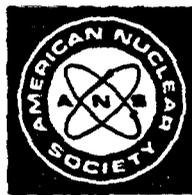


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TRIAxIAL- AND UNIAxIAL-COMPRESSION TESTING METHODS DEVELOPED FOR EXTRACTION
OF PORE WATER FROM UNSATURATED TUFF, YUCCA MOUNTAIN, NEVADA

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ABSTRACT

To support the study of the hydrologic system in the unsaturated zone at Yucca Mountain, Nevada, two extraction methods were examined to obtain representative, uncontaminated pore-water samples from unsaturated tuff. Results indicate that triaxial compression, which uses a standard cell, can remove pore water from nonwelded tuff that has an initial moisture content greater than 11% by weight; uniaxial compression, which uses a specifically fabricated cell, can extract pore water from nonwelded tuff that has an initial moisture content greater than 8% and from welded tuff that has an initial moisture content greater than 6.5%. For the ambient moisture conditions of Yucca Mountain tuffs, uniaxial compression is the most efficient method of pore-water extraction.

INTRODUCTION

The hydrologic system in the unsaturated tuff at Yucca Mountain, Nevada, is being evaluated for the U.S. Department of Energy as a potential site for a high-level radioactive waste repository. A hydrochemical study is being made to assess characteristics of the hydrologic system such as: traveltime, direction of flow, recharge and source relations, and types and magnitudes of chemical reactions in the unsaturated tuff. In addition, the information can be used to estimate dispersive and corrosive effects of unsaturated-zone water on radioactive-waste canisters. This paper examines methods used to obtain representative, uncontaminated samples of pore water from tuffs that have a small initial moisture content.

The objective of this study was to develop compression methods and experimental procedures for extracting uncontaminated pore water from cores of welded and nonwelded tuffs. Two prototype testing methods will be discussed. One method involved modifications to an existing extraction system that uses a triaxial cell to contain the core during compression¹. In the

second method, uniaxial compression, a thick, steel cylinder is used to confine the core during compression. Both experimental methods were designed to produce chemically uncontaminated pore-water samples. Experiments were made to determine the optimum stress and duration of compression for efficient extraction of pore water, and to avoid temperature increases in the core and changes in pore-water chemistry resulting from the compression process. Factors that were considered in the development of the testing methods were: 1) Water volume required for analysis; 2) rock composition that could change water chemistry in a high stress environment; 3) rock type as it relates to compaction of pore space; and 4) duration of loading with respect to maximum core compaction (and water extraction) and time of exposure of pore water to new mineral surfaces.

Cores used in this study were collected from drill holes UE-25 UZ #4 and UE-25 UZ #5 which are located along the east margin of Yucca Mountain, Nevada, and from the U12g tunnel complex at Rainier Mesa, Nevada. These sample sites are located on the Nevada Test Site (NTS) which is about 110 km northwest of Las Vegas, Nevada.

DEVELOPMENT OF PORE-WATER-EXTRACTION METHODS

Pore-Water Extraction by Compression

Pore-water extraction by compression is not a new concept. Previous investigators² developed methods of extracting pore water from nonwelded tuff cores using triaxial compression. The compression methods developed in this study use the application of stress to a core that causes compaction, decrease of pore volume, and expulsion of pore gas and water. Gas is expelled from the core during the initial stages of compaction, and the water saturation of the core increases. When the water saturation of the core nears 100%, additional stress produces an excess pore-water pressure, and water is expelled into the collection system. Pore gas is collected and stored in 10-ml glass syringes

for measurement of trace-gas composition by gas chromatography. Pore water is collected in 10-ml chemically inert plastic syringes and is filtered through a disposable 0.45- μ m filter before storage in polyethylene bottles for analysis of dissolved ionic chemistry. Immediately after filtration, the pH and specific conductance of each water sample are measured by using about 0.2 ml of the sample for each measurement.

Design of Triaxial Cell

The triaxial cell design for pore-water extraction used in this study was the same as one used previously¹. The design is based on the Hoek-Franklin triaxial cell³, which originally was intended to measure the behavior of rocks under realistic geologic stresses. Several modifications to this configuration have resulted in development of the pore-water-extraction system as shown schematically in Fig. 1. The triaxial cell is made of a heat-treated 4140-alloy steel body and end caps and a urethane membrane. Vented pore-pressure platens work well for transferring extracted water to external collectors. Plastic syringes for water collection were connected to the platens by oversized stainless-steel hypodermic needles and compression fittings.

