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Crushed Salt Constitutive Model

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Sandia Contract No. AG4911

ABSTRACT

The constitutive model used to describe the deformation of crushed salt is presented in this report. Two mechanisms X dislocation creep and grain boundary diffusional pressure solution X are combined to form the basis for the constitutive model governing the deformation of crushed salt. The constitutive model is generalized to represent three-dimensional states of stress. Upon complete consolidation, the crushed-salt model reproduces the Multimechanism Deformation (M-D) model typically used for the Waste Isolation Pilot Plant (WIPP) host geological formation salt. New shear consolidation tests are combined with an existing database that includes hydrostatic consolidation and shear consolidation tests conducted on WIPP and southeastern New Mexico salt. Nonlinear least-squares model fitting to the database produced two sets of material parameter values for the model X one for the shear consolidation tests and one for a combination of the shear and hydrostatic consolidation tests. Using the parameter values determined from the fitted database, the constitutive model is validated against constant strain-rate tests. Shaft seal problems are analyzed to demonstrate model-predicted consolidation of the shaft seal crushed-salt component. Based on the fitting statistics, the ability of the model to predict the test data, and the ability of the model to predict load paths and test data outside of the fitted database, the model appears to capture the creep consolidation behavior of crushed salt reasonably well.

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1.0 INTRODUCTION

1.1 BACKGROUND

Construction of the Waste Isolation Pilot Plant (WIPP) was initiated by the U.S. Department of Energy (DOE) in 1981 to develop the technology for the safe management, storage, and disposal of transuranic (TRU) radioactive wastes generated by the DOE defense programs. The WIPP, located in southeastern New Mexico at a depth of approximately 655 meters in bedded halites, is designed to be a full-scale geologic repository. Access to the facility is provided through vertical shafts. Since these shafts provide direct communication from the underground facilities through the upper lithologic units to the surface, they will be sealed to limit fluid flow into the repository and to prevent hazardous materials from migrating out of the repository. The U.S. Environmental Protection Agency (EPA) has determined that the WIPP can safely contain transuranic waste and that it will comply with EPA's radioactive waste disposal standards.

Crushed salt has been selected as one of the primary seal components for permanent sealing of the WIPP underground openings. Crushed salt's desirable characteristics include chemical compatibility, eventual mechanical similarity with the host salt formation, and ready availability from site excavation. Laboratory tests have shown that crushed salt achieves desirable permeability characteristics as consolidation increases the material density. In addition, voids and fractures close and heal in salt in response to applied loads. After sufficient time, loading of the crushed salt resulting from creep closure of the shaft will form a long-term seal component from the reconsolidated crushed salt. Development of an understanding of these consolidation processes in crushed salt has been fundamental to the design and analysis of a credible seal system.

Because crushed salt is an important seal material, its constitutive model must satisfy the needs of performance assessment and regulatory compliance. To gain an understanding of the crushed-salt consolidation processes, laboratory testing and theoretical model development have been conducted over the last several years. The WIPP crushed-salt material model or constitutive model, which relates stress and strain, predicts deformations and stresses in the underground sealing system. The magnitude of the stresses and strains throughout the isolation system determines the location and extent of the disturbed rock zone and serviceability of the seal components. Laboratory testing has been used to develop the constitutive model from a phenomenological viewpoint and to evaluate the material constants associated with the model. The objective of this report is to provide the current version of the mechanical material model appropriate for describing crushed-salt deformation.

1.2 EARLIER WORK

Crushed salt has received international attention over the past 20 years primarily within a repository setting. Thus, an earlier study [Callahan et al., 1995] searched the literature for constitutive models developed for crushed salt. Ten models, based to varying degrees on phenomenology, micromechanics, or empiricism, were found. Three of these models were selected for detailed examination. The three models are those attributable to Sjaardema and Krieg [1987], Zeuch and Holcomb [Zeuch, 1990], and Spiers and coworkers [Spiers and Brzesowsky, 1993]. These constitutive models were developed to reproduce hydrostatic (isostatic) consolidation laboratory tests and include only the volumetric strain component. The Sjaardema and Krieg model is empirical and was retained for comparative purposes since it has been used in the past for calculation of crushed-salt problems at the WIPP. The Zeuch and Holcomb model was constructed for nominally dry crushed salt and is based on isostatic hot-pressing models combined with dislocation creep. The Spiers and coworkers model was formulated for wet crushed-salt aggregates and is based on grain boundary diffusional pressure solution processes. These three models were modified to include other effects thought to be important for WIPP salt. A flow potential and associated three-dimensional generalization were developed for the models so that they could operate over a wide range of stress triaxialities (ratio of mean stress to effective or deviatoric stress) and be applicable to arbitrary states of stress. A database of applicable crushed-salt laboratory tests was constructed comprising 40 hydrostatic consolidation tests and 10 shear consolidation tests. The experimental data were fit to determine values for the material parameters associated with each of the models. The hydrostatic and shear consolidation tests and their combination were fit separately so that three different parameter value sets were obtained. If a constitutive model truly represents the material and the data are unbiased, changes in parameter values among fits would be minimal. However, in this earlier study, the change in the parameter values was significant. These three models performed about equally well with the modified Spiers model exhibiting moderate superiority.

Following completion of the earlier study [Callahan et al., 1995], the constitutive model formulation was found to be inadequate at high fractional densities. In addition, because of the heavy bias in the database toward hydrostatic consolidation tests and because none of the shear consolidation tests reached high enough fractional densities to exhibit positive lateral strains, the constants associated with the flow potential made it impossible for the simulated crushed salt to move toward a volume-preserving flow (as is exhibited by intact salt) as the fractional density approached one. Most of the test data in the crushed-salt laboratory database exhibit a positive lateral-to-axial strain-rate ratio; whereas, the lateral-to-axial strain-rate ratio is negative for a triaxial test conducted on intact salt. However, as the crushed salt consolidates, the lateral deformation must change direction at some density level (i.e., cease to move inward and begin to

move outward as is observed for the intact salt tests). In addition to being a function of the density, this change in lateral strain direction is also, undoubtedly, a function of the state of stress. Having identified these shortcomings in the crushed-salt model, two additional shear consolidation tests were conducted to expand the database at higher fractional densities near 0.8 [RE/SPEC Inc., 1996]. The functional form of the flow potential for the models was modified, and the models were refit to the database. This study, discussed in RE/SPEC Inc. [1996] and Callahan et al. [1996], resulted in satisfactory model predictions over a wide range of fractional densities and stress triaxialities. However, the governing deformation mechanisms for crushed salt with varying degrees of added moisture were contained independently in two separate models.

Thus, the next study [Callahan et al., 1998; Hansen et al., 1998] incorporated the governing mechanisms — dislocation creep and pressure solution — into a single model. In addition, four new laboratory shear consolidation experiments were conducted with fractional densities near the initial fractional density (approximately 0.9) expected in the dynamically compacted crushed-salt seal [Sandia National Laboratories, 1996]. These tests expanded the database into fractional density ranges previously untested and provide information on the crushed-salt flow behavior as its density increases. These tests were added to the experimental database, which was fit to obtain material parameter values for the crushed-salt, combined-mechanism constitutive model. Up to this point, laboratory tests had included only hydrostatic and shear consolidation tests.

Laboratory testing was conducted in parallel with the constitutive model refinement work reported here. The laboratory work is reported separately [Mellegard et al., 1999] and includes test results from six shear consolidation tests and three constant strain-rate tests. Results from four of the shear consolidation tests have previously been considered in the constitutive model evaluation. The constitutive model development work reported here includes: (1) determination of the material model parameter values from the database updated with the two additional shear consolidation tests, (2) verification of the constitutive model through prediction of the constant strain-rate tests, and (3) demonstration of the constitutive model predictions for typical shaft sealing problems and comparison with earlier results.

1.3 REPORT ORGANIZATION

This report focuses on the mechanical constitutive behavior of crushed salt. In particular, Chapter 2.0 summarizes the constitutive model, provides the three-dimensional generalization of the model, and reduces the general model form to response models for specific types of laboratory tests used in the model fitting process. Chapter 3.0 summarizes the crushed-salt experimental database, along with recently completed tests used to fit the constitutive model and determine its material constants. Chapter 4.0 describes the nonlinear least-squares fitting procedure used to fit the constitutive model to the experimental database and presents the resulting parameter values. Chapter 5.0 presents verification of the constitutive model through prediction of constant strain-rate tests. Chapter 6.0 presents the results of typical shaft sealing calculations and compares the results to earlier versions of the constitutive model. The final chapter (Chapter 7.0) includes a summary and conclusions, which is followed by a list of references and three appendices.

2.0 CRUSHED-SALT CONSTITUTIVE MODEL

Details of the crushed-salt constitutive model that combine the dislocation creep and pressure solution deformation mechanisms are presented in detail by Hansen et al. [1998]. Therefore, this chapter simply summarizes the constitutive model equations for use later in the report. The chapter includes the general form of the crushed-salt constitutive model, the three-dimensional generalization for the creep consolidation model, and the reduction of the constitutive model to specific laboratory test forms used to fit the laboratory data and evaluate the material model parameters. Tensile stresses and extensile strains are assumed to be positive throughout this report.

2.1 GENERAL FORM OF THE CRUSHED-SALT CONSTITUTIVE MODEL

The total strain rate for the crushed-salt constitutive model is assumed to consist of two components. The components include nonlinear elastic ($\dot{\epsilon}_{ij}^e$) and creep consolidation ($\dot{\epsilon}_{ij}^c$) contributions, and the total strain rate is written as:

$$\dot{\epsilon}_{ij} = \dot{\epsilon}_{ij}^e + \dot{\epsilon}_{ij}^c \quad (2-1)$$

When the strains become finite, the expressions for strain rate should be interpreted as the rate of deformation. Both the nonlinear elastic and creep consolidation portions of the model describe the material behavior in bulk (volumetric) and in shear (deviatoric). However, as shown later, when the fractional density approaches unity, the creep consolidation portion of the model only describes deviatoric material behavior and is, in fact, the creep deformation model used for intact salt. The nonlinear elastic portion of the model presented by Callahan et al. [1995] has not changed and will not be presented again. The creep consolidation portion of the model is included in Hansen et al. [1998] and is summarized for use in the model fitting process discussed in Chapter 4.0. However, note that in this summary, parameter values η_2 and κ_2 included in Hansen et al. [1998] have been dropped since both are equal to one.

2.2 CREEP CONSOLIDATION MODEL

The creep consolidation model is of primary concern, and thus, this section is divided into subsections that summarize important portions of the crushed-salt consolidation model. Typically, equations proposed to describe the behavior of a particular material are written in one-dimensional form or as scalar relationships. To be useful in numerical analyses and applicable to a variety of laboratory experiments with different load paths, constitutive models must be generalized to include three-dimensional states of stress. The first subsection presents the generalization of the creep consolidation model. The next subsection collapses or reduces the generalized form of the creep consolidation equation to specific laboratory test conditions, which yields simplified forms that can be used in fitting the model to the experimental database. The

third subsection presents the effective strain-rate model forms that represent the two mechanisms associated with the crushed-salt creep consolidation component of the constitutive model.

2.2.1 Creep Consolidation Model Generalization

The creep consolidation constitutive equation for crushed salt includes two operative deformation mechanisms — dislocation creep and grain boundary diffusional pressure solution — and may be written as [Hansen et al., 1998]:

$$\dot{\epsilon}_{ij}^c = \left[\dot{\epsilon}_{eq}^d(\sigma_{eq}^f) + \dot{\epsilon}_{eq}^w(\sigma_{eq}^f) \right] \frac{\partial \sigma_{eq}}{\partial \sigma_{ij}} \quad (2-2)$$

where $\dot{\epsilon}_{ij}^c$ is the inelastic strain rate tensor and σ_{eq}^f is an equivalent stress measure. The equivalent inelastic strain rate measures for dislocation creep ($\dot{\epsilon}_{eq}^d$) and pressure solution ($\dot{\epsilon}_{eq}^w$) are written as functions of the equivalent stress measure. For use in the flow potential, another equivalent stress measure, σ_{eq} , is used to provide a nonassociative type of formulation that provides flexibility in governing the magnitude of the volumetric behavior. The equivalent stress measures are homogeneous of degree one in terms of stress and are given by:

$$\begin{aligned} \sigma_{eq}^f &= \left[\eta_0 \Omega_f^{\eta_1} \sigma_m^2 + \left(\frac{2-D}{D} \right)^{\frac{2n_f}{n_f+1}} (\sigma_1 - \sigma_3)^2 \right]^{1/2} \\ \sigma_{eq} &= \left[\kappa_0 \Omega^{\kappa_1} \sigma_m^2 + \left(\frac{2-D}{D} \right)^{\frac{2n}{n+1}} (\sigma_1 - \sigma_3)^2 \right]^{1/2} \end{aligned} \quad (2-3)$$

$$\Omega_f = \left[\frac{(1-D) n_f}{[1 - (1-D)^{1/n_f}]^{n_f}} \right]^{\frac{2}{n_f+1}} \quad (2-4)$$

where:

$$\Omega = \left[\frac{(1-D_v) n}{[1 - (1-D_v)^{1/n}]^n} \right]^{\frac{2}{n+1}} \quad (2-5)$$

$$D_v = \begin{cases} D_t & D \leq D_t \\ D & D > D_t \end{cases} \quad (2-6)$$

D = current fractional density

$$\sigma_m = \text{mean stress} = \frac{\sigma_{kk}}{3}$$

σ_3 = minimum principal stress

σ_1 = maximum principal stress

$\eta_o, \eta_1, \kappa_o, \kappa_1,$
 $n_f, n,$ and D_t = material parameters.

As crushed salt approaches full consolidation (i.e., $D \rightarrow 1$), Ω_f and Ω approach zero, and the dependence on mean stress diminishes, which is required for an incompressible material matrix. Thus, letting $D = 1$, Equation 2-3 becomes:

$$\begin{aligned}\sigma_{eq}^f &= \sigma_1 - \sigma_3 \\ \sigma_{eq} &= \sigma_1 - \sigma_3\end{aligned}\tag{2-7}$$

Twice the maximum shear stress or Tresca equivalent stress is used in the equivalent stress measures to describe the shear behavior as is common for intact salt and is given by:

$$\sigma_1 - \sigma_3 = 2 \cos \psi J_2\tag{2-8}$$

with the second and third invariants (J_2 and J_3) of the deviator stress (s_{ij}) defined by:

$$\begin{aligned}J_2 &= \frac{1}{2} s_{ij} s_{ji} \\ J_3 &= \frac{1}{3} s_{ij} s_{jk} s_{ki}\end{aligned}\tag{2-9}$$

where the Lode angle (ψ), which is a convenient alternative invariant to J_3 , is given by:

$$\psi = \frac{1}{3} \sin^{-1} \left[\frac{-3\sqrt{3}J_3}{2J_2^{3/2}} \right], \left(-\frac{\pi}{6} \leq \psi \leq \frac{\pi}{6} \right)\tag{2-10}$$

The partial derivative given in Equation 2-2 may be determined using the chain rule as:

$$\frac{\partial \sigma_{eq}}{\partial \sigma_{ij}} = \frac{\partial \sigma_{eq}}{\partial \sigma_m} \frac{\partial \sigma_m}{\partial \sigma_{ij}} + \frac{\partial \sigma_{eq}}{\partial J_2} \frac{\partial J_2}{\partial \sigma_{ij}} + \frac{\partial \sigma_{eq}}{\partial \psi} \frac{\partial \psi}{\partial J_3} \frac{\partial J_3}{\partial \sigma_{ij}} \quad (2-11)$$

The derivatives of the invariants in Equation 2-11 are the same regardless of the invariant stress and strain measures selected. These derivatives are:

$$\begin{aligned} \frac{\partial \sigma_m}{\partial \sigma_{ij}} &= \frac{\delta_{ij}}{3} \\ \frac{\partial J_2}{\partial \sigma_{ij}} &= s_{ij} \\ \frac{\partial \psi}{\partial J_3} \frac{\partial J_3}{\partial \sigma_{ij}} &= - \frac{\sqrt{3}}{2 J_2^{3/2} \cos 3 \psi} t_{ij} \end{aligned} \quad (2-12)$$

where:

$$\delta_{ij} = \text{Kronecker delta}$$

$$t_{ij} = s_{ip} s_{pj} - \frac{2}{3} J_2 \delta_{ij}.$$

Equation 2-11, defining the flow potential, also requires the partial derivatives of the equivalent stress measure (Equation 2-3) with respect to stress. Performing the required differentiation yields:

$$\begin{aligned} \frac{\partial \sigma_{eq}}{\partial \sigma_m} &= \frac{\kappa_0 \Omega^{\kappa_1} \sigma_m}{\sigma_{eq}} \\ \frac{\partial \sigma_{eq}}{\partial J_2} &= \frac{2}{\sigma_{eq}} \left(\frac{2 - D}{D} \right)^{\frac{2n}{n+1}} \frac{\cos \psi \cos 2 \psi}{\cos 3 \psi} \\ \frac{\partial \sigma_{eq}}{\partial \psi} &= - \frac{4}{\sigma_{eq}} \left(\frac{2 - D}{D} \right)^{\frac{2n}{n+1}} \cos \psi \sin \psi J_2 \end{aligned} \quad (2-13)$$

Substituting Equations 2-11, 2-12, and 2-13 into Equation 2-2 provides the tensorial strain-rate components for the creep consolidation portion of the crushed-salt model, which is given by:

$$\dot{\epsilon}_{ij}^c = \frac{\dot{\epsilon}_{eq}^d + \dot{\epsilon}_{eq}^w}{\sigma_{eq}} \left\{ \frac{\kappa_0 \Omega^{\kappa_1} \sigma_m}{3} \delta_{ij} + \left(\frac{2-D}{D} \right)^{\frac{2n}{n+1}} 2 \sqrt{J_2} \cos \psi \right. \\ \left. \left(\left[\frac{\cos 2\psi}{\cos 3\psi} \right] \frac{s_{ij}}{\sqrt{J_2}} + \left[\frac{\sqrt{3} \sin \psi}{J_2 \cos 3\psi} \right] t_{ij} \right) \right\} \quad (2-14)$$

Equation 2-14 is seen to be undefined as the Lode angle approaches $\pm\pi/6$. In other words, the flow potential forms corners at $\psi = \pm\pi/6$, and the direction of straining is not unique. To eliminate this problem computationally, the flow potentials on either side of the corner are averaged, which produces an indeterminate form that is examined in the limit as $\psi \rightarrow \pm\pi/6$. Performing this limiting operation, Equation 2-14 becomes:

$$\dot{\epsilon}_{ij}^c = \frac{\dot{\epsilon}_{eq}^d + \dot{\epsilon}_{eq}^w}{\sigma_{eq}} \left\{ \frac{\kappa_0 \Omega^{\kappa_1} \sigma_m}{3} \delta_{ij} + \left(\frac{2-D}{D} \right)^{\frac{2n}{n+1}} \sqrt{3} J_2 \right. \\ \left. \left(\frac{s_{ij}}{\sqrt{3} J_2} \mp \frac{t_{ij}}{2 J_2} \right) \right\} \quad (2-15)$$

The flow potential contains four material parameters (κ_0 , κ_1 , D , and n) that need to be determined from laboratory experiments. To complete the crushed-salt creep consolidation description, the kinetic equations describing dislocation creep and pressure solution in crushed salt need to be defined. In general, these kinetic equations could be a form of any specific model that captures the desired characteristics of the material deformation. Discussion of these specific forms is included in Sections 2.2.3 and 2.2.4 following presentation of Equation 2-15 reduced to specific laboratory test conditions.

