Compaction of crushed salt for safe containment – Overview of phase 2 of the KOMPASS project

Larissa Friedenberg[1], Jeroen Bartol[3], James Bean[7], Oliver Czaikowski[1], Uwe Düsterloh[4], Ann-Kathrin Gartzke[5], Suzanne Hangx[8], Ben Laurich [5], Christian Lerch[2], Svetlana Lerche[4], Johanna Lippmann-Pipke[5], Wenting Liu[5], Christoph Lüdeling[6], Melissa Mills[7], Nina Müller-Hoeppe[2], Till Popp[6], Ole Rabbel[6], Michael Rahmig[2], Benjamin Reedlunn[7], Christopher Rölke[6], Christopher Spiers[8], Kristoff Svensson[5], Jan Thiedau[5], Bart van Oosterhout[8], Kornelia Zemke[5], Juan Zhao[4]*

[1]Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) gGmbH, Germany; [2]BGE TECHNOLOGY, Germany; [3]COVRA, Netherlands*; [4]Clausthal University of Technology (TUC),* Germany; [5]*Federal Institute for Geosciences and Natural Resources (BGR),* Germany; [6] *Institut für Gebirgsmechanik GmbH (IfG),* Germany; [7] *Sandia National Laboratories,* USA; [8] *Utrecht University,* Netherlands;

* *larissa.friedenberg@grs.de*

ABSTRACT: The KOMPASS project strives to improve the scientific basis behind using crushed salt for long-term isolation of high-level nuclear waste within rock salt repositories. Efforts to improve the prediction of crushed salt compaction began during the first phase of the KOMPASS project (KOMPASS-I, 2020). The second project phase (KOMPASS-II) just started in 2021. Its aim is foremost to quantify the effect of isolated experimental influencing factors on the compaction. Such influencing factors are for instance temperature, moisture or the chosen stress path. Used methods are laboratory tests, microstructural investigations and numerical simulations.

1 Introduction

In Germany, rock salt formations are possible host rock candidates for a repository for heat-emitting radioactive waste. Their safety concept includes a multibarrier system consisting of the geological barrier salt and geotechnical seals ensuring the safe containment. Due to its favorable properties and its easy availability (mined-off material), crushed salt is considered for backfilling of cavities and sealing measures in drifts and shafts. With time the creep of the surrounding rock salt leads to crushed salt's compaction due to convergence. Thereby, its initially high porosity in the range of 30 % - 40 % is thought to be reduced to a value comparable to the porosity of undisturbed rock salt (≤ 1 %). The compaction behavior of crushed salt is rather complex as it involves thermo-hydro-mechanical (THM) coupled processes (Kröhn et al. 2009; Hansen et al. 2014). Influencing factors are material intrinsic properties, like mineralogy, grain size distribution and humidity, as well as environmental conditions such as temperature, compaction rate or stress state. The current process understanding has some important gaps with respect to the material behavior. Thus, the experimental database and the numerical modelling need to be extended and validated, especially in low porosity ranges. Within the first phase of the KOMPASS project (KOMPASS-I) efforts to improve the prediction of crushed salt compaction began and are followed up in the second phase (KOMPASS-II) beginning in the middle of 2021.

2 Investigation work in KOMPASS-II

The KOMPASS project comprises working areas of experimental investigations, microstructural examinations and numerical simulation, all strongly connected to each other. The laboratory investigations serve to improve process understanding regarding the material behavior depending on various boundary conditions. Additionally, examinations on micro-scale are performed, relating microstructures to deformation mechanism, estimating the influence of humidity by observing dissolution/precipitation processes and to create a basis to compare crushed salt compacted in laboratory and in-situ. Therein, varying abundancies of microstructural deformation indicators are related to variations in the experimental compaction conditions.

Furthermore, the planning of the laboratory program servers the second aim of considering the numerical needs for model improvement.

