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Measurements of Uranium Mill Tailings Consolidation Characteristics

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Operated by
Battelle Memorial Institute

Prepared for
U.S. Nuclear Regulatory Commission

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ABSTRACT

A series of experiments were conducted on uranium mill tailings from the tailings pile in Grand Junction, Colorado, to determine their consolidation characteristics. Three materials (sand, sand/slimes mix, slimes) were loaded under saturated conditions to determine their saturated consolidation behavior. During a separate experiment, samples of the slimes material were kept under a constant load while the pore pressure was increased to determine the partially saturated consolidation behavior.

Results of the saturated tests compared well with published data. Sand consolidated the least, while slimes consolidated the most. As each material consolidated, the measured hydraulic conductivity decreased in a linear fashion with respect to the void ratio.

Partially saturated experiments with the slimes indicated that there was little consolidation as the pore pressure was increased progressively above 7 kPa. The small amount of consolidation that did occur was only a fraction of the amount of saturated consolidation. Preliminary measurements between pore pressures of 0 and 7 kPa indicated that measurable consolidation could occur in this range of pore pressure, but only if there was no load.

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FIGURES

ACKNOWLEDGMENTS

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EXECUTIVE SUMMARY

The tailings (waste) from uranium mills are usually slurried into pits that are open to the atmosphere. Regulations have been proposed to have these tailings piles covered to minimize the amount of radon gas that escapes and to drain the piles to minimize the leaching of contaminants to the ground water. One result of these actions is that the tailings will consolidate, with concurrent settlement of the pile surface. Since movement of the pile surface may rupture the cover, models have been proposed to assess the surface settlement problem. These models require data on tailings consolidation characteristics, of which little exists.

This report details the experimental procedures used in measuring tailings consolidation characteristics and the results generated at Pacific Northwest Laboratory (PNL) with the support of the U.S. Nuclear Regulatory Commission (NRC). Specifically, the procedures measuring saturated consolidation, hydraulic conductivity, and partially saturated consolidation are explained. The tests were conducted on three types of tailings material: slimes, sand/slimes mix, and sand.

Our results confirm previous reports that show slimes material consolidates the most of the three types. When the load on the sample was increased from 10 to 1255 kPa, we found that the slimes settled 21% in height, the sand/slimes mix 11%, and the sand 5%. Measured hydraulic conductivity values decreased with decreasing void ratio. When compared at similar void ratios, the slimes conductivity was an order of magnitude lower than the sand/slimes mix, which was two orders of magnitude lower than the sand.

Partially saturated testing was conducted only on the slimes material because time was limited and the slimes were expected to consolidate more than the other materials. For pore pressures up to 55 kPa, however, the amount of partially saturated consolidation was minimal compared to the amount measured under saturated loading. The consolidation during our desaturation tests was about 10% of that reported by others (Sherry 1982). We believe the discrepancy is the result of differences in measurement methodologies and recommend further work to reconcile the disparity between measurements.

Changes in the degree of saturation during the partially saturated tests were small for slimes. At 55 kPa pore pressure, the samples were still nearly saturated.

1.0 INTRODUCTION

Uranium mill tailings piles emit radon gas to the atmosphere and are a source of ground-water contamination. Various methods for mitigating these problems have been and are continuing to be investigated. Currently, the consensus among investigators is to place an earthen cover on the piles and drain them. The cover will limit the amount of escaping radon gas and dust, while the drains will remove the mechanism (free-water drainage) that carries contaminants to the ground water. Both techniques, however, contribute to the consolidation of the tailings material and thus the settlement of the tailings pile surface. The potential exists for the cover to be ruptured by such a surface settlement, thus rendering the cover less effective as a radon barrier.

To explore the possibilities of cover disruption as the piles settle, numerical models are used that can account for tailings consolidation under both saturated and partially saturated conditions. The models, however, are only as good as the input data, and data are lacking on the hydraulic and stress properties for tailings material.

Several researchers have measured some of the material properties required to simulate the tailings piles. Martin et al. (1980) examined and sampled two tailings piles (Grand Junction, Colorado, and the Vitro site, Salt Lake City, Utah). They found that the finer materials such as slimes held more water at a given pore pressure than the coarser materials. When samples were compacted to a higher density, they were able to hold more water at a given tension than under their looser, less-compacted condition. Veyera and Nelson (1981) also measured the moisture characteristics of tailings material. In addition, they extended their analysis to estimate unsaturated hydraulic conductivity functions for tailings using the method of Brooks and Corey (1964).

Sherry (1982) measured the void ratio and degree of saturation changes that occurred as he varied both the stress and tension exerted on his samples. With this data, he was able to construct three-dimensional surfaces that related the dependent variables (void ratio and degree of saturation) to the independent variables (effective stress and tension). This was done in accord with the work of Fredlund and Morgenstern (1976), who proposed using such surfaces to describe partially saturated consolidation. The surfaces generated, however, were unexpected because they indicated that swelling could occur as the samples dried (as the pore pressure was increased).

This report details the experimental work done at Pacific Northwest Laboratories (PNL) to measure tailings material properties. Specifically, it outlines the procedures used to measure saturated consolidation, saturated hydraulic conductivity at each step of the consolidation experiment, partially saturated consolidation, and the degree of saturation during the partially saturated testing. The report analyzes the experimental results and includes all of the generated data in an appendix. The tailings material was from the Grand Junction, Colorado, mill tailings pile.

2.0 CONCLUSIONS AND RECOMMENDATIONS

Models have been developed to simulate the consolidation and drainage of uranium mill tailings piles so that effective decisions can be made as to when to place covers that will reduce radon gas emissions from the piles. For these models to be useful, they must account for changes in both the saturated and partially saturated zones, and this requires extensive data on tailings consolidation characteristics.

An effort was made at PNL to measure the consolidation characteristics for three separate tailings materials: slimes, sand/slimes mix, and sand. Summarizing conclusions are listed below.

- Under saturated conditions, slimes consolidated the most (21%), followed by the sand/slimes mix (11%), and the sand (5%).
- Secondary consolidation was measurable and significant for the slimes.
- The hydraulic conductivity of the slimes and sand/slimes mix decreased nearly linearly as the void ratio was decreased during saturated consolidation. No major decrease occurred in the conductivity of the sands, probably because there was little consolidation.
- For up to a pore pressure of 55 kPa, partially saturated consolidation of slimes was minimal compared to consolidation under a load. This result contradicts previous work (Sherry 1982).
- Even at a pore pressure of 55 kPa, the slimes remained nearly saturated.

Based on the experimental results and on the experience gained in performing the experiments, we can think of several experimental improvements.

- The bubbling pressure of the porous plate used in the partially saturated consolidometer should be increased to at least 220 kPa to account for pore pressures to be expected in an actual tailings pile.
- The loading plate of the partially saturated consolidometer should be redesigned to be light enough so that the slimes material can bear its load. In that way, data could be gathered starting from saturation rather than at a pore pressure of 7 kPa, as was done.
- The sample preparation process should be standardized so that initial void ratios for a given material can be duplicated from experiment to experiment.

We recommend further research in two areas:

- An effort should be made to perform more partially saturated consolidation tests for slimes. The data generated for this report do not agree with data reported previously by Sherry (1982).
- Secondary consolidation was shown to be significant for slimes. Therefore, future research might endeavor to explore and quantify the degree of secondary consolidation in saturated as well as partially saturated tailings.

3.0 EXPERIMENTAL DEVICES AND PROCEDURES

Two separate types of consolidometers were used for the saturated and partially saturated consolidation tests. Because of the difference in both the equipment and methodology, the saturated and partially saturated tests are given separate discussions.

3.1 SATURATED CONSOLIDATION

Saturated consolidation tests have been conducted for several decades; thus, test equipment and procedures are well standardized and documented in nearly every soil mechanics text. The tests discussed here were conducted with a fixed-ring consolidometer (High Capacity Consolidation Apparatus, Double Unit),[a] as shown in Figure 1.

3.1.1 Device

The fixed-ring consolidometer consisted of a sample base and two rings, which held a cylindrical sample. The inner ring provided lateral confinement (zero radial strain) to the sample, and the outer ring formed a reservoir that allowed the sample to be submerged to maintain saturation. The base provided two outlets that were hydraulically connected to the sample base. One outlet was connected to a falling head permeameter for direct-sample permeability measurements, and a second was connected to an overflow reservoir. Two porous stones butted against the loaded faces of the sample, permitting free water drainage during consolidation. While the lower surface was fixed, the upper porous stone, backed by a rigid loading plate, moved downward under load to compress or consolidate the sample. Samples were 11.3 cm in diameter and up to 3.8 cm in height. Loads were applied to the sample using a system of weights and levers. This loading system provided a constant load pressure over a long period of time.

Changes in sample height were measured to determine the sample volume under applied loads. Two methods were employed. First, the sample height was measured indirectly by measuring the height of the upper loading plate surface above the inner ring. To account for tilting of the loading plate during the test, two measurements were made 180° apart on the edge of the plate and averaged to determine the true mean sample height. This direct measurement was added to the height of the upper ring to determine the sample height plus the combined thickness of the upper porous stone and loading plate. Subtracting the latter yielded the true sample height. Changes in sample height were also measured directly from a dial gauge mounted over the center of the upper loading plate and attached to the consolidometer base. While the dial gauge has a greater precision (2 μm or 0.002 mm) than the direct measurement (25 μm or 0.025 mm), both were employed as a check.

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[a] Product of SOIL TEST, Inc., Denver, CO 80239.