Several advantages exist for this design: (1) Pore water is collected from both ends of the core to maximize drainage efficiency; (2) quantities of extracted water may be measured during collection, which enables the calculation of pore-water-extraction rates; (3) water samples can be collected at various stresses without disassembly of the triaxial cell; and (4) to increase pore-water recovery, nitrogen gas can be forced through the pore space after the core has been compressed sufficiently to reach 100% saturation.

Pore-Water Extraction by Triaxial Compression

The triaxial cell is assembled by placing a core between two pore-pressure platens, wrapping the core with a layer of Teflon, and then enclosing the wrapped core with a urethane membrane. The entire assembly then is enclosed in the main barrel of the triaxial cell and the syringes are attached. Axial stress was applied to the core by a load frame that had a capacity of 4.5 MN. Lateral confining stress was applied with hydraulic oil. The triaxial cell has a maximum confining stress of 69 MPa and will accommodate cores that have a length of 98 to 113 mm and a diameter of 61 mm.

The core is loaded hydrostatically (axial stress = confining stress) up to about 69 MPa, which is the design stress limit for the urethane membrane. The confining stress is held constant while the axial stress is increased in

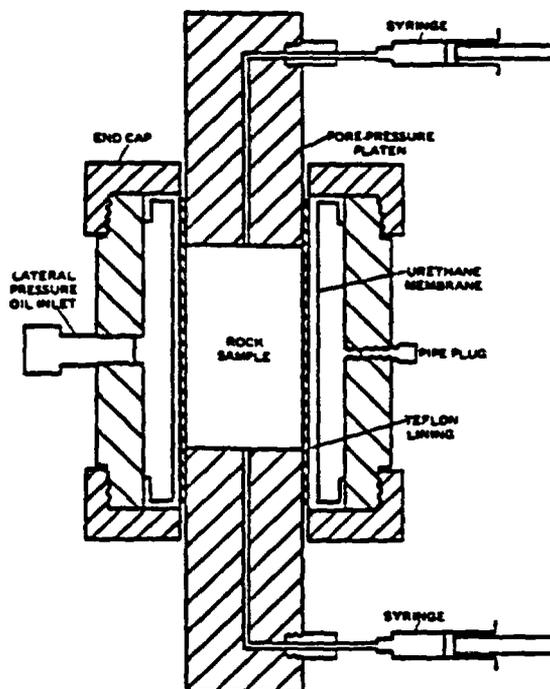


FIGURE 1. SCHEMATIC OF TRIAXIAL CELL

four steps to a maximum of 193 MPa; the load rate between steps is a constant 69 kPa/s. The four stress levels correspond to axial stresses of 76, 117, 152, and 193 MPa. Pore gas and water are collected in the syringes as the core compacts under load. When collected gas or water volumes are sufficient for the desired chemical analyses, syringes are replaced for additional sampling. Water samples are filtered, measured for pH and conductivity, and analyzed as soon as possible after collection.

At the maximum axial stress, after water expulsion ceases and the core stops compacting, additional pore water can be extracted by injecting nitrogen gas into the pore space and forcing out pore water. Nitrogen pressure that ranges from 1.4 to 4.1 MPa is applied through the upper platen from a nitrogen tank. The time required for water to be expelled by nitrogen injection depends on the final saturation state of the core and the core permeability. Cores that already have produced water by compression alone often produce water by nitrogen injection within a few minutes after injection begins; cores that have not produced water by compression may need more than 1 hour of injection before water is recovered. The permeability of the core matrix controls penetration rates of the nitrogen gas into the pore spaces; cores that have a low-permeability matrix (welded tuffs in particular) need a long period of nitrogen injection for this technique to be effective. Practical criteria for

stopping nitrogen injection are: (1) When sufficient water has been collected for analysis; or (2) when nitrogen injection has continued for at least 2 hours. The primary reasons for the 2-hour limit are to minimize the total test duration; and from experience, if no water is extracted by nitrogen injection within 2 hours, continued injection is not likely to produce pore water.

