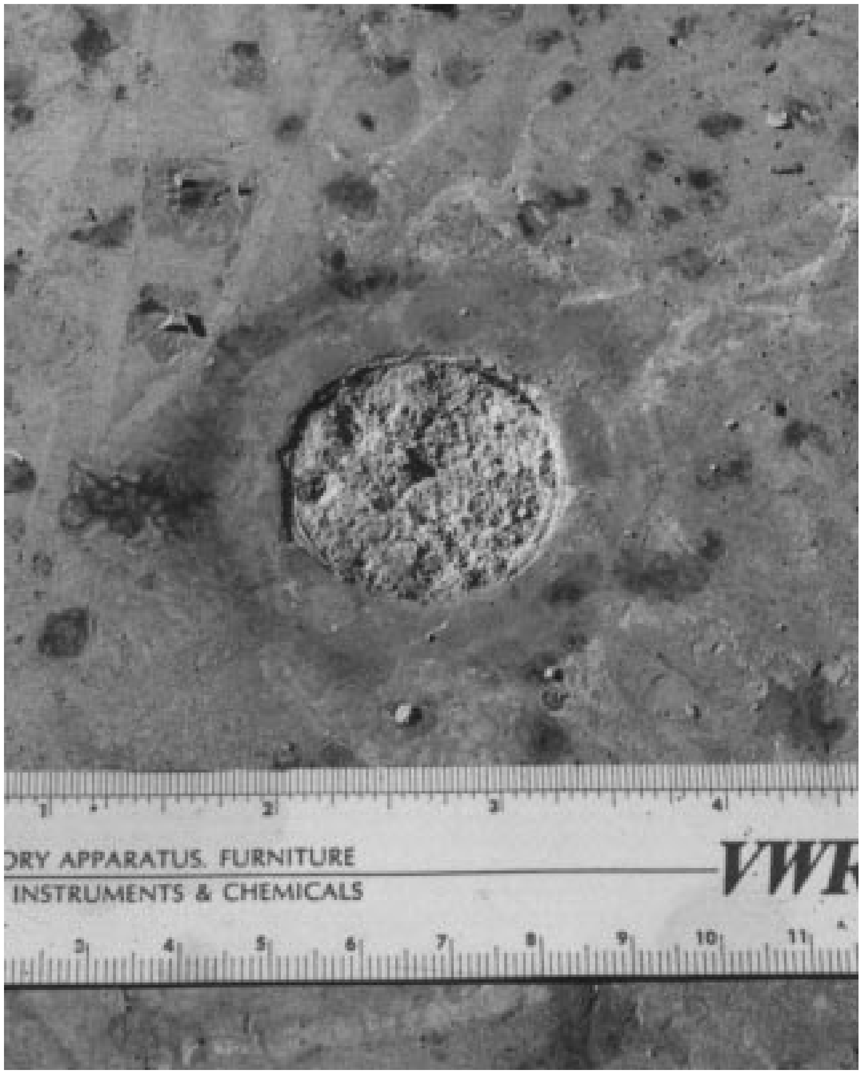


Fig. 6. View of sealed tube experiment exposed along the base of the second grout-filled drum after shock conditioning. The tool steel cylinder is oriented perpendicular to circular base of 55 gallon drum to yield a circular outline. This view is shown with metal drum base removed. Interior of the cylinder is filled with HSSL-50/50 (R-4) superlean grout, which originally surrounded the grout-filled drums after they were emplaced in the by pass drift of the DISTANT ZENITH event. HPNS-5 (R-1) grout surrounds the cylinder. Discoloration of the grout surface was caused by a coating on the interior of the 55 gallon steel drum. Top of scale is in inches, the bottom is in centimeters.

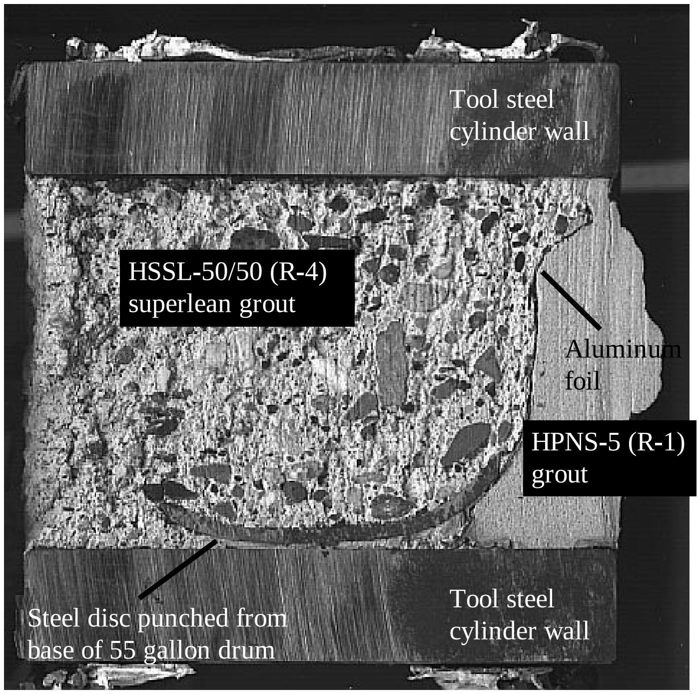


Fig. 7. Section along axis of the tool steel cylinder extracted from the second of two grout-filled drums which were subjected to a stress wave with average peak magnitude between 55.2 MPa and 74.8 MPa. The cylinder was originally void of material, sealed at both ends and placed in freshly poured HPNS-5 (R-1) grout at the base of a 55 gallon drum. The axis of the cylinder was oriented perpendicular to the flat circular base of the drum such that the left end of the cylinder, as viewed above, was against the base of the drum. The drum was then placed in the by pass drift of the DISTANT ZENITH event. In section, the cylinder was invaded from the left with HSSL-50/50 (R-4) superlean grout which punched a hole through the base of the 55 gallon steel drum. Superlean grout was the back fill used to button up pour #30 of the by pass drift. From the right HPNS-5 extruded a short distance into the cylinder pushing the aluminum foil end cap ahead of the advancing front. The cylinder wall length is 2 inches.

The triaxial and hydrostatic tests were conducted by WES and the data were reported by Akers and Reed (1993). In addition to the tests on shock conditioned grout, three uniaxial compression tests were conducted on pristine material collected 30 August 1991 for the U3-jz handling exercise. All mechanical tests were conducted over the period from September, 1992 to August, 1993 representing a cure period for the grout of more than 374 days. Because of the long cure time that elapsed prior to testing these specimens, the failure stress magnitudes and the transition stress levels between the various mechanical responses are not directly relevant to the grout at the time it was shock conditioned. However, the quasi-static tests are valued for interpreting the relative response sequence with stress level and the possible magnitude of the deformation.

## HYDROSTATIC RESPONSE

Undrained shock conditioned grout responds to increasing hydrostatic load first with linear elastic deformation, followed by collapse of pore structures (crushing), and finally by non-linear stiffening of the grout. Undrained means that the pore fluids, air and water filling the pore volume in the undeformed specimen, do not exchange with the environment during laboratory test. This is a reasonable scenario for shock loaded material.

