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Experimental investigation of the influence of pore pressure and porosity on the deformation of granular salt

Brandon C. Lampe[a,*,1], John C. Stormont[a], Timothy D. Lynn[a,2], Stephen J. Bauer[b]

[a] Department of Civil Engineering, University of New Mexico, Albuquerque, NM, USA
[b] Geomechanics Department, Sandia National Laboratories, Albuquerque, NM, USA

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ABSTRACT

The influence of pore pressure and porosity on the ductile deformation of granular salt was experimentally investigated under a isostatic compression at elevated temperatures. Confining and pore pressures were independently controlled while granular salt samples exhibited rate-dependent deformation that resulted in large decreases of sample volume and porosity. Over the experimental durations, which ranged from one to seven days, volumetric strain rates generally ranged from 10^{-2} down to 10^{-10} s^{-1}. The sample deformation rates were observed to correspond with both the sample porosity and the pressure difference between the confining and pore pressures. Experimental results show that the volumetric strain rate decreased when either the sample porosity or the pressure difference were decreased. Post-test observations revealed that the reduced porosity was caused by the solid particles deforming in a ductile manner into the pore volume. Insight into the cause of ductile deformation under isostatic compression was gained by considering the local stress distribution within a sample, which was approximated with the use of a representative volume element. Analysis of the local stress distribution showed how the magnitude of localized shear stress depends on both porosity and the pressure difference, which is consistent with the experimental results.

1. Introduction

Subsurface salt deposits are a proposed medium for nuclear waste storage repositories in the US and Europe, and a crucial component of such repositories are the seals designed to prevent the migration of hazardous gases, brines and water out of or into a repository's access shafts that join surface and subsurface facilities. Granular salt is a proposed sealing material for these shafts at horizons where they penetrate through the in-situ salt units and around waste canisters in disposal rooms.[1] Loose granular salt will be backfilled into these areas, and as external loads, from creep closure of the adjacent salt formation, are applied to the granular salt, it will undergo a sufficient decrease in porosity and permeability such that it acts as a barrier.

Previous studies have shown that a considerable amount of gas may be generated within a subsurface repository from the degradation of stored materials,[2–4] which may elevate pore pressure (P_p) within the void space of a sealed repository. In addition to the generation of gas, P_p may be further amplified within the granular salt backfill as porosity (ϕ) decreases during consolidation and the repository temperature increases from ambient to that of the in situ rock formation.[5] These transient conditions could also result in the pressurization of water present within the host formation (or any other fluid present within the granular salt backfill). The impact of pressurized pore fluid on the consolidation of granular salt has not previously been experimentally investigated, and researchers in the field have only postulated that it may impede consolidation and the ability of granular salt to act as a barrier.[1]

Proper understanding of the phenomena causing the deformation and associated consolidation of granular salt is imperative for the safe design of a repository seal; therefore, knowledge of how P_p influences the deformation of granular salt is needed. Many experimental and theoretical studies have been completed in an effort to understand the deformation of granular salt,[6–10] and practitioners in this field have widely assumed the influence of P_p is accurately described with the effective stress principle as proposed independently by Terzaghi[11] and Fillunger[12]. In essence, this principle states that P_p only influences spherical components of stress within a porous material, and it is often presented in the mathematical form proposed by Biot[13]:

* Corresponding author.
E-mail address: brandon.lampe@wsp.com (B.C. Lampe).
[1] Present Address: WSP USA 3824 Jet Drive, Rapid City, SD 57703, USA.
[2] Present Address: WSP USA 16200 Park Row, Houston, TX 77084, USA.

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$$\boldsymbol{\Sigma}' = \boldsymbol{\Sigma} - \alpha P_p \boldsymbol{i} \tag{1}$$

where $\boldsymbol{\Sigma}$ is the total stress tensor, $\boldsymbol{\Sigma}'$ is the effective stress tensor, α is termed Biot's parameter, P_p is the fluid pressure within the connected pore space of the material, and $\boldsymbol{i}$ is the second-order identity tensor. Biot[13] defines $\boldsymbol{\Sigma}$ as the average stress acting on a volume element containing both fluid and solid phases, and this element is sufficiently large to be considered homogeneous. This form of the effective stress principle has been experimentally validated by Nur and Byerlee[14] and many others for fluid-saturated isotropic materials undergoing linear-elastic deformation. However, the applicability of the effective stress principle to inelastic (nonrecoverable) deformation has not been theoretically proven or experimentally validated. Experimentalists considering the ductile deformation of materials typically do not evaluate the influence of P_p; as these materials are often understood to deform according to the von Mises or Tresca yield criteria that only consider the deviatoric components of stress (e.g., cast iron, steel, copper and aluminum,[15] pg. 83)). Consequently, the influence of P_p on the rate-dependent inelastic deformation of ductile materials, such as granular salt, is often overlooked.

This work presents an experimental investigation on how P_p and ϕ influence the ductile deformation of granular salt through a series of isostatic compression (commonly referred to as hydrostatic compression) experiments. Sample deformations were recorded during periods of both transient and creep loading, which allowed for yield to be evaluated during periods of variable and constant (creep) loading conditions. Experiments were performed over a range of pressure and temperature conditions that may exist in a subsurface waste repository. During these experiments confining pressures (), where $P_p < P_c$, ranged from 0 to 38.3 MPa, P_p ranged from 0 to 25 MPa, and samples were subjected to temperatures ranging from approximately 90 to 175 °C.