2.2.2 Evaluation of Laboratory Test Equation Forms

To compare the crushed-salt constitutive equations to laboratory experiments, one needs to reduce the equations to the applicable test conditions. In particular, tests of interest are the hydrostatic compression, triaxial compression, and triaxial extension tests. To derive these forms, one simply needs to substitute the applicable test conditions into the constitutive equations and reduce them to their simplest forms. The hydrostatic compression test conditions can be easily obtained from the triaxial compression test conditions by letting the stress difference $\Delta\sigma = \sqrt{3} J_2$ equal zero. The directions $\{zz, yy, xx\}$ are taken as $\{33, 22, 11\}$, and the $\{zz\}$ direction is taken to be the axial direction. For convenience, the following variables are defined:

$$\alpha = \frac{\kappa_0 \Omega^{\kappa_1} \sigma_m}{3}$$

$$\beta = \left[\frac{2 - D}{D} \right]^{\frac{2n}{n+1}} \sqrt{3 J_2}$$
(2-16)

Fitting of the constitutive model can be conveniently separated into two separate stages. The first step includes fitting the ratio of the lateral strain rate to the axial strain rate defined as $\mathbb{R}$ and written as:

$$\mathbb{R} = \frac{\dot{\epsilon}_l^c}{\dot{\epsilon}_a^c}$$
(2-17)

Fitting the strain-rate ratio allows the parameter values associated with the flow potential (i.e., κ_0 , κ_1 , D_v , and n contained in α and β in Equation 2-16) to be determined independently of the other material parameter values. Obviously, the test data must contain experiments where the stress triaxiality conditions lie between zero and infinity for the fitting to be successful. This can be accomplished with the shear consolidation tests.

Reduction to Triaxial Compression Creep Test ($\psi = \pi/6$)

The triaxial compression creep test is prescribed by controlling a constant stress state defined by $\sigma_{zz} < \sigma_{xx} = \sigma_{yy}$. The axial (a), lateral (l), and volumetric (v) strain components and strain-rate ratio for the creep consolidation portion of the model may be determined from Equations 2-15, 2-16, 2-17, and the applied stress condition as:

$$\dot{\epsilon}_a^c = [\alpha - \beta] \frac{\dot{\epsilon}_{eq}^d + \dot{\epsilon}_{eq}^w}{\sigma_{eq}}$$

$$\dot{\epsilon}_l^c = \left[\alpha + \frac{\beta}{2} \right] \frac{\dot{\epsilon}_{eq}^d + \dot{\epsilon}_{eq}^w}{\sigma_{eq}}$$

$$\dot{\epsilon}_v^c = 3\alpha \frac{\dot{\epsilon}_{eq}^d + \dot{\epsilon}_{eq}^w}{\sigma_{eq}}$$

$$\mathbb{R} = \frac{\alpha + \frac{\beta}{2}}{\alpha - \beta}$$
(2-18)

Reduction to Triaxial Extension Test ($\psi = -\pi/6$)

The triaxial extension creep test is prescribed by controlling a constant stress state defined by $\sigma_{zz} > \sigma_{xx} = \sigma_{yy}$. The axial (a), lateral (l), and volumetric (v) strain components and strain-rate ratio for the creep consolidation portion of the model may be determined from Equations 2-15, 2-16, 2-17, and the applied stress conditions as:

$$\begin{aligned}\dot{\epsilon}_a^c &= [\alpha + \beta] \frac{\dot{\epsilon}_{eq}^d + \dot{\epsilon}_{eq}^w}{\sigma_{eq}} \\ \dot{\epsilon}_l^c &= \left[\alpha - \frac{\beta}{2} \right] \frac{\dot{\epsilon}_{eq}^d + \dot{\epsilon}_{eq}^w}{\sigma_{eq}} \\ \dot{\epsilon}_v^c &= 3 \alpha \frac{\dot{\epsilon}_{eq}^d + \dot{\epsilon}_{eq}^w}{\sigma_{eq}} \\ R &= \frac{\alpha - \frac{\beta}{2}}{\alpha + \beta}\end{aligned}\tag{2-19}$$

2.2.3 Equivalent Inelastic Strain-Rate Form for Dislocation Creep

Dislocation creep of intact salt has been characterized by the Multimechanism Deformation (M-D) model [Munson, 1979; Munson and Dawson, 1979]. Thus, the equivalent inelastic strain rate measure for the dislocation creep portion of the crushed-salt model is taken to be the M-D material model. The only modification for application of the M-D model to crushed salt is replacing the intact salt effective stress measure with the effective stress measure given for crushed salt in Equation 2-3.

The model is written as:

$$\dot{\epsilon}_{eq}^d = F \dot{\epsilon}_s\tag{2-20}$$

where $\dot{\epsilon}_{eq}^d$ is the kinetic equation and $\dot{\epsilon}_s$ is the steady-state strain rate. The transient function F consists of three branches — a work-hardening branch, an equilibrium branch, and a recovery branch and is written in that order as:

$$F = \begin{cases} \exp\left[\Delta\left(1 - \frac{\zeta}{\epsilon_t^f}\right)^2\right] & \zeta < \epsilon_t^f \\ 1 & \zeta = \epsilon_t^f \\ \exp\left[-\delta\left(1 - \frac{\zeta}{\epsilon_t^f}\right)^2\right] & \zeta > \epsilon_t^f \end{cases} \quad (2-21)$$

Δ and δ are the work-hardening and recovery parameters, respectively, and ϵ_t^f is the transient strain-rate limit. The internal variable ζ is governed by the evolution equation:

$$\dot{\zeta} = (F - 1) \dot{\epsilon}_s \quad (2-22)$$

and the transient strain limit is given by:

$$\epsilon_t^f = K_0 e^{cT} \left(\frac{\sigma_{eq}^f}{\mu} \right)^m \quad (2-23)$$

where:

T = absolute temperature

μ = shear modulus

K_0 , c , and m = material parameters.

The work-hardening parameter is defined as a function of stress:

$$\Delta = \alpha + \beta \log\left(\frac{\sigma_{eq}^f}{\mu}\right) \quad (2-24)$$

where α and β are material parameters. Because of insufficient data, the recovery parameter (δ) is taken to be a constant. However, functional forms similar to Equation 2-24 are sometimes used for recovery; viz:

$$\delta = \alpha_r + \beta_r \log\left(\frac{\sigma_{eq}^f}{\mu}\right) \quad (2-25)$$

where α_r and β_r are material parameters.

The steady-state strain rate is the sum of the three individual strain-rate mechanisms acting together:

$$\dot{\epsilon}_s = \sum_{i=1}^3 \dot{\epsilon}_{s_i} \quad (2-26)$$

The three contributing mechanisms — dislocation climb, an undefined mechanism, and slip — are written respectively as:

$$\dot{\epsilon}_{s_1} = A_1 \left(\frac{\sigma_{eq}^f}{\mu} \right)^{n_1} \exp \left(- \frac{Q_1}{RT} \right) \quad (2-27)$$

$$\dot{\epsilon}_{s_2} = A_2 \left(\frac{\sigma_{eq}^f}{\mu} \right)^{n_2} \exp \left(- \frac{Q_2}{RT} \right) \quad (2-28)$$

$$\dot{\epsilon}_{s_3} = \left(B_1 e^{-Q_1/RT} + B_2 e^{-Q_2/RT} \right) \sinh \left[q \left(\frac{\sigma_{eq}^f - \sigma_0}{\mu} \right) \right] H(\sigma_{eq}^f - \sigma_0) \quad (2-29)$$

where:

μ = shear modulus

q = activation volume

$A_1, A_2, B_1, B_2, n_1, n_2,$

$Q_1, Q_2,$ and σ_0 = experimental constants

R = universal gas constant

$H(.)$ = Heaviside step function.

2.2.4 Equivalent Inelastic Strain-Rate Form for Pressure solution

Spiers and Brzesowsky [1993] presented a grain boundary diffusional pressure solution model for wet crushed salt as:

$$\dot{e}_v^w = A V_m \frac{\exp\left(-\frac{Q_s}{RT}\right)}{T} \left(\frac{\sigma_m - P}{d^p} \right) \left(\frac{(1 + e_v)^{r_3}}{|e_v|^{r_4}} \right) \Gamma \quad (2-30)$$

where $\dot{e}_v^w$ is the volumetric consolidation strain rate, A , V_m , Q_s , p , r_3 , and r_4 are material constants; T is absolute temperature; R is the universal gas constant; d is the grain size; and P is the pore pressure. The model consists of two functional forms — one for small strain and one for large strain, which are invoked depending on the prescribed value for Γ given as:

$$\Gamma = \begin{cases} 1 & \text{small strain } (e_v > -15\%) \\ \left[\frac{e_v + \phi_0}{\phi_0(e_v + 1)} \right]^{n_s} & \text{large strain } (e_v < -15\%) \end{cases} \quad (2-31)$$

where ϕ_0 is the initial porosity and n_s is a material parameter. Spiers and Brzesowsky [1993] developed the function Γ to account for increasing surface contact (increasing area and decreasing stress) as the strains become large. This geometrically interpreted variable serves to decrease the magnitude of the driving force.

Spiers and Brzesowsky's model is used to represent the equivalent inelastic strain-rate form for pressure solution with modifications. The functional form given in Equation 2-30 is modified by changing the stress-dependent term (using the equivalent stress measure defined in Equation 2-3) and adding the effect of moisture (w is the moisture fraction by weight). The moisture function (simply w raised to a power, a) eliminates any strain-rate contribution to the crushed-salt consolidation model when moisture content is zero. In addition, the pore pressure dependency (parameter P in Equation 2-30) has been dropped from the model because insufficient test data are available to include pore pressure as a state variable. With these modifications, the modified Spiers' model used to define the kinetic equation becomes:

$$\dot{e}_{eq}^w = \frac{r_1 w^a}{d^p} \frac{e^{-\frac{Q_s}{RT}}}{T} \left(\frac{(1 + e_v)^{r_3}}{|e_v|^{r_4}} \right) \Gamma \sigma_{eq}^f \quad (2-32)$$

Notice that material constants A and V_m appearing in Equation 2-30 have been combined into one parameter, r_1 , in Equation 2-32 defined as:

$$r_1 = AV_m = \text{material constant} \left[\frac{\text{m}^3 \cdot \text{K}}{\text{MPa} \cdot \text{s}} \right] \quad (2-33)$$

Moisture content and grain size are not implemented specifically in numerical models since their distributions are generally not known and they are assumed to be constants. However, the moisture and grain size effects are incorporated through the leading coefficient, which may be corrected for changes in grain size and moisture. Thus, the corrected leading coefficient is

$$r_1^* = \frac{r_1 w^a}{d^p} \quad (2-34)$$

To express the pressure solution model in terms of true strain (ϵ), consider the following relationships:

$$\begin{aligned} \epsilon_v &= \ln \left(\frac{\rho_0}{\rho} \right) \\ \epsilon_v &= \ln(1 + e_v) \\ \dot{\epsilon}_v &= \frac{\rho}{\rho_0} \dot{\epsilon}_v = e^{-\epsilon_v} \dot{\epsilon}_v \end{aligned} \quad (2-35)$$

Using Equation 2-35, Equation 2-32 may be written as:

$$\dot{\epsilon}_{eq}^w = r_1^* e^{-\epsilon_v} \left(\frac{e^{r_3 \epsilon_v}}{|e^{\epsilon_v} - 1|^{r_4}} \right) \frac{e^{-\frac{Q_s}{RT}}}{T} \Gamma \sigma_{eq}^f \quad (2-36)$$

which is the form incorporated into SPECTROM-32, a thermomechanical finite element stress analysis program [Callahan et al., 1989], with the geometric factor written as:

$$\Gamma = \begin{cases} 1 & \text{small strain } (e^{\epsilon_v} - 1 > -15\%) \\ \left[\frac{e^{\epsilon_v} + \phi_0 - 1}{\phi_0 e^{\epsilon_v}} \right]^{n_s} & \text{large strain } (e^{\epsilon_v} - 1 < -15\%) \end{cases} \quad (2-37)$$

A problem is evident in Spiers' model at time zero. Equation 2-30 or 2-36 can be indeterminate since when $\sigma_{eq}^f = 0$, the initial volumetric strain is zero. To eliminate this problem during computations, some initial value must be assumed for the volumetric strain. Typically, this initial strain value will be computed based on an original fractional density of 0.64, which is the approximate fractional density for random-dense packing of single size spheres (Fischmeister and Arzt [1983] and Helle et al. [1985]), and the fractional density at the beginning of creep consolidation. The pressure solution model has seven material constants — a, p, Q_s, r_1, r_3, r_4 , and n_s , excluding those that appear in the effective stress measure.

2.3 SUMMARY OF THE CRUSHED-SALT CONSOLIDATION MODEL

The equation describing the combined-mechanism, crushed-salt constitutive model, which includes dislocation creep and pressure solution, is summarized in this section. The final equation for the total creep consolidation strain rate is obtained by substituting Equations 2-20 and 2-36 into Equation 2-14:

$$\dot{\epsilon}_{ij}^c = \frac{1}{\sigma_{eq}} \left\{ \frac{r_1 w^a}{d^p} e^{-\epsilon_v} \left(\frac{e^{r_3 \epsilon_v}}{|e^{\epsilon_v} - 1|^{r_4}} \right) \frac{e^{-\frac{Q_s}{RT}}}{T} \Gamma \sigma_{eq}^f + F \dot{\epsilon}_s \right\} \times \left\{ \frac{\kappa_0 \Omega^{\kappa_1} \sigma_m}{3} \delta_{ij} + \left(\frac{2-D}{D} \right)^{\frac{2n}{n+1}} \left(2 \cos \psi \sqrt{J_2} \right) \left(\left[\frac{\cos 2\psi}{\cos 3\psi} \right] \frac{s_{ij}}{\sqrt{J_2}} + \left[\frac{\sqrt{3} \sin \psi}{J_2 \cos 3\psi} \right] t_{ij} \right) \right\} \quad (2-38)$$

As the material approaches full consolidation, the fractional density approaches 1, and the M-D model creep component becomes the same as that for intact salt. Simultaneously, the pressure solution portion of the model diminishes as the material approaches full consolidation. This decrease is implemented through the geometric Γ function, which becomes zero at full consolidation. Thus, at complete consolidation (i.e., $D = 1$), Equation 2-38 may be written as:

$$\dot{\epsilon}_{ij}^c = F \dot{\epsilon}_s \left(\left[\frac{\cos 2\psi}{\cos 3\psi} \right] \frac{s_{ij}}{\sqrt{J_2}} + \left[\frac{\sqrt{3} \sin \psi}{J_2 \cos 3\psi} \right] t_{ij} \right) \quad (2-39)$$

which is identical to the M-D model for intact salt.

3.0 EXPERIMENTAL DATABASE

A database of crushed-salt consolidation laboratory test results was assembled, analyzed, and reported in previous work [Callahan et al., 1995; 1998a]. This previous work initiated the process of formulating the functional form of a constitutive model for crushed salt and assembled existing test data into a database to obtain quantitative estimates for the material parameters appearing in the model. The assembled database consists of a collection of tests conducted for a variety of reasons. Thus, the database contains biases and shortcomings when viewed strictly from the standpoint of developing constitutive models. The crushed-salt constitutive model has deviatoric and mean stress components that drive the strain response, and the database has shear and hydrostatic consolidation tests used for evaluating the parameters within those respective stress components. Since this initial work was completed, additional tests have been conducted to fill gaps in the database. Two additional shear consolidation tests [RE/SPEC Inc., 1996; Callahan et al., 1998a] were conducted and added to the database following compilation of the initial database. These two tests represent the first tests with high initial fractional densities (near 0.8) that emulate intact salt behavior accompanied by volumetric consolidation. Subsequently, four additional tests were conducted to add test data to the shear consolidation portion of the extant database because that portion of the database was relatively sparse, particularly in the higher initial fractional density range expected at WIPP. These four additional shear consolidation tests on dynamically compacted crushed salt are summarized by Hansen et al. [1998] and Mellegard et al. [1999].

Two new shear consolidation tests were conducted in parallel with the current study to add test data to the shear consolidation portion of the database and verify earlier test results. In addition, three constant strain-rate tests were performed to provide experimental results and load paths outside of the fitted database for verification of the constitutive model. The remainder of this chapter is divided into two sections; the first section summarizes the status of the database used for evaluation of material parameter values and the second section presents details on the two new shear consolidation tests. The three constant strain-rate tests that were performed in parallel with the current effort are discussed in chapter 5.0.

3.1 SUMMARY OF EXISTING TEST DATA

Creation of the database was initiated with an extensive library search and compilation of potentially useful test results [Pfeifle, 1995]. The test data were compiled from the original studies conducted by Holcomb and Hannum [1982], Pfeifle and Senseny [1985], Holcomb and Shields [1987], Zeuch et al. [1991], and Brodsky [1994]. That compilation was reviewed to document those tests deemed inappropriate for parameter estimation and the surviving tests formed the database for parameter estimation work [Callahan et al., 1995]. Subsequently, six shear consolidation tests were added to the database for constitutive model evaluation and

parameter estimation in two different studies: Callahan et al. [1998a] — two tests and Hansen et al. [1998] — four tests. The database is constructed from two types of tests: hydrostatic consolidation and shear consolidation. The two parts of the database are shown separately in Tables 3-1 and 3-2, which summarize the tests for the hydrostatic and shear consolidation groupings, respectively.