Data for Triaxial Compression

Data collected from 17 pore-water extraction tests by using triaxial compression are summarized in table 1. The data are divided into 2 sets according to degree of welding. The initial water saturation of 9 of the cores used for triaxial testing was artificially increased to provide a greater range of saturations than was available from undisturbed cores. The initial moisture content of these cores that ranged from 5 to 12% was increased to 13 to 32% by weight (all moisture-content values are given by weight). The initial degree of saturation that ranged from 20 to 39% was increased to 42 to 56%.

TABLE 1. DATA FOR TRIAXIAL COMPRESSION

SAMPLE NAME	INITIAL MOISTURE CONTENT (%)	EXTRACTED PORE-WATER VOLUME (ml)	MAXIMUM AXIAL STRESS (MPa)	TOTAL TEST DURATION (min)
NONWELDED TUFF				
UE-25 UZ5-330	12.4	0	117	87
UE-25 UZ5-223	¹ 25.7	42	138	90
UE-25 UZ5-334	21.0	18	152	146
UE-25 UZ4-190	¹ 24.1	47	152	149
USW UZ13-354	¹ 17.2	30	152	300
UE-25 UZ4-182	¹ 32.3	60	97	310
UE-25 UZ4-242	¹ 12.6	18	165	265
UE-25 UZ4-241	¹ 16.5	23.5	117	343
UE-25 UZ4-240	¹ 17.5	16.5	76	264
UE-25 UZ4-238	¹ 16.3	28	117	240
UE-25 UZ4-237	¹ 16.3	21	152	399
UE-25 UZ5-334B	9.6	0	152	133
UE-25 UZ5-246	11.8	11	179	507
UE-25 UZ5-269	11.0	6	179	288
UE-25 UZ5-235	6.8	0	193	292
MODERATELY WELDED TUFF				
USW UZM46-8	3.1	0	34	9
USW UZM46-33	7.6	6	193	237

¹ initial moisture content artificially increased

Triaxial compression resulted in porosity decreases in nonwelded cores of 32 to 55%, and the average decrease was 43%, based on initial porosity values. Total axial strains for nonwelded tests ranged from 8 to 37%, and the average value was 23%. These values for total axial strain closely compare with data acquired by triaxial testing reported by Yang and others¹. This porosity reduction resulted in extraction of 14 to 64% of the total available water for nonwelded tuff, and the average extraction success was 38%. (Extraction success is the total volume of water extracted expressed

as a percentage of the total volume of water in the core.)

The results of pore-water extraction from nonwelded tuff using triaxial compression are shown in Fig. 2. This figure shows a comparison (before nitrogen injection) of the volume of water extracted only by compression in this study with similar data collected by Yang and others¹. The two data sets indicate close agreement; in both data sets, the minimum water content at which extraction of pore water occurred was about 13%. Data from this study that include additional pore-water recovery by nitrogen injection also are shown in Fig 2. The same general trend is present; however, it is clear that injection of nitrogen gas while the core is held at its maximum compression substantially increases the volume of pore water recovered. Based on the compression-only and nitrogen-injection data, 6 to 9 ml of additional pore water is expelled by nitrogen injection. The minimum core-water content necessary for pore-water extraction was decreased from 13% to 11% by using nitrogen injection; the data on Fig. 2 indicate that the minimum water content for successful pore-water extraction may be as low as 7%, but no tests were made on cores in the 7 to 11% range. The temperature of the core during compression was measured during 12 of the 17 triaxial tests by using a thermocouple in contact with the core. No temperature changes were noted during any of the tests.