The volumetric strain response of the shock conditioned grout to 400 MPa (58.0 ksi) hydrostatic stress is represented in Fig. 8. The curve in this figure displays an initial steep rise in response to linear elastic deformation that is interrupted with a long shallow slope corresponding to elimination of pore volume before the slope returns again to a steep rise. The proportionality between hydrostatic stress and volume strain occurs from ambient stress to 8.5 - 10.5 MPa (1.23 - 1.52 ksi). The average slope of the line representing this relationship is 5.51 ±0.28 GPa (799.4 ±40.6 ksi), which is the effective elastic bulk modulus ($K_{\text{effective}}$) for the shock conditioned HPNS-5 grout. This constant is known as an "effective" constant because the grout is not responding solely as a solid material but as a solid structurally modified with microcracks (microfractures) and pores. Individual elastic ranges determined for seven test specimens and their corresponding $K_{\text{effective}}$ values are listed in Table 2.

Above 10.5 MPa hydrostatic stress, the elastic behavior is lost. The stress is sufficient to cause microstructural damage to the grout matrix surrounding pores and incipient microcracks. The effect is one of crushing and elimination of pore volume. Depending on stress magnitude, the amount of volumetric compaction may be significant , i.e. volume strain will exceed 2% - 5% and can reach 17% or greater. The slope of this curve in Fig. 8 is shallow

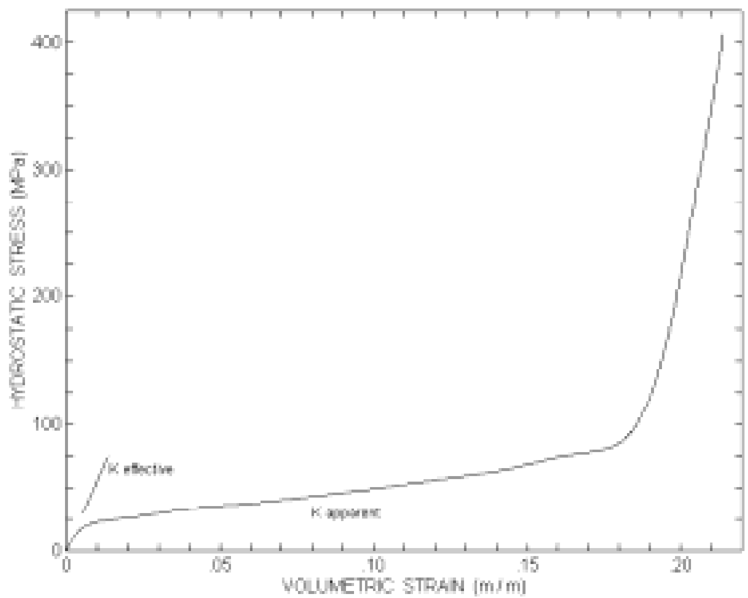


Fig. 8. Volume strain response of shock conditioned HPNS-5 (R-1) grout to hydrostatic stress. Linear elastic behavior occurs from ambient to 10.5 MPa stress. The effective elastic bulk modulus, $K_{effective}$, is represented with the slope of the indicated line segment. Between 10.5 MPa and about 80 MPa the grout is subjected to crushing and the elimination of pore volume. For this stress range the linear segment is represented with slope $K_{apparent}$, the apparent bulk modulus. Above 80 MPa the grout responds with stiffening or loading of the grout matrix.

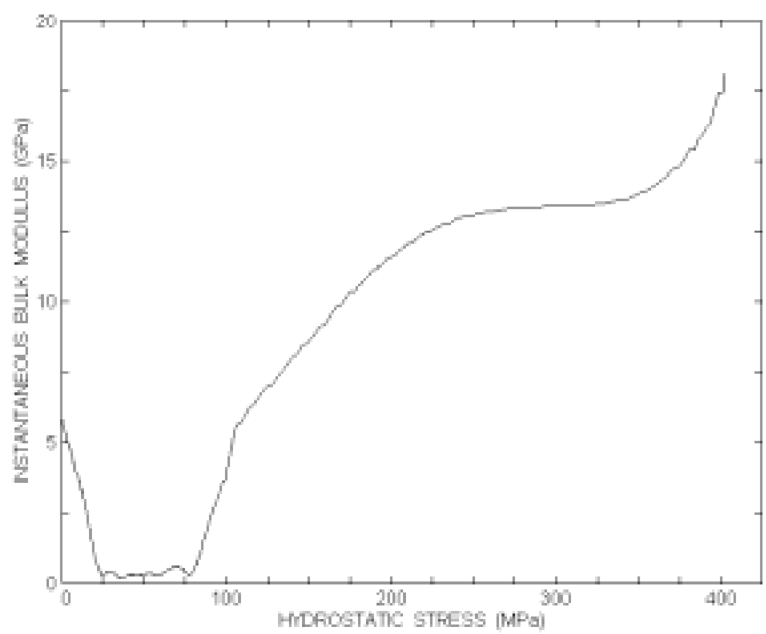


Fig. 9. Instantaneous bulk modulus of shock conditioned HPNS-5 (R-1) grout as a function of hydrostatic stress.

Table 2. Effective and apparent bulk moduli for shock conditioned HPNS-5 (R-1) grout.

| TEST SPECIMEN | MAXIMUM HYDROSTATIC TEST LOAD | | LINEAR-ELASTIC BEHAVIOR | | | |
|---|---|---|---|---|---|---|
| | | | HYDROSTATIC STRESS RANGE | | EFFECTIVE BULK MODULUS (K-EFFECTIVE) | |
| 301 | 5 MPa | 725 psi | 0 - 5.0 MPa | 0 - 725 psi | 5.75 GPa | 834.0 ksi |
| 302 | 5 MPa | 725 psi | 0 - 5.0 MPa | 0 - 725 psi | 5.02 GPa | 728.1 ksi |
| 303 | 25 MPa | 3625 psi | 0 - 8.5 MPa | 0 - 1235 psi | 5.66 GPa | 820.9 ksi |
| 304 | 25 MPa | 3625 psi | 0 - 9.5 MPa | 0 - 1380 psi | 5.35 GPa | 776.0 ksi |
| 305 | 400 Mpa | 58.0 ksi | 0 - 8.5 MPa | 0 - 1235 psi | 5.63 GPa | 816.6 ksi |
| 306 | 100 Mpa | 14.5 ksi | 0 - 10.5 MPa | 0 - 1525 psi | 5.37 GPa | 778.9 ksi |
| 307 | 100 MPa | 14.5 ksi | 0 - 9.0 MPa | 0 - 1305 psi | 5.80 GPa | 841.2 ksi |

| TEST SPECIMEN | PORE CRUSH BEHAVIOR | | | |
|---|---|---|---|---|
| | STRESS RANGE FOR LINEAR VOLUMETRIC STRAIN RESPONSE | | APPARENT BULK MODULUS (K-APPARENT) | |
| 305 | 13.7 - 70.0 MPa | 2.0 - 10.2 ksi | 0.32 GPa | 46.4 ksi |
| 306 | 28.0 - 100.0 MPa | 4.1 - 14.5 ksi | 0.36 GPa | 52.2 ksi |
| 307 | 28.0 - 72.5 MPa | 4.1 - 10.5 ksi | 0.30 GPa | 43.5 ksi |

compared to that for elastic deformation, and is approximately linear with an apparent bulk modulus value $K_{apparent}$ of 0.33 ±0.03 GPa (47.4 ±4.4 ksi). Experimentally derived apparent bulk moduli for the crush zone are listed in Table 2. The instantaneous bulk modulus as a function of confining stress is shown in Fig. 9, where the initial negative slope and the subsequent low but undulating values of $K$ represent the stress range for crush. Between about 75 - 80 MPa (10.9 - 11.6 ksi) stress the slope of the curve abruptly increases, signifying that much of the pore volume has been eliminated and the grout response has shifted to loading the matrix.