Table 3-1 lists 40 tests contained in the hydrostatic consolidation portion of the database. All of the testing was performed in a drained condition; i.e., the pore pressure was zero. The database discussed by Callahan et al. [1995] contained 45 tests. Five of the hydrostatic consolidation tests were eliminated from the database, as recommended by Callahan et al. [1995]. These tests were performed under saturated conditions and were not very well drained, which resulted in the generation of pore pressures with reduced deformation. The maximum and minimum principal stresses are listed under the columns titled σ_1 and σ_3 . The principal stresses are equal for the hydrostatic case, but the formatting of the table has been maintained for both types of tests. The initial dry density of the specimens, the density at the beginning of the consolidation stage, and the final density at the end of the test are given under the respective column headings titled ρ_o , ρ_i , and ρ_f .

Table 3-2 lists the shear consolidation tests in the database and is formatted the same as Table 3-1. The table contains the 16 tests that were used in previous work and two additional tests that were conducted in parallel with the current work. As with the hydrostatic consolidation tests, all of the shear consolidation tests were performed in a drained condition.

The tests listed in Tables 3-1 and 3-2 represent 58 tests (40 hydrostatic consolidation tests and 18 shear consolidation tests) and comprise the entire database used for parameter estimation discussed in Chapter 4.0. The original data files often contained thousands of data points, which presented an impractical size for regression analyses. Each data file was reduced in size to create representative data sets containing only 100 data points with the first and last data points always being retained and the remaining data points uniformly sampled. This sampling technique is the same as was used in previous work. Tables 3-1 and 3-2 present the nominal or target test conditions for temperature and stress. The actual test conditions achieved are shown in Tables 3-3 and 3-4. The values for temperature and stress in these tables were determined by computing the time-weighted averages from the 100-point data files. As can be seen, the actual test conditions are moderately different than the targeted test conditions.

Table 3-1. Summary of Hydrostatic Test Conditions (Page 1 of 3)

Test I.D.	Test Type	T (K)	σ_1 (MPa)	σ_3 (MPa)	Mean Grain Size (mm)	Added Water (%)	Test Duration (days)	ρ_o (kg/m ³)	ρ_i (kg/m ³)	ρ_f (kg/m ³)	Source ^(a)
CS1	1	298	-1.72	-1.72	2.30	0	4.0	1,430	1,490	1,548	4
CS2	1	298	-1.72	-1.72	1.36	0	4.3	1,480	1,570	1,720	4
CS3	1	298	-1.72	-1.72	0.77	0	4.0	1,410	1,480	1,552	4
CS4	1	298	-1.72	-1.72	0.42	0	4.0	1,290	1,400	1,485	4
CS5	1	298	-1.72	-1.72	2.30	4.44	3.8	1,360	1,440	1,697	4
CS6	1	298	-1.72	-1.72	1.36	4.28	4.0	1,440	1,500	1,775	4
CS7	1	298	-1.72	-1.72	0.77	4.57	4.3	1,420	1,470	1,572	4
CS8	1	298	-1.72	-1.72	0.42	4.61	4.0	1,400	1,430	1,822	4
CS9	1	298	-1.72	-1.72	2.30	0	37.0	1,480	1,530	1,759	4
CS10	1	298	-3.45	-3.45	2.30	0	34.2	1,470	1,570	1,648	4
HC1A	1	298	-1.72	-1.72	1.56	Sat	28.8	1,462	1,539	1,921	1
HC2A	1	298	-1.72	-1.72	1.56	Sat	98.7	1,388	1,574	2,026	1
HC3A	1	298	-3.45	-3.45	1.56	Sat	49.9	1,448	1,550	2,042	1
HC4A	1	298	-3.45	-3.45	1.56	Sat	110.8	1,409	1,610	2,065	1
HC5A	1	298	-6.90	-6.90	1.56	Sat	53.0	1,496	1,741	2,124	1
HC6A	1	298	-6.90	-6.90	1.56	Sat	77.9	1,395	1,721	2,125	1
27JUL82	1	294	-1.72	-1.72	2.5	0	2.7	1,273	1,390	1,440	2

^(a)1-Brodsky [1994], 2-Holcomb and Hannum [1982], 3-Holcomb and Shields [1987], and 4-Pfeifle and Senseny [1985]

Table 3-1. Summary of Hydrostatic Test Conditions (Page 2 of 3)

Test I.D.	Test Type	T (K)	σ_1 (MPa)	σ_3 (MPa)	Mean Grain Size (mm)	Added Water (%)	Test Duration (days)	ρ_o (kg/m ³)	ρ_i (kg/m ³)	ρ_f (kg/m ³)	Source ^(a)
04MAY82	1	313	-1.72	-1.72	2.5	0	2.8	1,396	1,563	1,621	2
30APR82	1	333	-1.72	-1.72	2.5	0	3.0	1,448	1,605	1,677	2
07MAY82	1	353	-1.72	-1.72	2.5	0	2.9	1,240	1,415	1,492	2
12MAY82	1	373	-1.72	-1.72	2.5	0	4.8	1,371	1,621	1,738	2
05FEB82	1	294	-3.44	-3.44	2.5	0	3.4	1,263	1,432	1,466	2
09APR82	1	313	-3.44	-3.44	2.5	0	3.0	1,330	1,495	1,561	2
26MAR82	1	333	-3.44	-3.44	2.5	0	3.9	1,242	1,393	1,451	2
02APR82	1	353	-3.44	-3.44	2.5	0	2.7	1,249	1,428	1,501	2
13APR82	1	373	-3.44	-3.44	2.5	0	2.8	1,240	1,424	1,522	2
29JAN82	1	294	-6.70	-6.70	2.5	0	3.2	1,279	1,506	1,557	2
26FEB82	1	294	-10.1	-10.1	2.5	0	3.1	1,256	1,538	1,601	2
27JU61	1	293	-0.69	-0.69	1.75	2.5	31.8	1,440	1,493	1,732	3
23JUL51	1	293	-1.72	-1.72	1.75	0.5	19.7	1,498	1,593	1,827	3
14NOV51	1	293	-1.72	-1.72	1.75	1.5	24.1	1,477	1,571	1,860	3
25FEB61	1	293	-1.72	-1.72	1.75	2.0	36.6	1,455	1,548	1,853	3
10MAY51	1	293	-1.72	-1.72	1.75	2.4	28.9	1,412	1,601	1,890	3

^(a)1-Brodsky [1994], 2-Holcomb and Hannum [1982], 3-Holcomb and Shields [1987], and 4-Pfeifle and Senseny [1985]

Table 3-1. Summary of Hydrostatic Test Conditions (Page 3 of 3)

Test I.D.	Test Type	T (K)	σ_1 (MPa)	σ_3 (MPa)	Mean Grain Size (mm)	Added Water (%)	Test Duration (days)	ρ_o (kg/m ³)	ρ_i (kg/m ³)	ρ_f (kg/m ³)	Source ^(a)
20AUG51	1	293	-1.72	-1.72	1.75	3.0	20.0	1,348	1,516	1,821	3
16JUL51	1	293	-3.44	-3.44	1.75	0.5	20.6	1,391	1,608	1,920	3
18JUL51	1	293	-3.44	-3.44	1.75	1.0	21.6	1,455	1,668	1,930	3
30OCT51	1	293	-3.44	-3.44	1.75	1.5	13.8	1,477	1,648	1,930	3
16JAN61	1	293	-3.44	-3.44	1.75	2.0	27.9	1,489	1,640	1,950	3
19DEC44	1	293	-3.44	-3.44	1.75	2.4	52.1	1,434	1,566	1,899	3
13AUG51	1	293	-3.44	-3.44	1.75	3.0	21.7	1,370	1,586	1,899	3

^(a)1-Brodsky [1994], 2-Holcomb and Hannum [1982], 3-Holcomb and Shields [1987], and 4-Pfeifle and Senseny [1985]

Table 3-2. Summary of Shear Consolidation Test Conditions

Test I.D.	Test Type	T (K)	σ_1 (MPa)	σ_3 (MPa)	Mean Grain Size (mm)	Added Water (%)	Test Duration (days)	ρ_o (kg/m ³)	ρ_i (kg/m ³)	ρ_r (kg/m ³)	Source ^(a)
SC1B	2	298	-3.45	-4.14	1.56	2.34	62.9	1,449	1,574	2,009	1
SC2A	2	298	-3.45	-4.83	1.56	2.25	61.9	1,479	1,608	2,014	1
SC3A	2	298	-3.45	-5.52	1.56	2.21	61.7	1,448	1,575	2,005	1
SC4A	2	298	-6.90	-7.59	1.56	2.27	60.9	1,428	1,607	2,007	1
SC5A	2	298	-6.90	-8.97	1.56	2.52	61.4	1,522	1,764	2,135	1
SC6A	2	298	-6.90	-10.34	1.56	2.19	67.9	1,375	1,701	2,053	1
SC7A	2	298	-5.17	-6.55	1.56	2.33	66.0	1,455	1,665	2,091	1
SC8A	2	298	-5.17	-7.93	1.56	2.29	60.8	1,423	1,611	2,000	1
SC9B	2	298	-5.17	-9.31	1.56	2.33	60.9	1,415	1,683	2,080	1
SC10	2	298	-1.00	-6.00	1.56	0	28.1	1,531	1,808	1,819	1
SC11	2	298	-1.00	-6.00	1.56	0	17.0	1,483	1,688	1,724	1
120C891	2	298	-3.26	-3.70	2.00	2.40	33.8	1,284	1,516	1,805	3
RS/DCCS/1	2	298	-1.00	-5.00	0.5 ^(b)	1.66	6.2	1,953	2,000	2,035	2
RS/DCCS/3	2	298	-2.00	-6.00	0.5 ^(b)	1.63	37.1	1,954	1,964	2,087	2
RS/DCCS/4	2	298	-3.00	-7.00	0.5 ^(b)	1.59	57.0	1,953	2,011	2,139	2
RS/DCCS/5	2	298	-4.00	-8.00	0.5 ^(b)	1.55	59.1	1,939	1,953	2,093	2
RS/DCCS/10	2	298	-5.00	-9.00	0.5 ^(b)	1.49	47.0	1,958	1,981	2,146	2
RS/DCCS/15	2	298	-1.00	-5.00	0.5 ^(b)	1.77	5.9	1,946	1,960	2,042	2

(a) 1-Brodsky [1994], 2-Mellegard et al. [1999], and 3-Zeuch et al. [1991].

(b) Grain size was assumed to be 0.5 because dynamic compaction reduces grain sizes.

**Table 3-3. Time-Weighted Average Test Conditions for the Hydrostatic
Consolidation Tests (Page 1 of 2)**

Test	Datapoint in File comb.dat	Temp. (K)	Axial Stress (MPa)	Lateral Stress (MPa)
CS1	1 through 100	298	-1.70	-1.70
CS2	101 through 200	298	-1.70	-1.70
CS3	201 through 300	298	-1.70	-1.70
CS4	301 through 400	298	-1.72	-1.72
CS5	401 through 500	298	-1.67	-1.67
CS6	501 through 600	298	-1.70	-1.70
CS7	601 through 700	298	-1.70	-1.70
CS8	701 through 800	298	-1.70	-1.70
CS9	801 through 900	298	-1.73	-1.73
CS10	901 through 1000	298	-3.41	-3.41
HC1A	1001 through 1100	298	-1.72	-1.72
HC2A	1101 through 1200	298	-1.72	-1.72
HC3A	1201 through 1300	298	-3.45	-3.45
HC4A	1301 through 1400	298	-3.46	-3.46
HC5A	1401 through 1500	298	-6.91	-6.91
HC6A	1501 through 1600	298	-6.88	-6.88
27JUL82	1601 through 1700	294	-1.69	-1.69
04MAY82	1701 through 1800	313	-1.72	-1.72
30APR82	1801 through 1900	333	-1.74	-1.74
07MAY82	1901 through 2000	353	-1.76	-1.76
12MAY82	2001 through 2100	373	-1.77	-1.77
05FEB82	2101 through 2200	294	-3.44	-3.44
09APR82	2201 through 2300	313	-3.49	-3.49
26MAR82	2301 through 2400	333	-3.44	-3.44
02APR82	2401 through 2500	353	-3.36	-3.36
13APR82	2501 through 2600	373	-3.39	-3.39
29JAN82	2601 through 2700	294	-6.67	-6.67
26FEB82	2701 through 2800	294	-9.53	-9.53
27JU61	2801 through 2900	297	-0.70	-0.70
23JL51	2901 through 3000	293	-1.81	-1.81
14NV51	3001 through 3100	293	-1.73	-1.73
25FE61	3101 through 3200	293	-1.74	-1.74

Table 3-3. Time-Weighted Average Test Conditions for the Hydrostatic Consolidation Tests (Page 2 of 2)

Test	Datapoint in File comb.dat	Temp. (K)	Axial Stress (MPa)	Lateral Stress (MPa)
10MY51	3201 through 3300	293	-1.74	-1.74
20AU51	3301 through 3400	293	-1.74	-1.74
16JL51	3401 through 3500	293	-3.46	-3.46
18JU51	3501 through 3600	293	-3.47	-3.47
30OC51	3601 through 3700	296	-3.50	-3.50
16JA61	3701 through 3800	295	-3.41	-3.41
19DC44	3801 through 3900	293	-3.44	-3.44
13AU51	3901 through 4000	293	-3.47	-3.47

3.2 DESCRIPTION OF RECENT LABORATORY TESTS

Since the status of the crushed-salt constitutive model was reported by Callahan et al. [1998b] and Hansen et al. [1998], five additional laboratory tests have been completed and are included in the present work. Two of these tests are shear consolidation tests; three of the tests are constant strain-rate tests. These tests have been reported separately by Mellegard et al. [1999]. The shear consolidation tests are included in the crushed-salt database used to determine parameter values for the constitutive model and will be summarized here. The constant strain-rate tests are used to verify the constitutive model and are discussed in chapter 5.0.

The two shear consolidation creep tests were performed on dynamically compacted crushed-salt specimens that were fabricated with a laboratory-scale device following a procedure similar to that used for dynamic compaction of large-scale samples [Hansen and Ahrens, 1998]. This device simulated of the compaction technique envisioned for the shaft sealing design. The laboratory-scale device used two Proctor split compaction molds (American Society for Testing and Materials [1991a, 1991b]) to receive the disaggregated salt. After compaction, the molds were removed and the ends of the cylindrical samples were machined to produce testable specimens with nominal dimensions of 100 millimeters in diameter and 200 millimeters in length. The starting material was wetted with a brine so that the specimen moisture content was nominally 1.6 % by weight. The dry density of the specimens was about $1,950 \text{ kg/m}^3$, which is a fractional density of approximately 0.9 (assuming intact salt density of $2,160 \text{ kg/m}^3$). The energy input to create this density was approximately 2.6 times the modified Proctor energy (American Society for Testing and Materials [1991a, 1991b]). The specimens fabricated with the laboratory-scale device were identified with the unique labels, RS/DCCS/*n*, where *n* took on values of 10 and 15 to designate individual specimens. As shown in Table 3-2, four other shear consolidation tests on dynamically compacted crushed salt were performed previously.

Table 3-4. Time-Weighted Average Test Conditions for the Shear Consolidation Tests

Test	Datapoint in File shear.dat	Temp. (K)	Axial Stress (MPa)	Lateral Stress (MPa)
SC1B	1 through 100	298	-4.15	-3.45
SC2A	101 through 200	298	-4.82	-3.46
SC3A	201 through 300	298	-5.52	-3.45
SC4A	301 through 400	298	-7.58	-6.90
SC5A	401 through 500	298	-8.97	-6.92
SC6A	501 through 600	298	-10.33	-6.91
SC7A	601 through 700	298	-6.54	-5.17
SC8A	701 through 800	298	-7.92	-5.17
SC9A	801 through 900	298	-9.33	-5.17
SC10	901 through 1000	298	-6.01	-1.01
SC11	1001 through 1100	298	-6.00	-1.02
12OC891	1101 through 1200	293	-3.70	-3.26
RS/DCCS/1	1201 through 1300	297	-4.95	-1.01
RS/DCCS/3	1301 through 1400	297	-5.98	-2.00
RS/DCCS/4	1401 through 1500	297	-6.99	-3.00
RS/DCCS/5	1501 through 1600	298	-7.99	-4.00
RS/DCCS/10	1601 through 1700	297	-9.01	-5.00
RS/DCCS/15	1701 through 1800	298	-5.00	-1.01

The two shear consolidation tests were effectively standard triaxial compression creep tests ($\psi = \pi/6$) and typical test procedures have been described previously [Callahan et al., 1995; Brodsky, 1994]. The specimens were initially loaded hydrostatically to the level of specified confining pressure (lateral stress) and allowed to stabilize. The specified confining pressure levels for the two tests were -5 and -1 MPa. Data were collected during the hydrostatic loading phase. Following stabilization, the axial compressive stress for each test was increased by 4 MPa while holding the confining pressure constant so that each specimen was subjected to a stress difference of $\Delta\sigma = 4$ MPa; only the confining pressure was different for the two tests. Data were also acquired when the axial stress difference was applied. After the axial stress difference was imposed, it was held constant while data were acquired during the shear consolidation creep phase. The test matrix for the shear consolidation creep tests is shown in Table 3-5 where the first column contains the specimen identification and the following three columns give the axial stress, lateral stress, and temperature, respectively, based on the time-weighted average of the actual laboratory data. Both tests were performed in a drained condition; i.e., the pore pressure was zero.

Table 3-5. Shear Consolidation Creep Test Matrix

Specimen Identification	Test Conditions		
	Axial Stress (MPa)	Lateral Stress (MPa)	Temperature (°C)
RS/DCCS/10	-9.01	-5.00	24
RS/DCCS/15	-5.00	-1.01	25

Earlier analyses (based on the constitutive model) predicted that a stress state existed where the lateral strain rate would initially be negative (compaction) and then reverse direction and become positive as the specimen density increased. The scheme for finding this stress state was to change the mean stress by testing at different confining pressures while holding the axial stress difference constant, as reported by Hansen et al. [1998]. The four tests completed previously (see Table 3-2) were run at confining pressures of -1, -2, -3, and -4 MPa all with a stress difference of 4 MPa. Thus, Test RS/DCCS/10 is simply the next test in that progression; whereas, Test RS/DCCS/15 is a repeat of the first test. The creep strain results from the two tests are compared in Figure 3-1, which plots axial and lateral creep strains as a function of time.

