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ABSTRACT: Lateral and vertical variabilities in the bulk and mechanical properties of silicic volcanic tuff at the potential nuclear waste repository site in Yucca Mountain, NV have been evaluated. Laboratory measurements have been performed on tuff specimens recovered from boreholes located to support the design of the Exploratory Studies Facility / North Ramp (ESF/NR). The data include dry and saturated bulk densities, average grain density, porosity, compressional and shear wave velocities, elastic moduli, and compressional and tensional fracture strengths. Data from eight boreholes aligned in a northwest-southeast direction have been collected under the required quality assurance program. Three boreholes (UE25 NRG-5, USW NRG-6 and USW NRG-7/7A) have penetrated the potential repository horizon. The information collected provides for an accurate appraisal of the variability of rock properties in the vicinity of the boreholes. As expected, there is substantial variability in the bulk and mechanical properties of the tuff with depth (lithology). This is due to variations in gross characteristics of the tuffs (e.g., cooling units, mode of deposition, etc.), as well as smaller scale features (welding, porosity, and internal structures) that have developed as a result of depositional and post-depositional mechanisms.

An evaluation of the lateral variability in bulk and mechanical properties is somewhat limited, at this time, due to a lack of borehole control to the north and south (parallel to the depositional flow direction). Initial observations indicate that there is minimal lateral variability within lithologic units. There are observable differences however, that can be related to variability in specific properties (e.g., porosity, and internal structures).

1 INTRODUCTION

An integral part of the licensing procedure for the potential nuclear waste repository at Yucca Mountain, Nevada, involves characterization of the *in-situ* rheology for design and construction of the facility and placement of the high level radioactive waste canisters. The data used to model the thermal and mechanical behavior of the repository include dry and saturated bulk densities, average grain density, porosity, compressional and shear wave velocities, elastic moduli, and compressional and tensional fracture strengths. These measurements have been performed on cores recovered from boreholes along the northwest-southeast trending line of the proposed Exploratory Studies Facility / North Ramp (ESF/NR) at Yucca Mountain. The boreholes drilled to support ESF/NR design penetrate the Paintbrush tuff, which has been subdivided into thermal/mechanical (T/M) units (Ortiz, et al., 1985) in order to group

horizons of similar thermal and mechanical properties for the purpose of modeling.

Substantial variability in all properties of volcanic tuff result from differences in the mode of deposition (ash flow vs ash fall), the cooling history, the composition, and the distance from the source vent. Mechanical and bulk properties, measured for specimens recovered from ESF/NR design support boreholes, clearly express this characteristic. Variability from unit-to-unit (vertical) is particularly evident, and is directly associated with changes in lithology (due to mode of deposition, cooling, and composition).

Additional boreholes are currently being drilled that will penetrate the potential repository horizon south of the existing boreholes. These data will be available within several months. At that time a more detailed analysis of the lateral variability in rock properties throughout the mountain and the potential repository horizon will be possible. The data analyzed for the results collected on the three

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deep wells presently available suggest that the lateral variability in the tuff may be small over relatively short separation distances, and that the changes in rock properties with depth are strongly correlated with lithology (welding and porosity).

2 LABORATORY MEASUREMENTS

Intact (unfractured) cores of tuff recovered from boreholes located along the proposed path of the ESF/NR were prepared and tested in the laboratory in order to determine the bulk and mechanical properties of the tuff under baseline conditions. Deformation experiments consisted of unconfined compression, triaxial compression, and indirect tensile strength (Brazil) tests. Average grain density was also measured, and dry bulk density, saturated bulk density, and porosity were calculated for each depth interval represented by the selected cores. In addition, specimens tested in unconfined and confined compression were further characterized by measuring compressional and shear wave velocities.

Two hundred and fifty core intervals from the three boreholes that have penetrated the potential repository horizon (TSw2) have been examined. One hundred and six unconfined compression, one hundred and forty one Brazil, and forty three triaxial compression tests were performed on samples from those boreholes. Bulk properties were determined for every depth interval represented by the cores. Detailed characterization of the physical properties of the tuff is possible as a result of this extensive data set.

Deformation tests were performed on nominally water saturated specimens at ambient temperature. Confined and unconfined compression tests were performed at a strain rate of 10^{-5} s^{-1} on right cylindrical specimens with a length-to-diameter ratio of 2:1. Unconfined compression test specimens were 50.8 mm in diameter, and triaxial compression test specimens were 25.4 mm in diameter. Brazil test specimens were also cylindrical, with a diameter of 50.8 mm and a length of 38.1 mm. Average grain density was measured on powdered subsamples of the cored intervals using water pycnometry.