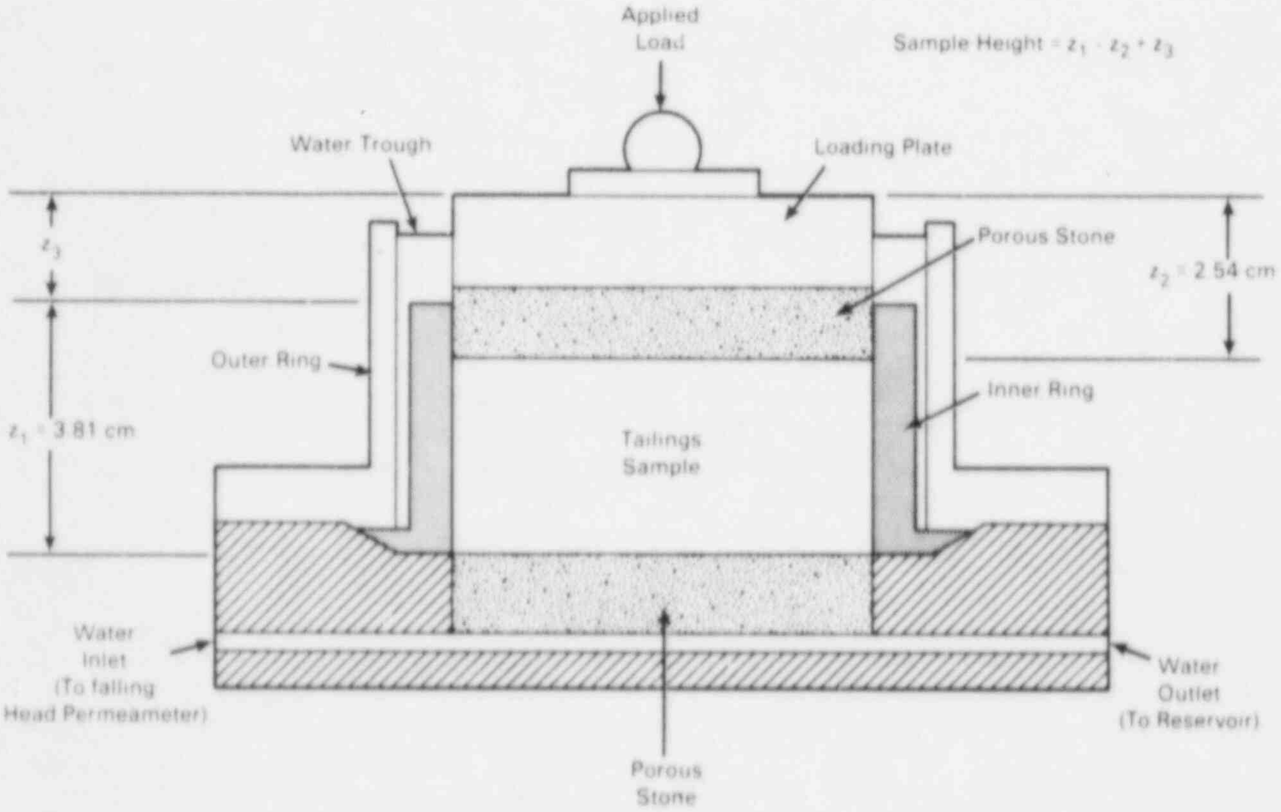

FIGURE 1. Fixed-Ring Consolidometer

3.1.2 Procedure

To simulate field conditions of tailings emplacement by sedimentation, the sample was emplaced in a loose initial state. For tailings slimes, this was achieved by creating a liquid slurry consisting of two parts tailings to three parts distilled water by weight. The mixture was dispersed in a high-speed blender and then poured into the inner ring of the consolidometer. The sample then stood for 24 h to allow for sedimentation. Because of their rapid rate of sedimentation, some of the tailings sand samples were emplaced in a different manner. The inner ring of the consolidometer was filled with water and the sands added slowly in a dry state until a suitable sample height was attained.

Following sample emplacement, the consolidometer was capped with the upper porous stone and loading plate and installed in the loading frame. An initial sample height was then measured and a load increment applied. Changes in the sample height, as read from the dial gauge, were recorded versus elapsed time with time between readings increasing with elapsed time. Because displacement initially varies approximately as the square root of time, readings were typically taken at 0.09, 0.25, 0.49, 1.0, 2.25, 4.0, 6.25, 9.0, 16.0, 25.0, 36.0 min, etc., following each load application. This process was continued until the rate of displacement decreased drastically. Tailings slimes were generally observed closely for about 2 h, while tailings sands required only about 30 min. A few additional readings were taken thereafter for a minimum period of about 24 h. Some tests were run for 48 to 72 h to better evaluate secondary consolidation effects; others were run for several days because of testing schedule interruptions. The test was then repeated by doubling the existing applied load pressure. The smallest applied load pressure was 10 kPa and the largest 1255 kPa. Sample permeability was measured at the end of a load increment test using the falling head permeameter.

After completing the last load-increment test, the sample was removed from the consolidometer, weighed, oven dried for 24 h, and reweighed. Ten-gram samples representing each tailings material were then used to determine particle density. These data were necessary to determine the void ratio and final saturation from the measured sample volume change data.

3.2 PARTIALLY SATURATED CONSOLIDATION

In contrast to saturated tests, partially saturated tests have been conducted by only a few experimenters. The majority of such tests have been conducted using a modified triaxial test apparatus. Triaxial tests have the advantage of permitting three-dimensional deformation, since the zero radial strain boundary is replaced by a constant radial stress boundary. For a slurried sample, however, a rigid radial boundary is necessary to support the sample because it lacks structure. A Rowe consolidometer (Rowe and Barden 1966) was modified to conduct the partially saturated tests discussed here. This device is similar in design but considerably larger than the device used previously by Sherry (1982) to measure partially saturated consolidation of uranium mill tailings.

3.2.1 Device

A diagram of the modified Rowe consolidometer used for these tests is shown in Figure 2. As with the fixed-ring consolidometer, a cylindrical sample was loaded axially with lateral confinement. Sample diameter was 25 cm and sample height from 3.5 to 4.3 cm. The principle of operation was the same as for the fixed-ring consolidometer with several differences. First, the vertical load was applied to the upper loading plate via a pressurized rubber diaphragm as opposed to weights and levers. As a consequence, the upper portion of the consolidometer was sealed off from the atmosphere. Second, to permit free drainage of pore water through the upper porous plate, a connecting tube was provided. This tube also provided a convenient means of measuring sample displacement and height in a similar manner to that previously described for the fixed-ring consolidometer.

Further modifications of the Rowe consolidometer were required to adapt the device to partially saturated consolidation measurements. Foremost was the connection of a pore air-pressure line. Positive pore air pressure was applied through the connecting tube mentioned previously. To facilitate drainage, a high air-entry porous plate (100 kPa bubbling pressure) was placed in the consolidometer base. A spiral groove connected to central and peripheral outlets was used to remove air bubbles that diffused through the porous plate.

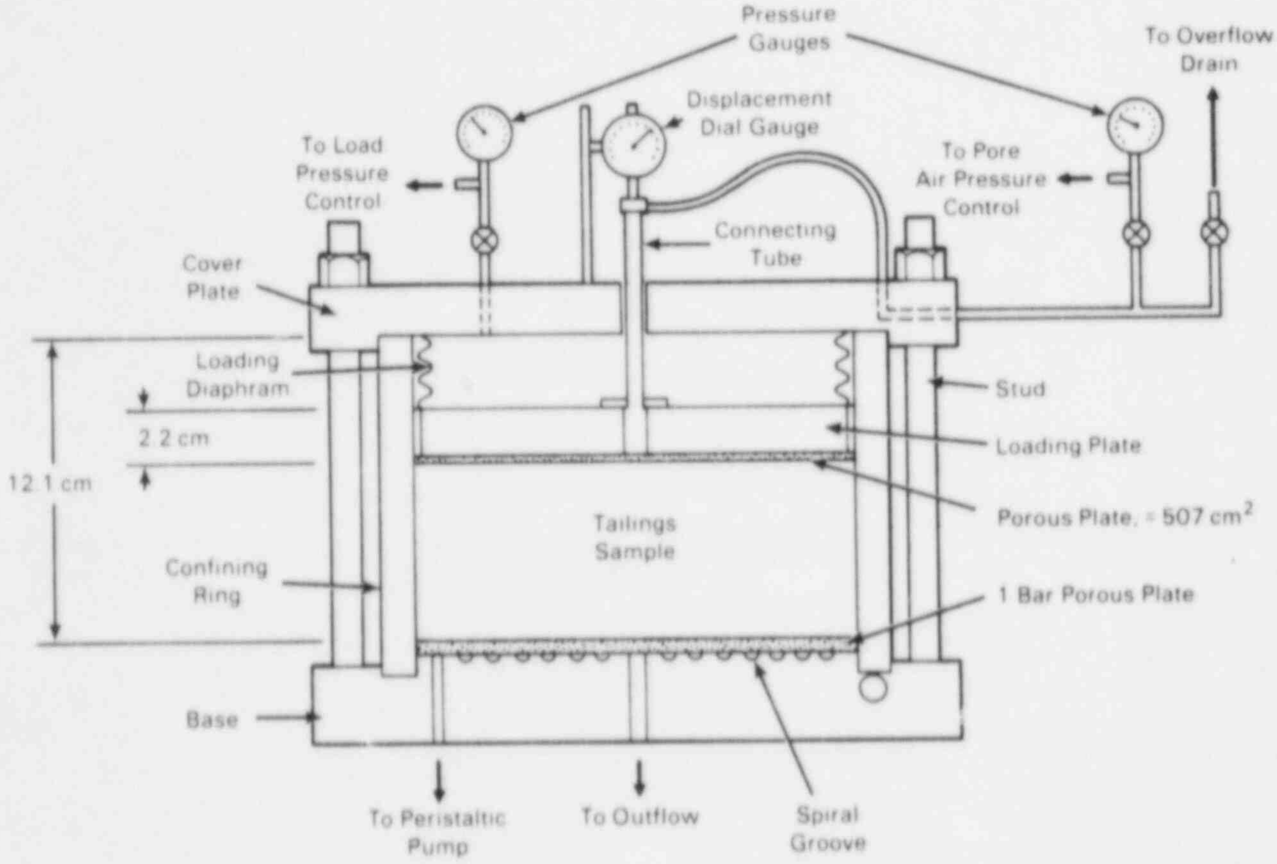

FIGURE 2. Modified Rowe Consolidometer

External connections to the Rowe consolidometer are shown schematically in Figure 3. A pressurized air supply was connected to a pressure regulating manifold, which controlled both the axial load and pore air pressures via regulators R1 and R2, respectively. When applying pore air pressure, one of the differential pressure regulators (D1 or D2) was employed. These regulators automatically increased the load pressure to compensate for the increasing pore air pressure and maintained a constant effective load pressure ($\sigma - u_a$), where σ is the total load and u_a is the air pressure.

A drainage loop connected to the Rowe consolidometer's grooved base was used to measure changes in sample water content and purge air from the loop. When a sample was draining, outflow was routed to the graduated cylinder for measurement. Periodically, the peristaltic pump was used to circulate water through the loop to remove entrapped air bubbles from the system. The bubbles were caught in the inverted pipette. Their volume was used to correct the recorded outflow reading.