A very significant phenomenon is observed in Test RS/DCCS/10: *the lateral strain rate was initially negative (specimen diameter decreasing) and after some densification of the specimen, the lateral strain rate decreased and ultimately changed sign and became positive (specimen diameter increasing)*. This observation is important to the work presented in Chapter 4.0, where the parameters of the crushed-salt constitutive model are determined. As stated earlier, this behavior is known to exist because as crushed salt consolidates and approaches full consolidation, its behavior has to become similar to that of intact salt. However, to be able to accurately capture this behavior in a constitutive model, the phenomenon must be included in the database so that the fitted parameter values capture the full range of material behavior.

Figure 3-1. Axial and lateral strain as a function of time for two, shear consolidation creep tests on dynamically compacted crushed salt.

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4.0 MODEL FITTING

4.1 INTRODUCTION

The crushed-salt constitutive model given in Equation 2-38 contains 31 material parameters. Seventeen of these material parameters are contained in the dislocation creep (M-D) portion of the model. The M-D model parameters were fixed at the values provided by Munson et al. [1989] for clean salt. The pressure solution portion of the model contains seven material parameters, and the remaining seven material parameters comprise four flow potential material parameters and three equivalent stress measure parameters. These 14 remaining parameters were determined by fitting the equations that define the crushed-salt constitutive model to the laboratory data such that the weighted squared difference between the measured and calculated response was minimized. First, the flow potential parameters (κ_0 , κ_1 , n , and D_t) were determined by fitting Equation 2-18, which defines the lateral-to-axial strain-rate ratio, to the data measured in the 18 shear consolidation tests. Second, these flow rate parameters were fixed and the ten creep consolidation parameters (η_0 , η_1 , n_f , a , p , n_s , r_1 , r_3 , r_4 , and Q_s/R) were determined by fitting the rate equations that define the axial and lateral strains to the data measured in the 18 shear consolidation and 40 hydrostatic consolidation tests. These nonlinear regressions were performed using the personal-computer platform BioMedical Data Processing (BMDP, Version 7.01) statistical software package.

4.2 MODELING PROCEDURE

The *object function* is the mathematical function that is to be minimized in the least-squares sense. For example, when performing a least-squares fit of some data to a straight line, the object function is the squared difference between the measured response (the data) and the predicted response from the equation for the straight line. The equation for the straight line when performing linear regression is called the *response model*.

The object function is evaluated at discrete points. These points are the points where data have been taken or are available. Some of the measurements may be more important than others and should hold more importance or *weight* than other data points. Mathematically, the relative importance of the level of fit to each data point is accommodated through a *weighting function*.

Application of least-squares minimization results in an estimation of the parameters of the response model. In the example cited above, application of least-squares will result in the estimation of the two parameters necessary to specify a straight line under the implicit assump-

tion that the measurements will be distributed about the response model for fixed values of the (hopefully) independent parameters. For complex nonlinear models, the independence of the parameters is not always obvious before fitting. The parameters obtained from a least-squares fit to a nonlinear model may not be appropriate if the parameters are highly correlated.

The response model will almost never reproduce all of the measurements exactly. The difference between the measured data points and the predicted model response is termed the *residual*. When a weighting function is used in the model fitting, the weighted residual is also of interest. The weighted residual is the usual residual multiplied by the weighting function value for the specific observation or data point.

The object function for the crushed-salt constitutive model was developed under the following assumptions and reflects the relative importance associated to individual data points:

- Within a given test, there are an equal number of measurement points (100). Each data point was assumed to have equal weight.
- Within each test, the data are not uniformly distributed with respect to time; the data are more dense early in time when the strain rates are highest. Thus, the weight function that was used in the model fitting reflects the time-step size relative to each data point in each test, such that higher weights are assigned to data points at the end of the test than are assigned to early-time data points.
- Tests of longer duration were assumed to be more important than tests of shorter time duration.
- Residuals were normalized. They are represented as percent deviations from the measured data. Thus, a 10-% deviation from a very small strain results in the same error in the object function as a 10-% deviation from a very large strain.

4.2.1 Response Functions

In the shear consolidation tests, there are two independent measurements (superscript m is used to indicate measurements); namely, the volumetric strain (ϵ_v^m) and the axial strain (ϵ_a^m). The lateral strain (ϵ_l^m) is calculated as:

$$\epsilon_l^m = \frac{\epsilon_v^m - \epsilon_a^m}{2} \quad (4-1)$$

The axial strain rate ($\dot{\epsilon}_a^m$) was calculated from the measurement of axial strain and elapsed time as follows. At every data point in the original test data file (some contained thousands of data points), the axial strain rate was calculated as the linear least-square fit to a small interval of data (window) centered on the point in time. The window was then shifted by one data point to

the next point in time and the linear fit was repeated. This process was repeated until a point was reached where the width of the window reached the end of the data file for each test. A 50-point window was used in this process. The lateral strain rate ($\dot{\epsilon}_l^m$) was calculated in a similar fashion. The measured lateral-to-axial strain-rate ratio (R^m) is defined as (cf. Equations 2-17 and 2-18):

$$R^m = \frac{\dot{\epsilon}_l^m}{\dot{\epsilon}_a^m} \quad (4-2)$$

Following the development in Chapter 2.0, the response function used to determine the flow potential parameters is:

$$R^p = \frac{\alpha + \frac{\beta}{2}}{\alpha - \beta} \quad (4-3)$$

where:

R^p = predicted lateral-to-axial strain-rate ratio

$$\alpha = \frac{\kappa_0 \Omega^{\kappa_1} \sigma_m}{3}$$

$$\beta = \left(\frac{2 - D}{D} \right)^{\frac{2n}{n+1}} (\sigma_1 - \sigma_3)$$

$$\Omega = \left\{ \frac{(1 - D_v)n}{[1 - (1 - D_v)^{1/n}]^n} \right\}^{\frac{2}{n+1}}$$

$$D_v = \begin{cases} D_t & D \leq D_t \\ D & D > D_t \end{cases}$$

D = current fractional density

σ_m = mean stress = $(\sigma_3 + 2\sigma_1)/3$

σ_3 = minimum principal stress

σ_1 = maximum principal stress

and

κ_0 , κ_1 , n , and D_t = flow potential parameters.

The response function (λ) used to determine the creep consolidation parameters is:

$$\lambda = 1 - \left\{ \left[(1 - R_1)^2 + (1 - R_2)^2 \right] w t \right\}^{1/2} \quad (4-4)$$

where:

$$R_1 = \epsilon_a^p / \epsilon_a^m$$

$$R_2 = \epsilon_l^p / \epsilon_l^m$$

$$w t = \Delta t / \bar{t} = \text{weighting function}$$

$$\Delta t = \text{time-step size}$$

$$\bar{t} = \text{normalizing time} = 10^6(\text{s})$$

$$\epsilon_l^p = \text{predicted lateral strain} = \int_0^t \dot{\epsilon}_l^p dt$$

$$\epsilon_a^p = \text{predicted axial strain} = \int_0^t \dot{\epsilon}_a^p dt$$

$$\dot{\epsilon}_l^p = \text{predicted lateral strain rate} = (\alpha + \beta/2) \frac{\dot{\epsilon}_{eq}}{\sigma_{eq}}$$

$$\dot{\epsilon}_a^p = \text{predicted axial strain rate} = (\alpha - \beta) \frac{\dot{\epsilon}_{eq}}{\sigma_{eq}}$$

$$\dot{\epsilon}_{eq} = \text{equivalent inelastic strain rate} = \dot{\epsilon}_{eq}^d + \dot{\epsilon}_{eq}^w$$

$$\sigma_{eq} = \text{equivalent stress measure} = \left[\kappa_o \Omega^{\kappa_1} \sigma_m^2 + \left(\frac{2 - D}{D} \right)^{\frac{2n}{n+1}} (\sigma_1 - \sigma_3)^2 \right]^{1/2}$$

$$\dot{\epsilon}_{eq}^d = \text{Munson-Dawson dislocation creep strain-rate model given in Equations 2-20 to 2-29}$$

$$\dot{\epsilon}_{eq}^w = \text{Spiers pressure-solution inelastic strain-rate model given in Equations 2-36 and 2-37}$$

and:

$\eta_0, \eta_1, n_p, a, p, n_s,$
 $r_1, r_3, r_4,$ and Q_s/R = creep consolidation parameters.

The Munson-Dawson dislocation creep model has 17 parameters, which are given in Table 4-1 for clean WIPP salt.

Table 4-1. M-D Model Parameter Values for Clean Salt

Parameter	Units	Clean Salt
A_1	yr ⁻¹	2.645·10 ³⁰
	s ⁻¹	8.386·10 ²²
A_2	yr ⁻¹	3.050·10 ²⁰
	s ⁻¹	9.672·10 ¹²
Q_1/R	K	12,581
Q_1	cal/mol	25,000
Q_2/R	K	5,033
	cal/mol	10,000
n_1	—	5.5
n_2	—	5.0
B_1	yr ⁻¹	1.919·10 ¹⁴
	s ⁻¹	6.0856·10 ⁶
B_2	yr ⁻¹	9.568·10 ⁵
	s ⁻¹	3.034·10 ⁻²
q	—	5,335
σ_o	MPa	20.57
μ	MPa	12,400
m	—	3.0
K_o	—	6.275·10 ⁵
c	K ⁻¹	9.198·10 ⁻³
α	—	-17.37
β	—	-7.738
δ	—	0.58

4.2.2 Object Function

The object function is the sum-of-squared errors (SS_E). In determining the flow rate parameters, the sum-of-squared error is defined as:

$$SS_E = \sum_{i=1}^N \left(R_i^p - R_i^m \right)^2 \quad (4-5)$$

where:

R_i^p = predicted lateral-to-axial strain rate ratio for the i^{th} data point (Equation 4-3)

R_i^m = measured lateral-to-axial strain rate ratio for the i^{th} data point (Equation 4-2)

N = number of data points in test database.

To determine the creep consolidation parameters, the sum-of-squared error is defined as:

$$SS_E = \sum_{i=1}^N \left(1 - \lambda_i \right)^2 \quad (4-6)$$

where:

λ_i = response function defined in Equation 4-4
for the i^{th} data point.

4.3 STATISTICAL MEASURES

One key aspect of the model-fitting effort is deciding if the model fit to one database is better than the fit to the other database. In this section, the statistical measures for evaluating and comparing fits to the crushed-salt constitutive model are discussed.

4.3.1 Weighted Residual

In all types of regression, the summation of weighted, squared residuals is the function that is minimized, where the residual is defined as the difference between the observed and predicted functional values. The sum-of-squared error term defined in Equation 4-6 was used in evaluating the model fits to two databases: (1) the shear consolidation tests only and (2) the combined shear and hydrostatic consolidation tests.

The specific weighting function associated with the sum-of-squared error is equal to the reciprocal of the measured axial strain squared $(\epsilon_a^m)^2$, the reciprocal of the measured lateral strain squared $(\epsilon_l^m)^2$, the time increment (Δt) , and the reciprocal of a normalizing time (10^6 s) . Thus, if the response model (Equation 4-4) predicts zero axial strain and zero lateral strain over the duration of all tests in the database, the term SS_E in Equation 4-6 will have a value of twice the number of million seconds in the database. This is termed the maximum value of the sum-of-squared error $(SS_E^{\max})$. The 40 hydrostatic consolidation tests constitute a total of $76.02(10^6) \text{ s}$. The 18 shear consolidation tests total $73.93(10^6) \text{ s}$. Therefore, $SS_E^{\max} = 147.86$ in the fit to the shear tests, and $SS_E^{\max} = 299.90$ in the fit to the combined test database.

In a similar fashion, if the response model is a perfect predictor for all of the tests in the database, the sum-of-squared error will be exactly zero. This is the minimum value of the sum-of-squared error.

For each model fit, the sum-of-squared error was normalized as follows:

$$0 \leq \overline{SS_E} \leq 1 \quad (4-7)$$

where:

$$\overline{SS_E} = SS_E / SS_E^{\max}$$

The normalized sum-of-squared error is used to compare the model fits to the two databases.

4.3.2 Parameter Multicollinearity

When fitting a mathematical relation to a set of laboratory-measured data, it is desirable to have enough information in the measured database to ensure that each of the parameters can be uniquely determined. Two possibilities can occur that will not allow for a unique determination of each parameter in a mathematical relation. First, the mathematical relation may inherently include parameters that are dependent upon one another. For example, in the relation:

$$F = A + B \quad (4-8)$$

the parameters A and B cannot be determined uniquely.

Second, there may not be sufficient data in the database to uniquely determine the magnitude of certain model parameters. For example, there is minimal variation in grain size (d), moisture content (w), and temperature (T) in the shear consolidation tests ($\Delta\sigma \neq 0$). Thus, in fitting the crushed-salt constitutive model to these tests, the parameters p , a , and Q_s/R contained in the product of the functional forms containing them; i.e.,

$$\xi(d, w, T) = \frac{w^a}{d^p T} \exp(-Q_s/RT) \quad (4-9)$$

cannot be uniquely determined.

When either of the two aforementioned conditions exist, a condition of multicollinearity is said to exist [Montgomery and Peck, 1982]. An examination of the parameter covariance matrix illustrates the degree to which the material parameters are correlated to each other. The higher the parameter covariance, the higher the parameter collinearity. When a multicollinearity situation exists, one must (1) expand the database of measurements or (2) modify the functional form of the model.

The elements of the correlation matrix (C_{ij}) can be expressed as [Montgomery and Peck, 1982]:

$$C_{ij} = \frac{q_{ij}}{\sqrt{q_{ii} q_{jj}}} \quad (4-10)$$

where:

$$q_{ij} = [z_{ip} \ z_{pj}]^{-1}$$

$$z_{ij} = \frac{\partial \epsilon^m(x_j, \bar{p})}{\partial p_i}$$

$\bar{p}$ = set of parameters taken at their mean values

p_i = i^{th} parameter

x_j = j^{th} model variable

ϵ^m = measured response.

If the parameters are uncorrelated, then $C_{ij} = 0$. Conversely, the correlation coefficient is one if the parameters are totally correlated. The parameters are highly correlated if $|C_{ij}| \geq 0.90$ and a state of parameter multicollinearity may exist.

A scalar quantity, termed the parameter correlation measure (pcm), was used in this study as a global measure of the parameter correlations associated with each model's fit to each database.

This measure is defined as:

$$\text{pcm} = \frac{\frac{1}{2} \left(\sum_{i=1}^p \sum_{j=1}^p C_{ij}^2 - p \right)}{\sum_{i=1}^{p-1} i} = \frac{2 \sum_{i=2}^p \sum_{j=1}^{i-1} C_{ij}^2}{p^2 - p} \quad (4-11)$$

where p is the number of parameters in the model and $0 \leq \text{pcm} \leq 1$. The numerator in Equation 4-11 is the sum of the squares of the lower triangular components of the parameter correlation matrix (Equation 4-10), and the denominator simply normalizes the result by the number of components in the sum. Obviously, the lower the parameter correlations, the lower the magnitude of the parameter correlation measure. Finally, an average parameter correlation ($\bar{c}$) can be quantified as:

$$\bar{c} = \sqrt{\text{pcm}} \quad (4-12)$$

4.3.3 Parameter Variation Among Fits

The crushed-salt constitutive model was fit to two databases: (1) the shear consolidation tests only and (2) the combination of shear and hydrostatic consolidation tests. If a specific model is the true constitutive law for representing the consolidation of crushed salt, the material parameters in each of the different fits should be the same or nearly the same. To evaluate the parameter variation obtained in the fits, the ratio of the parameter values obtained in the two fits (combined database parameter values divided by shear database parameter values) are examined. If the parameter values change less than the one order of magnitude, the resulting ratio should be between 0.1 and 10.

4.3.4 Predictive Capability

The aptness of the crushed-salt constitutive model (predictive capability) can be demonstrated using the parameter values determined by fitting to the individual test databases. The material parameters determined in the fit to the shear consolidation tests were used to predict each of the hydrostatic consolidation tests. A quantitative measure of the predictive capability is simply the sum-of-squared error (Equations 4-5 and 4-6). This measure was calculated using the

BMDP Program AR (Section 4.4) by fixing the parameter values at those determined in the fit to the shear consolidation tests and fitting (predicting) the hydrostatic consolidation tests.

4.4 BMDP STATISTICAL SOFTWARE

This section describes the BioMedical Data Processing (BMDP) nonlinear regression Programs 3R and AR used in the model fitting. BMDP is a statistical software package developed at the University of California at Berkeley supported by grants from the Biotechnology Resources Branch of the National Institutes of Health and the National Science Foundation.

BMDP Program AR is a nonlinear regression program that estimates the parameters of a nonlinear function by least squares using a pseudo Gauss-Newton algorithm. The response model can be specified as a system of coupled rate equations. The response model derivatives are evaluated numerically based on the initial parameter estimates and are not updated during the regression. In addition to calculating the weighted sum-of-squared error (SS_E), the program calculates the coefficient of multiple determination (R_p^2), the residual mean-squared error (MS_E), and the coefficients of the parameter correlation matrix (C_{ij}). The various program features and supporting documentation of AR are provided in various BMDP technical reports. AR was used in determining the creep consolidation parameters.

BMDP Program 3R is identical to AR with the following exceptions: (1) the model function cannot be expressed as a system of coupled rate equations and (2) the response model derivatives are updated continuously during the regression. 3R was used to determine the flow potential parameters.

The input files required to execute an AR or 3R analysis are described in detail by Dixon et al. [1985] and in the BMDP Users' Digest [Hill, 1984]. The BMDP input files for the model fits are given in Appendix A.

4.5 RESULTS

This section presents the results of the model fits. The results are discussed in terms of the model parameters and the statistical measures defined in Section 4.3.