A load and unload cycle of hydrostatic stress with peak stress beyond the elastic range does not allow the grout full strain recovery. The unrecovered strain is known as permanent set. Permanent set as a function of peak hydrostatic load for stress conditioned grout is shown in Fig. 10. From about 25 MPa (3.6 ksi) to 60 MPa (8.7 ksi) peak stress the permanent set dramatically increases from about 1% volume strain to more than 15% strain.

The ramification of a large permanent volume reduction for a rigid HPNS-5 plug in a vertical borehole may be significant. A similarly large permanent set for some emplacement mediums (moderately to strongly welded tuffs and lavas, and highly saturated rocks in general) found in the borehole wall would not be expected. Passage of an explosively driven stress wave could create a large compressive mean stress component for both plug and surrounding rock. As both plug and rock recover from passage of the stress wave it is conceivable that the plug may not recover sufficient volume to dimensionally bridge the borehole outline. This would render the plug ineffective as a gas flow impediment if challenged from below. For other emplacement rocks, such as alluvium and nonwelded tuffs, crush response may be very similar to that of the grout.

## ULTIMATE STRENGTH

Ultimate strength of the unconfined grout as a function of cure time may be estimated from uniaxial compressive strength data obtained from break tests. These strength data represent the grout's fracture failure strength. Figure 11 shows the uniaxial compressive strength of HPNS-5 (R-1) grout as a function of days cured. These data were obtained for grout collected during several batching activities, including the deep rigid plug emplacement for the DIVIDER event in borehole U3-ml. The solid curve through the data represents a polynomial fit to the U3-ml data set. At a cure time of one day the grout exhibits an ultimate strength of about 3.5 MPa (510 psi) increasing to 12.7 MPa (1.84 ksi) at 20 cure days. The containerized grout placed in the

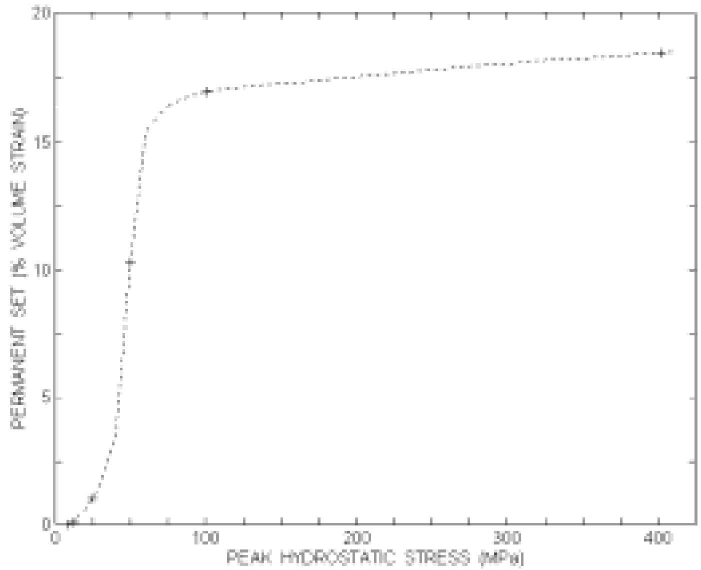


Fig. 10. Permanent set for shock conditioned HPNS-5 (R-1) grout as a function of peak hydrostatic stress. Data obtained from mechanical tests are indicated with ' + ' marker.

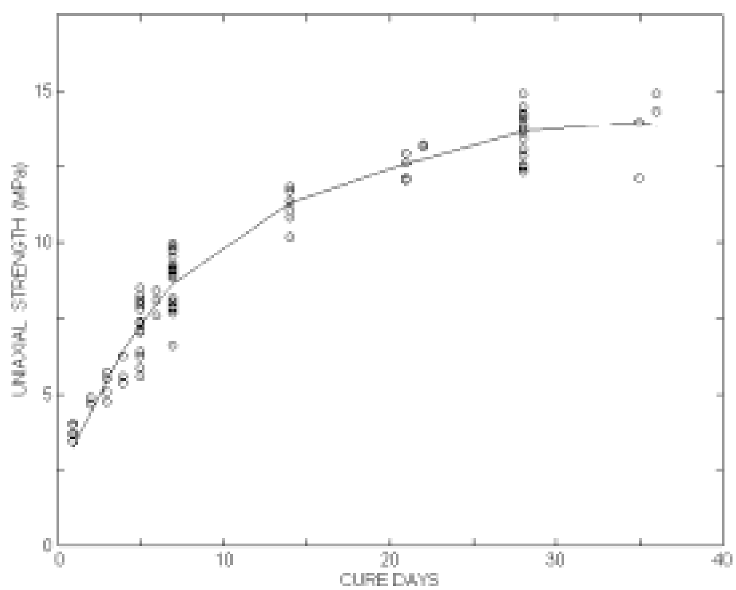


Fig. 11. Uniaxial compressive strength of pristine HPNS-5 (R-1) grout as a function of days cured. This data set was obtained from grout prepared for the U3-ml emplacement and satellite boreholes. A polynomial fit to the data set is shown with the curved line.

DISTANT ZENITH event would have exhibited an unconfined conpressive strength of about 12.7 MPa at the time of event detonation.

The ultimate strength for unconfined grout cured for more than 374 days was determined from standard uniaxial compressive strength tests to be 18.0 - 33.2 MPa (2.61 - 4.82 ksi) for pristine grout and 17.8 -24.6 MPa (258 - 3.57 ksi) for shock conditioned grout. As with the break tests, these strength data represent the grout's fracture failure strength. The strength values are a function of moisture content (Table 3; Fig. 12) with the ultimate strength increasing as moisture content and bulk density values decrease. At about 29% moisture content both pristine and shock conditioned grouts display similar strengths. The rate at which the grout strength increases with decrease in moisture content is otherwise dissimilar for pristine and shock conditioned materials.

At a confining stress of 25 MPa (3.63 ksi) the ultimate strength of shock conditioned grout with 19 - 20% moisture content increases to 59.6 MPa (8.65 ksi). Above 25 MPa confining stress the rate of increase substantially diminishes such that at 100 MPa (14.50 ksi) the strength is 62.9 MPa (9.13 ksi). Again, the strength values are a function of moisture content. Similar data for pristine grout is not available. Between ambient and 5 MPa confining stress the failure mechanism for the grout at ultimate strength changes from brittle fracture to ductile behavior. This characteristic of the grout is discussed further in a separate section.