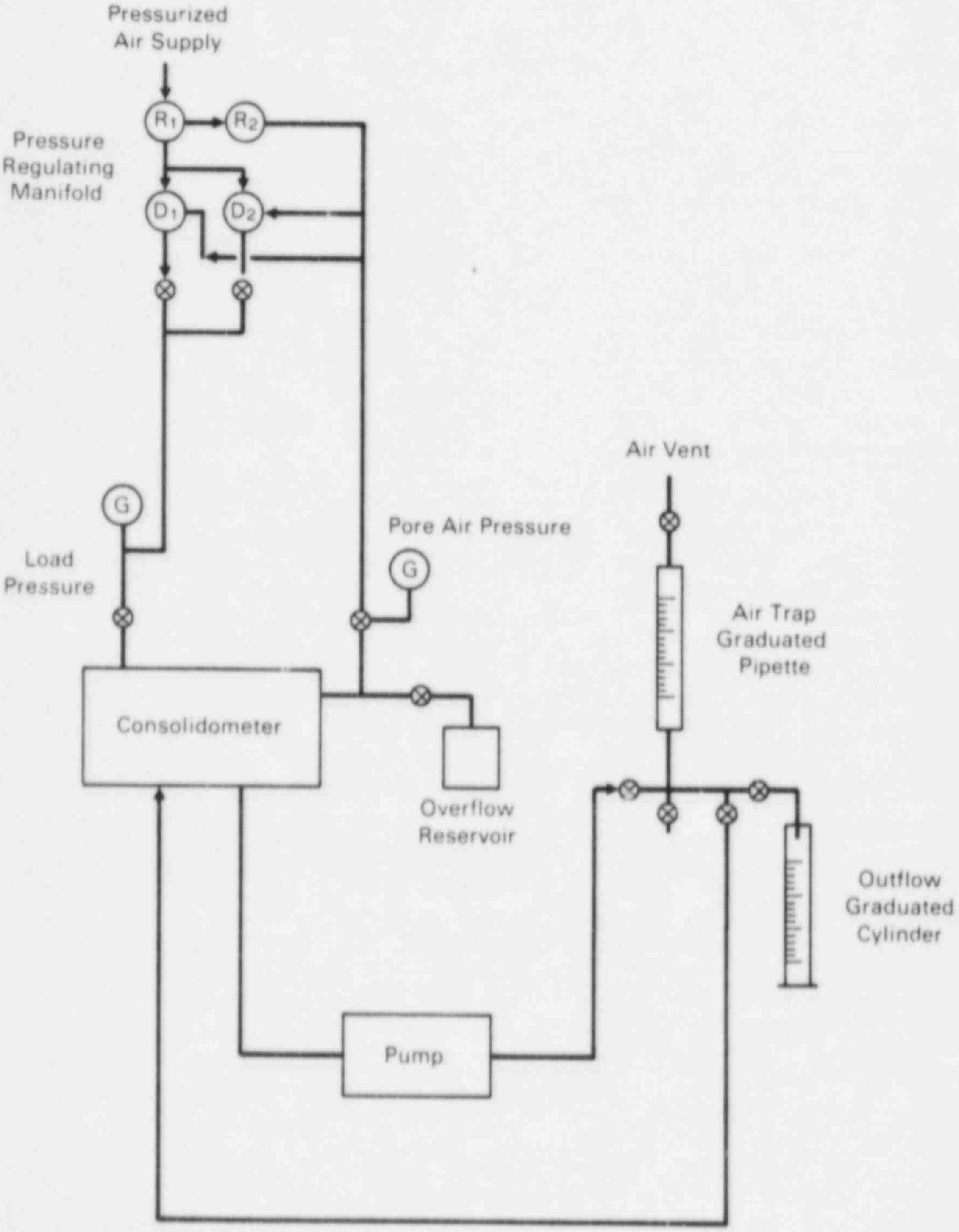

FIGURE 3. Schematic of External Components of the Modified Rowe Consolidometer

3.2.2 Procedure

Sample preparation for the Rowe consolidometer was identical to that described previously for the fixed-ring consolidometer, except that the water-slimes ratio was 5:2 instead of 3:2. After a slimes sample was slurried into the apparatus, it was allowed to drain to equilibrium with the outlet about 8 cm below the porous plate. The sample height was measured directly. The outlet was then lowered to 70 cm below the plate and the sample drained until it was in equilibrium (pore pressure = 7 kPa). The height was again measured. We were forced to start each experiment with a pore pressure of 7 kPa instead of zero because saturated slimes would not hold the platen (the upper loading plate) up; the platen would sink into the slimes. Once the pore pressure reached 7 kPa, the platen could be added. The loading diaphragm and cover plate were then added and bolted in place. One of the differential pressure regulators was set to the maximum desired effective load pressure (σ-u_a). Regulator R1 was subsequently used to control the load pressure, σ, under saturated conditions (u_a=0).

Once the system stabilized, the initial height of the connecting tube, as referenced to the cover plate surface, was measured and the dial gauge zeroed. A load increment was applied, and dial gauge readings were recorded in a similar fashion as described for the fixed-ring consolidometer. This process was repeated until the maximum effective load pressure was reached, at which point the differential regulator took over control of the load pressure.

Time was allowed for the sample to fully consolidate at the maximum load pressure before desaturating. The peristaltic pump was then used to purge air from the drainage loop. Initial readings were then recorded for the dial gauge, outflow graduated cylinder, and air-trap pipette. To accommodate water outflow and maintain a constant back pressure in the drainage loop, the outflow tube to the graduated cylinder was kept 10 cm below the porous plate level. Desaturation was begun by increasing the pore air pressure via regulator R2. The load pressure was automatically increased simultaneously, thus maintaining a constant effective load pressure. Changes in sample height and outflow were subsequently monitored. The outflow rate decreased with time until it stopped, then air started to enter the outflow tube. We tried to end each experiment just as the outflow rate reached zero. Upon reflection, we realized that the movement of air into the outflow tube may have signified sorption by the sample before a final equilibrium was reached. The solution would have been to connect the outflow to a fluid reservoir. This is true only if no air leaks or vapor losses were occurring from the system.

Following stabilization (when water ceased to flow out of the sample), air was purged from the system, all readings were recorded, the pore air pressure incremented, and the process repeated. Periodically, the outflow valve was closed and the pump turned on to purge the system of air. This usually lasted less than 5 min, then the pump was turned off and the outflow valve reopened. The volume of air that collected in the air trap was used to correct the outflow reading. For example, if 10 ml of water flowed out and 5 ml of air were collected, the corrected outflow amount was 10 minus 5, or 5 ml. Occasionally during an experiment, the air trap was completely filled with air and had to be reset. This was accomplished by closing all valves to the consolidometer and outflow and refilling the air trap with water. The outflow was then opened and the system allowed to equilibrate. Only then were the valves to the consolidometer opened. When equilibration at the maximum applied pore air pressure was completed, the sample was removed and a new sample loaded.

To map out the void ratio surface as a function of the state variables $(\sigma-u_a)$ and (u_a-u_w), where u_w is the pore water pressure, each sample was consolidated under near-saturated conditions to a different desired effective load pressure $(\sigma-u_a)$, and then desaturated. Values of the stress state variables (u_a-u_w) and $(\sigma-u_a)$ for which void ratio values were determined are shown in Figure 4.

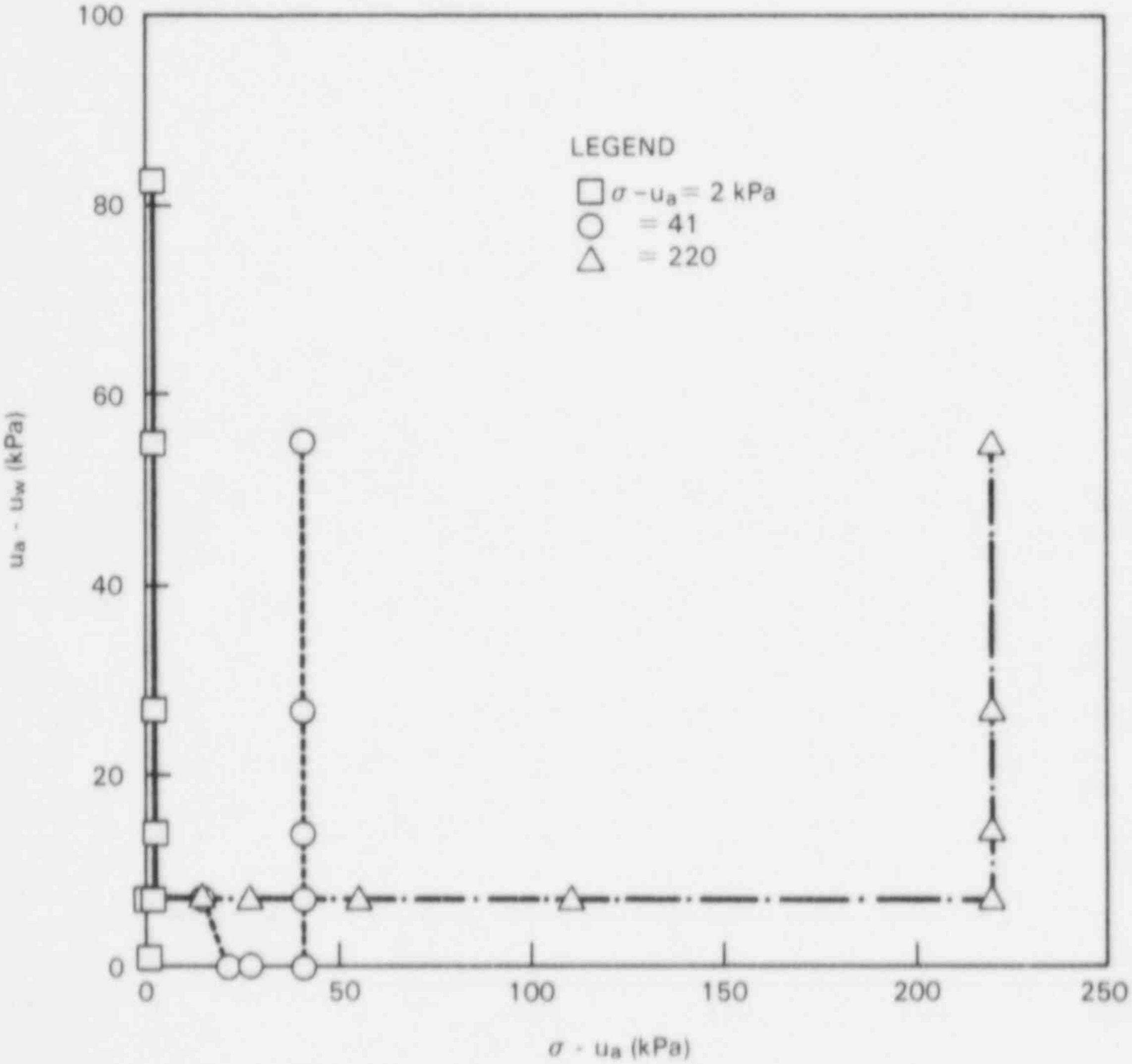

FIGURE 4. Stress Paths for Partially Saturated Consolidation Experiments

4.0 RESULTS

Representative samples of three tailings materials were taken from the uranium mill tailings pile in Grand Junction, Colorado for analysis. Particle-size distribution curves for the three materials, which we have called sand (SA), sand/slimes mix (SS), and slimes (SL), are shown in Figure 5. Table 1 shows the percentages of sand, silt, and clay. A total of 16 saturated consolidation tests were performed: 5 on sands (SA-3 to 7), 5 on the mix (SS-1 to 5), and 6 on the slimes (SL-1 to 4, 7, and 8). Three partially saturated consolidation tests were performed with the slimes material only (SL-9, 10, and 12). Only a portion of the data will be presented here. A complete summary of all data can be found in Appendix A.