2.1 Experimental investigations

Basis for the experimental investigation is the KOMPASS reference material which was specified in the beginning of the project (KOMPASS-I 2020). With the determination of an easily available and reproducible reference material generic investigations are possible independent from site-specific material conditions, like lithological composition and grain size distribution. Crushed salt representing the Staßfurt-sequence in a bedded Zechstein salt formation with an optimized grain size distribution was chosen (Figure 1).

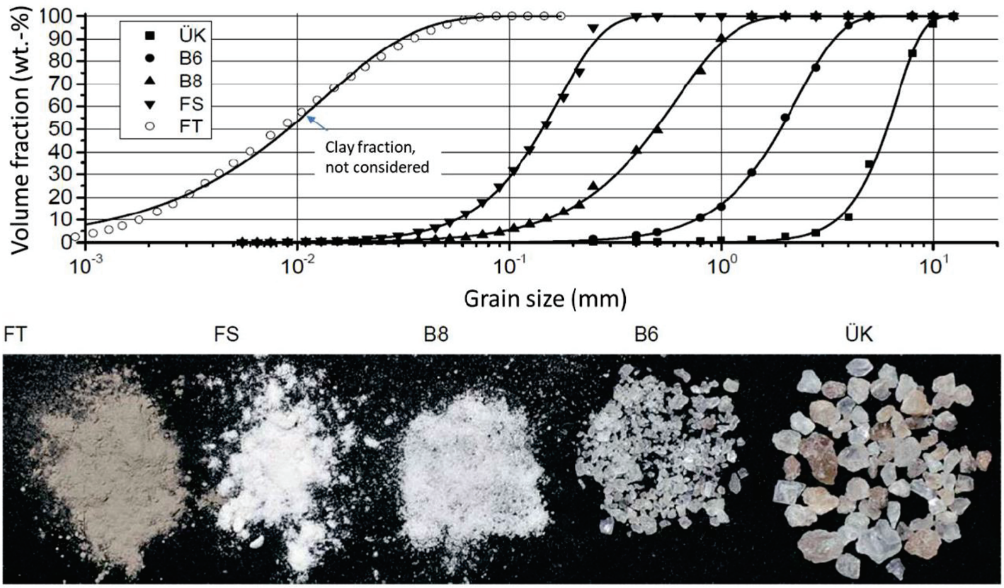

Figure 1:Salt grain fractions and grain size distribution of the KOMPASS reference material (Glaubach et al. 2016)

2.1.1 Pre-compaction methods

Within KOMPASS-I two new pre-compaction methods were developed. In general, pre-compaction aims to rapidly produce cohesive samples from the lose reference material within days to weeks. The samples are desired to exhibit a low porosity and a natural grain structure, such that they can subsequently be used for long-term, in-situ realistic THM investigations that commonly last for month to years. Without the rapid pre-compaction procedure, experiments with in-situ like strain rates would even last for tens of years before reaching the desired small porosity states.

First, there is the plane-strain compaction method developed by the TUC, where fixed end plates and an increasing radial confining pressure simulate the radial compaction of crushed salt due to drift convergence (Figure 2a). Second, the IfG applied a so-called “Big-compaction cell” with a diameter-to-height ratio of 0.5 facilitating the controlled pre-compaction of a significant sample with a specified porosity. From this large sample, several subsamples were taken with different orientations and geometry (Figure 2b).