## MECHANICAL BEHAVIOR BELOW ULTIMATE STRENGTH

Quasi-static triaxial compression tests were performed to examine the mechanics occurring within the grout during application of a differential stress. These tests initially start with hydrostatic stress loading. An axial compressive stress is then applied as the hydrostatic stress is maintained constant. Axial compression continues until either the specimen fails in fracture, or distortion exceeds measurement, physical or theoretical constraints. Seven tests that were performed on shock conditioned HPNS-5 grout provided stress-strain data for comprehensive analysis. Three of these were uniaxial compression tests, which were conducted at ambient pressure (unconfined). No jacketing material surrounded these specimens during test. Two tests were performed at a confining stress of 5 MPa (725 psi), and two at a confining stress of 100 MPa (14.50 ksi). These tests were jacketed and undrained. Stress - strain data from a single uniaxial compression test of pristine grout was also analyzed. Moisture content of the shock conditioned grout specimens was 17.0% to 21.3% (ASTM D2216-90). The pristine grout specimen had significantly lower moisture content (6.8%),

Table 3. Ultimate strength, bulk density and moisture content of HPNS-5 (R-1) grout test specimens.

| TEST SPECIMEN | CONFINING STRESS | | ULTIMATE STRENGTH [1] | | BULK DENSITY [2,5] | MOISTURE [3] |
|---|---|---|---|---|---|---|
| | ( MPa ) | ( psi ) | ( MPa ) | ( psi ) | ( g/cm^3 ) | ( % ) |
| PRISTINE GROUT | | | | | | |
| HPNS5-U1 | UNCONFINED | UNCONFINED | 18.0 | 2611 | 2.120 | 28.6 |
| HPNS5-U2 | UNCONFINED | UNCONFINED | 21.8 | 3162 | 2.089 | 16.5 |
| HPNS5-U3 | UNCONFINED | UNCONFINED | 33.2 | 4815 | 1.787 | 6.8 |
| SHOCK CONDITIONED GROUT | | | | | | |
| HPNS5-DZ-T1 [4] | UNCONFINED | UNCONFINED | -1.4 | -203 | n/determined | n/determined |
| HPNS5-DZ-T2 [4] | UNCONFINED | UNCONFINED | -1.2 | -174 | n/determined | n/determined |
| HPNS5-DZ1 | UNCONFINED | UNCONFINED | 19.3 | 2799 | 2.136 | 26.0 |
| HPNS5-DZ2 | UNCONFINED | UNCONFINED | 17.8 | 2582 | 2.138 | 29.5 |
| HPNS5-DZ3 | UNCONFINED | UNCONFINED | 21.4 | 3104 | 2.108 | 23.6 |
| HPNS5-DZ-DRM2#1 | UNCONFINED | UNCONFINED | 24.6 | 3578 | 2.024 | 21.4 |
| HPNS5-DZ-DRM2#2 | UNCONFINED | UNCONFINED | 24.6 | 3568 | 2.033 | 20.8 |
| HPNS5-DZ-DRM2#3 | UNCONFINED | UNCONFINED | 23.1 | 3350 | 2.032 | 20.4 |
| 301 | 5 | 725 | 25.9 | 3756 | 2.004 | 21.3 |
| 302 | 5 | 725 | 28.0 | 4061 | 1.995 | 20.2 |
| 303 | 25 | 3626 | 59.6 | 8644 | 1.982 | 19.9 |
| 304 | 25 | 3626 | 64.2 | 9311 | 1.930 | 15.2 |
| 306 | 100 | 14504 | 74.5 | 10805 | 1.942 | 17.0 |
| 307 | 100 | 14504 | 62.9 | 9123 | 1.984 | 19.2 |

NOTES:

[1] Expressed as a differential stress.

[2] Determined by geometric method prior to mechanical test.

[3] Determined as (mass of moist specimen x 100 / mass of specimen solids) per ASTM2216-90 after mechanical test.

[4] Tensile test.

[5] Grain density = 3.04 g/cm^3 (Akers and Reed, 1993).

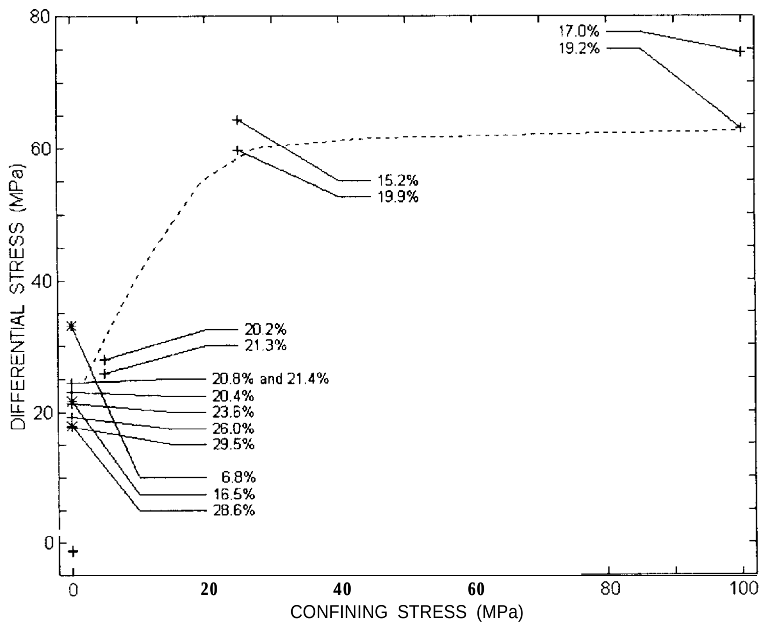


Fig. 12. Ultimate strength of pristine (*) and shock conditioned grout (+) cured for more than 374 days. Moisture content of test specimens are indicated with percentage values. Moisture contents for the two tensile tests were not determined. Dashed line approximately represents the ultimate strength of shock conditioned grout at 20% moisture content as a function of confining stress.

which has the effect of increasing the transition stress levels associated with response characteristics.

With application of a differential stress, brittle geologic materials respond mechanically with crack closure, linear elastic deformation, dilatancy and fracture failure (Walsh, 1965; Brace, Paulding and Scholz, 1966; Bordia, 1972). These response characteristics are sequential in the order listed if each characteristic is present. Mechanical responses, and the stress range for which they apply, are determined either with static measurement of volume strain with stress or by elastic wave velocity with stress. The former is used in the present analysis. The mechanical behavior of brittle geosynthetic materials, such as grout and concrete, are determined in like fashion.

Crack closure refers to closure of microcracks existing in the brittle material at ambient conditions. Without an applied directional or hydrostatic stress, the microcrack structure is relaxed and has an open volume which can be detected during the initial loading. This response is typically observed in uniaxial compression tests as a small compaction strain as the axial compression stress preferentially closes microcracks having an orientation predominantly normal to the applied stress. The effect is not typically observed in triaxial compression tests because the initial hydrostatic loading of the specimen closes microcracks of all orientations. Little emphasis is placed on this microcrack volume, as it is possible that the volume was created during handling operations and specimen preparation. Crack closure was detected in two uniaxial compression tests: HPNS5-U3, a pristine grout, and HPNS5-DZ-DRM2#3, a shock conditioned grout (Table 4).