4.1 SATURATED CONSOLIDATION

Test results for slimes sample number SL-3 are shown in Figure 6. Displacement is shown as a function of the square root of elapsed time for each load increment. The following observations are of note:

- The initial load increment resulted in the largest observed total displacement. This results from the lack of distinct soil structure while in the initial slurried state.
- All curves indicate an initial, large displacement upon loading, the magnitude of which increases with increasing pressure increments. This initial displacement probably results from the compressibility of small amounts of air trapped within the soil pores (Lowe et al. 1964). If so, the trapped air may be present as a result of sample preparation in a high-speed blender.
- Following the initial large displacement, the curves are approximately linear, with the linear portion increasing in length for larger applied pressures. This linear portion corresponds to theoretical predictions of primary consolidation (Taylor 1948; McNabb 1960); that is, the portion of the consolidation curve corresponding to dissipation of excess pore water pressure. At larger applied pressures, soil permeability was significantly reduced, lengthening the time period required for primary consolidation.
- The continued consolidation of the sample, even after periods exceeding one day, indicates that time-dependent strain (secondary consolidation) is a measurable component of total consolidation of slimes. Measured sample conductivities indicate that primary consolidation was completed after a few hours. The large magnitude of the observed secondary consolidation is likely a result of the loose structure of the tailings slimes. Similar behavior has been observed for highly sensitive clays (Lo 1961; Walker 1969) as well as a variety of other silts and clays (Mesri 1973) with high natural water contents. The depositional environment of these soils is often

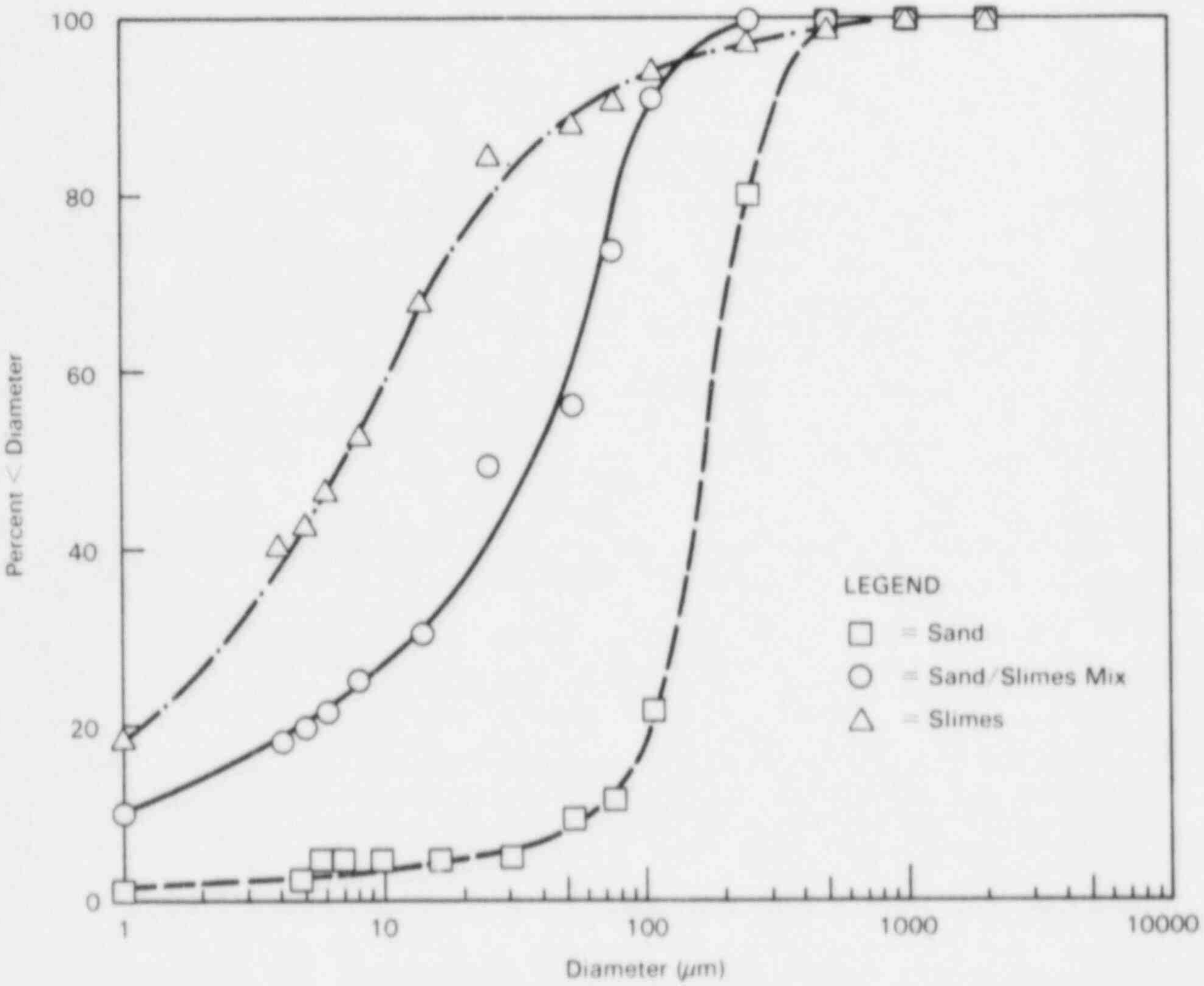

FIGURE 5. Particle-Size Distribution for Tailings Materials

TABLE 1. Particle Size Breakdown for Three Tailings Materials (sand, 2-0.5 mm; silt, 0.5-0.002 mm; clay <0.002 mm)

Material	Sand %	Silt %	Clay %
Slimes	36	43	21
Sand/Slimes Mix	55	33	12
Sand	85	6	9

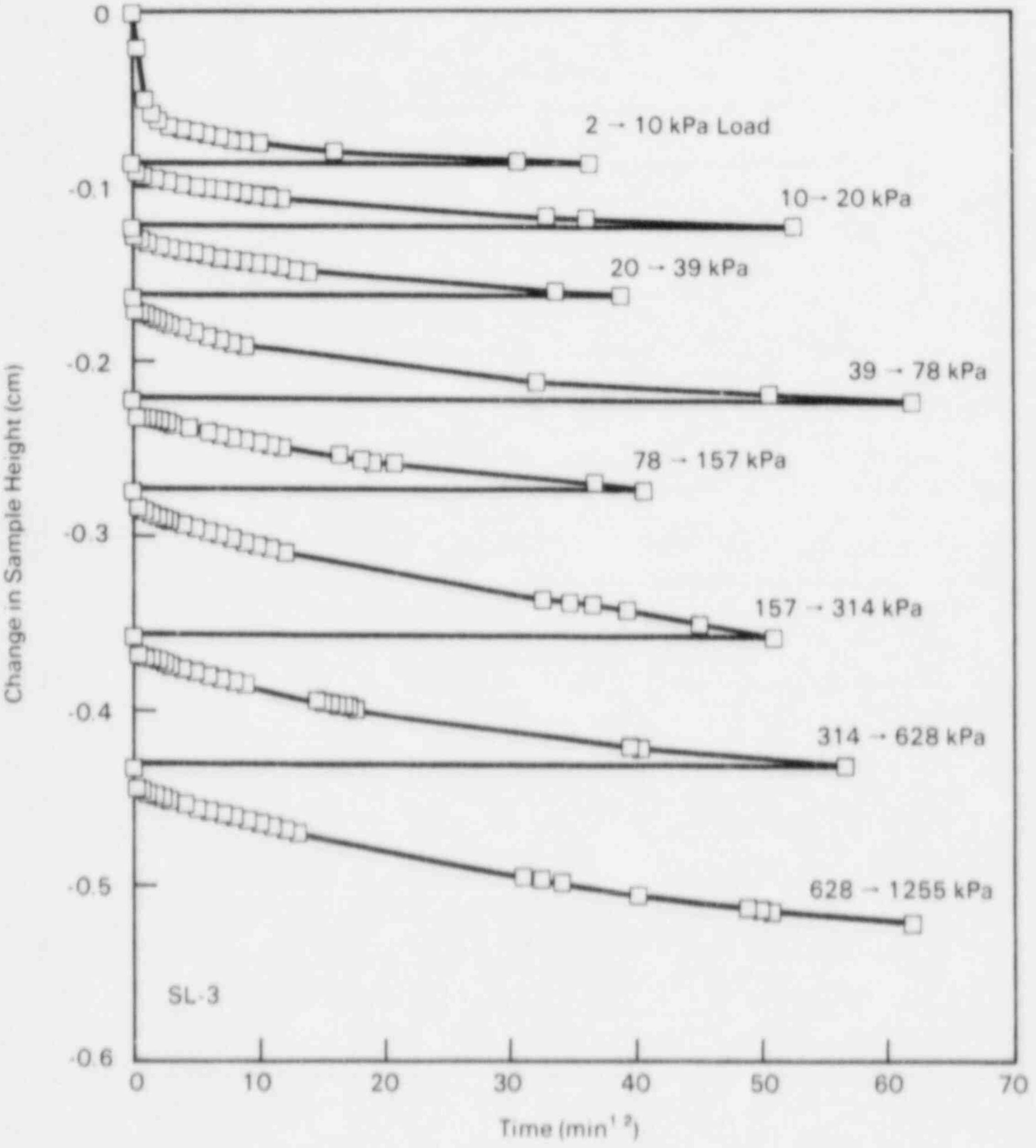

FIGURE 6. Change in Height of Slimes Sample SL-3 Versus Elapsed Time Following Each Loading Increment

quite similar to that of tailings. The degree of secondary consolidation increases with the size of the applied pressure increment.

Test results for sands sample number SA-3 are shown in Figure 7 in the same manner as for the slimes sample. The following observations are of note:

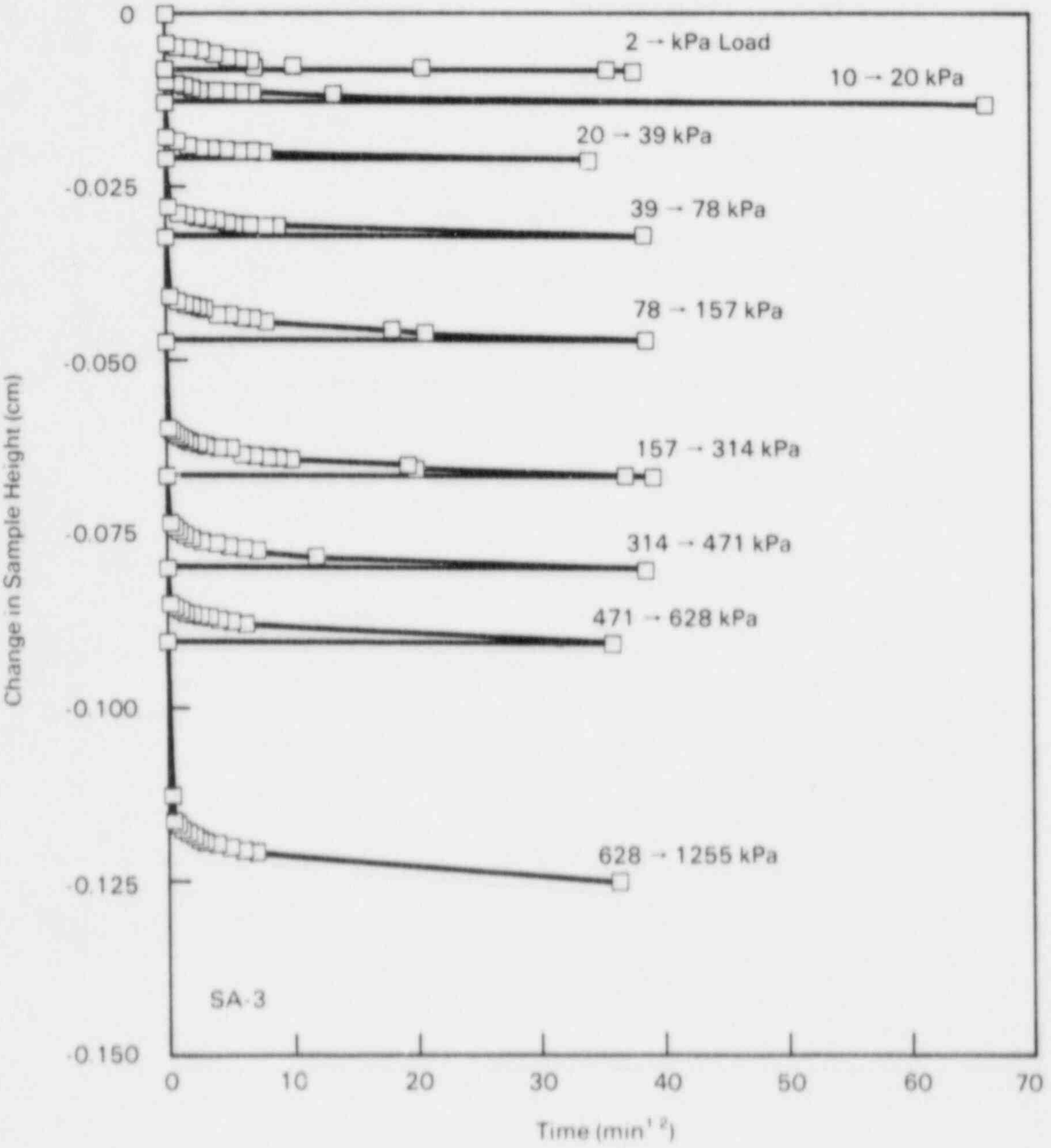

FIGURE 7. Change in Height of Sand Sample SA-3 Versus Elapsed Time Following Each Loading Increment

- The initial load increment did not create as large an initial displacement as it did with the slimes.

- Following the initial displacement, little further displacement occurred. The relatively high conductivity of the sands, combined with the small height of the sample, allowed primary consolidation to occur almost instantaneously.

- The total change in sample height was about one-fourth that of the slimes sample SL-3. Although some secondary consolidation occurred, its magnitude also was considerably less than that of the slimes.

Void ratios were computed for each sample following each loading increment. These results are presented in Figures 8 through 10 for the three tailings materials. Following standard convention, we have plotted void ratio versus the log of effective stress, which in this case was the total applied load at the end of each loading increment. Many soils are characterized by a linear relationship between void ratio and log effective stress, at least at effective stresses exceeding any preconsolidation stress. When such a linear relationship is observed, the slope of the line is called the compression index. While most standard settlement calculations assume a constant compression index, this was not the case for the tailings material tested here. Similar results were obtained by Nelson et al. (1983) for tests on uranium tailings from Shiprock, New Mexico.

Although there was reasonable agreement among the tailings slimes data of Figure 8, there was a small difference between samples 1 through 4 and 7 and 8. Samples 7 and 8 exhibited slightly lower initial void ratios and higher final void ratios. After running samples 1 through 4, the supply of tailings was nearly exhausted. New tailings material was obtained from Grand Junction, and we found that the new slimes material particle-size distribution was slightly different from the old. The old slimes material sand, silt, and clay percentages were 36, 43, and 21, respectively, whereas the new material percentages were 12, 68, and 20. Because samples 7 and 8 were run with the new material, this may have accounted for the differences from samples 1 through 4.

Less agreement was found among the sand/slimes mix data of Figure 9, even though the samples were taken from the same batch. The initial void ratios varied from 0.8 to 1.25, which may indicate an inconsistency in the preparation method. The decreases in void ratio were similar for all samples as the effective stress was increased, although samples with higher initial void ratios had greater decreases in void ratio than those with lower initial void ratios.

Good agreement was found among the sand samples, although samples 5 through 7 were prepared differently than samples 3 and 4. The sand was mixed with water before pouring it into the consolidometer for samples 3 and 4. Samples 5 through 7 were air dry when poured into the consolidometer, which was filled with water. We changed the preparation method because we suspected that the sands might quickly segregate in the consolidometer before the excess water drained, causing the sands to layer. If that were so, there did not appear to be much difference between the two sample preparation methods.

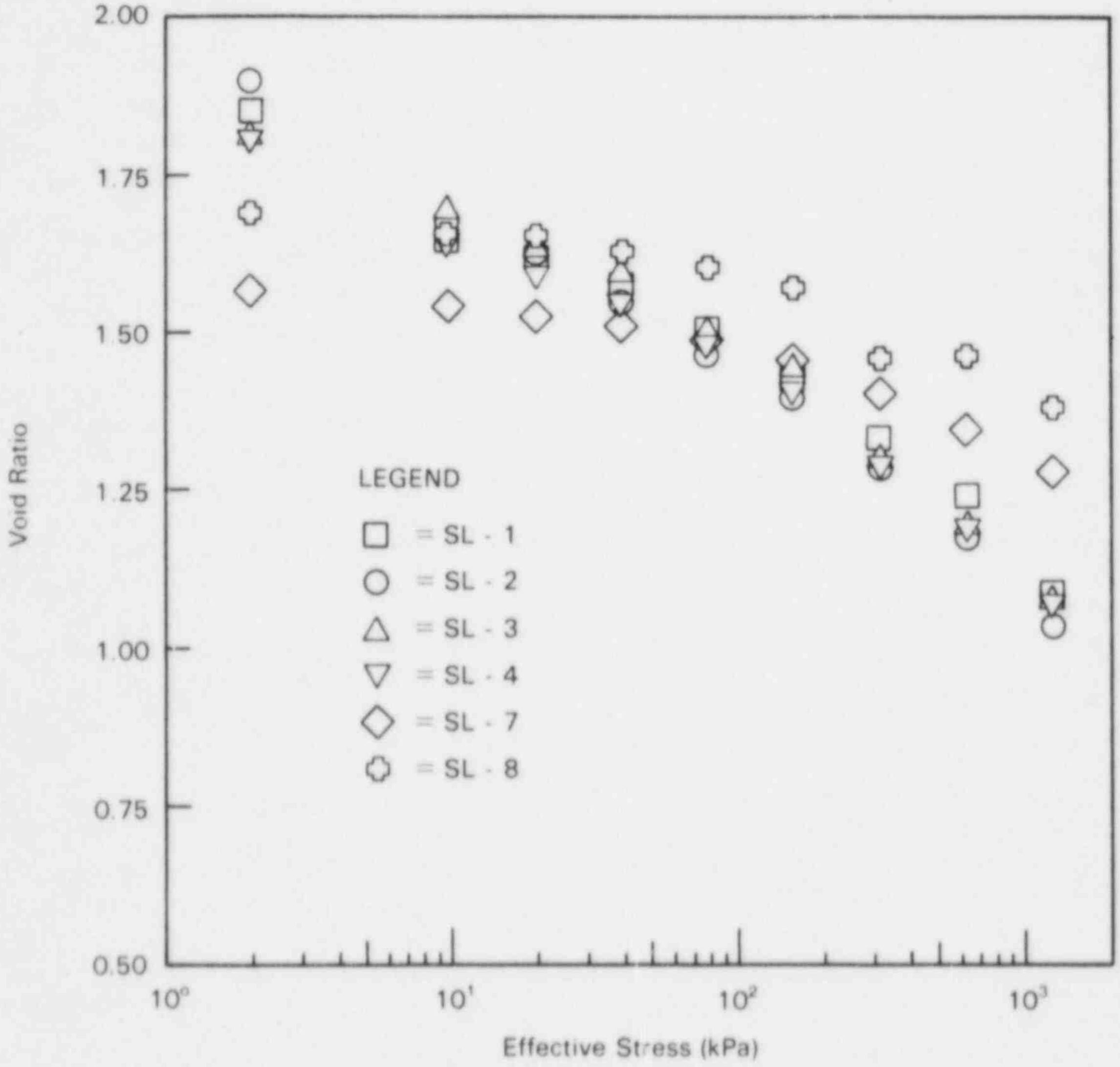

FIGURE 8. Slimes Void Ratio Versus Effective Stress

Of the three materials, the slimes consolidated most. The average percentage decrease in height of the slimes samples was 21%, it was 11% for the sand/slimes mix and only 5% for the sands.

Direct measurements of sample conductivities were conducted for all slimes and sand/slimes mix samples and for sand sample SA-7. The average conductivity of each material is plotted versus effective stress in Figure 11. In general, we found that

- The more silt and clay present in the sample, the lower the conductivity.