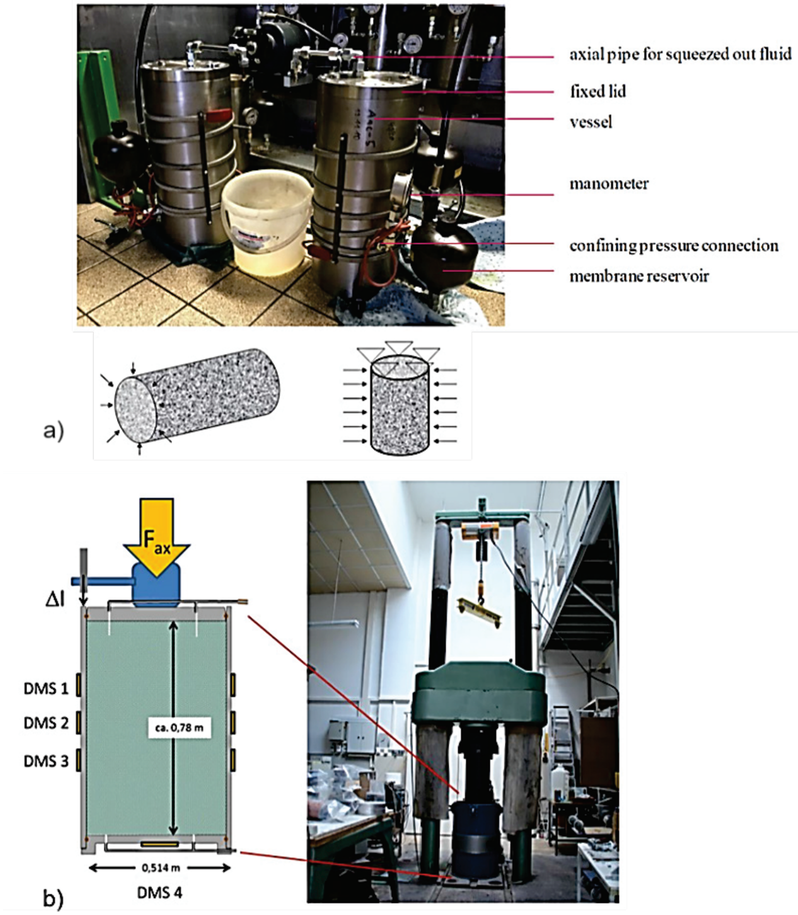

Figure 2: Pre-compaction methods developed in KOMPASS. a) Plane-strain compaction cell of TUC, b) “Big-compaction cell” of IfG (KOMPASS-I 2020)

Both methods are able to successfully produce various specimen varying in water content, time and applied stress (Figure 3). In the next step (KOMPASS-II), it is required to establish of reproducible and predictable correlations between stress regime, test duration, moisture and the respective target tensity.

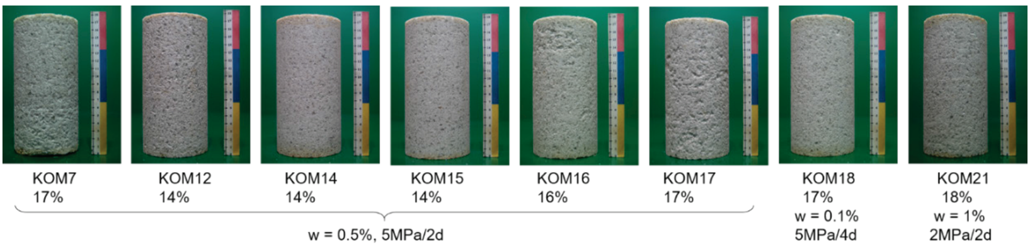

Figure 3: Successfully produced pre-compacted crushed salt specimen with the plain-strain approach – water content and confining pressure below

2.1.2 Long-term compaction experiments

Systematic investigations of crushed salt compaction and hydraulic behavior are needed to demonstrate its long-term tightness as backfill. Therefore, an extended laboratory program for the systematical analysis of the THM-coupled behavior of crushed salt was elaborated aiming at the factors influencing compaction behavior (Figure 4). These are:

- Porosity
- Stress regime (isotropic, deviatoric)
- Moisture content
- Stress geometry (isotropic, TC/UC or TE conditions)
- Test method (strain-controlled vs stress controlled)
- Pre-compaction method

Besides testing pre-compaction methods, due to project specific time restrictions prioritized experiments were chosen and first experiments are already executed within KOMPASS-I. One long-term experiment was started within KOMPASS-I by TUC and executed over 750 days continuing within KOMPASS-II. It comprises five different influencing factors and therefore, covers a wide range of planned experiments (Düsterloh et al. 2022).