The crushed-salt constitutive model contains a total of 14 fitted parameters. Four of these parameters are termed the flow potential parameters (κ_0 , κ_1 , n , and D_1). These parameters were determined by fitting the crushed-salt constitutive model to the lateral-to-axial strain-rate ratios measured in the 18 shear consolidation tests. The remaining 10 parameters in the crushed-salt constitutive model are termed the creep consolidation parameters (η_0 , η_1 , n_f , a , p , n_s , r_1 , r_3 , r_4 , and Q_s/R). Two sets of creep consolidation parameters were determined; namely, one set each resulting from fits to a database composed of 18 shear consolidation tests and to a combined database composed of the 18 shear and 40 hydrostatic consolidation tests. The parameters were determined by fitting the crushed-salt constitutive model to the axial and lateral strains measured

in each of the tests. The parameters η_0 , η_1 , and n_f define the stress measure σ_{eq}^f (Equation 2-3). Moisture dependence, grain-size dependence, and temperature dependence are defined by the parameters a , p , and Q_s/R , respectively (Equations 2-34 and 2-36). The remaining parameters (r_1 , r_3 , and r_4) are for the pressure-solutioning portion of the model (Equations 2-36 and 2-37).

4.5.1 Flow Potential Parameters

The flow potential parameters are given in Table 4-2. Plots of the predicted and measured lateral-to-axial strain-rate ratios as a function of density for each of the 18 shear consolidation tests are given in Appendix B.

Table 4-2. Flow Potential Parameters

Parameter	Magnitude	Units
κ_0	10.119	—
κ_1	1.005	—
n	1.331	—
D_t	0.896	—

4.5.2 Creep Consolidation Parameters

The creep consolidation parameters for each of the two model fits are given in Table 4-3. Plots of the predicted and measured lateral and axial strains for each of the 18 shear consolidation tests and 40 hydrostatic consolidation tests are given in Appendix C.

Table 4-3. Creep Consolidation Parameters (Page 1 of 2)

Parameter	Units	Shear Tests	Combined Tests
η_0	—	0.1029	0.0140
η_1	—	3.9387	3.3881
n_f	—	3.5122	3.9660
a	—	0.3147	$1.0(10^{-5})$
p	—	1.6332	1.0341

Table 4-3. Creep Consolidation Parameters (Page 2 of 2)

Parameter	Units	Shear Tests	Combined Tests
n_s	—	0.5576	1.5318
r_1	$m^p \cdot K / (\text{MPa} \cdot s)$	$1.041(10^{-6})$	$2.663(10^{-5})$
r_1^*	$K / (\text{MPa} \cdot s)$	0.0194	0.3369
r_3	—	15.1281	0.1286
r_4	—	0.1678	0.1680
Q_s/R	K	1,077.46	2,897.08

r_1^* assumes grain size (d) = 1 mm and moisture content (w) = 1 %.

4.6 STATISTICAL MEASURES

4.6.1 Sum-of-Squared Error

The sum-of-squared error (SS_E) was calculated using Equation 4-6 for each of the model fits to the shear test database and the combined test database. Using these results and Equation 4-7, the normalized sum-of-squared error ($\overline{SS_E}$) was calculated for each of the model fits. These results are given in Table 4-4.

Table 4-4. Sum-of-Squared Error, SS_E

Test Database	SS_E	$\overline{SS_E}$
Shear	23.52	0.159
Combined	46.76	0.156

These results indicate that the model fit to the two databases are qualitatively about the same; i.e., about 16-% relative error.

4.6.2 Parameter Multicollinearity

The parameter correlation coefficient matrices for each of the model fits to the two databases are given in Tables 4-5 and 4-6. High parameter correlations ($>|\pm 0.9|$) are indicative of possible parameter multicollinearity. As pointed out in Section 4.3.2, high parameter correlations are indicative of either (1) deficiencies in the functional form of the crushed-salt constitutive model or (2) deficiencies (or gaps) in the test database.

In general, most of the parameter correlations are low ($<|\pm 0.9|$) for both fits. However, three sets of parameters in the fit to the shear test database ($a - p$, $r_3 - Q_s/R$, and $r_4 - Q_s/R$) and one set of parameters in the fit to the combined test database ($n_f - \eta_1$) have correlation coefficients greater than $|\pm 0.90|$. As discussed in Section 4.3.2, the shear test database parameter correlations were expected (cf. Equation 4-9).

The parameter correlation measure (pcm) and the average correlation coefficient ($\bar{c}$) were evaluated using Equations 4-11 and 4-12, respectively. These results are given in Table 4-7 for each of the model fits.

These results indicate that the parameters are slightly less correlated in the fit to the combined test database. However, the average correlation coefficient is less than $|\pm 0.5|$ in both fits, which indicates that the possibility of parameter multicollinearity is low.

4.6.3 Parameter Variation Among Fits

A quantitative measure of the parameter variation between the crushed-salt constitutive model fits to the two databases is defined in Section 4.3.3. The ratio simply indicates the magnitude of the change in each of the parameter values between the fits to the combined test database and the shear consolidation test database. The ratios of the parameter values from the two fits are given in Table 4-8. As can be seen in the table, parameters a , r_1 , and r_3 varied by more than one order of magnitude (i.e., parameter ratio <0.1 or >10). This is a significant improvement over earlier work (e.g., Callahan et al. [1995]) where the parameter values were seen to change by several orders of magnitude between the different database fits. Qualitatively, the parameters did not change appreciably overall in the two model fits.

Table 4-5. Parameter Correlation Coefficient Matrix — Model Fit to Shear Consolidation Tests

	η_0	η_1	η_t	a	p	n_s	r_1	r_3	r_4	Q_s/R
η_0	1.0									
η_1	0.1454	1.0								
η_t	-0.8584	-0.6289	1.0							
a	0.0063	0.1278	-0.0724	1.0						
p	-0.0036	-0.0525	0.0295	0.9199	1.0					
n_s	0.0542	0.5542	-0.3274	0.4195	0.1507	1.0				
r_1	-0.0096	0.0100	0.0026	-0.0027	0.0051	-0.1039	1.0			
r_3	-0.0481	-0.1704	0.1242	0.1430	0.3079	-0.6258	0.1888	1.0		
r_4	0.0476	-0.1819	0.0535	-0.2545	-0.2196	0.1028	-0.1882	-0.7864	1.0	
Q_s/R	0.0451	-0.0605	-0.0051	-0.0731	-0.1263	0.3782	-0.1892	-0.9115	0.9516	1.0

Table 4-6. Parameter Correlation Coefficient Matrix — Model Fit to Combined Test Database

	η_0	η_1	η_t	a	p	n_s	r_1	r_3	r_4	Q_e/R
η_0	1.0									
η_1	-0.3350	1.0								
η_t	0.0103	-0.9388	1.0							
a	0.0532	0.2820	-0.3276	1.0						
p	0.3415	-0.5970	0.5266	-0.1563	1.0					
n_s	-0.2313	0.3124	-0.2501	0.1854	-0.0169	1.0				
r_1	-0.0742	0.0442	-0.0207	-0.0070	-0.0174	-0.0906	1.0			
r_3	0.2468	-0.4138	0.3495	-0.2035	0.3888	-0.8495	0.2795	1.0		
r_4	0.4188	-0.3070	0.1607	-0.4692	0.3324	-0.3722	-0.4033	0.3078	1.0	
Q_e/R	0.1698	0.0489	-0.1124	-0.0133	-0.2102	0.2801	-0.0826	-0.5790	0.2697	1.0

The value for the exponent on moisture content, a , given in Table 4-3 for the combined database fit is 10^{-5} , which is the smallest value allowed during the fitting process. During the fitting, the value of a was driven to zero. In other words, the moisture function was driven to act like a Heaviside function turning the pressure solution portion of the model on and off, depending on whether or not moisture was present. However, when moisture content is zero (i.e., $w = 0$) and the exponent is zero, an indeterminate form is created. Thus, the value of the exponent a was limited to the small number to avoid the indeterminate form. Thus, the same conclusion is arrived at as discussed by Hansen et al. [1998] — no improvement in goodness of fit could be achieved by accounting for moisture variation once moisture was present. Further pertinent discussion on moisture is included in Chapter 6.0 of Hansen et al. [1998]. The other two parameter values exhibiting a significant change (r_1 and r_3) are also strongly correlated to the temperature parameter (Q_s/R) as shown in Tables 4-5 and 4-6. The combination of these three parameters can be examined with the function:

$$\chi(r_1, r_3, Q_s/R) = r_1 \exp\left(\frac{Q_s}{RT}\right) \exp(r_3 \epsilon_v) \quad (4-13)$$

Table 4-7. Parameter Correlation Measure

Test Database	pcm	$\bar{C}$
Shear	0.133	0.365
Combined	0.115	0.339

Table 4-8. Parameter Variation

Parameter	Parameter Set Ratio
η_0	0.14
η_1	0.86
n_f	1.13
a	0.00
p	0.63
n_s	2.75
r_1	17.37
r_3	0.01
r_4	1.00
Q_s/R	2.69

If a temperature of 298 K is assumed, the ratios of χ computed with the combined database parameters to the shear database parameters for volumetric strains of -0.10 and -0.15 are found to be 0.173 and 0.367. Thus, the combined effect of the significant change in the individual parameters is not significant. The cause of these changes is probably the lack of temperature variation in the shear consolidation database resulting in correlation of the parameter values. Overall, the change in parameter values from the two database fits is relatively minor.

4.6.4 Predictive Capability

The predictive capability of the crushed-salt constitutive model is measured qualitatively by how well the model fits to the shear consolidation tests are able to predict the hydrostatic consolidation tests. In other words, the shear consolidation test parameter values given in Table 4-3 were used to predict the hydrostatic consolidation tests with the goodness of fit determined by the sum-of-squared error. For comparison, the combined database parameter values given in Table 4-3 were also used to predict the same sets of tests. Different subsets of the hydrostatic tests were considered to see if the shear consolidation parameter values predicted any specific group of tests better than others. The hydrostatic test database subsets include: (1) dry (tests without any added moisture), (2) wet (test with added moisture), and (3) hydrostatic (the entire hydrostatic test database, including tests with and without added moisture). The sum-of-squared error was computed for each of these databases and are presented in Table 4-9. The shear and combined test databases are also included in Table 4-9 for comparison. Each of these databases exclude two tests: 29JAN82 and 26FEB82. These tests were excluded because they lie outside of the predictive range for the shear test-derived parameter values. This occurs because of the high mean stress and relatively low initial fractional densities for these two tests, which are outside of the shear test database. Table 4-9 shows that the shear test parameter set predicts the wet tests much better than the dry tests. Figures comparing the predicted results with the test data from the hydrostatic tests are given in Appendix C; specifically, Figures C-1 through C-40.

Table 4-9. Sum-of-Squared Error in Hydrostatic Consolidation Tests

Database Parameter Set	SS _E for Predicted Database				
	Shear	Dry ^(a)	Wet ^(a)	Hydrostatic ^(a)	Combined ^(a)
Shear	23.52	49.20	22.00	71.20	94.72
Combined	23.59	15.22	7.22	22.44	46.04

^(a) Database excludes tests 29JAN82 and 26FEB82.

Upon visual examination of Figures C-1 through C-4, the shear database parameter value set appears to predict the dry tests better than the combined database parameter value set. However,

examination of Figures C-17 to C-28 shows that the model fit to the shear test database does not predict the hydrostatic tests that are dry very well, particularly as the mean stress increases. As can be seen in Table 4-9, the sum-of-squared error from predicting the wet hydrostatic tests (22.00) is about the same as the combined database parameter set fit to all of the hydrostatic tests (22.44).

These results suggest that the crushed-salt constitutive model (with parameter values determined from the shear consolidation tests) has reasonable predictive ability. As evidenced in Table 4-9, the model predicts the wet hydrostatic tests nearly as well as the model fits all of the hydrostatic tests. However, since the shear consolidation test database only includes two dry tests, the prediction of the dry hydrostatic consolidation tests is not as good. As further evidenced in the figures in Appendix C, visual comparison of the two fits shows qualitative sameness, even though the parameter values themselves might appear to be quite different (Table 4-3). The model contains both a volumetric (hydrostatic) component and a deviatoric (shear) component, both of which are present in the shear consolidation tests. Thus, the model not only characterizes (fits) the shear data well, it can reproduce (predict) simpler conditions nearly as well. This provides strong evidence that the model has the potential for predicting the consolidation of crushed salt in other, more complex, conditions as well, including the behavior of the shaft seal. This is explored further in Chapter 5.0, which presents the model predictions of constant strain-rate tests.

5.0 MODEL VERIFICATION

After a material model has been developed, the question remains as to how well it represents real-world problems. Constitutive model verification is best accomplished through the prediction of carefully conducted in situ experiments. When these in situ experiments do not exist, confidence in the model and partial verification can be accomplished by predicting bench-scale and other laboratory tests outside of the database upon which the model development relied. This was demonstrated in Chapter 4.0 where the shear consolidation parameter value set was used to predict the hydrostatic consolidation tests. In this chapter, model verification is pursued further by predicting three constant strain-rate tests using both the shear and combined database parameter value sets. The constant strain-rate tests provide an excellent verification test of the constitutive model since these tests provide a constant strain-rate and varying stress rate; whereas, the constitutive model was developed based on tests that included a constant stress and a varying strain rate. Since the constant strain-rate tests were not included in the model fitting database and represent a totally different load path than the creep consolidation tests, they are ideal for testing the predictive ability of the constitutive model.

5.1 DESCRIPTION OF CONSTANT STRAIN-RATE TESTS

Three constant strain-rate tests were performed on laboratory-scale specimens. The specimens were dynamically compacted using the same technique and raw crushed-salt materials that were employed for fabrication of the shear consolidation specimens. Thus, the constant strain-rate specimens had nominal lengths of 200 millimeters, nominal diameters of 100 millimeters, and nominal fractional densities of 0.9. All three tests were performed at a confining pressure of -1 MPa, a temperature of 20°C , and a constant axial strain rate. Essentially, the test procedure included applying a -1 MPa confining pressure, monitoring the axial strain rate, and initiating the constant axial strain rate when the monitored rate was less than the targeted test axial strain rate. The constant axial strain rate was different for each test, as shown in Table 5-1.

Specimen RS/DCCS/6 was used to perform the first constant strain-rate test on crushed salt, and this first test served to refine the test procedure as stated above. The first two attempts at performing this test were aborted, but the third attempt was successful. The first attempt was aborted because the constant strain-rate phase of the test was entered before the consolidation rate in the preceding hydrostatic phase had slowed to a value less than $-1 \times 10^{-7} \text{ s}^{-1}$. This caused

the test system to unload. The second attempt was aborted by failure of an electronic power supply in the test system shortly after the constant strain-rate phase had begun. After determining new specimen dimensions (there was some deformation induced during the first two aborted attempts), a third attempt was successful. At the start of the third attempt, the specimen had a length of 190.3 millimeters, a diameter of 101.6 millimeters, and a fractional density of about 0.92. The test duration was about 1 week, and the controlled test variables were maintained. The radial strain rate was initially compressive and eventually changed sign and became extensile as the specimen density increased. The other two constant strain-rate tests, RS/DCCS/11 and RS/DCCS/21, were performed without incident at axial strain rates of one-half and double, respectively, the strain rate used for RS/DCCS/6. Additional details of the constant strain-rate test equipment, procedures, and results can be found in Mellegard et al. [1999].

Table 5-1. Test Matrix for Constant Strain-Rate Experiments

Specimen I.D.	Initial Fractional Density	Axial Strain Rate (10^{-7} s^{-1})	Confining Pressure (MPa)	Temperature (°C)
RS/DCCS/11	0.912	-0.5	-1	20
RS/DCCS/6	0.921	-1.0	-1	20
RS/DCCS/21	0.907	-2.0	-1	20

5.2 PREDICTION OF CONSTANT STRAIN-RATE TESTS

The crushed-salt constitutive model described in Chapter 2.0 was incorporated into the thermomechanical finite element stress analysis program SPECTROM-32 [Callahan et al., 1989], Version 4.10. Thus, prediction of the constant strain-rate tests was performed using the finite element program with one element. For each test simulation, an element was initially subjected to the time-weighted average axial and lateral stress conditions realized in each test. The stress condition was designed to be a hydrostatic load of -1 MPa; however, the actual test conditions achieved were slightly different than the design condition. The stress conditions were maintained for the *hydrostatic* duration realized in the tests. Then, time-weighted average, time-wise kinematic boundary conditions were applied to the element that matched the constant strain-rate conditions achieved in the tests. The actual time-weighted test conditions for confining pressure

and axial strain rate, as well as the duration of the hydrostatic phase for each of the tests, are given in Table 5-2.

Table 5-2. Time-Weighted Average Test Conditions for Constant Strain-Rate Experiments

Specimen I.D.	Hydrostatic Duration (s)	Axial Stress (MPa)	Lateral Stress (MPa)	Axial Strain Rate (10^{-7} s^{-1})
RS/DCCS/11	93,150	-1.025	-0.998	-0.504
RS/DCCS/6	13,127	-0.999	-0.987	-1.008
RS/DCCS/21	55,870	-1.047	-0.985	-2.040

Thus, the constant strain-rate test simulations used the average actual test conditions. Simulations were performed using both the shear database and combined database parameter sets given in Table 4-3.

Axial and lateral strain simulation results obtained for the three constant strain-rate tests are shown in Figures 5-1 through 5-3 plotted with the laboratory data.

Predicted results are shown for the two different parameter value sets given in Table 4-3. In all three figures, the axial and lateral strain simulation results reproduce the laboratory data reasonably well; however, an offset is noticeable in the strains that appears to be generated by the hydrostatic portion of the tests. The laboratory data exhibit a curious lateral and axial strain response during the presumed hydrostatic portion of the tests. Normally, one would expect the axial and lateral strain to be the same during hydrostatic compression of a homogeneous material. However, the axial and lateral strains are noticeably different in all three of the constant strain-rate tests during the hydrostatic loading phase of the tests. There are three possible explanations for this anomalous behavior related to (1) stress difference, (2) other modes of deformation, and (3) specimen inhomogeneity. Each of these items is briefly discussed separately.

Figure 5-1. Comparison of predicted strains and laboratory data for test RS/DCCS/11 ($-0.5 \cdot 10^{-7} \text{ s}^{-1}$).

Figure 5-2. Comparison of predicted strains and laboratory data for test RS/DCCS/6 ($-1.0 \cdot 10^{-7} \text{ s}^{-1}$).

Figure 5-3. Comparison of predicted strains and laboratory data for test RS/DCCS/21 ($-2.0 \cdot 10^{-7} \text{s}^{-1}$).