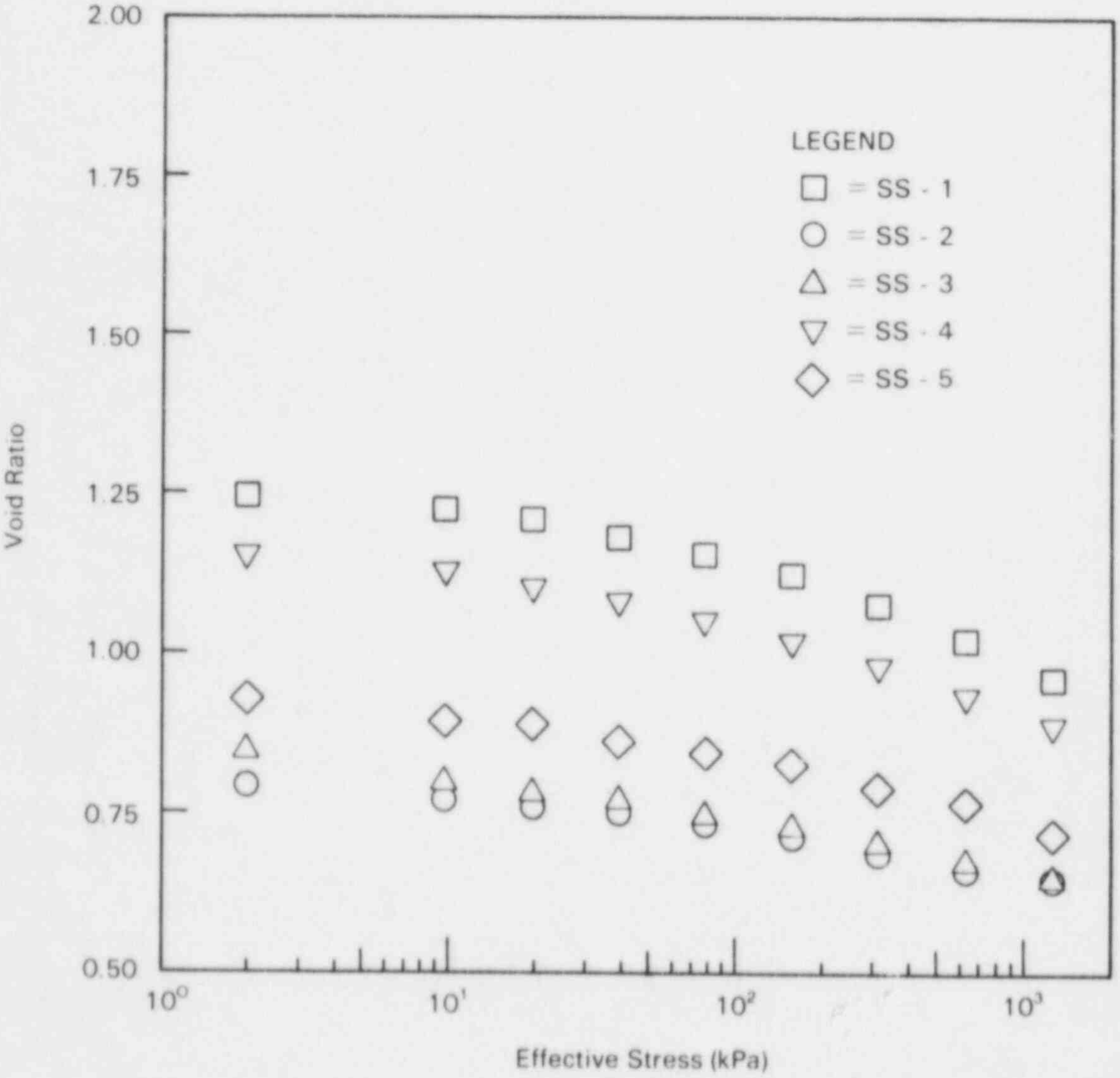

FIGURE 9. Sand/Slimes Mix Void Ratio Versus Effective Stress

- For the slimes and sand/slimes mix materials, the conductivity decreased as the void ratio decreased.
- The measured conductivity values varied considerably from sample to sample, most likely because of differences in sample packing.

4.2 PARTIALLY SATURATED CONSOLIDATION

Three separate partially saturated consolidation tests were conducted with the slimes material under stresses (σ-u_a) of 2, 41, and 220 kPa. The stress of 2 kPa (the weight of the platen and an aluminum spacer) was smaller than most stresses expected in a tailings pile and thus served as a lower boundary condition. The stress of 220 kPa is the stress that would be felt at

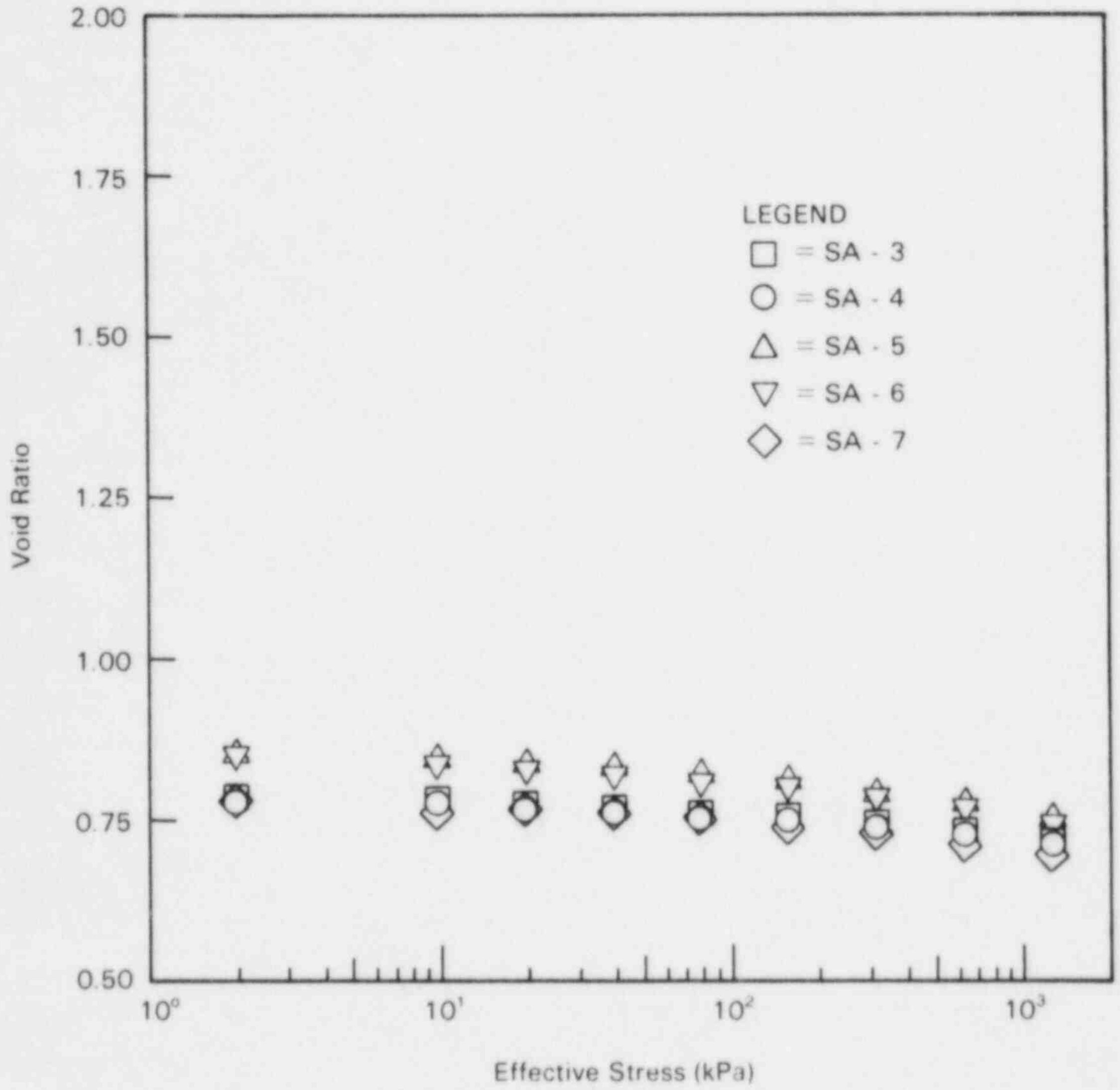

FIGURE 10. Sand Void Ratio Versus Effective Stress

the bottom of a 12.2-m tailings pile that had a cover stress of 60 kPa and was completely desaturated; it acted as an upper boundary condition. The stress of 41 kPa served to define, to some degree, the surface between the two boundaries.

The first observation to note about these experiments is the time required to complete them. On the average, it took 50 days from the time the sample was emplaced until the experiment with that sample was completed. There are two reasons: First, it takes a long time for any sample to reach equilibrium after being subjected to a step increase in load or pore pressure. As equilibrium is approached, the hydraulic gradient driving flow decreases, and outflow slows down. Therefore, the more steps in the experiment, the longer the total experiment time. Secondly, the conductivity of partially saturated material is

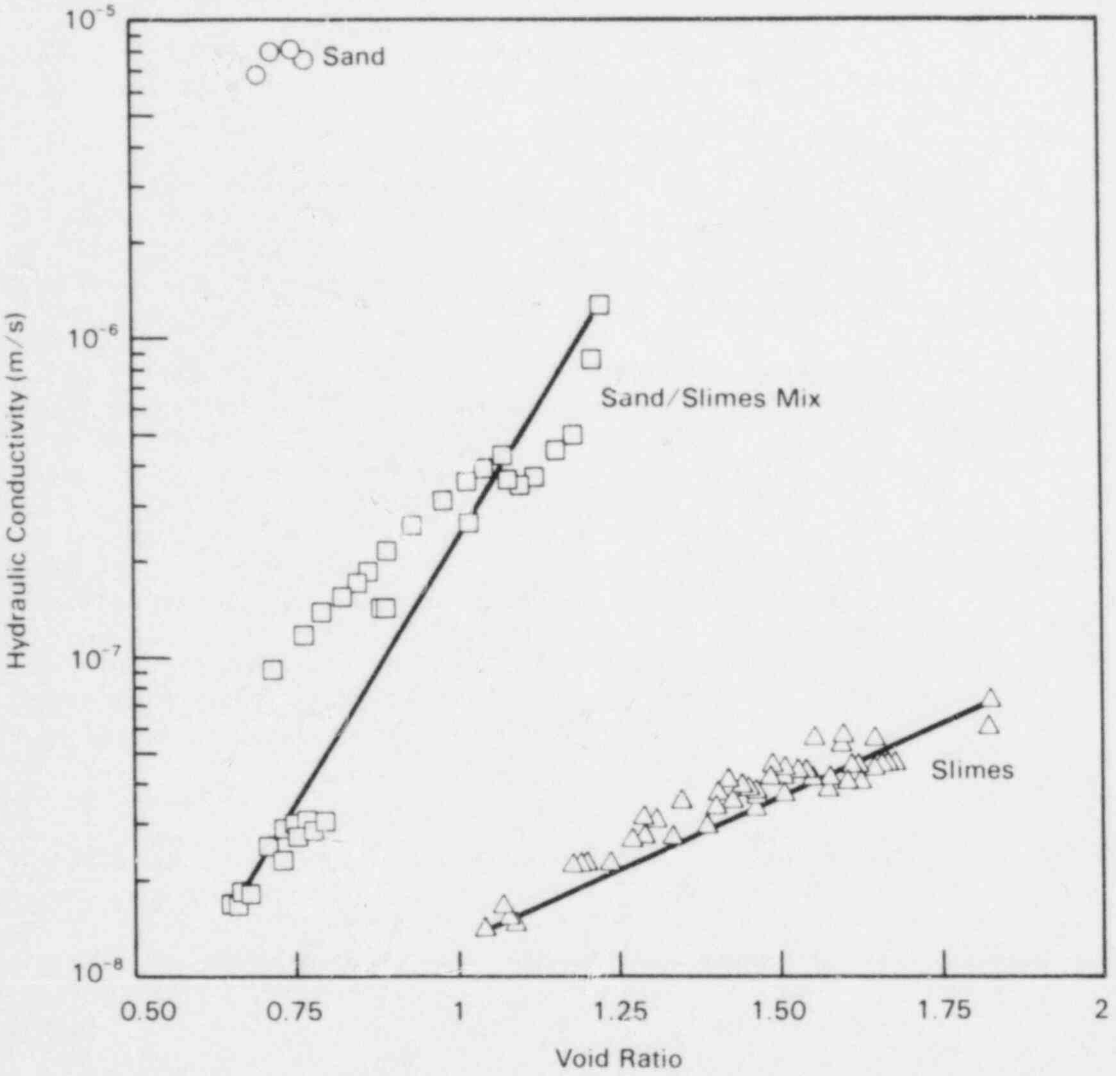

FIGURE 11. Hydraulic Conductivity Versus Void Ratio for All Materials

much lower than its saturated counterpart. Lower conductivity means reduced flux and longer times till equilibrium is attained.

The second observation is the state of the samples once the experiments were finished. Sample SL-9 had concentric cracks in the surface. The cracks were less than 1 mm in thickness and of unknown depth. The implication is that consolidation in this case was not one-dimensional. The experiment, however, measured only vertical consolidation and not total consolidation. This finding has ramifications for determining void ratio and degree of saturation values. By ignoring consolidation in other than the vertical dimension, calculated void ratios are overestimated and degree of saturation values underestimated. Samples SL-10 and SL-12 did not exhibit surface cracking. This might be explained by the fact that those samples were loaded quite heavily (41 and 220 kPa) prior to desaturation; whereas, sample SL-9 only experienced a load of 2 kPa.