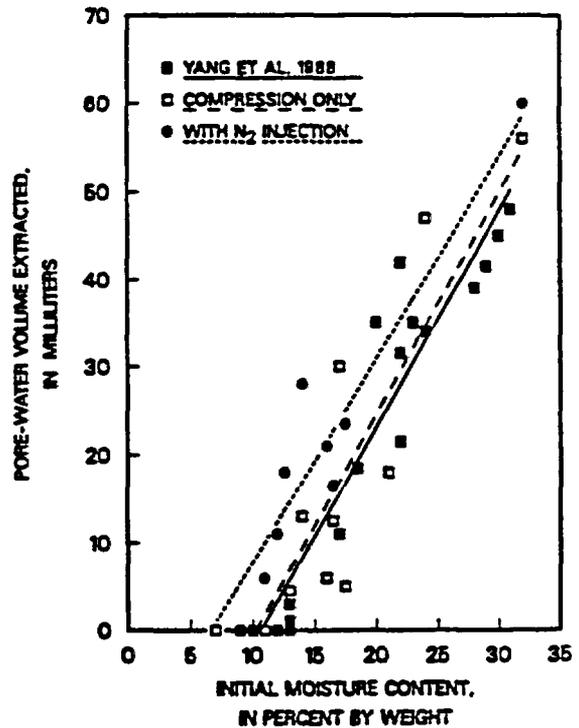


FIGURE 2. PORE-WATER VOLUME EXTRACTED VS. INITIAL MOISTURE CONTENT FOR TRIAXIAL COMPRESSION

Design of Uniaxial Cell

Calculations indicated that the triaxial compression could not apply enough stress to extract water from densely welded cores; therefore, the uniaxial compression system was designed and fabricated specifically for this study. The system is based on uniaxial compression cells used in concrete research⁴. The primary objectives were to: (1) Design a system that did not incorporate the inherent difficulties of the triaxial system, such as membrane leakage; (2) make a simpler system to operate; and (3) make a system that would operate efficiently over a large range of stresses so that welded and nonwelded tuff could be compressed.

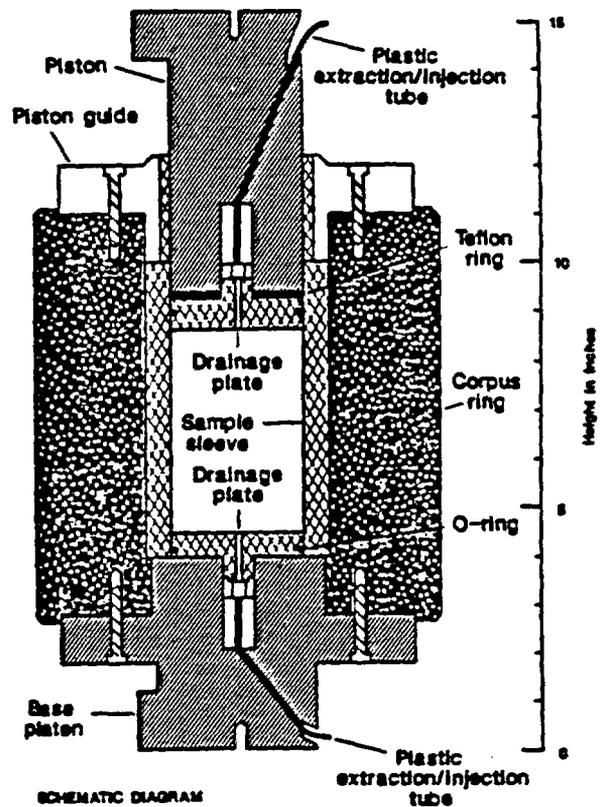
The prototype uniaxial compression system is shown schematically in Fig. 3. The major components, made of heat-treated 4340-alloy steel, are the corpus ring, base platen, and piston. The piston guide is untreated 4340 steel. The sample sleeve and drainage plates are formed from age-hardened Monel K500 nickel alloy. The core is wrapped in a Teflon sheet and confined in the sample sleeve (rather than a membrane surrounded by oil under pressure as in the triaxial cell). The drainage plates have holes for pore-water drainage and are connected to syringes for gas and water collection. The sample chamber is sealed by use of O-rings and a Teflon disk on the upper drainage plate. The uniaxial cell has a maximum stress rating of 552 MPa and can accommodate cores up to 102 mm long.

Pore-Water Extraction by Uniaxial Compression

The uniaxial cell is assembled as shown in Fig. 3. Axial stress was applied to the core by a load frame that had a capacity of 2.7 MN. Pore gas and water are collected in the syringes as the core compacts under load. When adequate volumes of gas or water are collected for analysis, syringes are replaced for additional sampling. Loading continues in increments of 69 MPa from the test start until the final stress level of 552 MPa is reached. Water samples are handled as described previously. At the maximum axial stress, after water expulsion ceases and the core stops compacting, additional pore water is extracted by injecting nitrogen in the same manner as for triaxial compression. Practical criteria for stopping nitrogen injection are the same as those used for triaxial compression.

Data for Uniaxial Compression

Selected mechanical data collected from 21 pore-water-extraction tests using uniaxial compression are summarized in table 2. The data are divided into two sets according to degree of welding.