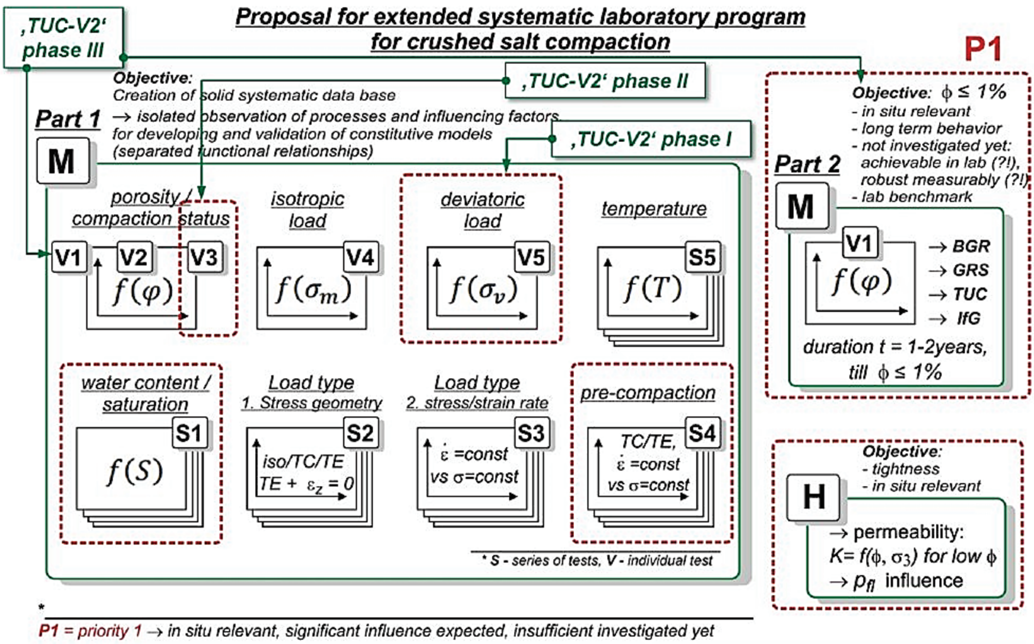

Figure 4: Test program for the systematically analysis of the THM-coupled behavior of crushed salt with prioritization and allocation of the TUC-V2 test (KOMPASS-I 2020)

Especially, the hydraulic behavior and the change of transport properties during the crushed salt compaction is of great importance for the long-term sealing function. Thus, permeability measurements will be performed during or after sample consolidation as part of the laboratory program. However, the measurement and quantification of low porosity ranges is challenging, and therefore part of current research. In the frame of KOMPASS-I, the IfG developed a design for the “New IfG-compaction cell” allowing a record of measurement data during the testing time and combining parallel measuring methods for determination of porosity and permeability (Figure 5). Realization of this compaction cell is planned within KOMPASS-II.