3 VERTICAL VARIABILITY

The Paintbrush Tuff at Yucca Mountain represents a typical volcanic tuff deposit. Mostly due to the mode of deposition, the numerous units that make up the Paintbrush Tuff are either generally welded (ash flow) or nonwelded (air fall). Within the individual units there are further zonal variations

due to cooling effects and post-depositional alterations, resulting in a highly heterogeneous lithology.

Analysis of the bulk and mechanical properties data collected in this study also reflects the heterogeneous nature of the Paintbrush Tuff. Boreholes that have penetrated the potential repository horizon (TSw2 T/M unit) all exhibit the broad characteristics illustrated in Figures 1 and 2 for USW NRG-6 and USW NRG-7/7A respectively.

There are two scales at which the data in these figures can be evaluated. First, the gross characteristics evidenced by intervals having similar properties can be delineated. These intervals are well defined by the contacts between T/M units determined by core descriptions. The most obvious illustration of these characteristics is the difference between the properties of the generally nonwelded PTn unit and the welded TCw and TSw1 units above and below it, respectively. The PTn has significantly higher porosity, and lower strength, elastic moduli, grain density and compressional wave velocity than the welded units. The concentration of data is such that the contacts between the units can be accurately located using only the bulk and mechanical properties data, in much the same manner as in the analysis of a standard electric log.

The contact between the typically lithophysal TSw1 unit and the generally nonlithophysal TSw2 unit (both welded) is not as easily distinguished. The gradational contact leads to subtle changes in the physical properties across it but, there is a progressive change toward lower porosity, and higher strength and elastic moduli values in the TSw2 unit then in the TSw1 unit.

An examination of the data at a smaller scale shows that within each T/M unit the properties also vary in a consistent manner. For instance, although the TSw1 unit is welded over most of its interval, there are significant differences in its properties at different depths. Typically (as seen in the welded vs nonwelded comparison) where porosity increases, strength, elastic moduli, and compressional wave velocity decrease. Intervals where that relationship isn't obvious, or is reversed can often be explained by investigating the nature (size, shape and orientation) of the pores and/or altered zones (Price et al., 1994a).

The magnitude of the variability in bulk and mechanical properties along the path of the boreholes is consistent with the degree of heterogeneity between the various lithologies. The welded lithologies have greatly different properties than those that are nonwelded. Individual intervals

within the same general lithology have less obvious but, equally consistent relationships. This consistency allows for greater accuracy, and more confidence in interborehole correlations of tuff units.

4 LATERAL VARIABILITY

Lateral variability in bulk and mechanical properties of the Paintbrush Tuff would be most likely due to differences in distance from the source vent. The

Figure 1: The correlation between the stratigraphic and thermal/mechanical units for borehole USW NRG-6 at Yucca Mountain, Nevada.

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Figure 2: The correlation between the stratigraphic and thermal/mechanical units for borehole USW NRG-7/7A at Yucca Mountain, Nevada.

deposits are generally blanket in nature having been deposited in the same manner (ash flow or air fall) over wide areas. Therefore, their composition and cooling histories should be comparable at similar distances parallel to the flow direction.

Sinnock (1982) reported that the source vent for the Paintbrush Tuff sequence is located in the Claim Canyon Caldera, located nearly due north of Yucca Mountain (Figure 3). This implies that at Yucca Mountain the flow direction would have been from north to south, and thinning of the various tuff units would be expected in the same direction, with modifications due to topography and erosional activities between eruption events. This is apparent from an analysis of the stratigraphic columns of the available boreholes. The alignment of the boreholes for which physical properties have been measured is oriented along the proposed ESF/NR, or nearly perpendicular to the flow direction. It is expected that variability in all properties of the tuff will be minimal between adjacent areas situated at nearly equal distances from the source vent. A comparison of the thickness of the TSw1 unit in Figures 1 and 2 for instance, shows that there is a maximum difference of only thirty five feet between these wells. On the other hand, TSw1 is as much as one hundred and fifty feet thinner approximately two kilometers to the south in borehole UZ-16.