SCHEMATIC DIAGRAM

FIGURE 3. SCHEMATIC OF UNIAXIAL CELL

TABLE 2. DATA FOR UNIAXIAL COMPRESSION

SAMPLE NAME	INITIAL MOISTURE CONTENT (%)	EXTRACTED PORE-WATER VOLUME (ml)	MAXIMUM AXIAL STRESS (MPa)	TOTAL TEST DURATION (min)
NONWELDED TUFF				
UE-25 UZ5-217	9.5	0	221	106
UE-25 UZA-115	12.5	15	427	244
UE-25 UZA-338	9.5	0	434	309
UE-25 UZ5-230	7.6	6	434	321
UE-25 UZ5-327	9.4	5	434	305
UE-25 UZ5-345	12.0	7	552	357
GT-EX-DN3-2	30.8	39	552	325
GT-EX-DN3-3	30.8	61.5	552	455
UE-25 UZ5-347	18.8	16.5	552	415
DENSELY WELDED TUFF				
GT-LD-AC2-5	8.4	5	552	175
USU UZ13-62	1.5	0	552	204
GTG-LD-UB-3-1	3.5	0	552	257
GT-LD-AC2-17	6.5	cr	552	241
GT-LD-AC2-26	6.6	1.5	552	328
GT-LD-AC2-25	6.7	2.5	552	473
GT-LD-AC2-41	6.5	1.2	552	446
GT-LD-AC2-42	6.5	1.2	552	480
GT-LD-AC2-18	6.6	0.8	552	491
GT-LD-AC2-35	7.7	6.2	552	1305
GT-LD-AC2-62	6.6	5.8	552	1341
GT-LD-AC2-63	6.6	3.2	552	485

Uniaxial compression is an effective means of decreasing core porosity. Porosity decreases of 32 to 74% that have an average decrease of 56% (based on initial porosity values) were

measured from nonwelded tuff tests. Welded tuff decreases ranged from 14 to 33%, and the average reduction was 26%. Total axial strains for nonwelded tests ranged from 31 to 49%, and the average was 39%; welded test strains varied from 6 to 11%, and the average was 8%. This porosity decrease resulted in an extraction success of 18 to 60% of the total available water for nonwelded tuff and 2 to 17% for welded tuff. The average extraction success was 36% for nonwelded tuff, and 9% for welded tuff.

As a core compacts and loses porosity during a uniaxial compression test, its water saturation increases. Cores that have a large initial moisture content reach 100% saturation (and begin producing water) sooner and produce more water than cores that have a smaller moisture content. The nonwelded test data in Fig. 4 show this relation; the data for welded cores do not indicate a clear relation between initial moisture content and volume of water extracted. This may be because welded tuff compresses much less than nonwelded tuff, and that the volume of water extracted from welded tuff is more sensitive to the total axial strain than to initial moisture content. The relation between volume of water extracted and total axial strain for welded tuff tests is shown in Fig. 5. No relation between volume of water extracted and total axial strain could be demonstrated for the nonwelded tuff tests.