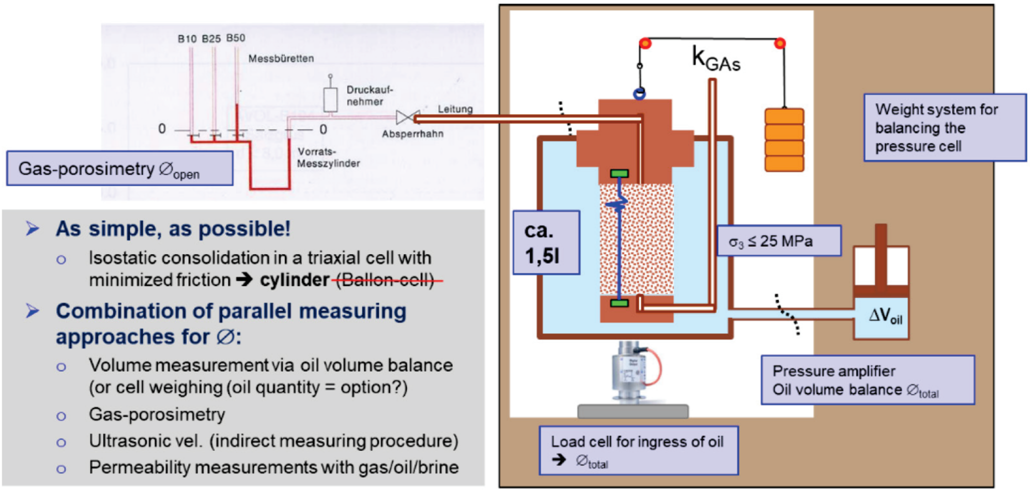

Figure 5: General design concept of the "New IfG-compaction cell" (KOMPASS-I 2020)

2.2 Microstructural investigations

The compaction of crushed salt is facilitated by several microstructural deformation mechanisms, which are well known from former material studies, foremost in the field of rock salt rheology (Hansen et al. 2014; Jackson & Hudec 2017; Spiers et al. 1990; Urai & Spiers 2007). However, each mechanisms' overall contribution to the crushed salt compaction remains yet unknown and varies depending on compaction state and acting material as well as environmental influencing factors. Within KOMPASS-I microstructural investigation methods were established. In KOMPASS-II, the abundancy of microstructural deformation indicators is related to the compaction conditions. Moreover, the micro-structure of samples with and without rapid pre-compaction are compared. The latter samples originating from real-used backfill material in the Sigmundshall mine near Hannover, Germany. Therefore, Figure 6 compares the abundance of microstructural deformation indicators for the raw material, pre-compacted crushed salt and long-term compacted crushed salt. The given quantity is based on subjective impression only and in total 16 thin sections were examined so far. Figure 6 also shows three exemplary micrographs to illustrate indicators for cataclasis (intra-granular fracturing), diffusive mass transfer by pressure solution (flush grain boundaries and deformation at grains' edges) and intracrystalline deformation by dislocation creep (subgrain formation).