Linear elastic deformation refers to a nearly linear, and reversible, relationship observed between applied differential stress and axial strain deformation. The constant of proportionality for this relationship is defined as Young's modulus or elastic modulus. With increased stress a measurable compaction strain results. Assuming constant values for the elastic constants, Young's modulus and Poisson's ratio, the volumetric strain of the material during compression is also a linear function of the applied differential stress (Jaeger and Cook, 1979). It is assumed that HPNS-5 grout can be characterized as an isotropic material, and that the elastic constants are independent of orientation. As with the elastic bulk modulus values ($K_{effective}$) listed in Table 2, values of Young's modulus and Poisson's ratio measured and reported in Table 4 are effective constants, that is, the solid matrix is modified by microcracks and pore volume, which has an effect on the elastic response.

As an unconfined specimen, shock conditioned HPNS-5 grout in compression has an elastic modulus of 6.12 - 6.98 GPa (888 - 1012 ksi). In tension, the

Table 4. Mechanical behavior of HPNS-5 grout below ultimate strength.

| TEST SPECIMEN | CONFINING STRESS | | LINEAR ELASTIC DEFORMATION | | | | |
|---|---|---|---|---|---|---|---|
| | | | DIFFERENTIAL STRESS RANGE | | EFFECTIVE ELASTIC MODULUS | | EFFECTIVE POISSON'S RATIO |
| | ( MPa ) | ( psi ) | ( MPa ) | ( psi) | ( GPa ) | ( ksi ) | |
| PRISTINE GROUT | | | | | | | |
| HPNS5-U3 | UNCONFINED | UNCONFINED | 6.5 - 15.5 [1] | 943 - 2248 [1] | 4.93 | 715.0 | 0.144 |
| SHOCK CONDITIONED GROUT | | | | | | | |
| HPNS5--DZ-T1 | UNCONFINED | UNCONFINED | 0 - (-1.4) <T> [2] | 0 - (-203) <T> [2] | 6.89 | 999.3 | n/determined |
| HPNS5-DZ-T2 | UNCONFINED | UNCONFINED | 0 - (-1.2) <T> [2] | 0 - (-174) <T> [2] | 7.00 | 1015.3 | n/determined |
| HPNS5-DZ-DRM2#1 | UNCONFINED | UNCONFINED | 0 - 10.5 | 0 - 1523 | 6.12 | 887.6 | 0.173 |
| HPNS5-DZ-DRM2#2 | UNCONFINED | UNCONFINED | 0 - 7.0 | 0 - 1015 | 6.60 | 957.3 | 0.201 |
| HPNS5-DZ-DRM2#3 | UNCONFINED | UNCONFINED | 0.5 - 9.0 [3] | 73 - 1305 [3] | 6.98 | 1012.4 | 0.195 |
| 301 | 5 | 725 | 0 - 7.5 | 0 - 1088 | 7.95 | 1153.1 | 0.127 |
| 302 | 5 | 725 | 0 - 8.4 | 0 - 1218 | 5.71 | 828.2 | 0.157 |
| 306 | 100 | 14504 | 0 - 8.0 | 0 - 1160 | 5.92 | 858.6 | 0.035 |
| 307 | 100 | 14504 | 0 - 14.2 | 0 - 2060 | 6.53 | 947.1 | 0.112 |

| TEST SPECIMEN | INTERSTICE COLLAPSE | | DILATANCY | |
|---|---|---|---|---|
| | DIFFERENTIAL STRESS RANGE | | DIFFERENTIAL STRESS RANGE | |
| | ( MPa ) | ( psi ) | ( MPa ) | ( psi ) |
| PRISTINE GROUT | | | | |
| HPNS5-U3 | 15.5 - 33.2 <F> | 2248 - 4815 <F> | - | - |
| SHOCK CONDITIONED GROUT | | | | |
| HPNS5--DZ-T1 | - | - | - | - |
| HPNS5-DZ-T2 | - | - | - | - |
| HPNS5-DZ-DRM2#1 | 10.5 - 23.5 | 1523 - 3408 | 23.5 - 24.6 <F> | 3408 - 3568 <F> |
| HPNS5-DZ-DRM2#2 | 7.0 - 24.6 <F> | 1015 - 3568 <F> | - | - |
| HPNS5-DZ-DRM2#3 | 9.0 - 22.5 | 1305 - 3263 | 22.5 - 23.1 <F> | 3263 - 3350 <F> |
| 301 | 5.0 - 24.7 | 725 - 3582 | 24.7 - 25.9 <D> | 3582 - 3756 <F> |
| 302 | 8.4 - 25.0 | 1218 - 3626 | 25.0 - 28.0 <D> | 3626 - 4061 <D> |
| 306 | 8.0 - 44.0 | 1160 - 6382 | 44.0 - 74.5 <D> | 6382 - 10805 <D> |
| 307 | 14.2 - 35.8 | 2060 - 5192 | 35.8 - 62.9 <D> | 5192 - 9123 <D> |

NOTES:

[1] Test specimen HPNS5-U3 exhibited crack closure for the stress range from 0 to 6.5 MPa (943 psi).

[2] Negative value indicates tensile stress.

[3] Test specimen HPNS5-DZ-DRM2#3 exhibited crack closure for the stress range from 0 to 0.5 MPa (73 psi).

[4] Failure modes correspond to <T> tensile fracture failure; <F> fracture failure; and <D> ductile behavior.

elastic modulus is 6.89 - 7.00 GPa (999 - 1015 ksi). Poisson's ratio was not determined for the tensile tests, but was measured as 0.173 - 0.201 in uniaxial compression. Linear elastic behavior occurs to a maximum differential compressive stress level of 10.5 MPa. In tension, test specimens fail in tensile fracture at 1.4 MPa tensile stress as an elastic material.

At confining stresses other than ambient, the elastic modulus has some variability with values ranging from 5.71 - 7.95 GPa (828 - 1153 ksi). No trend is observed between modulus and confining stress. The stress range for elastic behavior closely approximates the elastic range observed among unconfined specimens. The value for Poisson's ratio shows some tendency to decrease with increasing confining stress.

For most brittle rock, linear elastic deformation is followed by dilatancy as differential stress is increased. Dilatancy is an inelastic volume increase resulting from microcracking. It first develops by extending existing crack tips into the matrix microstructure, and then by creating new cracks. The volume increase is superimposed on the compaction strain of the matrix microstructure caused by linear elastic deformation. For both the pristine and shock conditioned HPNS-5 grout, linear elastic deformation is not followed with dilatancy but with an added component of compaction. This volume reduction would appear to come at the expense of the pore volume through collapse of the interstice wall structures. At still greater differential stress, the microcrack-created volume associated with dilatancy is detectable in most specimens of grout.

It is important to note that the mechanics associated with partial collapse of the grout interstices is not a mechanical behavior initiated by shock conditioning. The behavior is observed in the pristine specimen. This demonstrates that HPNS-5 (R-1) grout inherently has a matrix microstructure that will not respond to differential stress loading as would most brittle rocks. Whereas rock would respond to loading with elastic deformation followed with microcrack growth, the grout may eliminate a portion of its porosity and possibly lower its permeability over the same interval of stress loading. As a rigid plug material loaded statically in a borehole there may be advantages to this mechanical deviation. However, for a dynamically loaded rigid plug rapidly reducing pore volume, the resultant pore fluid pressurization may decrease the effective strength of the grout, causing it to fail prematurely by fracture.