The third qualitative observation is that all three samples were still quite wet at pore pressures of 55 kPa. In fact, samples SL-9 and SL-12 and the upper half of sample SL-10 were so wet that, with a little vibration from our hand, they became somewhat liquified and flowed. The observation that the slimes were very wet was borne out by the saturation data, where saturation values were in the 95 to 99% range for samples SL-9 and SL-12.

We noted that the lower half of sample SL-10 was sandier than the top half and that it did not flow when vibrated. Sample SL-10 also had a lower degree of saturation (80%) at a pore pressure of 55 kPa than the other samples. In going from a pore pressure of 27 to 55 kPa, we saw a large amount of outflow. So much outflow occurred that it exceeded the capacity of the outflow graduated cylinder. At first, we thought there was a leak in the system, but a subsequent investigation found no apparent leaks. After the experiment had ended, however, we found that the sample was layered such that the upper half was slime-like and the lower half sandy. This could have resulted from the sample preparation method, where we allowed the slurried material to settle. We reasoned that in changing the pore pressure from 27 to 55 kPa, we exceeded the air-entry value of the upper finer layer and saw the rapid drainage of the lower sandy layer. We cannot prove this, but we did perform some experiments to illustrate the problem.

In the first experiment, we poured a water:slime slurry (5:2 ratio) into filter funnels, allowed the slurry to drain to a pore pressure of 1 kPa, dried the sample, then sampled the upper and lower halves for particle-size analysis. The average sand, silt, and clay percentages for three repetitions were 0, 63, and 37 for the upper halves and 18, 65, and 17 for the lower halves. This experiment confirmed that particle-size segregation could occur during sample emplacement.

Samples SL-9 and SL-12 did not exhibit particle-size layering; this was probably because these samples were reslurried in the Rowe consolidometer after the platen started to sink (before we decided to take the sample to a pore pressure of 7 kPa in advance of placing the platen). The platen was removed, water added, and the sample reslurried. We performed a second set of experiments to duplicate this. Again, we poured a water:slime slurry (5:2 ratio) into filter funnels and allowed the mixture to drain to a pore pressure of 1 kPa. At that point, water was added to the sample, but the water:slime ratio was 3:2 instead of 5:2. The samples were remixed, drained, dried, and sampled as before. The average sand, silt, and clay percentages were 6, 75, and 19 for the upper half and 6, 74, and 20 for the lower half. Essentially no particle-size differentiation occurred between the upper and lower halves of the samples, which would indicate that samples SL-9 and SL-12 were homogenous. Although it is likely that sample SL-10 was layered, we still performed the consolidation calculations and included them in this report.

Results of the change in height of sample SL-9 versus time are shown in Figure 12 ($\sigma - u_a$ was 2 kPa). Of the four pore pressure step increases,

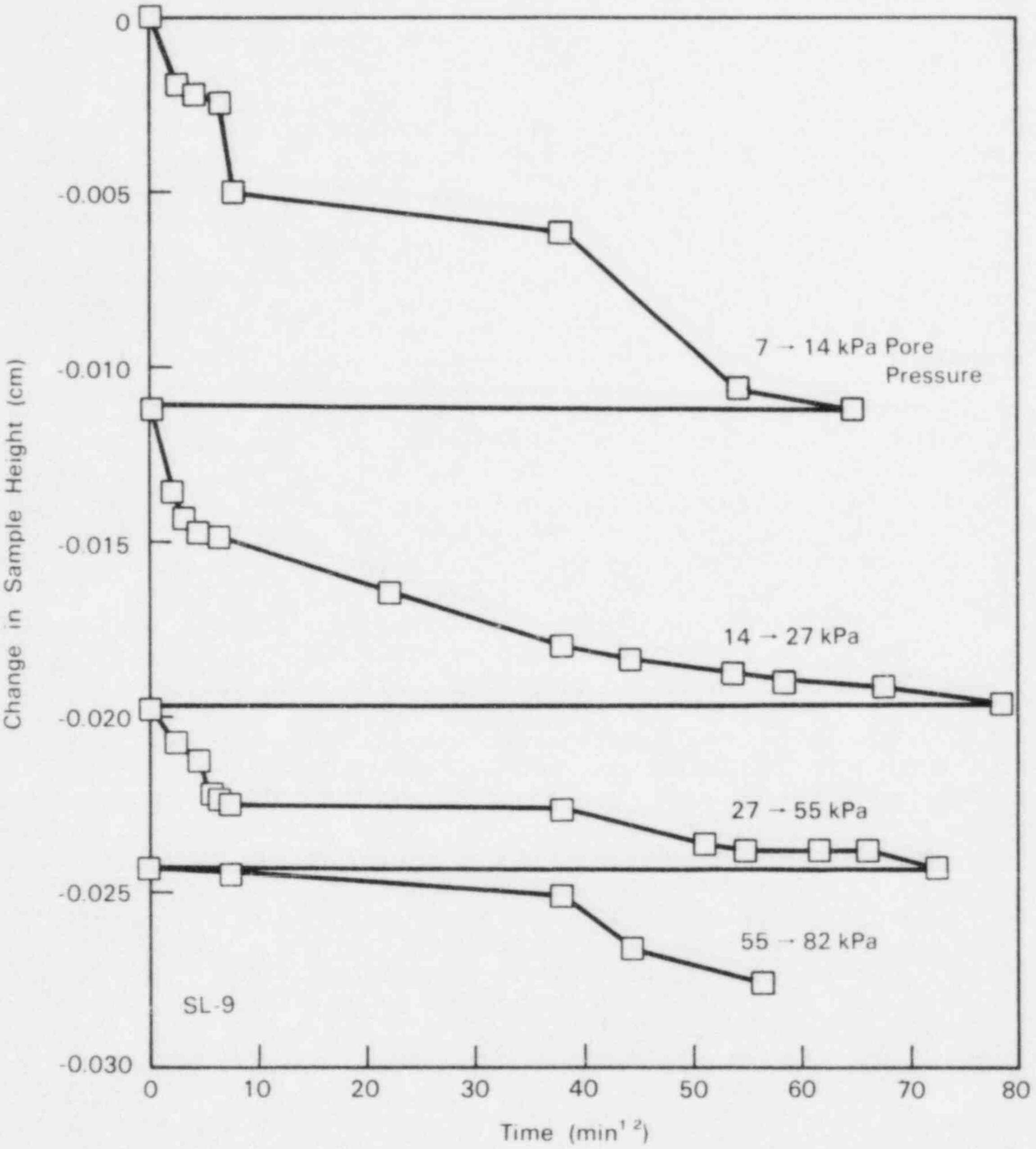

FIGURE 12. Change in Height of Slimes Sample SL-9 Versus Elapsed Time Following Each Pore Pressure Increment

the largest consolidation occurred following a pore pressure increase from 7 to 14 kPa. Total consolidation caused by desaturation over the pore pressure range of 7 to 82 kPa appears to have been considerably less than that caused by sample loading under saturated conditions; e.g., the total change in sample height for sample SL-9 was 0.028 cm. Looking back at Figure 6 and sample SL-6, note that every load increase resulted in a greater change in sample height than the total change by desaturation from 7 to 82 kPa.

Figure 13 contains plots of void ratio versus pore pressure for the three stress levels examined for slimes. Note the large drop in void ratio as the samples were taken from a pore pressure of 1 to 7 kPa before any load was placed on the samples. The load was applied only after the pore pressure was 7 kPa because the samples could not sustain the load when saturated. We do not know if the large changes in void ratio between pore pressures of 1 and 7 kPa would have occurred if the sample had been preloaded before the pore pressure was increased. For increases in pore pressure above 7 kPa, little change occurred in void ratio, no matter which stress level was used.

Following the consolidation caused by the load addition at 7 kPa pore pressure, the void ratio decreased monotonically as the sample was desaturated (see Figure 13). In contrast, Sherry (1982) reported that the void ratio for slimes increased then decreased as the sample was desaturated. Sherry, however, followed different stress paths than we did, and we believe his results reflected the hysteresis inherent in the paths chosen. As the sample was desaturated, we saw about 10% of the change Sherry reported in the void ratio. For instance, from our data the calculated slope (C_a) of the void ratio versus pore pressure curve for a stress of 2 kPa is 0.02. We calculated a slope of 0.32 from Sherry's data for a stress of 7 kPa. Several possible explanations exist. First, we used material from Grand Junction, Colorado, as opposed to Shiprock, New Mexico. Second, we used different equipment and procedures. Third, we followed stress paths chosen to avoid hysteresis, and Sherry did not.

The degree of saturation data is sparse (Table A.2, Appendix A). Comparisons between stress levels should be limited, because the initial void ratios were so varied (1.7, 1.9, and 2.1). In addition, sample SL-10 experienced significant drainage, which we attributed to sample layering. The degree of saturation of sample SL-10 at a 55 kPa pore pressure was 80.3%; and the corresponding values for samples SL-9 and SL-12 were 96.9 and 99.5%, respectively. The latter two values bear out the visual observations that the samples were quite wet, even at pore pressures of 55 kPa. Sherry (1982) reported saturation values of 82 to 98% under similar conditions. These values are slightly drier than the values we have reported, but they are still very wet. Differences can also be attributed to material characteristics because Sherry used different slimes material than were used in our tests. Sherry extended some of his experiments to a 220 kPa pore pressure, for which his lowest recorded saturation value was 70% for a stress of 7 kPa.