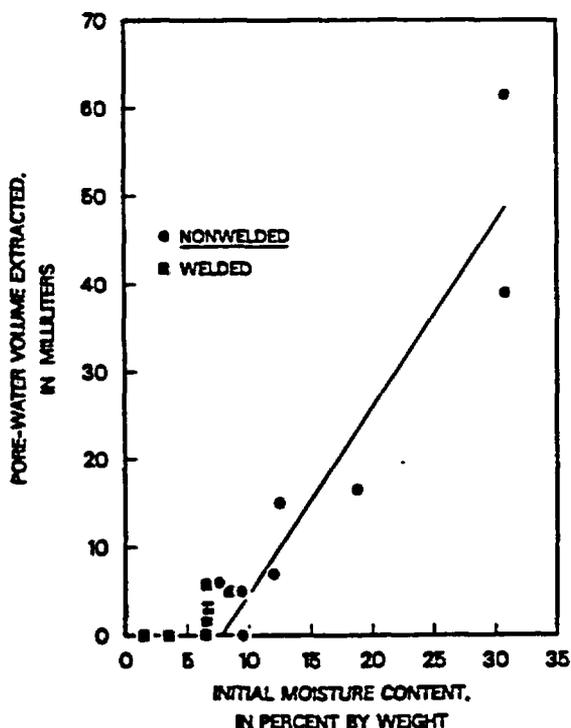


FIGURE 4. PORE-WATER VOLUME EXTRACTED VS. INITIAL MOISTURE CONTENT FOR UNIAXIAL COMPRESSION

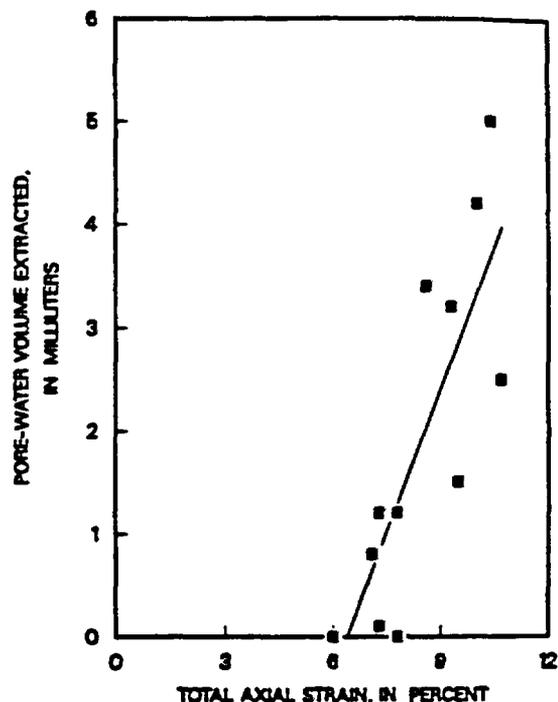


FIGURE 5. PORE-WATER VOLUME EXTRACTED VS. TOTAL AXIAL STRAIN FOR UNIAXIAL COMPRESSION OF WELDED TUFF

Almost no water was recovered by compression alone on any of the welded tuff tests; nearly all collected water was produced by displacement of pore water by nitrogen gas. The volume of water extracted is dependent on the duration of nitrogen injection; longer periods of nitrogen injection resulted in larger water recovery volumes. (Note that the duration of nitrogen injection is equal for all the welded tuff data presented on Fig. 5.) The temperature of the core during compression was measured during 5 of the 21 uniaxial tests. No temperature changes were noted during any of the tests.

Comparison of Test Data

A plot of initial moisture content versus pore-water volume extracted for all the compression tests conducted on nonwelded tuff is shown in Fig. 6. The regression lines in Fig. 6 are very similar for triaxial and uniaxial compression. Data for both extraction methods indicate that the minimum moisture content is 7 to 8% (minimum saturation 16 to 20%) for pore-water extraction from nonwelded tuff. The reason for the similarity between the methods may be simply that they are applied to the same type of tuff. However, the data in Fig. 6 indicate that uniaxial compression is more successful than triaxial compression in extracting pore water at a smaller initial moisture content. The minimum initial moisture

content for nonwelded tuff tested by uniaxial compression was 7.6%; the minimum saturation was 18%. For triaxial compression, the minimum initial moisture content was 11.0%; minimum saturation was 24%. This conclusion is important because, at ambient conditions, the nonwelded tuffs at Yucca Mountain have small initial moisture contents and saturations¹.

Because initial moisture content and extracted pore-water volume do not show good correlation for the welded tuff cores tested, plots of welded tuff test data similar to Fig. 6 would be of little value. The minimum moisture content for pore-water extraction from welded tuff cores by uniaxial compression is 6.5% (minimum saturation about 70%).