The differential stress required for transition from interstice collapse to dilatancy is relatively insensitive to confining stresses between ambient and 5 MPa. That transition stress is 22.5 - 25.0 MPa (3.26 - 3.63 ksi). For these same test specimens the stress range for dilatancy is either 'not detectable' or is no greater than 3.0 MPa (435 psi) before culminating at ultimate strength. The consistency among samples loaded to 5 MPa confining stress may reflect the fact that they are all loaded within the hydrostatic linear elastic response (≤10.5 MPa hydrostatic; Table 2). The transition stress between collapse of interstices and dilatancy, and the breadth of the stress zone for dilatancy, may apply for grout loaded anywhere within the elastic hydrostatic stress range. At 100 MPa confining stress the transition stress has significantly increased to at least 35.8 MPa (5.19 ksi) differential stress, and the breadth of the stress zone for dilatancy has increased to greater than 27.1 MPa (3.93 ksi).

The deformation of the specimen during application of a differential stress may be partitioned into its elastic and non-elastic components. Component responses to differential stress are shown graphically in Figs. 13-16 for four specimens. The elastic response (part 'b' of each figure) is the elastic modulus obtained from test and applied over the entire test stress range. The microcrack volume strain (part 'a' of each figure) is obtained by removing the elastic response from the total volume strain of the specimen at each measured stress. Positive strain values imply compaction, while less positive values imply dilatancy. The advantage of viewing the deformation as component parts is to realize the significance of the various behavioral responses to the overall deformation.

Three stages of mechanical response are recognized from Fig. 13a for pristine grout specimen HPNS5-U3 in uniaxial compression. The trace which starts left of zero and approaches zero strain with increasing stress identifies the initial stage as crack closure (compaction). Crack closure gives to linear elastic deformation as the crack volume approaches, and then maintains, a value of about zero strain. At this point the total contribution to specimen deformation shifts to linear elasticity. As the trace for crack volume deviates from zero strain it progresses to positive strain values (compaction) indicatig interstice collapse. Dilatancy is not detected in this trace. As the differential stress approaches ultimate strength, the elastic strain contribution (Fig. 13b), which is also a compactional strain, dominates specimen deformation.

The effect of shock conditioning on strain response is evaluated by comparing specimen HPNS5-DZ-DRM2#2 (Fig. 14a) with HPNS5-U3 (Fig. 13a). Both specimens were tested in uniaxial compression. Overlooking the omission of a crack closure response, the significant difference in the traces comes with the magnitude of the microcrack strain response during interstice collapse. This compaction strain contribution overtakes that resulting from elastic deformation, and dominates up to ultimate strength. This behavior among shock conditioned specimens continues and is more pronounced at a confining

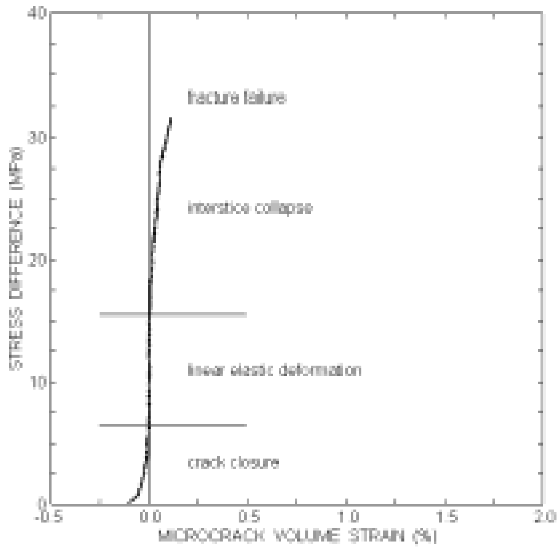


Fig. 13a. Deviation from linear elastic deformation for pristine specimen HPNS5-U3 subjected to uniaxial compression. Vertical line at zero strain represents elastic behavior. Deviations trending to more positive values with increasing stress imply compaction strain. Horizontal lines are stress levels separating types of mechanical behavior.

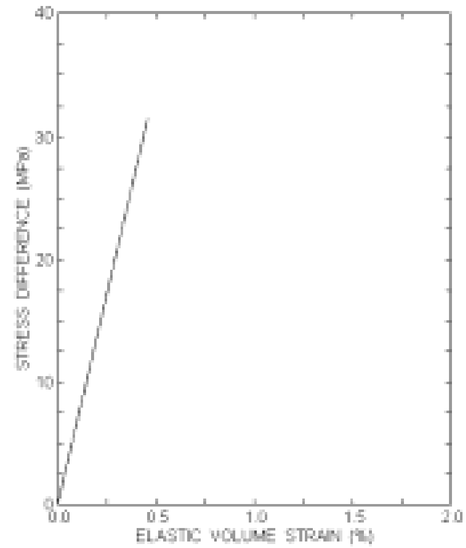


Fig. 13b. Elastic volume strain contribution to specimen HPNS5-U3 in uniaxial compression.

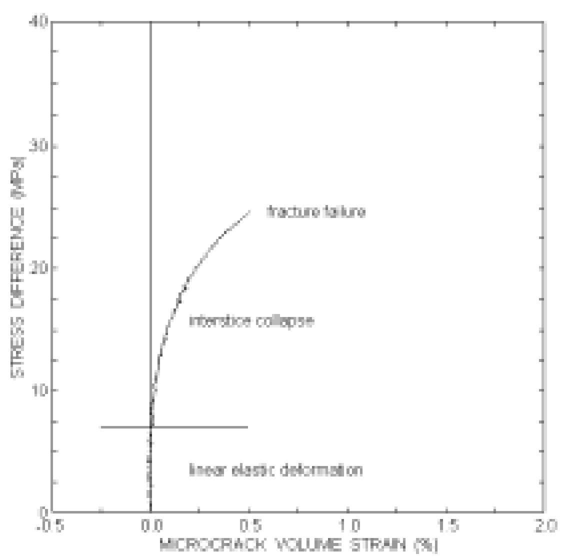


Fig. 14a. Deviation from linear elastic deformation for shock conditioned specimen HPNS5-DZ-DRM2#2 subjected to uniaxial compression.

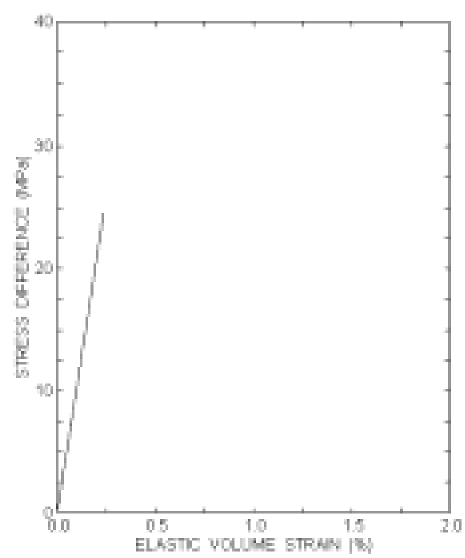


Fig. 14b. Elastic volume strain contribution to specimen HPNS5-DZ-DRM2#2 in uniaxial compression.