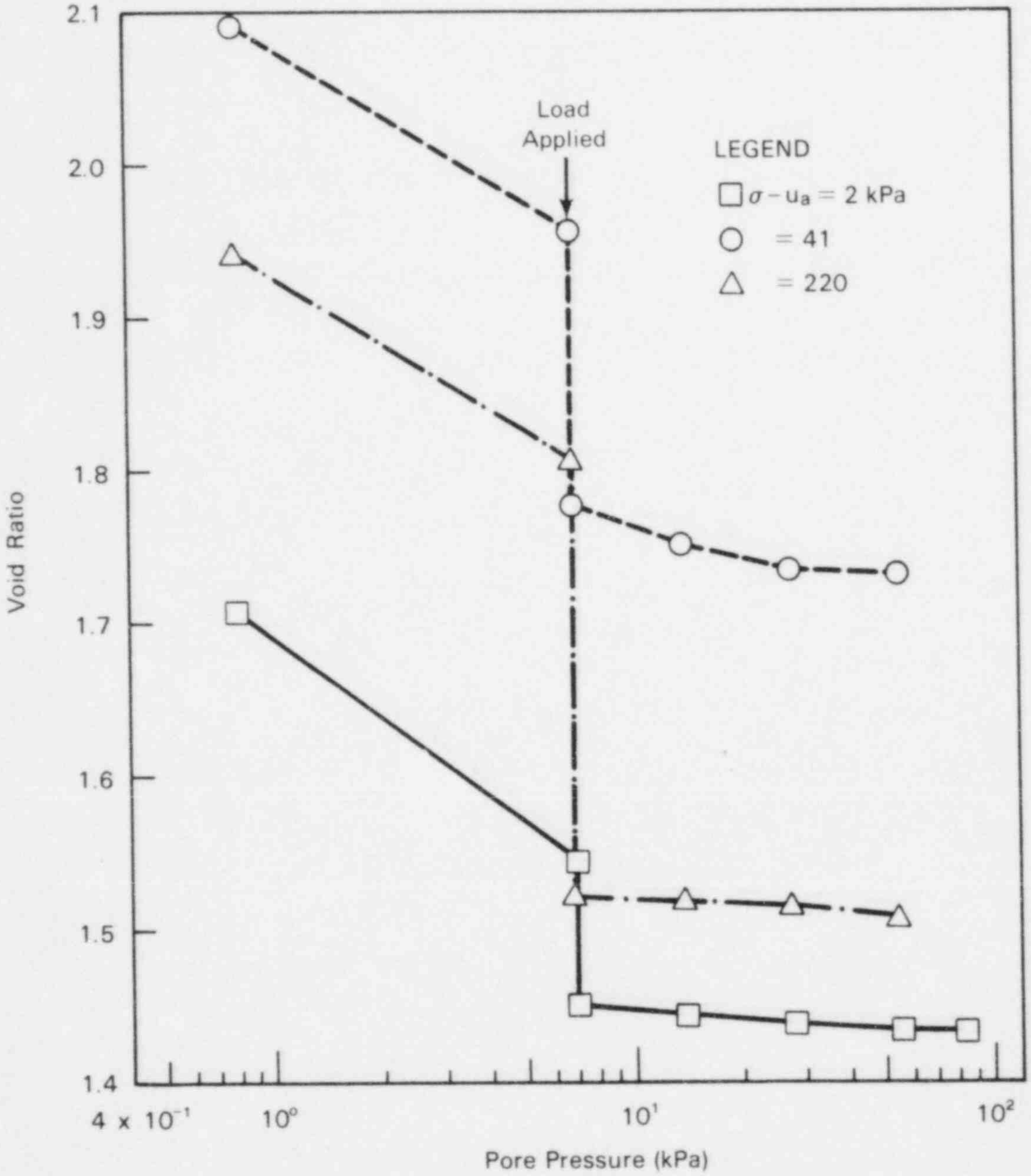

FIGURE 13. Slimes Void Ratio Versus Pore Pressure at Different Stress Levels

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APPENDIX A

EXPERIMENTAL DATA

TABLE A.1. Results of Saturated Consolidation Tests

Sample Number	Applied Stress (kPa)	Sample Height (cm)	Void Ratio	Hydraulic Conductivity (m/s x 10^7)
SA-3	2	3.396	0.785	--
	10	3.387	0.784	
	20	3.383	0.778	
	39	3.375	0.773	
	78	3.364	0.765	
	157	3.349	0.760	
	314	3.329	0.749	
	471	3.316	0.742	
	628	3.305	0.736	
	1255	3.271	0.720	
SA-4	2	3.294	0.777	--
	10	3.289	0.774	
	20	3.282	0.770	
	39	3.273	0.766	
	78	3.257	0.755	
	157	3.243	0.751	
	314	3.220	0.740	
	471	3.204	0.732	
	628	3.191	0.729	
	1255	3.156	0.715	
SA-5	2	2.860	0.855	--
	10	2.848	0.848	
	20	2.839	0.843	
	39	2.829	0.837	
	78	2.812	0.825	
	157	2.797	0.817	
	314	2.775	0.800	
	628	2.747	0.784	
	1255	2.706	0.756	
SA-6	2	2.835	0.854	--
	10	2.820	0.842	
	20	2.809	0.834	
	39	2.797	0.824	
	78	2.779	0.814	
	157	2.762	0.807	
	314	2.737	0.789	
	628	2.705	0.769	
	1255	2.663	0.741	

TABLE A.1. (Contd)

Sample Number	Applied Stress (kPa)	Sample Height (cm)	Void Ratio	Hydraulic Conductivity (m/s x 10^7)
SA-7	10	3.061	0.772	--
	20	3.054	0.769	75.3
	39	3.042	0.768	75.3
	78	3.029	0.754	80.7
	157	3.011	0.750	80.5
	314	2.988	0.738	--
	628	2.959	0.719	79.1
	1255	2.920	0.699	67.3
SS-1	1	1.334	1.253	--
	2	1.328	1.243	--
	10	1.317	1.225	12.50
	20	1.307	1.209	8.54
	39	1.292	1.182	4.78
	78	1.276	1.156	4.40
	157	1.255	1.121	--
	314	1.230	1.078	3.59
	628	1.196	1.021	2.65
	1255	1.160	0.960	--
SS-2	1	3.320	0.805	--
	2	3.300	0.794	--
	10	3.261	0.773	--
	20	3.249	0.767	0.305
	39	3.223	0.753	0.300
	78	3.190	0.735	0.285
	157	3.152	0.714	0.256
	314	3.109	0.691	--
	628	3.066	0.667	0.183
	1255	3.030	0.648	0.167
SS-3	1	3.485	0.857	--
	2	3.477	0.853	--
	10	3.386	0.804	--
	20	3.355	0.788	0.299
	39	3.333	0.775	0.289
	78	3.289	0.752	0.275
	157	3.254	0.733	0.230
	314	3.198	0.704	--
	628	3.155	0.681	0.182
	1255	3.112	0.658	0.163

TABLE A.1. (Contd)

Sample Number	Applied Stress (kPa)	Sample Height (cm)	Void Ratio	Hydraulic Conductivity (m/s x 10^7)
SS-4	2	2.705	1.147	--
	10	2.672	1.121	3.71
	20	2.654	1.099	3.50
	39	2.626	1.075	3.84
	78	2.591	1.046	3.85
	157	2.549	1.016	3.52
	314	2.505	0.978	3.09
	628	2.439	0.931	2.51
	1255	2.429	0.889	2.11
SS-5	2	2.515	0.922	--
	10	2.482	0.889	1.43
	20	2.466	0.882	1.43
	39	2.443	0.862	1.59
	78	2.415	0.847	1.69
	157	2.380	0.823	1.53
	314	2.342	0.792	1.36
	628	2.286	0.765	1.16
	1255	2.229	0.715	0.905
SL-1	2	1.969	1.849	--
	10	1.831	1.651	0.460
	20	1.809	1.618	0.458
	39	1.781	1.577	0.420
	78	1.732	1.507	0.376
	157	1.676	1.426	0.347
	314	1.613	1.335	0.274
	628	1.547	1.239	0.227
	1255	1.443	1.088	0.146
SL-2	2	1.849	1.900	--
	10	1.707	1.677	0.460
	20	1.666	1.614	0.458
	39	1.626	1.550	0.420
	78	1.572	1.466	0.376
	157	1.532	1.402	0.347
	314	1.458	1.287	0.274
	628	1.392	1.183	0.221
	1255	1.301	1.040	0.140

TABLE A.1. (Contd)

Sample Number	Applied Stress (kPa)	Sample Height (cm)	Void Ratio	Hydraulic Conductivity (m/s x 10^7)
SL-3	1	1.930	1.868	--
	2	1.897	1.819	0.607
	10	1.816	1.698	
	20	1.783	1.649	0.560
	39	1.748	1.596	0.549
	78	1.689	1.509	0.457
	157	1.646	1.445	0.401
	314	1.552	1.306	0.307
	628	1.481	1.200	0.229
	1255	1.400	1.079	0.159
SL-4	1	1.826	1.842	--
	2	1.814	1.822	0.726
	10	1.704	1.652	--
	20	1.669	1.597	0.571
	39	1.641	1.553	0.542
	78	1.600	1.490	0.465
	157	1.555	1.419	0.409
	314	1.471	1.289	0.312
	628	1.410	1.194	0.226
	1255	1.331	1.071	0.168
SL-7	2	2.868	1.566	--
	10	2.840	1.541	0.449
	20	2.827	1.530	0.447
	39	2.804	1.509	0.429
	78	2.776	1.484	0.419
	157	2.743	1.455	0.389
	314	2.690	1.407	0.371
	628	2.624	1.348	0.352
	1255	2.540	1.273	0.267
SL-8	2	2.934	1.686	--
	10	2.906	1.661	0.463
	20	2.891	1.647	0.452
	39	2.868	1.626	0.413
	78	2.842	1.602	0.409
	157	2.809	1.572	0.389
	314	2.756	1.523	0.355
	628	2.687	1.461	0.328
	1255	2.609	1.388	0.301

TABLE A.2. Results of Partially Saturated Consolidation Tests

Sample Number	$u_a - u_w$ (kPa)	$\sigma - u_a$ (kPa)	Sample Height (cm)	Void Ratio	Degree of Saturation (%)
SL-9	1	0	4.321	1.695	100.0
	7	0	4.059	1.531	--
	7	2	3.955	1.466	--
	7	2	3.917	1.443	99.5
	14	2	3.907	1.437	99.4
	27	2	3.896	1.429	98.9
	55	2	3.891	1.427	96.9
	82	2	3.884	1.422	95.9
SL-10	1	0	3.604	2.091	100.0
	7	0	3.437	1.948	--
	7	14	3.327	1.855	--
	1	21	3.312	1.841	--
	1	27	3.284	1.817	--
	1	41	3.274	1.809	--
	7	41	3.236	1.777	--
	14	41	3.208	1.751	--
	27	41	3.188	1.734	--
	55	41	3.183	1.731	80.3
SL-12	1	0	3.528	1.942	100.0
	7	0	3.366	1.806	--
	7	2	3.335	1.781	--
	7	14	3.259	1.717	--
	7	27	3.203	1.571	--
	7	55	3.152	1.628	--
	7	110	3.076	1.566	--
	7	220	3.035	1.531	--
	7	220	3.023	1.520	--
	14	220	3.020	1.518	--
	27	220	3.015	1.515	--
	55	220	3.007	1.508	99.5

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12. SUPPLEMENTARY NOTES

13. ABSTRACT (200 words or less)

Experiments were conducted on uranium mill tailings from the tailings pile in Grand Junction, Colorado, to determine their consolidation characteristics. Three materials (sand, sand/slimes mix, slimes) were loaded under saturated conditions to determine their saturated consolidation behavior. During a separate experiment, samples of the slimes material were kept under a constant load while the pore pressure was increased to determine the partially saturated consolidation behavior.

Results of the saturated tests compared well with published data. Sand consolidated the least, while slimes consolidated the most. As each material consolidated, the measured hydraulic conductivity decreased in a linear fashion with respect to the void ratio.

Partially saturated experiments with the slimes indicated that there was little consolidation as the pore pressure was increased progressively above 7 kPa. The small amount of consolidation that did occur was only a fraction of the amount of saturated consolidation. Preliminary measurements between pore pressures of 0 and 7 kPa indicated that measurable consolidation could occur in this range of pore pressure, but only if there was no load.

14. DOCUMENT ANALYSIS – a. KEYWORDS/DESCRIPTORS
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