2. Theory and background

The following subsections present an overview of significant theory and experimental work that forms the current understanding of how of P_p and ϕ influence the ductile deformation of intact and granular salt.

2.1. Investigations on intact salt

Numerous experimental studies, starting in the mid 1970's, have been performed on intact salt; however, the influence of P_p on the deformation of intact salt has largely been ignored. This paucity of experimental work by researchers in the field is understood to result from the common assumption that intact salt is impermeable and not influenced by P_p; however, this is questionable and especially not valid for dilated (damaged) rock salt.[16] The few experimental studies that have evaluated the influence of P_p on the deformation of intact salt have either done so only qualitatively[17,18] or in the context of the poroelastic paradigm of Eq. (1), which requires the determination of α.

For porous materials that are macroscopically isotropic and exhibit linear-elastic deformation, α takes the form:

$$\alpha = 1 - \frac{K_B}{K_S} \tag{2}$$

where K_B and K_S are the drained bulk modulus and unjacketed bulk modulus of the porous material, respectively.[19,20,14] This formulation assumes the pore space is occupied by a single fluid phase of either gas or liquid and the solid phase is incompressible. Experimentally, K_B is determined by measuring the ratio of the to volumetric strain while maintaining a constant P_p (often $P_p = 0$). Whereas K_S is determined in a similar manner but with P_p equal to the , which results in a differential pressure ($P_c - P_p$) being zero. Because experimentally determining K_S is often difficult, a common assumption is that K_S is exactly the bulk modulus of the solid phase of a porous material, which is theoretically true if the solid phase is composed of a single mineral type.[21] For materials where the solid phase can be considered incompressible relative to the bulk material, which results in bulk volume changes being the consequence of changes in pore volume only, α can be assumed equal to unity; this is often applicable to loose granular materials such as a sand.[22]

McTigue[23] experimentally determined Skempton's B parameter, which relates changes in P_p and under undrained conditions,[24] along with many other bulk properties for rock salt recovered from the Salado formation in southern New Mexico that had $\phi = 0.001$. From the experimentally determined values of $B = 0.93$, $K_B = 20.7\ GPa$, and $K_S = 23.5\ GPa$[23]; $\alpha = 0.128$ was inferred for intact rock salt from the following relationship:

$$\alpha = \frac{K_S - K_B}{BK_S}. \tag{3}$$

This relationship, as provided by Wang,[25] is more general and does not rely on the assumption of an incompressible solid phase to determine α. Both Alkan et al.[26] and Kansy[27] performed experiments on intact and dilated salt from Germany, and their results showed that α ranged from 0.05 to 0.5 for specimen with ϕ less than 0.01. Although these works highlighted the influence of P_p and ϕ on the poroelastic deformation of intact rock salt, no experimental investigations or corresponding theory have been completed to determine the influence P_p and ϕ on the inelastic deformation or inelastic rate-dependent deformation of intact rock salt.

2.2. Investigations on granular salt

Similar to intact salt, experimental work on granular salt began in the 1970's, and this work largely focused on the use of granular salt as backfill material in a waste repository. Because the deformation of both intact and granular salt varies with time, many experimental studies have focused on understanding the rate-dependent deformation of these materials. General observations of how material parameters influenced the volumetric strain rate ($\dot{\varepsilon}_{vol}$) of granular salt were made by many early researchers in this field. The influence of particle size on the $\dot{\varepsilon}_{vol}$ was first observed by Shor et al.[28] and Holcomb and Hannum[29, pg. 17] concluded this influence was caused by local stress variations around particle contacts that changed with particle geometry, and the magnitude of this influence was altered as samples deformed.

Holcomb and Shields[30] studied the influence of pore liquid on the consolidation of granular WIPP salt by performing a series of creep tests at an ambient temperature of 30 °C, ranging from 0.69 to 6.9 MPa, and added water content ranging from none to 2.5% of the sample mass. During these tests, flow measurements were intermittently made (with argon gas) to determine sample permeability (k). During this testing, samples were consolidated for durations ranging from 20 to 52 days, and final ϕ values from 0.23 down to 0.06 with k as low as $10^{-20} m^2$ were achieved. Holcomb and Shields[30, pg. 19] noted that in order to measure flow through samples with low k, the argon pressure had to be temporarily increased to $P_p = 5.5$ MPa (while the was 6.9 MPa), which resulted in a transient decrease of the $\dot{\varepsilon}_{vol}$. A detailed description as to why the $\dot{\varepsilon}_{vol}$ was influenced by the P_p was not given except for attributing this phenomena to "decreasing the effective ".

The influence of a pore liquid and particle size on the deformation of granular salt was further evaluated by Spiers et al.[31] where experiments concentrated on understanding the impact of saturating a granular salt sample with a liquid phase (salt brine) during deformation. Creep experiments were performed using a uniaxial consolidation device (oedometer) that allowed for samples to undergo axial (one-dimensional) deformation while lateral deformation was mitigated by a rigid confining cell. Samples were composed of analytical grade sodium chloride with uniform particle sizes, and these samples were tested at 22 °C for up to 20 days under an effective uniaxial stress (Σ'_{unx}), where $\Sigma'_{unx} = \Sigma_{unx} - P_p$. During these experiments, the Σ'_{unx} ranged from 0.5 to 8.0 MPa with a constant $P_p = 1$ atmosphere absolute (0.1 MPa abs.)