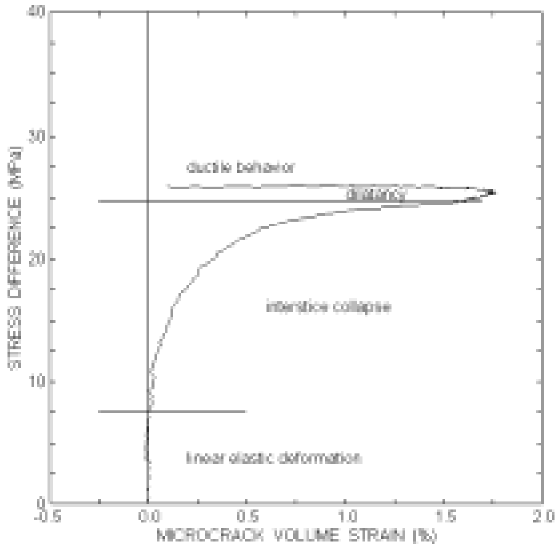


Fig. 15a. Deviation from linear elastic deformation for shock conditioned specimen 301 subjected to a differential stress while maintained at 5 MPa confining stress.

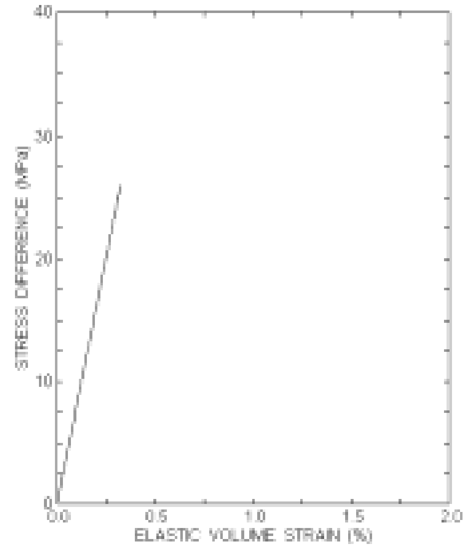


Fig. 15b. Elastic volume strain contribution to specimen 301 in triaxial compression.

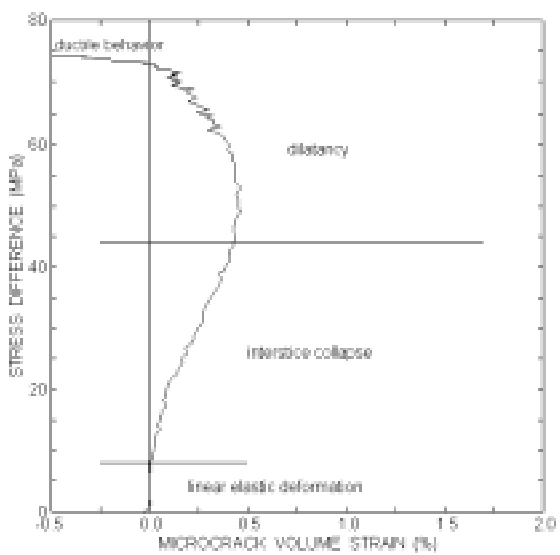


Fig. 16a. Deviation from linear elastic deformation for shock conditioned specimen 306 subjected to a differential stress while maintained at 100 MPa confining stress.

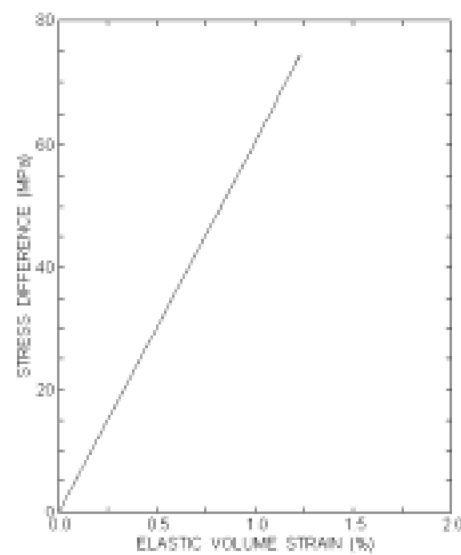


Fig. 16b. Elastic volume strain contribution to specimen 306 in triaxial compression.

stress of 5 MPa (Figs. 15a and b). The characteristic is lost in specimens maintained at 100 MPa confining stress (Fig. 16a and b).

In Figs. 15a and 16a a stress level is indicated for the transition between interstice collapse and dilatancy marking the initiation of microcrack growth. Microcrack growth creates volume strain and counters the contributions to compaction strain due to both elastic response and interstice collapse. The net result is a decrease in compaction strain. Ultimately the specimen exhibits a net volume change that is expansive. That is, it is possible to have the final grout volume, intact with no macroscopic fractures, equal or exceed its original volume.

## DUCTILE BEHAVIOR

Shock conditioned and pristine HPNS-5 grout specimens tested in uniaxial compression culminated at ultimate strength with fracture failure (Table 4). Failure by fracture was not achieved, however, among the suite of grout specimens tested at confining stresses greater than or equal to 5 MPa (725 psi) because the grout deformed to measurement or physical limits prior to achieving fracture. Materials that can sustained large amounts of strain, typically 3 - 5% strain, without loss of cohesion display characteristics referred to as ductile or 'plastic' behavior (Heard, 1960; Jaeger and Cook, 1979). The transition from brittle fracture failure to ductile behavior for shock conditioned HPNS-5 grout occurs at a confining stress between ambient and 5 MPa.

Figure 17 shows axial strain as a function of differential stress for three shock conditioned specimens, one specimen that was tested unconfined, and one specimen each at 5 MPa and 100 MPa confining stress. The form of this figure conveys the characteristics of ductile behavior. For the unconfined specimen the trace of its axial strain rises steeply with stress to about 17.5 MPa (2.54 ksi) before the slope of the trace yields, significantly decreases, and finally terminates with fracture failure at 24.6 MPa (3.57 ksi). The specimen maintained at 5 MPa confining stress follows nearly the identical trace as the unconfined specimen. However, specimen distortion with greater than 10% axial strain is observed as the specimen attains and sustains ultimate strength. This specimen was incapable of sustaining a differential stress greater than 25.9 MPa (3.76 ksi) but as long as that stress was sustained the specimen was capable of flowing until restricted by some physical boundary. This characteristic reasonably describes 'fully ductile' behavior (Jaegar and Cook, 1979) as the terminology is applied to ductile metals.