Stress Difference: As given in Table 5-2, the actual axial and lateral stresses applied during the *hydrostatic* portion of the test are not equal as desired. In all three tests, the time-weighted average axial stress is greater than the lateral stress. However, the largest stress difference is only 0.0619 MPa for Test Specimen RS/DCCS/21. While this stress difference contributes to the larger axial strains, it does not appear to be large enough to be solely responsible for the differences in axial and lateral strains. This judgment is made based on the predicted test results which show almost no difference between the axial and lateral stresses. The constitutive model predicts the shear consolidation tests reasonably well; however, these tests involve larger stress differences. This leads one to believe other factors are involved in the axial and lateral strain differences.

Deformation Modes: Upon loading the specimen, there is a certain amount of cataclastic deformation and sliding along the particle interfaces. These deformation mechanisms could create axial and lateral strain differences, which would be amplified by the stress difference.

Specimen Inhomogeneity: Preparation of the dynamically compacted crushed-salt specimens is discussed in detail by Mellegard et al. [1999]. Basically, a laboratory-scale compaction device that approximates the envisioned shaft seal compaction method was used to fabricate the specimens. The specimens were fabricated in three lifts, which created layers of finely pulverized salt about 10 millimeters thick at one-third and two-thirds of the specimen height. These bands of fines, perpendicular to the specimen axis, form significant specimen inhomogeneities that may have contributed to the anisotropic deformation behavior of the specimens. These bands would not affect the axial deformation significantly but could have acted as stiffeners restricting the lateral compaction of the specimens.

With the data available, the importance of these three factors' impact on the specimen deformation cannot be quantified. All three factors may be contributing to the observed deformation behavior of the specimens.

Figures 5-4 through 5-6 plot only the constant strain-rate portion of the tests. This portion of the test begins after the hydrostatic portion ends, as given in Table 5-2. In Figures 5-4 through 5-6, the axial and lateral strains and time have been translated so that the values are all zero at the beginning of the constant strain-rate portion for each test. These results show that the simulation results reproduce the laboratory data quite well. Of course, the axial strain rate is an imposed condition that should be reproduced exactly, and the fact that the axial strain simulation results overlay the axial laboratory data provides a check that the correct strain rate was used in the simulations. Figures 5-7 through 5-9 plot the lateral strains only for the constant strain-rate portion of the tests so that comparison of the computed results and laboratory data can be made

more readily. These figures show decreasing agreement between computed results and laboratory data as the strain rate increases. However, the prediction of the lateral strains is still quite good even at the highest strain rate when one considers the fact that both the test data and load path for the constant strain-rate tests are outside of the database upon which the constitutive model parameters are based. Figures 5-1 through 5-9 show minor differences between the predicted results for the shear and combined database parameter value sets even though some of the parameter values in the two sets appear to be quite different.

The predicted axial stress results for the three constant strain-rate tests are compared in Figures 5-10 through 5-12. The lateral stresses (or confining pressures) are constant throughout the duration of the tests at the values given in Table 5-2. The predicted stress magnitudes are in the range of the laboratory results but consistently over predict the laboratory data following application of the constant strain rate. The over prediction is amplified as the constant strain rate increases. The discontinuities in the axial stress measurement were traced back to a test system control problem, as discussed by Mellegard et al. [1999]. This problem was eliminated, but not until after all three constant strain-rate tests had been conducted. As seen in Figures 5-10 through 5-12, the laboratory measured axial stresses do not increase significantly as the strain rate increases, despite RS/DCCS/21 strain rate being four times that of RS/DCCS/6; whereas, the increase of the predicted axial stresses is significant with increasing strain rate. A rapid rise in axial stress is seen in each of the test simulation results following application of the constant strain rate. There are undoubtedly cataclastic deformation mechanisms operative in these crushed-salt specimens. These mechanisms, which are not included in the crushed-salt constitutive model, are most likely responsible for the moderate stress rises observed in the laboratory tests as compared to the rapid rise in the stress seen in the predictions.

The numerical prediction of the constant strain-rate tests shows that the crushed-salt constitutive model is able to predict the strains quite well. The prediction of the stresses is not as good as the strain predictions and indicates that deficiencies remain in the model. These deficiencies are believed to be embodied in the lack of cataclastic deformation mechanisms in the model. However, the importance of the cataclastic deformation will not be as important in the actual crushed-salt seal components where the strain rates will be more than an order of magnitude less than the slowest strain rate used in the laboratory tests.

Figure 5-4. Comparison of predicted strains and laboratory data for the constant strain-rate portion of test RS/DCCS/11 ($-0.5 \cdot 10^{-7} \text{s}^{-1}$).

Figure 5-5. Comparison of predicted strains and laboratory data for the constant strain-rate portion of test RS/DCCS/6 ($-1.0 \cdot 10^{-7} \text{ s}^{-1}$).

Figure 5-6. Comparison of predicted strains and laboratory data for the constant strain-rate portion of test RS/DCCS/21 ($-2.0 \cdot 10^{-7} \text{ s}^{-1}$).

Figure 5-7. Comparison of predicted lateral strains and laboratory data for the constant strain-rate portion of test RS/DCCS/11 ($-0.5 \cdot 10^{-7} \text{ s}^{-1}$).

Figure 5-8. Comparison of predicted lateral strains and laboratory data for the constant strain-rate portion of test RS/DCCS/6 ($-1.0 \cdot 10^{-7} \text{ s}^{-1}$).

Figure 5-9. Comparison of predicted lateral strains and laboratory data for the constant strain-rate portion of test RS/DCCS/21 ($-2.0 \cdot 10^{-7} \text{ s}^{-1}$).

Figure 5-10. Comparison of predicted axial stress and laboratory data for test RS/DCCS/11 ($-0.5 \cdot 10^{-7} \text{ s}^{-1}$).

Figure 5-11. Comparison of predicted axial stress and laboratory data for test RS/DCCS/6 ($-1.0 \cdot 10^{-7} \text{s}^{-1}$).

Figure 5-12. Comparison of predicted axial stress and laboratory data for test RS/DCCS/21 ($-2.0 \cdot 10^{-7} \text{ s}^{-1}$).

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6.0 SHAFT SEAL CALCULATIONS

The current seal designs for the WIPP specify the emplacement of various materials (asphalt, compacted clay, concrete, and crushed salt) in the shafts from the earth's surface to the repository horizon. Crushed salt will be emplaced within the shafts at depths ranging from 430 meters to 600 meters and dynamically compacted to a fractional density of about 0.9. The flow characteristics of the crushed-salt seal are of primary importance since the long-term function of the seal is to prevent the flow of water into the repository from overlying aquifers and to prevent the flow of gas out of the repository. Closure of the shaft resulting from creep of the surrounding intact salt will consolidate the crushed salt over time. The consolidation process reduces the permeability of the crushed salt from its emplaced state to its intact state, creating an effective long-term seal.

The purpose of this chapter is to demonstrate the creep consolidation behavior of a typical crushed-salt shaft seal problem using the model and material parameter values described in Chapters 2.0 and 4.0. The problem selected is identical to the one presented by Loken [1998]. In this earlier study, Loken [1998] compared the combined-mechanism, crushed-salt constitutive model shaft seal simulation results using material properties from Hansen et al. [1998] to shaft seal simulation results obtained using three earlier candidate crushed-salt constitutive models described by Callahan et al. [1995]. Thus, the results obtained in this chapter are compared with the results generated by prior versions of the crushed-salt model.

6.1 SHAFT PROBLEM DESCRIPTION AND ASSUMPTIONS

The shaft configuration chosen to demonstrate the crushed-salt seal behavior is the simplest configuration that can be used to evaluate the seal system. The model is an axisymmetric representation of the shaft and host rock at a fixed depth. By changing the initial stress and temperature conditions, different depths may be examined. The following assumptions apply to the selected model and govern the simulation procedure:

- A condition of plane strain is assumed to exist with respect to the axial (vertical) direction.
- The stratigraphy at the WIPP is ignored. The intact salt surrounding the shaft is assumed to be composed entirely of argillaceous salt governed by the multimechanism deformation creep fracture (MDCF) model [Chan et al., 1998].
- The initial stress state before shaft excavation is lithostatic.
- The shaft is excavated into the lithostatic stress field at time zero.
- The shaft is assumed to be open for 50 years and then instantaneously filled with crushed salt dynamically compacted to a fractional density of 90-%.
- The weight of the crushed-salt backfill is ignored.

- The shaft is assumed to be sufficiently isolated to exclude the influence from other excavations and shafts.
- The deformation and strains predicted during the simulation period are sufficiently large such that finite strain analysis is required.

Figure 6-1 provides a schematic representation of the shaft seal problem. The radius of the shaft was taken as unity, and the outer boundary was placed at 100 radii to be far enough removed so as not to influence the results. For time $t < 0$ years, the shaft is not present and an initial lithostatic stress field exists in the host rock such that the three principal stresses are identical. At time $t = 0$ years, the cylindrical shaft is excavated and the surrounding host salt formation creeps into the shaft for a period of 50 years. At time $t = 50$ years, crushed salt with an initial density of $1,944 \text{ kg/m}^3$ (90-% of intact salt density) is emplaced within the shaft. The salt surrounding the shaft continues to creep and transfers load to the crushed-salt seal, causing the crushed-salt to consolidate. The total simulation period is 500 years.

A representative depth of 550 meters is used to compare the results predicted by the crushed-salt combined mechanism model with those predicted using previous models. Three additional depths (430 meters, 515 meters, and 600 meters) are used to illustrate the magnitude of consolidation as a function of depth for the combined mechanism model. Temperature and initial stress conditions consistent with the host rock at the four depths considered in the calculations are given in Table 6-1.

6.2 MATERIAL MODELS AND PARAMETER VALUES

Two types of material models are required to solve the shaft seal problem based on the problem definition given in Section 6.1. Material models include: (1) a material model to describe the creep behavior of the host salt formation and (2) material models to describe the consolidation of the crushed-salt seal material. The host salt material model used for all of the comparative analyses was the same so that differences in the material models used for the crushed-salt seal could be observed. In all of the crushed-salt consolidation models, the average grain size and moisture content was assumed to be 1 millimeter and 1-% by weight, respectively. The constitutive models used in this study are described briefly in Section 6.2.1.

Figure 6-1. Schematic representation of the shaft seal problem.

6.2.1 Intact Salt Model

The material behavior of intact salt was modeled using the MDCF model for argillaceous halite. A description of the MDCF model is given by Chan et al. [1998], along with associated parameter values for WIPP argillaceous salt. Loken [1998] provides additional discussion of the parameters used in the analyses. The same intact salt model was used regardless of the constitutive model used to represent the crushed-salt seal. Thus, the host salt formation's driving force on the seal was identical in all analyses until host salt-seal interaction became important.

Table 6-1. Initial Temperature and Stress Conditions at WIPP for Various Depths within the Salado Formations

Depth (m)	Initial Conditions	
	Temperature ^(a) (°C)	Stress ^(b) (MPa)
430	24.8	9.85
515	25.65	11.76
550	26.0	12.57
600	26.5	13.68

^(a) Based on a temperature of 27° at 650-m depth and a geothermal gradient of 10°C/km [Sass et al., 1971].

^(b) Based on an in situ stress of 14.8 MPa at 650-m depth [Bailey et al., 1992] and an average overburden density in the Salado Formation of 2,300 kg/m³ [Krieg, 1984].

6.2.2 Previous Consolidation Models

Loken [1998] used parameter values derived from an earlier crushed-salt database and compared the combined-mechanism crushed-salt model results to those obtained from three earlier creep consolidation models developed for crushed salt. These three earlier creep consolidation models are described by Callahan et al. [1995] and include the modified Sjaardema-Krieg model, the modified Zeuch model, and the modified Spiers model. The Sjaardema-Krieg model is an empirical model. The Zeuch model was derived from a hot-isostatic pressing model for dry crushed salt. The Spiers model is a grain boundary diffusional pressure solution model, appropriate for wet crushed salt. The parameter values that define each of these models are given by Callahan et al. [1998a]. Each of these models also contain a nonlinear elastic model proposed by Sjaardema and Krieg [1987] and described by Callahan et

al. [1995]. Mellegard et al. [1999] show reasonable agreement of additional test data compared with the bulk modulus functional form used by Sjaardema and Krieg [1987]. Finally, each of the creep consolidation models contain a Munson-Dawson (M-D) deviatoric portion using the parameter values given in Table 4-1.

6.2.3 Combined Mechanism Model

The combined mechanism model comprises two mechanisms, dislocation creep and grain boundary diffusional pressure solution, and is described in detail in Chapter 2.0. The same nonlinear elastic model is used with this model as described for the previous consolidation models. Three different sets of parameter values were used for the combined mechanism model for analyses of the shaft seal problem. The first set of parameters, reported by Hansen et al. [1998], was determined from the least-squares fit to the database that includes both the shear and hydrostatic consolidation tests but excludes the recent tests discussed in Chapter 3.0. The results of the shaft analyses using these parameter values are documented in Loken [1998]. The other two sets of parameter values, used in the current analyses, are given in Table 4-3 and are referred to as the *shear parameters* and *combined parameters*. The flow potential parameter values are given in Table 4-2.

6.3 CALCULATION RESULTS

Finite element program SPECTROM-32 [Callahan et al., 1989], Version 4.10, was used to predict the creep deformation of the host rock and the consolidation of the crushed-salt seal material. The finite element model used in solving this problem comprises a single row of 51 isoparametric elements. Fifteen elements were used to represent the shaft and 36 elements were used to model the surrounding intact salt. The outer boundary condition consisted of a constant traction boundary condition consistent with the initial stress level for each respective depth analyzed. Kinematic constraints were applied along the horizontal boundaries to prevent axial displacements.

Eight shaft seal analyses were performed, which resulted from using the shear and combined parameter values sets for the combined mechanism model at each of the four depths. The results of these eight calculations are compared with the results of Loken [1998] for shaft analyses using the modified Sjaardema-Krieg, modified Zeuch, and modified Spiers consolidation models and the combined mechanism model with a different combined database parameter value set. Figure 6-2 presents a comparison of the fractional densities predicted by four creep consolidation models at a depth of 550 meters.

Figure 6-2. Comparison of four creep consolidation models for prediction of crushed-salt fractional density as a function of time at a depth of 550 meters.

These results indicate that the responses are similar for all four models up to a fractional density of 95-%. For this representative depth, approximately 50 years are required to consolidate the crushed salt from 90 to 95-% for all four models. At higher fractional densities, the model results diverge. The results shown in this figure also indicate that the combined mechanism model predicts the fastest consolidation rate when the fractional density is less than 98-%. A relative ranking of the four models in terms of their predicted consolidation rates (from fastest to slowest) is: (1) the combined mechanism model, (2) the modified Sjaardema-Krieg model, (3) the modified Zeuch model, and (4) the modified Spiers model. The results show that the predicted fractional density is nearly a linear function of time for the modified Sjaardema-Krieg model; whereas, the responses of the combined mechanism, modified Zeuch, and modified Spiers models are nonlinear. The Sjaardema-Krieg model predicts full consolidation within 100 years; the other models do not predict that the crushed salt will reach the density of intact salt during the 450-year simulation period following emplacement of the crushed salt. This occurs because the empirical Sjaardema and Krieg model does not stop consolidating when the density of intact salt is reached. The consolidation is simply stopped numerically when the fractional density reaches 100-%.

For comparison, the times required to achieve fractional densities of 92, 94, 96, and 98-% for all four models are given in Table 6-2. Table 6-2 also includes the associated times predicted by the combined mechanism model using the parameter estimates obtained from the fit to the database consisting of 18 shear consolidation tests.

Table 6-2. Time (Years) Required to Reach Fractional Densities for Four Consolidation Models at a Depth of 550 Meters

Fractional Density (%)	Combined Mechanism Model		Modified Sjaardema-Krieg Model	Modified Zeuch Model	Modified Spiers Model
	Shear Parameters	Combined Parameters			
92	16	16	17	17	17
94	32	32	35	35	37
96	49	49	55	57	65
98	67	66	75	100	135
100	—	—	100	—	—

Figure 6-3 shows the calculated fractional densities as a function of time at depths of 430, 515, and 600 meters using the combined mechanism model with the three different parameter sets. The results indicate that the crushed salt will reach 99-% of the density of intact salt within 300 years after emplacement, regardless of depth. The transition from deformation dominated by grain boundary diffusional pressure solution to dislocation creep at very high fractional densities (fractional densities greater than 99-%) is slower for the current parameter estimates than those predicted by Loken [1998] with an earlier derived combined database parameter set.

Figure 6-3 shows that the consolidation rate using the shear and combined test parameters deviates from Loken's results at a fractional density of approximately 98-%. As a result, the time required to consolidate crushed salt to the density of intact salt (fractional density of one) is greater for the shear and combined test parameter values than Loken [1998] computed. Specifically, the times predicted by the combined mechanism model to reach the density of intact salt at a depth of 600 meters are approximately 60 years and 170 years for the Loken [1998] calculations and shear test parameter values, respectively; whereas, the new combined test parameters did not predict full consolidation during the 450-year simulation period. Similar differences are observed at the shallower depths, as illustrated in Figure 6-3.

Figure 6-4 illustrates the time to reach 99.9-% of the intact density of salt predicted by the combined mechanism model as a function of depth for the three parameter sets. As shown in this figure, the time to compact the crushed salt is a nonlinear function of depth. The difference in the model predictions illustrated in this figure is caused by the different consolidation rates determined by the combined mechanism model for fractional densities greater than 98-%. For fractional densities less than 98-%, all models consolidate at approximately the same rate for a given depth, with higher consolidation rates calculated at greater depths as shown in Figure 6-3.

Figure 6-3. Fractional density as a function of time at depths of 430, 515, and 600 meters using the combined mechanism model.

Figure 6-4. Time to consolidate to 99.9 percent fractional density as a function of depth using the combined mechanism model.

In summary, the consolidation rates predicted by the combined mechanism model for a shaft seal problem are nearly the same using the shear and combined parameter values as those predicted using the earlier derived combined parameter values for fractional densities less than 98 -%. For fractional densities above 98-%, significantly slower consolidation rates are predicted using the new parameter values, resulting in a smooth transition to intact salt behavior at full consolidation. Based on the results shown in these analyses, the consolidation rates at high fractional densities (densities greater than 98-% of the density of intact salt) are slightly greater using the shear database values than those predicted using the combined database values. Additionally, the consolidation rates predicted using the combined mechanism model are greater than the consolidation rates predicted using the modified Zeuch and Spiers models. The consolidation rate of the combined mechanism model can either be greater than or less than that predicted by the modified Sjaardema-Krieg model, depending on the fractional density. The modified Sjaardema-Krieg model predicts a nearly linear consolidation rate for all fractional densities; whereas, the consolidation rate predicted by the combined mechanism model is initially greater than that predicted by the modified Sjaardema-Krieg model but is significantly reduced at fractional densities greater than 98-%, which is more representative of observed laboratory data.