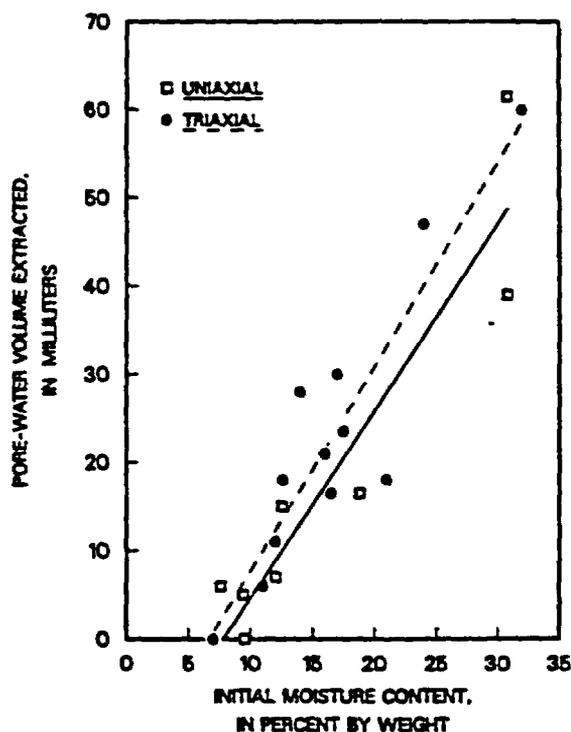


FIGURE 6. PORE-WATER VOLUME EXTRACTED VS. INITIAL MOISTURE CONTENT FOR ALL NONWELDED TESTS

DISCUSSION

Advantages of Uniaxial Compression

In addition to enabling extraction of water from tuff at a smaller initial moisture content, uniaxial compression has greater mechanical advantages than triaxial compression:

1. Higher stress. Uniaxial compression can apply more than 2.5 times the axial stress to a core than triaxial compression. Higher axial stress produces decreased pore space and increased water expulsion.

2. Quantitative volumetric measurements. Because the core diameter is rigidly constrained during uniaxial compression, accurate volumetric measurements are possible. Measurements of changes in core volume during compression are useful in predicting timing and volume of water expulsion.

3. Smaller system volume. The uniaxial compression cell has a drainage-system volume of less than 1 ml; the triaxial cell drainage-system volume is about 8 ml. A smaller system volume enables more rapid detection of water expulsion and minimizes loss of water that adheres to the inside of the drainage pathway.

4. Variable core length. The uniaxial cell can accommodate a large range of core lengths; triaxial test cores need to be of a closely constrained length.

5. Lower contamination risk. Because steel applies the confining force in the uniaxial cell, there is no risk of contamination by leakage of the confining fluid as can occur in the triaxial cell.

Selection of Stress Paths

The stress path that facilitates the extraction of pore water from a core by using uniaxial or triaxial compression is composed of two variables: Magnitude of applied axial stress and duration of stress application. The selection of appropriate values for these variables is influenced by three parameters: Water volume needed for analysis, water chemistry, and rock type.

Unless water from two or more extraction tests is combined in a composite sample, the extraction needs to continue until sufficient water is obtained for analysis. The minimum water volume needed is dependent on the type of analysis to be made. Analysis of dissolved ionic constituents requires a minimum sample of 2 ml; isotopic studies often require larger samples (measurement of tritium content, for example, requires at least 10 ml). Sample handling, filtration, and measurement of sample pH and specific conductance all together require an additional 0.5 ml. The 3-ml target volume may determine when an intermediate sample is collected or it may determine the end of a test.

Several factors that may affect the chemistry of the extracted pore water also affect stress path selection. These factors are:

1. Mineralogy. Because some NTS tuff cores contain clay minerals and zeolites, lower applied stresses are selected to minimize any changes in water chemistry that might be caused by the extraction of bound water.

2. Strength. The type of tuff used in the extraction test has an impact on the stress path selection primarily because different tuffs have different strengths. Welded tuff tested in this

study has a small clay content⁴⁷ and high strength⁴⁸; therefore, welded tuff does not compact much. Consequently, for pore water extraction from welded tuff, a stress path that produces the maximum compaction is used even if this requires high stresses for an extended time. Nonwelded tuff has low strength⁴⁹ and variable clay content⁵¹. If the initial water saturation of the core is large (> 70%), the extraction test will produce adequate water for analysis in a short time at low axial stress. However, if the initial water saturation of the core is small (< 20%), maximum compaction is needed and high stresses for an extended time will be necessary to produce sufficient water for analysis.

3. Loading rate. A slow loading rate allows the core to undergo maximum compaction (and water extraction) and maximizes the volume of water extracted at low stress levels (which minimizes the water contact time on new mineral surfaces). The loading rate also was selected to enable completion of the test within 6 to 8 hours. A loading rate of 69 kPa/s was chosen to meet these criteria.