The available bulk and mechanical properties data also indicate that there is small lateral variability perpendicular to the flow direction. In fact, subtle trends in the data can be correlated and the values of the properties are very consistent between the boreholes. Because the separation distances between the boreholes are not great (less than one kilometer), and because of their relative east-west orientation, a thorough evaluation of the lateral variability in bulk and mechanical properties is not possible.

However, a detailed comparison of the NRG-6 and NRG-7/7A data indicates that there may be some differences in properties within lithological units from one location to another. Although these boreholes are only 750 meters apart, NRG-6 is farther to the southeast (farther from the source vent). The stratigraphic column at NRG-6 is significantly thinner, and there are subtle differences in the physical properties over the short distance.

Figure 3: General location of Yucca Mountain, and known and inferred eruptive centers in the NTS vicinity, Southern Nevada (after Sinnock, 1982).

The Yucca Mountain member, for instance, is not present at NRG-6. This results in a large amount of thinning (93 feet) in the PTn unit. The physical properties data support the lithologic pick very well in this case, as can be observed by comparing the porosity data in NRG-6 over the entire PTn interval with that for NRG-7/7A between 175 and 300 feet. The Yucca Mountain member is easily delineated in the porosity data for NRG-7/7A.

A more subtle relationship is observable in the TSw1 unit. A comparison of the 475 to 600 foot interval in NRG-6 with the 500 to 650 foot interval in NRG-7/7A shows that, although these are likely the same lithologic units, there is an indication that the zone in NRG-6 has generally higher porosity. Because mechanical properties of the tuff are highly dependent on its porosity (Price et al., 1994b), this indication that the porosity of the tuff may vary within the same lithologic units, even over very short distances, insinuates that other physical properties are likely to be variable as well.

5 CONCLUSIONS

The tuffs at Yucca Mountain have highly variable bulk and mechanical properties. The differences are greater in the vertical direction (between lithologies) than in the east-west lateral direction. However, a thorough evaluation requires more complete borehole control, particularly parallel to the flow direction of the Paintbrush Tuff sequence.

The data illustrated in Figures 1 and 2 indicate a systematic trend between the properties of the tuff

as a function of depth. For example, as the porosity increases, the grain density, unconfined compressive strength, Young's modulus, tensile strength, and dry compressional wave velocity decrease. The non-welded Yucca Mountain and Pah Canyon members (PTn) of the Paintbrush Tuff exhibit the greatest porosities, lowest grain densities, and also the lowest strengths, moduli and compressional wave velocities. In contrast, the welded units (TCw, TSw1, and TSw2) exhibit lower porosities, higher grain densities, relatively greater strengths and elastic properties. There is also considerable vertical variability in bulk and mechanical properties even within each T/M unit. This can be correlated with the porosity and pore morphology of the units. For the welded units, these differences typically can be related to the nature of the lithophysae and vapor-phase altered zones. The T/M units accurately group horizons having similar bulk and mechanical properties into manageable divisions for modeling purposes. The contacts between T/M units based on core descriptions are clearly distinguished by significant changes in the bulk and mechanical properties.

Lateral variability in bulk and mechanical properties can not be as clearly evaluated due to limited borehole control over the site. Initial observations, based on the boreholes for which testing under a quality affecting program are available for analysis, indicate that lateral variability is significantly less than that for the vertical direction. Data have been acquired from boreholes along the projected ESF/NR path, which is oriented nearly perpendicular to the flow direction of the subject tuffs. Therefore, lateral variability due to differences in the distance from the source vent, cooling history, and composition is expected to be minimal between these boreholes. This can be observed by comparing the data presented in Figures 1 and 2. These boreholes are located only 750 meters from one another, with NRG-6 positioned southeast of NRG-7/7A. Note the thinning of units in NRG-6. It is likely that greater changes in properties of the tuff will be expressed between more widely separated points along a north-south course.

The establishment of thermal/mechanical units is sufficient to accurately group lithologies with similar bulk and mechanical properties. Since the data control is extensive, the contacts between the T/M units established from core descriptions can be verified by the laboratory bulk and mechanical properties data.

An analysis such as this does require large quantities of data that are not typically available for most geotechnical projects. Fortunately, the

importance of remotely evaluating the vertical and lateral variability in the rock properties at Yucca Mountain has been recognized and sufficient data is becoming available. It is clear that even narrow selections of lithologic intervals can have widely different bulk and mechanical properties. Therefore, in order to accurately compare the same horizon from one location to another, its physical features must be well documented.

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FIGURE 1

FIGURE 2

FIGURE 3