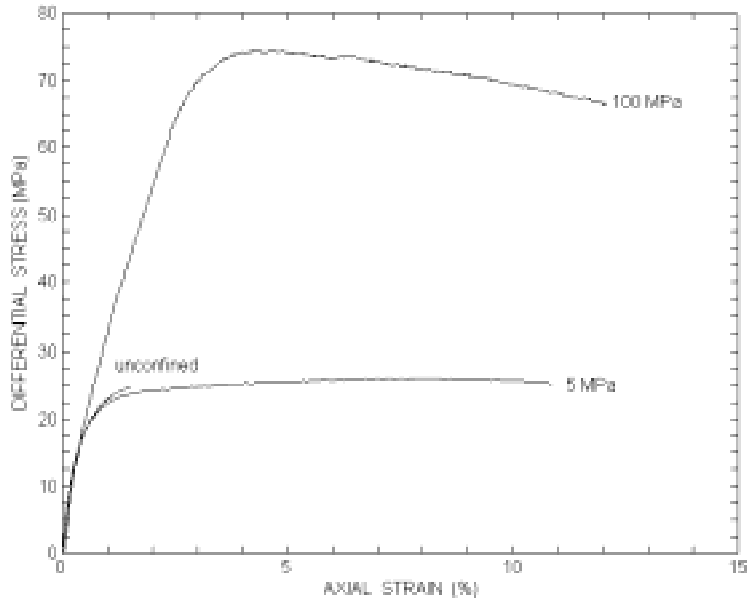


Fig. 17. Comparison of axial strain response of shock conditioned HPNS-5 (R-1) grout to triaxial loading at three different confining stresses. Confining stress is indicated at terminus of each trace. Trace for unconfined specimen HPNS5-DZ-DRM2#2 culminates with brittle fracture failure at 24.6 MPa differential stress and 1.53% compaction strain. At 5 MPa confining stress, specimen 301 followed nearly an identical strain response as HPNS5-DZ-DRM2#2, but instead of failing in brittle fracture made the transition to ductile behavior. As a ductile material the grout sustained a differential stress of about 25.9 MPa. With this sustained stress the specimen was capable of flowing until restricted by some physical boundary. The mechanical test was terminated prior to ductile fracture failure. Specimen 306, having a significant reduction in pore volume resulting from hydrostatic loading to 100 MPa confining stress, attained an ultimate strength of 74.5 MPa differential stress at 4.6% compaction strain. Like specimen 301, this grout made the transition to ductile behavior, however, could not sustain the ultimate strength of 74.5 MPa. As the specimen continued to deform, its instantaneous strength diminished. Again, the mechanical test was terminated before the grout failed in ductile fracture.

At 100 MPa confining stress the trace of the axial strain shows that the specimen achieved an ultimate strength of 74.5 MPa. Unlike the specimen at 5 MPa confining stress, this specimen was incapable of maintaining ultimate strength. As the grout lost strength it continued to show large strain distortions. By maintaining instantaneous ultimate strength the specimen was capable of flowing indefinitely unless physically restricted. This characteristic of the stress-strain envelope reasonably describes work softening.

## SUMMARY

Two 55-gallon drums of HPNS-5 (R-1) grout placed in pour 30 of the Distant Zenith U12p.04 by pass drift were subjected to a nuclear-driven stress wave with an average peak stress between 55.2 MPa (8.0 ksi) and 74.8 MPa (10.8 ksi). The HPNS-5 grout had cured 20 days at the time of device detonation. The unconfined compressive strength of the grout with a 20-day cure is estimated to be 12.7 MPa (1.8 ksi) based on break test data Included in the drums at the time of their preparation was a sealed, hollow tube experiment designed to explore the possibility that the HPNS grout mixes might "flow" upon passage of an explosively driven stress wave.

The drums of shock conditioned grout were retrieved from the DISTANT ZENITH event and the hollow tube experiments within the base of each drum were extracted for examination. The tubes, originally sealed and empty, were filled with grout following the event. The extrusion of HPNS-5 grout into the tubes is consistent with ductile flow. Mechanical tests of shock conditioned grout reveal a transition from brittle fracture failure to ductile behavior at a confining stress less than or equal to 5 MPa (725 psi). The differential stress required to induce ductile flow at 5 MPa confining stress is about 26 MPa (3.76 ksi), increasing to 63 - 75 MPa (9.1 - 10.8 ksi) at 100 MPa (14.5 ksi) confining stress, depending on moisture content. The dryer the grout the higher the required stress difference. As long as these stress magnitudes are maintained the grout is capable of flowing until physically constrained.

Mechanical tests show that under hydrostatic load the shock conditioned grout has a linear elastic response to a maximum of 10.5 MPa (1.52 ksi). The effective bulk modulus ($K_{effective}$) for this response is 5.51 ±0.28 GPa (799 ±40 ksi). Above 10.5 MPa the porosity (45% by volume; Akers and Reed, 1993) is reduced through crushing of the matrix microstructure. Between 28 MPa (4.1 ksi) and 70 MPa (10.2 ksi) stress, the volume strain response to hydrostatic load is again nearly linear, with an apparent bulk modulus ($K_{apparent}$) of 0.327 ±0.031 GPa (47.4 ±4.4 ksi). Much of the deformation caused by crush is not recoverable and results in irreversible volume reduction known as permanent set. The most significant change in permanent set occurs between 25 MPa (3.6 ksi) to 60 MPa (8.7 ksi) peak mean stress, which corresponds to a change from 1% to greater than 15% unrecoverable volume strain. At hydrostatic stresses above 100 MPa (14.5

ksi) the matrix microstructure stiffens and the instantaneous bulk modulus rises above 5 GPa.

Below ultimate strength, uniaxial and triaxial tests reveal that the mechanical response of both pristine and shock conditioned HPNS-5 grout deviates from the 'classic' behavior of brittle rock with the introduction of a stress - strain field for interstice collapse. Typically the sequence in mechanics with increasing differential stress is crack closure, linear elastic deformation, dilatancy and, at ultimate strength, fracture failure. The sequence for this grout includes these and introduces interstice collapse between linear elastic deformation and dilatancy. Interstice collapse is inherent to the pristine grout and not a consequence of stress loading, although the magnitude and form of the strain response appreciably changes with shock conditioning. Once microcrack growth is initiated, dilatancy rapidly dominates and counters the compactional strain effects caused by linear elastic deformation and interstice collapse. The volume expansion caused by dilatancy may result in a final grout volume, intact with no macroscopic fractures, that equals or exceeds its original volume.

The elastic range for grout in uniaxial and triaxial compression is from ambient to a maximum of 14.2 MPa (2.1 ksi) differential stress and does not appear to vary as a function of confining stress. The elastic modulus in compression is 6.54 ±0.76 GPa (949 ±110 ksi) and also appears to be independent of confining stress. The average value for Poisson's ratio is 0.171 at less than or equal to 5 MPa and decreases to values of 0.035 - 0.112 at 100 MPa. Shock conditioned grout in tension has little strength. The grout failed in tension at 1.2 - 1.4 MPa (174 - 203 psi) and exhibited an elastic modulus of 6.9 GPa (1,000 ksi).

Although this report is intended primarily as documentation of the mechanical response characteristics of HPNS-5 grout, a few comments are in order regarding the efficacy of using HPNS-5 as a containment plug material. Following are some of the more salient points:

1) The relative ease with which the plug undergoes ductile flow, as opposed to brittle failure, is viewed by this author as a plus. Under ductile flow, the plug should remain as an intact unit with no significant increase in fracture permeability to compromise its primary function as an impedance to gas flow;

2) The plug's subsidiary role as a stemming support is not severely compromised by shock conditioning. The shear strength of "shocked" HPNS is about the same as that for the unshocked material; and,

3) Differential compaction between the HPNS-5 plug and the surrounding rock is a complicated issue. Under certain loading and emplacement conditions, one can envision a plug whose physical dimensions are modified in such a way as to compromise the dimensional bridging of the emplacement borehole. Computer modeling parameter studies, using the mechanical properties described in this report, would be useful in addressing the various possibilities. The models should include

the effects of both compaction and dilation as well as various isotropic and anisotropic loading states.

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