The recommended stress paths for pore-water extraction by uniaxial compression of welded and nonwelded tuff cores, based on experimental trials in this study, are shown in Fig. 7. At a specified loading rate, the only controlled variable remaining is the time spent at each stress level. The stress paths in Fig. 7 are representative guides; the following criteria are suggested to determine when load application should continue from one stress level to the next: (1) Water expulsion into the collection system ceases (no volume change in syringes in 10 to 15 minutes); (2) core compaction rate decreases to less than 25 μm in a 5-minute interval; and (3) total time at the stress level reaches at least 10 minutes. Because core permeability is low, water expulsion can be slow. Experience from testing indicates as long as 10 minutes may be necessary for the start of water movement into the drainage system. The recommended stress path for pore-water extraction by triaxial compression from nonwelded tuff also is shown in Fig. 7. The criteria for advancing between stress levels are the same as for uniaxial compression except the core compaction criterion is eliminated (because lateral strain is possible in triaxial compression).

Water Extraction Relations

The volume of expelled water is directly proportional to the volume of pore space eliminated. Initial water saturation and total axial strain may be used as parameters to roughly estimate the success of future pore-water extraction tests using uniaxial compression. For nonwelded tuff, an initial degree of saturation of at least 20% is needed to extract pore water; in terms of initial

moisture content, 8% is the approximate lower limit (assuming porosity values in the 40-55% range). The group of 22 nonwelded tuff cores from either UE-25 UZ #4 or UE-25 UZ #5 tested in this study had an average initial moisture content of about 10% and an average initial saturation of about 27%. Based on the above estimate, most of the nonwelded tuffs from Yucca Mountain should produce water under uniaxial compression.

To estimate the success of pore-water extraction using uniaxial compression for welded tuff, initial saturation and total axial strain must be known. Although the minimum water-saturation and minimum axial-strain values are not well defined, they can be used as guidelines. For welded tuff, an initial water saturation of about 80% and a total axial strain of at least 7% are necessary to enable water extraction. Welded tuff that has a smaller initial water saturation (about 70%) will produce water if the total axial strain is greater (about 11%). The average water saturation of 50 welded tuff samples from Yucca Mountain was 65%¹². Depending on the total axial strain, tuff that has an average moisture content may yield water by uniaxial compression using long-duration (>3 hours) tests and nitrogen injection; however, testing is not complete enough to fully substantiate this statement.

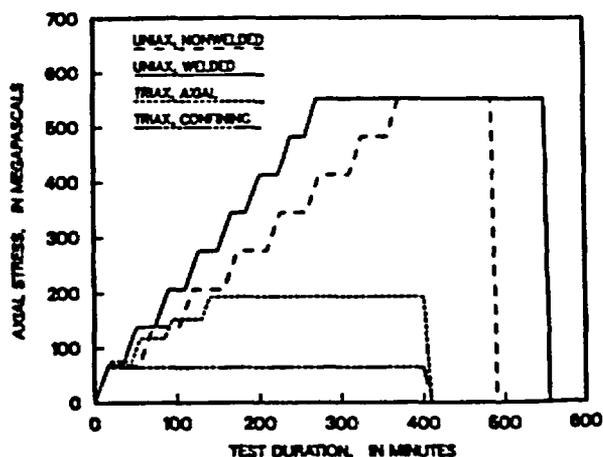


FIGURE 7. RECOMMENDED STRESS PATHS FOR PORE-WATER EXTRACTION

SUMMARY AND CONCLUSION

Two compression methods--triaxial compression and uniaxial compression--have been examined for extracting pore water from unsaturated tuff. The use of nitrogen injection while the core is at maximum compression increased the pore-water recovery for both methods. Triaxial compression, combined with nitrogen injection, is useful for extracting

pore water from nonwelded tuff that has an initial moisture content greater than 11%. Uniaxial compression, also using nitrogen injection, can extract pore water from nonwelded tuff that has an initial moisture content as small as 8% and from welded tuff that has an initial moisture content as small as 6.5%.

For the tuffs at Yucca Mountain, the uniaxial compression cell is much better suited for pore-water extraction than is the triaxial cell. The ability to extract pore water from welded or nonwelded tuffs that have small initial moisture contents, and additional mechanical advantages make the uniaxial cell a more efficient and useful pore-water extraction device.

Current work on pore-water extraction by compression involves the study of changes in the chemistry of the extracted water in relation to the stress applied to extract the water. Additional study of the mineralogy and pore structure of tuff and knowledge of changes in pore-water chemistry will enable use of these compression techniques to extract uncontaminated, unaltered pore water for hydrochemical studies.

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