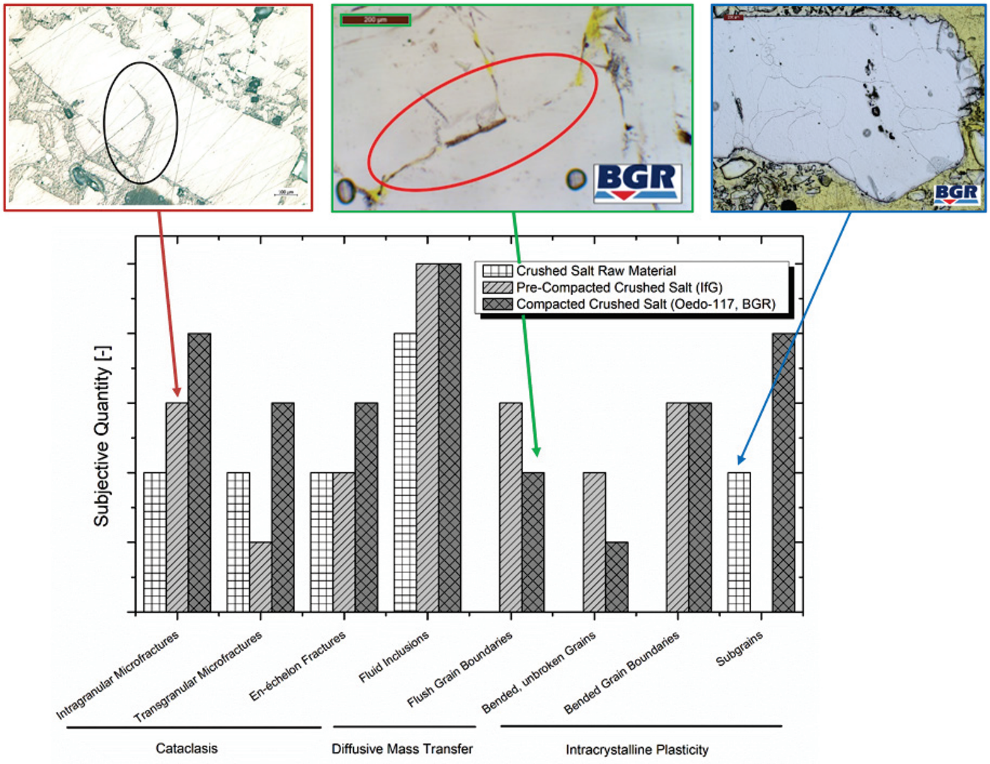

Figure 6: Observed microstructures in different compaction stages of the KOMPASS reference material. Red: intra-granular fracture in pre-compacted material, green: flush grain boundaries in long-term compacted material, blue: subgrains in raw, lose material (fine black lines inside the grain mark the subgrain boundaries). Bottom: subjective quantities of observed microstructures. Note: No subgrains were determined for pre-compacted IfG-samples (Modified after KOMPASS-I 2020)

2.3 Numerical modelling

Several constitutive models for crushed salt are currently in use for numerical simulations. Within KOMPASS-I, a wide range of models are applied and comparatively analyzed (Figure 7), therefore, the models were separated to phenomenological models and models with microstructural grounds (KOMPASS-I).

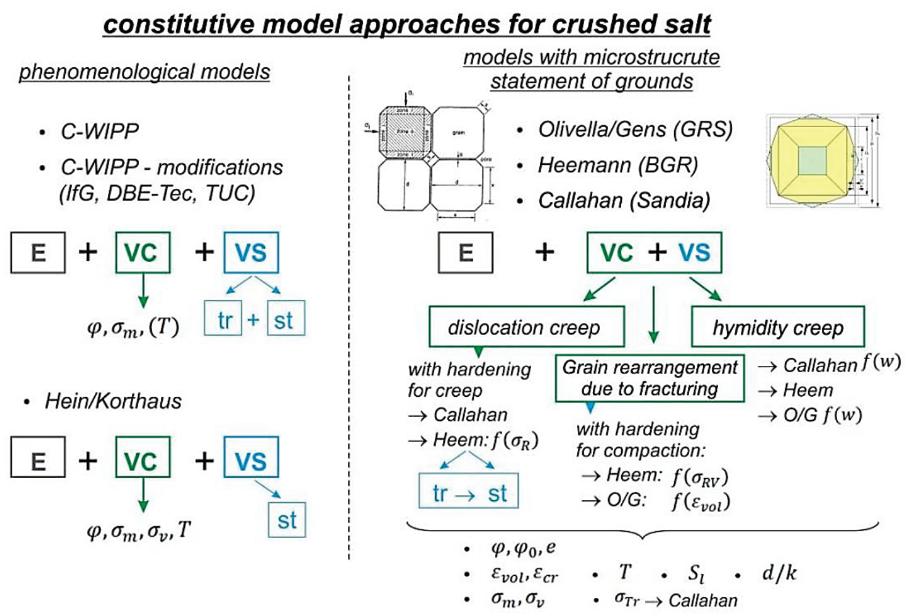

Figure 7: Schematic composition of the material models for crushed salt: basic structures and considered main influencing factors in comparison (KOMPASS-I 2020)

The current available constitutive models were investigated by benchmarking against laboratory data of three long-term triaxial tests. Figure 8 shows an example the differently modelled volumetric strain as well as the actual, measured strain for the long-term multistage test TUC-V2. Additionally, two inset diagrams of the test are given, focusing on strain and strain rate from runtime day 124 to 148 (KOMPASS-I 2020). The detail shows that the deviatoric load phases cause inaccuracies in the recalculation for almost all tested models. From these results and the comparative analysis, the need for further developments is evident. In correlation with the laboratory plans for KOMPASS-II (Figure 4) a systematic model validation of a wide range of influencing factors is possible due to calibration and benchmarking of the crushed salt constitutive models against the long-term compaction tests.