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7.0 SUMMARY AND CONCLUSIONS

Crushed salt is planned to be a major long-term component of the shaft seal system at the WIPP site. The crushed-salt seal gradually becomes effective over time as consolidation, caused by creep of the surrounding intact salt, produces shaft closure and loading of the crushed salt. The ability to predict creep consolidation of crushed salt has been important to the design and evaluation of WIPP seals and will undoubtedly be useful in the pending recertification required of the WIPP site. The work reported here represents a culmination of several laboratory and analytical studies devoted to constitutive models for crushed-salt reconsolidation. These earlier studies provided the theoretical bases and laboratory data that support the crushed-salt, combined-mechanism constitutive model. The prior studies, discussed in Section 1.2, have been documented in publications and reports and are summarized by Hansen et al. [1998].

In this study, additional laboratory tests were added to the crushed-salt database. Two new laboratory shear consolidation experiments were conducted with fractional densities near the initial fractional density expected in the dynamically compacted crushed-salt seal (approximately 0.9). These tests expand the database in the fractional density ranges expected in situ and provide information on the crushed-salt flow behavior as its density increases. The expanded database was fit to obtain material parameter values for the crushed-salt constitutive model. The results of the model fitting produced material parameter values representative of the entire database. Two separate fits were performed. The first fit used only the shear consolidation tests in the database, and the second fit used both the shear and hydrostatic consolidation tests. In our previous studies before development of the combined-mechanism model, dramatic changes in the parameter values were observed when the different tests were fit. In the present study, these separate fits produced similar parameter values, which indicates that the constitutive model is more representative of the physics of creep consolidation of crushed salt than were the previous models. These parameter values were used to validate the model against tests outside of the database with different load paths. Three constant strain-rate tests were predicted with the crushed-salt model and compared to the laboratory data. The predicted strains were found to compare quite well with laboratory results; whereas, the predicted axial stress was generally greater than the laboratory measured stresses. Application of the model was demonstrated for typical shaft sealing analysis problems, which illustrate the expected change in fractional density with time for different depths of the shaft seals.

As a result of this study, a constitutive model for crushed salt is available that contains the observed mechanisms for crushed-salt consolidation. When consolidation is complete, the model

predicts intact salt behavior. The model characterizes the experimental data quite well over a wide range of porosities and stress triaxialities and performs reasonably well for stress conditions and load paths outside of the database used for its development.

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APPENDIX A

INPUT FILES TO BMDP, NONLINEAR REGRESSION PROGRAMS 3R AND AR

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APPENDIX A

INPUT FILES TO BMDP, NONLINEAR REGRESSION PROGRAMS 3R AND AR

A.1 DESCRIPTION

The input files required to execute BMDP Program AR and 3R analyses are included in this appendix; specifically, three input files are included. The first file (FLOW.INP) is the input file to the BMDP Program 3R, which was used to determine the flow rate parameters. The second and third files (SHEAR.INP and COMB.INP) are the input files to BMDP Program AR. The input files were used to determine two sets of creep consolidation parameters fit to the shear consolidation database (SHEAR.INP) and the combined shear and hydrostatic consolidation database (COMB.INP).

Basically, the input files can be thought of as a series of paragraphs which are further subdivided into sentences using keywords. Each paragraph is activated by a backslash (/) followed immediately by a keyword. Each of these sentences is activated by keywords and ended with periods. All comment cards are noted using the pound symbol (#). These input files are composed of 12 paragraphs. The first paragraph (/INPUT) contains the title card, the database file name, the format to be used in reading the data, and the number of variables in the database. The second paragraph (/VARIABLES) names each of the 18 variables contained in the database file. The third paragraph (/TRANS) identifies the defined variables (or functions of variables) that are specific to the response model. Specifically, MS and DS are the mean stress and stress difference, respectively. Similarly, D0 and DI are the emplaced and initial fractional density, respectively. The variable USE identifies which test database is to be used in the fit, and the variable WT is the weight function. The fourth paragraph (/REGRESS) identifies the dependent variable (DEPEND), the number of parameters in the model, which variable is the weight function (WEIGHT), which variable number is the integration variable (ITIME) in the rate equations, the number of differential equations (NEQN), the number of iterations (ITER), the number of interval halvings for each iteration (HALVINGS), and the maximum number of integration steps (MAXC). The fifth paragraph (/PARAMETER) identifies the parameter names and the initial estimates, as well as the maximum and minimum values for each of the parameters. The sixth paragraph (/DIFIN) identifies the initial values for each of the dependent variables in the rate equations ($Z(i), i=1, NEQN$). The seventh paragraph (/DIFEQ) specifies the functional form of the rate equations ($DZ(i), i=1, NEQN$). The eighth paragraph (/FUN) identifies the dependent variable (response) function (F). The ninth through eleventh paragraphs (/SAVE, /PRINT, and /PLOT) specify output options for the program. The last paragraph (/END) identifies the end of the input file.

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```

# file = M:\325\fit98\flowp\flow.inp
#
# fit to shear consolidation tests only (itype = 2)
#
=====
#
# This code uses the BMDP routine 3R to fit the equations
# that describe the axial-to-lateral strain rate ratios and
# determine parameter values for the flow potential.
# The following variables are used:
#
# 1. mean stress (MS)
# 2. stress difference (DS)
# 3. current density (RHO)
# 4. axial stress (AS)
# 5. lateral stress (LS)
# 6. fractional density (D)
# 7. axial strain rate (EAR)
# 8. lateral strain rate (ELR)
# 9. lateral-to-axial strain rate ratio (RAT)
#
=====
#
# INPUT PARAGRAPH
#
/INPUT
TITLE = 'COMBINED MECHANISM MODEL FIT TO SHEAR LAT/AX STRAIN RATE'.
FILE = 'M:\325\fit98\flowp\flow.dat'. # Data file name
FORMAT = '(2F10.2, E12.6, 2e15.5)'.
VARIABLES = 5.
#
# VARIABLES PARAGRAPH
#
/VARIABLE
NAMES=AS,LS,D,EAR,ELR.
#
# TRANSFORMATION PARAGRAPH
#
/TRANS
MS = (2.0*LS+AS)/3.0. # mean stress, as=axial stress, ls=conf. pres.
DS = LS - AS. # stress difference
RHO = D*2160. # CURRENT density
RAT = ELR/EAR. # regression function
#
# FIXED FLOW PARAMETERS
#
KAP2 = 1.00.
WT = 1. # uniform weight function
#
# REGRESS PARAGRAPH
#
/REGRESS
DEPEND = RAT. # Dependent variable
PARAMETERS=4. # Number of regression parameters
WEIGHT = WT. # WEIGHT VARIABLE
ITER = 20. # NUMBER OF ITERATIONS
HALVINGS = 3. # NUMBER OF INTERVAL HALVINGS

```

```

#
# ----- PARAMETERS PARAGRAPH -----
#
# Specify the names, initial estimates, and the range of the FOUR
# regression parameters, where KAP0, KAP1, DDT, AND NK determine the
# the equivalent stress measure for the flow potential. KAP2 is fixed
# at a value of one so that the flow potential reproduces intact salt
# at complete consolidation (D=1).
#
/PARAMETER
  NAMES = KAP0,KAP1,DDT,NK.

  INITIAL = 10.11891, 1.005131, .896281, 1.331212.

MINIMUM = 4 * 0.0.
MAXIMUM = 4 * 50.0.
#
# ----- SPECIFY FUNCTION -----
#
/FUN
  IF(D LE DDT) THEN VAR = DDT.
  IF(D GT DDT) THEN VAR = D.
  NUM = (1 - VAR)*NK.
  DEN = (1 -(1-VAR)**(1/NK) ) ** NK.
  OMEGAK = (NUM/DEN) ** (2/(NK+1)).
  KAP = KAP0 * OMEGAK**KAP1.
  TERMK = ( (2-D)/D )**( 2*NK/(NK+1) ).

  ALPHA2 = KAP * MS/3.
  BETA2 = KAP2 * TERMK * DS.

  F2A = (ALPHA2 - BETA2).
  F2L = (ALPHA2 + 0.5*BETA2).
  F = F2L/F2A.
#
# ----- SPECIFY VARIOUS PRINTING AND PLOTTING OPTIONS -----
#
/SAVE
  FILE = 'M:\325\fit98\flowp\flow.SAV'.
  NEW.
  KEEP = rho,RAT.
  FORMAT = '(f10.3,5E12.3)'.

/PRINT
  FORMAT = E.

/PLOT
  RESIDUAL.

/END

```

```

# file = m:\325\fit98\shear\SHEAR.inp
#
# fit to shear consolidation tests only (itype = 2)
#
# -----
#
# This code uses the BMDP routine AR to fit the differential
# equations that describe the axial and lateral strain in the
# shear consolidation tests to determine the parameter values
# for the crushed-salt, combined-mechanism constitutive model.
# The parameter values for the flow potential are determined
# first and then fixed during the fitting in this routine.
# The parameter values for M-D constitutive model are fixed at
# the values for clean intact salt. Ten parameter values
# remain to be determined that describe the effective stress
# measure (ETA0, ETA1, NA) with ETA2 fixed=1, the moisture and
# grain size parameters (AA1, PP), and the pressure solutioning
# parameter values (R1, R3, R4, QSR, NSP). The independent
# parameters are:
#
# 1. mean stress (MS)
# 2. stress difference (DS)
# 3. emplaced fractional density (D0)
# 4. initial fractional density (DI)
# 5. grain size (DD)
# 6. absolute temperature (T)
# 7. moisture content (W)
#
# -----
#
# INPUT PARAGRAPH
#
# /INPUT
# TITLE = 'Combined-Mechanism Model fit to shear consolidation tests'.
# FILE = 'm:\325\fit98\shear\shear.dat'. # Test data file name
# FORMAT = '(2I3,3F10.0,F6.1,2F9.4,4F9.5,F9.3,F9.6,2F9.3,F5.2,F7.2)'.
# VARIABLES = 18.
#
# ----- VARIABLES PARAGRAPH -----
#
# /VARIABLE
# NAMES=ICASE,ITEST,TIME,DT,TF,TEMP,AS,LS,EVT,EVC,EAT,EAC,RHO,D,RHO0,RHOI,DD,W.
#
# ----- TRANSFORMATION PARAGRAPH -----
#
# /TRANS
# MS = (2.0*LS+AS)/3.0. # mean stress, as=axial stress, ls=conf. pres.
# DS = LS - AS. # stress difference
# ELC = (EVC - EAC)/2. # lateral strain, evt=vol. strain, eat=ax.strain
# D0 = 1382.4/2160. # emplaced fractional density
# DI = RHOI/2160. # initial fractional density
# ONE = 1.0. # regression function
#
# FLOW POTENTIAL PARAMETER VALUES
#
# KAP0 = 10.119.
# KAP1 = 1.005.

```

KAP2 = 1.0.
 NK = 1.3312.
 DDT = 0.8963.

17 MUNSON-DAWSON CREEP PARAMETERS FOR CLEAN SALT (FIXED)

A1 = 8.386E+22.
 A2 = 9.672E+12.
 Q1R = 12581.
 Q2R = 5033.
 N1 = 5.5.
 N2 = 5.0.
 B1 = 6.0856E+6.
 B2 = 3.034E-2.
 Q = 5335.
 S0 = 20.57.
 M = 3.
 K0 = 6.275E+5.
 C = 9.198E-3.
 ALPHA = -17.37.
 BETA = -7.738.
 DELTA = 0.58.
 MU = 12400. # SHEAR MODULUS

FIX VALUE OF KAP2 AT ONE

ETA2 = 1.0.

WEIGHT FUNCTIONS

WT1 = DT/1.E+6.
 WT = 1.0. # uniform weight function

ESTIMATE GRAIN SIZE FOR DCCS TESTS

DC = DD.
 IF(KASE GT 1200) THEN DC = 0.5.

 # ——— REGRESS PARAGRAPH ———
 #
 /REGRESS

DEPEND = ONE.	# Dependent variable
PARAMETERS=10.	# Number of regression parameters
WEIGHT = WT.	# WEIGHT VARIABLE
ITIME = 3.	# INTEGRATION VARIABLE NUMBER
NEQN = 3.	# Number of differential equations
ITER = 20.	# NUMBER OF ITERATIONS
HALVINGS = 3.	# NUMBER OF INTERVAL HALVINGS
MAXC = 300000.	# MAXIMUM NUMBER OF TIMES 'DIFEQ' IS USED
PRINT = 0.	# SUPPRESS PRINT ASSOCIATED WITH VARIABLES

 # ——— PARAMETERS PARAGRAPH ———
 #

Specify the names, initial estimates, and the range of the ten
 # regression parameters, where R1 is the over all leading parameter; R3, R4,
 # and N are strain dependent parameters; KAPPA0, KAPPA1, KAPPA2, N determine

```
# the equivalent stress measure for the flow-rule; ETA0, ETA1, ETA2, and Nf
# determine the equivalent stress measure in strain rate measure; A
# is water-content dependent parameters; P defines grain size dependence;
# and QSR defines temperature effect.
```

```
#
/PARAMETER
```

```
NAMES =      ETA0,      ETA1,      NA,
             AA1,      PP,      NSP,
             R1,      R3,      R4,      QSR.
```

```
INITIAL = .102854,      3.9387,      3.5122,
           0.3147,      1.6332,      .557621,
           8.69760,      15.1281,      .167765,      2897.09.
```

```
FIXED = QSR.
```

```
MINIMUM =      3 * 0.0,      0.3147,      6 * 0.0.
MAXIMUM =      10 * 5000.0.
DELTA =      9 * 0.001,      1.0.
```

```
# ——— INITIAL VALUES FOR DIFERENTIAL EQUATIONS ———
```

```
#
/DIFIN
```

```
Z1 = EAC.
Z2 = ELC.
Z3 = 0.
```

```
#
# ——— SPECIFY THE DIFFERENTIAL EQUATION ———
```

```
#
/DIFEQ
```

```
IF(TIME NE 0) THEN (
```

```
    VOL = Z1 + 2*Z2.
    VOLT = VOL + LN(0.64/DI).
    DEN = DI / EXP(VOL).
```

```
IF(DEN GE 1.0) THEN (
    MD = 0.
    SP = 0. ).
```

```
IF(DEN LT 1.0) THEN (
```

```
    IF(DEN LE DDT) THEN VAR = DDT.
    IF(DEN GT DDT) THEN VAR = DEN.
    OMEGAA = ((1.-DEN)*NA / (1-(1-DEN)**(1/NA))**NA)**(2/(NA+1)).
    OMEGAK = ((1.-VAR)*NK / (1-(1-VAR)**(1/NK))**NK)**(2/(NK+1)).
    ETA = ETA0 * OMEGAA**ETA1.
    KAP = KAP0 * OMEGAK**KAP1.
    TERMA = ((2-DEN)/DEN)**(2*NA/(NA+1)).
    TERMK = ((2-DEN)/DEN)**(2*NK/(NK+1)).
    SEQF = SQRT(ETA * MS**2 + ETA2 * TERMA * DS**2).
    SEQ = SQRT(KAP * MS**2 + KAP2 * TERMK * DS**2).
```

```
ALPHA2 = KAP * MS/3.
BETA2 = KAP2 * TERMK * DS.
```



```
F2A = (ALPHA2 - BETA2) / SEQ.
F2L = (ALPHA2 + 0.5*BETA2) / SEQ.
```

```
ES1 = A1*(SEQF/MU)**N1 * EXP (-Q1R / TEMP).
ES2 = A2*(SEQF/MU)**N2 * EXP (-Q2R / TEMP).
ES3 = 0.
```

```
IF(SEQF GT S0) THEN (
  ARG = Q * (SEQF-S0)/MU.
  ES3 = 0.5*( B1*EXP(-Q1R/TEMP) + B2*EXP(-Q2R/TEMP) )
    * ( EXP(ARG) - EXP(-ARG) ) ).
```

```
ESS = ES1 + ES2 + ES3.
```

```
EFT = K0*EXP(C*TEMP)*(SEQF/MU)**M.
BIGD = ALPHA + BETA * LOG(SEQF/MU).
```

```
IF(Z3 LT EFT) THEN FU = EXP( BIGD*(1-Z3/EFT)**2).
IF(Z3 EQ EFT) THEN FU = 1.
IF(Z3 GT EFT) THEN FU = EXP(-DELTA*(1-Z3/EFT)**2).
```

```
MD = FU * ESS.
```

```
CR = ABS(EXP(VOLT)-1).
```

```
IF(CR LE 0.15) THEN GAMMA = 1.0.
IF(CR GT 0.15) THEN (
  GAMMA = (ABS((D0-EXP(VOLT))/((1-D0)*EXP(VOLT))))**NSP. ).
```