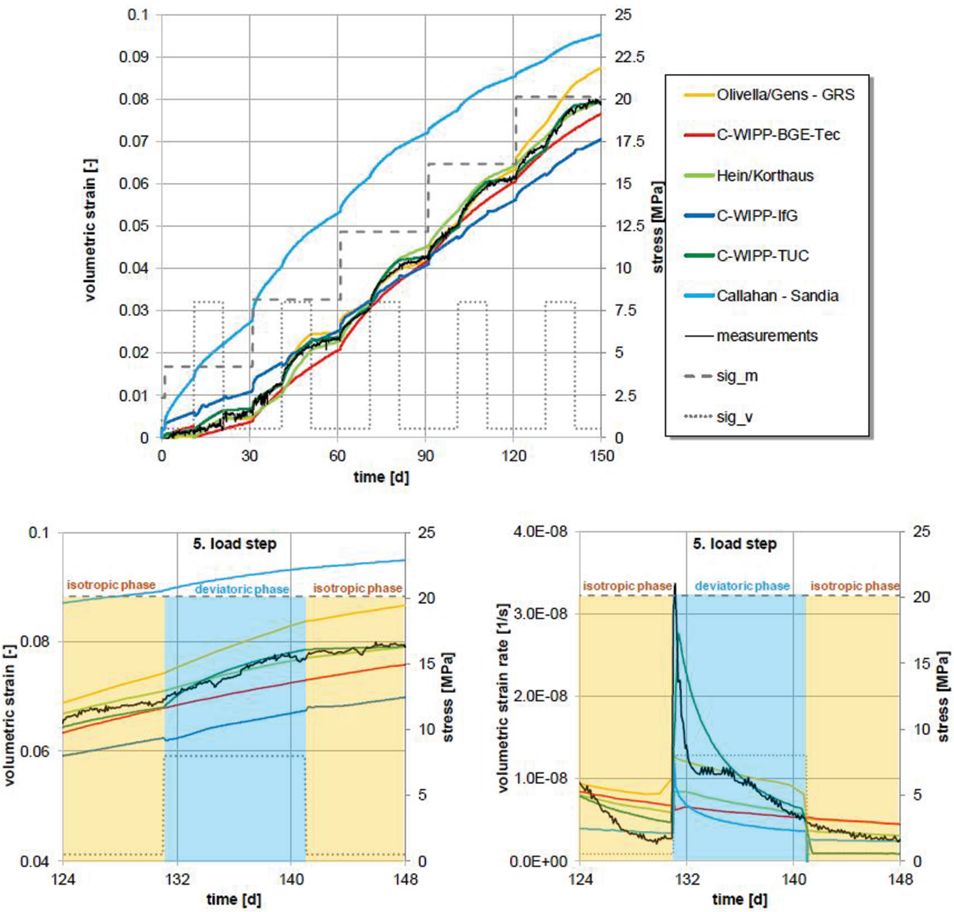

Figure 8: Recalculation results for the long-term multistage test TUC-V2 (KOMPASS-I 2020)

3 Conclusions

Based on the outcomes of KOMPASS-I, the improvement of the scientific basis behind using crushed salt as backfill for high-level nuclear waste is continued in KOMPASS-II. One of the main objectives is the microstructural comparison of grain structure of pre-compacted samples to in-situ compacted material for the verification of the new pre-compaction methods. Additionally, the microstructural methods will be further developed and applied for investigating humidity influence on compaction behavior. Another main objective is the further development of pre-compaction methods and the execution of long-term experiments. In correlation with the laboratory work, calibration and benchmarking will be done for improving the numerical models for crushed salt.

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