```
X3 = EXP((R3-1)*VOLT)/(ABS(1-EXP(VOLT)))**R4.
```

```
IF(W EQ 0) THEN M2 = 0.
IF(W GE 0) THEN M2 = W**AA1.
G2 = 1/DC**PP.
T2 = EXP(-QSR/TEMP)/TEMP.
```

```
SP = R1*M2*G2*T2*X3*GAMMA*SEQF.).
```

```
DZ1 = (MD + SP) * F2A.
DZ2 = (MD + SP) * F2L.
DZ3 = (FU-1) * ESS. ).
```

```
IF(TIME EQ 0) THEN (
```

```
DZ1 = 0.
DZ2 = 0.
DZ3 = 0. ).
```

```
#
# ——— SPECIFY THE DEPENDENT VARIABLE FUNCTION
#
/FUN
```

```
IF(TIME NE 0.) THEN (
  AA = Z1/EAC.
  BB = Z2/ELC.
  F = 1.0- SQRT(((1-AA)**2 + (1-BB)**2)*WT1). ).
```

```
IF(TIME EQ 0.) THEN (
```

```
  NEW = 0.
```

```
  Z1 = EAC.
```

```
  Z2 = ELC.
```

```
  Z3 = 0.
```

```
  F = 1.0. ).
```

```
#
```

```
# ——— SPECIFY VARIOUS PRINTING AND PLOTTING OPTIONS ———
```

```
#
```

```
/SAVE
```

```
  FILE = 'm:\325\fit98\shear\shear.SAV'.
```

```
  NEW.
```

```
  KEEP = TIME,ONE.
```

```
  FORMAT = '(5E15.4)'.
```

```
#/PRINT
```

```
#
```

```
  FORMAT = E.
```

```
#/PLOT
```

```
#
```

```
  RESIDUAL.
```

```
/END
```

```

# file = m:\325\fit98\comb\comb.inp
#
# Fit to hydrostatic and shear consolidation tests (icase = 1 & 2)
#
# -----
#
# This code uses the BMDP routine AR to fit the differential
# equations that describe the axial and lateral strain in the
# both the hydrostatic consolidation tests and the
# shear consolidation tests to determine the parameter values
# for the crushed-salt, combined-mechanism constitutive model.
# The parameter values for the flow potential are determined
# first and then fixed during the fitting in this routine.
# The parameter values for the M-D constitutive model are fixed
# at the values for clean intact salt. Ten parameter values
# remain to be determined that describe the effective stress
# measure (ETA0, ETA1, NF) with ETA2 fixed=1, the moisture and
# grain size parameters (AA1, PP), and the pressure solutioning
# parameter values (R1, R3, R4, QSR, NSP). The independent
# parameters are:
#
# 1. mean stress (MS)
# 2. stress difference (DS)
# 3. emplaced fractional density (D0)
# 4. initial fractional density (DI)
# 5. grain size (DC)
# 6. absolute temperature (T)
# 7. moisture content (W)
#
# -----
#
# INPUT PARAGRAPH
#
/INPUT
  TITLE = 'Combined-Mechanism Model fit to combined consolidation tests'.
  FILE = 'm:\325\fit98\comb\comb.dat'. # Test data file name
  FORMAT = '(2I3,3F10.0,F6.1,2F9.4,4F9.5,F9.3,F9.6,2F9.3,F5.2,F7.2)'.
  VARIABLES = 18.
#
# ----- VARIABLES PARAGRAPH -----
#
/VARIABLE
  NAMES=ICASE, ITEST, TIME, DT, TF, TEMP, AS, LS, EVT, EVC, EAT, EAC, RHO, D, RHO0, RHOI, DC, W.
#
# ----- TRANSFORMATION PARAGRAPH -----
#
/TRANS
  MS = (2.0*LS+AS)/3.0. # mean stress, as=axial stress, ls=conf. pres.
  DS = LS - AS. # stress difference
  ELC = (EVC - EAC)/2. # lateral strain, evt=vol. strain, eat=ax.strain
  D0 = 1382.4/2160. # emplaced fractional density
  DI = RHOI/2160. # initial fractional density
  ONE = 1.0. # regression function
#
# FLOW POTENTIAL PARAMETER VALUES
#
  KAP0 = 10.119.

```

KAP1 = 1.005.
 KAP2 = 1.0.
 NK = 1.3312.
 DDT = 0.8963.

17 MUNSON-DAWSON CREEP PARAMETERS FOR CLEAN SALT (FIXED)

A1 = 8.386E+22.
 A2 = 9.672E+12.
 Q1R = 12581.
 Q2R = 5033.
 N1 = 5.5.
 N2 = 5.0.
 B1 = 6.0856E+6.
 B2 = 3.034E-2.
 Q = 5335.
 S0 = 20.57.
 M = 3.
 K0 = 6.275E+5.
 C = 9.198E-3.
 ALPHA = -17.37.
 BETA = -7.738.
 DELTA = 0.58.
 MU = 12400. # SHEAR MODULUS

FIX VALUE OF KAP2 AT ONE

ETA2 = 1.0.

WEIGHT FUNCTIONS

WT1 = DT/1.E+6.
 WT = 1.0. # uniform weight function

——— REGRESS PARAGRAPH ———

/REGRESS

DEPEND = ONE.	# Dependent variable
PARAMETERS=10.	# Number of regression parameters
WEIGHT = WT.	# WEIGHT VARIABLE
ITIME = 3.	# INTEGRATION VARIABLE NUMBER
NEQN = 3.	# Number of differential equations
ITER = 1.	# NUMBER OF ITERATIONS
HALVINGS = 3.	# NUMBER OF INTERVAL HALVINGS
MAXC = 300000.	# MAXIMUM NUMBER OF TIMES 'DIFEQ' IS USED
PRINT = 0.	# SUPPRESS PRINT ASSOCIATED WITH VARIABLES

——— PARAMETERS PARAGRAPH ———

Specify the names, initial estimates, and the range of the ten
 # regression parameters, where R1 is the over all leading parameter; R3, R4,
 # and N are strain dependent parameters; KAPPA0, KAPPA1, KAPPA2, N determine
 # the equivalent stress measure for the flow-rule; ETA0, ETA1, ETA2, and Nf
 # determine the equivalent stress measure in strain rate measure; A
 # is water-content dependent parameters; P defines grain size dependence;
 # and QSR defines temperature effect.

#

/PARAMETER

NAMES = ETA0, ETA1, NF,
 AA1, PP, NSP,
 R1, R3, R4, QSR.

INITIAL = 0.01399, 3.38812, 3.96597,
 0.00001, 1.03407, 1.53176,
 0.33690, 0.12857, 0.16797, 2897.087.

MINIMUM = 0.01, 2 * 0.0, 1.0E-6, 3 * 0.0, 1.E-5, 0.10, 0.0.

MAXIMUM = 10 * 5000.0.

DELTA = 9 * 0.001, 1.0.

#

——— INITIAL VALUES FOR DIFERENTIAL EQUATIONS ———

#

/DIFIN

Z1 = EAC.

Z2 = ELC.

Z3 = 0.

#

——— SPECIFY THE DIFFERENTIAL EQUATION ———

#

/DIFEQ

IF(TIME NE 0) THEN (

VOL = Z1 + 2*Z2.

VOLT = VOL + LN(0.64/DI).

DEN = DI / EXP(VOL).

IF(DEN GE 1.0) THEN (

MD = 0.

SP = 0.).

IF(DEN LT 1.0) THEN (

IF(DEN LE DDT) THEN VAR = DDT.

IF(DEN GT DDT) THEN VAR = DEN.

OMEGAA = ((1.-DEN)*NF / (1-(1-DEN)**(1/NF))**NF)**(2/(NF+1)).

OMEGAK = ((1.-VAR)*NK / (1-(1-VAR)**(1/NK))**NK)**(2/(NK+1)).

ETA = ETA0 * OMEGAA**ETA1.

KAP = KAP0 * OMEGAK**KAP1.

TERMA = ((2-DEN)/DEN)**(2*NF/(NF+1)).

TERMK = ((2-DEN)/DEN)**(2*NK/(NK+1)).

SEQF = SQRT(ETA * MS**2 + ETA2 * TERMA * DS**2).

SEQ = SQRT(KAP * MS**2 + KAP2 * TERMK * DS**2).

ALPHA2 = KAP * MS/3.

BETA2 = KAP2 * TERMK * DS.

F2A = (ALPHA2 - BETA2) / SEQ.

F2L = (ALPHA2 + 0.5*BETA2) / SEQ.

ES1 = A1*(SEQF/MU)**N1 * EXP (-Q1R / TEMP).

```
ES2 = A2*(SEQF/MU)**N2 * EXP (-Q2R / TEMP).
ES3 = 0.
```

```
IF(SEQF GT S0) THEN (
  ARG = Q * (SEQF-S0)/MU.
  ES3 = 0.5*( B1*EXP(-Q1R/TEMP) + B2*EXP(-Q2R/TEMP) )
    * ( EXP(ARG) - EXP(-ARG) ) ).
```

```
ESS = ES1 + ES2 + ES3.
```

```
EFT = K0*EXP(C*TEMP)*(SEQF/MU)**M.
BIGD = ALPHA + BETA * LOG(SEQF/MU).
```

```
IF(Z3 LT EFT) THEN FU = EXP( BIGD*(1-Z3/EFT)**2).
IF(Z3 EQ EFT) THEN FU = 1.
IF(Z3 GT EFT) THEN FU = EXP(-DELTA*(1-Z3/EFT)**2).
```

```
MD = FU * ESS.
```

```
CR = ABS(EXP(VOLT)-1).
```

```
IF(CR LE 0.15) THEN GAMMA = 1.0.
IF(CR GT 0.15) THEN (
  GAMMA = (ABS((D0-EXP(VOLT))/((1-D0)*EXP(VOLT))))**NSP. ).
```

```
X3 = EXP((R3-1)*VOLT)/(ABS(1-EXP(VOLT)))**R4.
```

```
IF(W EQ 0) THEN M2 = 0.
IF(W GE 0) THEN M2 = W**AA1.
G2 = 1/DC**PP.
T2 = EXP(-QSR/TEMP)/TEMP.
```

```
SP = R1*M2*G2*T2*X3*GAMMA*SEQF.).
```

```
DZ1 = (MD + SP) * F2A.
DZ2 = (MD + SP) * F2L.
DZ3 = (FU-1) * ESS. ).
```

```
IF(TIME EQ 0) THEN (
```

```
DZ1 = 0.
DZ2 = 0.
DZ3 = 0. ).
```

```
#
# ——— SPECIFY THE DEPENDENT VARIABLE FUNCTION
#
```

```
/FUN
```

```
IF(TIME NE 0.) THEN (
  AA = Z1/EAC.
  BB = Z2/ELC.
  F = 1.0- SQRT(((1-AA)**2 + (1-BB)**2)*WT1). ).
IF(TIME EQ 0.) THEN (
  NEW = 0.
  Z1 = EAC.
  Z2 = ELC.
  Z3 = 0.
```

```
      F = 1.0. ).  
#  
#  _____ SPECIFY VARIOUS PRINTING AND PLOTTING OPTIONS _____  
#  
/SAVE  
      FILE = 'm:\325\fit98\comb\comb.sav'.  
      NEW.  
      KEEP = TIME,ONE.  
      FORMAT = '(5E15.4)'.  
#/PRINT  
#      FORMAT = E.  
#/PLOT  
#      RESIDUAL.  
/END
```

APPENDIX B

LATERAL-TO-AXIAL STRAIN-RATE RATIO MODEL FITS TO THE SHEAR CONSOLIDATION TESTS

This appendix contains the plots of the model fits to the 18 shear consolidation tests used to determine the flow potential parameters. Each plot shows the measured and predicted lateral-to-axial strain-rate ratios as a function of density for each of the 18 tests. Test conditions included on the figures correspond to the target test conditions given in Table 3-2.

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Figure B-1. Lateral-to-Axial Strain-Rate Ratio as a Function of Density for Shear Consolidation Test SC1B.

Figure B-2. Lateral-to-Axial Strain-Rate Ratio as a Function of Density for Shear Consolidation Test SC2A.

Figure B-3. Lateral-to-Axial Strain-Rate Ratio as a Function of Density for Shear Consolidation Test SC3A.

Figure B-4. Lateral-to-Axial Strain-Rate Ratio as a Function of Density for Shear Consolidation Test SC4A.

Figure B-5. Lateral-to-Axial Strain-Rate Ratio as a Function of Density for Shear Consolidation Test SC5A.

Figure B-6. Lateral-to-Axial Strain-Rate Ratio as a Function of Density for Shear Consolidation Test SC6A.

Figure B-7. Lateral-to-Axial Strain-Rate Ratio as a Function of Density for Shear Consolidation Test SC7A.

Figure B-8. Lateral-to-Axial Strain-Rate Ratio as a Function of Density for Shear Consolidation Test SC8A.

Figure B-9. Lateral-to-Axial Strain-Rate Ratio as a Function of Density for Shear Consolidation Test SC9B.

Figure B-10. Lateral-to-Axial Strain-Rate Ratio as a Function of Density for Shear Consolidation Test 120C891.

Figure B-11. Lateral-to-Axial Strain-Rate Ratio as a Function of Density for Shear Consolidation Test SC10.

Figure B-12. Lateral-to-Axial Strain-Rate Ratio as a Function of Density for Shear Consolidation Test SC11.

Figure B-13. Lateral-to-Axial Strain-Rate Ratio as a Function of Density for Shear Consolidation Test RS/DCCS/1.

Figure B-14. Lateral-to-Axial Strain-Rate Ratio as a Function of Density for Shear Consolidation Test RS/DCCS/3.

Figure B-15. Lateral-to-Axial Strain-Rate Ratio as a Function of Density for Shear Consolidation Test RS/DCCS/4.

Figure B-16. Lateral-to-Axial Strain-Rate Ratio as a Function of Density for Shear Consolidation Test RS/DCCS/5.

Figure B-17. Lateral-to-Axial Strain-Rate Ratio as a Function of Density for Shear Consolidation Test RS/DCCS/10.

Figure B-18. Lateral-to-Axial Strain-Rate Ratio as a Function of Density for Shear Consolidation Test RS/DCCS/15.

APPENDIX C

CRUSHED-SALT CONSTITUTIVE MODEL FITS TO THE HYDROSTATIC AND SHEAR CONSOLIDATION TESTS

This appendix contains plots of the crushed-salt, combined-mechanism constitutive model fits to the 40 hydrostatic consolidation tests and the 18 shear consolidation tests. Two plots are included for each test depicting the fits to two test databases; namely, (1) a database containing the 18 shear consolidation tests only and (2) a database containing the combined 58 shear and hydrostatic consolidation tests.

The appendix contains 58 figures. Each figure shows the two model fits to each particular laboratory test; either a hydrostatic consolidation test (Figures C-1 through C-40) or a shear consolidation test (Figures C-41 through C-58). The plots labeled *Shear Database* represent the crushed-salt constitutive model fit to the shear test database, and the plots labeled *Combined Database* represent the crushed-salt constitutive model fit to the combined test database. As discussed in Section 4.6.4, shear database curve fits do not appear for Figures C-27 and C-28 because the tests are outside the range of the shear database parameter values.

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Figure C-1. Hydrostatic Consolidation Test CS1.

— Test Data Model Prediction

Figure C-2. Hydrostatic Consolidation Test CS2.

C-5

— Test Data Model Prediction

Figure C-3. Hydrostatic Consolidation Test CS3.

— Test Data Model Prediction

Figure C-4. Hydrostatic Consolidation Test CS4.

Figure C-5. Hydrostatic Consolidation Test CS5.

Figure C-6. Hydrostatic Consolidation Test CS6.

Figure C-7. Hydrostatic Consolidation Test CS7.

Figure C-8. Hydrostatic Consolidation Test CS8.

— Test Data Model Prediction

Figure C-9. Hydrostatic Consolidation Test CS9.

— Test Data Model Prediction

Figure C-10. Hydrostatic Consolidation Test CS10.

C-13

Figure C-11. Hydrostatic Consolidation Test HC1A.

— Test Data Model Prediction

Figure C-12. Hydrostatic Consolidation Test HC2A.

— Test Data Model Prediction

Figure C-13. Hydrostatic Consolidation Test HC3A.

Figure C-14. Hydrostatic Consolidation Test HC4A.

— Test Data Model Prediction

Figure C-15. Hydrostatic Consolidation Test HC5A.

Figure C-16. Hydrostatic Consolidation Test HC6A.

— Test Data Model Prediction

Figure C-17. Hydrostatic Consolidation Test 27JUL82.

— Test Data Model Prediction

Figure C-18. Hydrostatic Consolidation Test 04MAY82.

Figure C-19. Hydrostatic Consolidation Test 30APR82.

— Test Data Model Prediction

Figure C-20. Hydrostatic Consolidation Test 07MAY82.

Figure C-21. Hydrostatic Consolidation Test 12MAY82.

— Test Data Model Prediction

Figure C-22. Hydrostatic Consolidation Test 05FEB82.

— Test Data Model Prediction

Figure C-23. Hydrostatic Consolidation Test 09APR82.

Figure C-24. Hydrostatic Consolidation Test 26MAR82.

Figure C-25. Hydrostatic Consolidation Test 02APR82.

— Test Data Model Prediction

Figure C-26. Hydrostatic Consolidation Test 13APR82.

— Test Data Model Prediction

Figure C-27. Hydrostatic Consolidation Test 29JAN82.

Figure C-28. Hydrostatic Consolidation Test 26FEB82.

— Test Data Model Prediction

Figure C-29. Hydrostatic Consolidation Test 27JU61.

— Test Data Model Prediction

Figure C-30. Hydrostatic Consolidation Test 23JL51.

— Test Data Model Prediction

Figure C-31. Hydrostatic Consolidation Test 14NV51.

— Test Data Model Prediction

Figure C-32. Hydrostatic Consolidation Test 25FE61.

Figure C-33. Hydrostatic Consolidation Test 10MY51.

— Test Data Model Prediction

Figure C-34. Hydrostatic Consolidation Test 20AU51.

Figure C-35. Hydrostatic Consolidation Test 16JL51.

— Test Data Model Prediction

Figure C-36. Hydrostatic Consolidation Test 18JU51.

— Test Data Model Prediction

Figure C-37. Hydrostatic Consolidation Test 30OC51.

Figure C-38. Hydrostatic Consolidation Test 16JA61.

Figure C-39. Hydrostatic Consolidation Test 19DC44.

— Test Data Model Prediction

Figure C-40. Hydrostatic Consolidation Test 13AU51.

Figure C-41. Shear Consolidation Test SC1B.

Figure C-42. Shear Consolidation Test SC2A.

Figure C-43. Shear Consolidation Test SC3A.

Figure C-44. Shear Consolidation Test SC4A.

— Test Data Model Prediction

Figure C-45. Shear Consolidation Test SC5A.

— Test Data Model Prediction

Figure C-46. Shear Consolidation Test SC6A.

Figure C-47. Shear Consolidation Test SC7A.

— Test Data Model Prediction

Figure C-48. Shear Consolidation Test SC8A.

Figure C-49. Shear Consolidation Test SC9B.

— Test Data Model Prediction

Figure C-50. Shear Consolidation Test SC10.

Figure C-51. Shear Consolidation Test SC11.

Figure C-52. Shear Consolidation Test 120C891.

Figure C-53. Shear Consolidation Test RS/DCCS/1.

Figure C-54. Shear Consolidation Test RS/DCCS/3.

Figure C-55. Shear Consolidation Test RS/DCCS/4.

Figure C-56. Shear Consolidation Test RS/DCCS/5.

— Test Data Model Prediction

Figure C-57. Shear Consolidation Test RS/DCCS/10.

— Test Data Model Prediction

Figure C-58. Shear Consolidation Test RS/DCCS/15.

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