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The effect of grain size distribution on compaction creep rates of granular NaCl

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Introduction and Motivation

Salt rock formations are widely considered as a suitable host rock for a geological repository of nuclear waste. To promote the sealing of a repository, the openings are filled with crushed rock salt (backfill). Due to the stresses of the surrounding host rock this backfill will converge and seal over time by compaction creep. There are several studies that investigate the compaction rate of backfill, either on single grain sizes [1][2] or on crushed rock salt with a specific distribution [3].

Compaction experiments on single grain sizes show a strong dependence on grain sizes, with rates increasing in smaller grain sizes ($\dot{\varepsilon} \propto d^{-3}$) [1]. Hence, in a mixture it is expected that the smaller grains control the overall compaction rate. Nevertheless, nearly all models use a single grain size as input parameter [5], by simply taking an average grain size or using a grain size such that the model fits the rates observed in a lab experiment. However, this makes extrapolation beyond laboratory conditions questionable and relies on using the exact same distribution in a real repository.

We have done compaction experiments on single grain sizes and mixtures to investigate the effect of a mixture on compaction rates. We have developed two models which can be considered as an upper and lower bound. The experimental results fit with these models and therefore this model can be used to more accurately predict the timescales required for sealing.

Method

- NaCl was sieved into grain size fractions. This material was then inserted into a 1D-compaction apparatus, placed in an INSTRON testing machine at 28ºC.
- All samples were pre-compacted, brine was introduced, and a series of stress relaxation experiments were conducted at porosities of 20, 15, 10 and 5%.
- 5 different experiments were conducted: two on single grain sizes (137 and 450 µm) and three different mixtures (Figure 1)

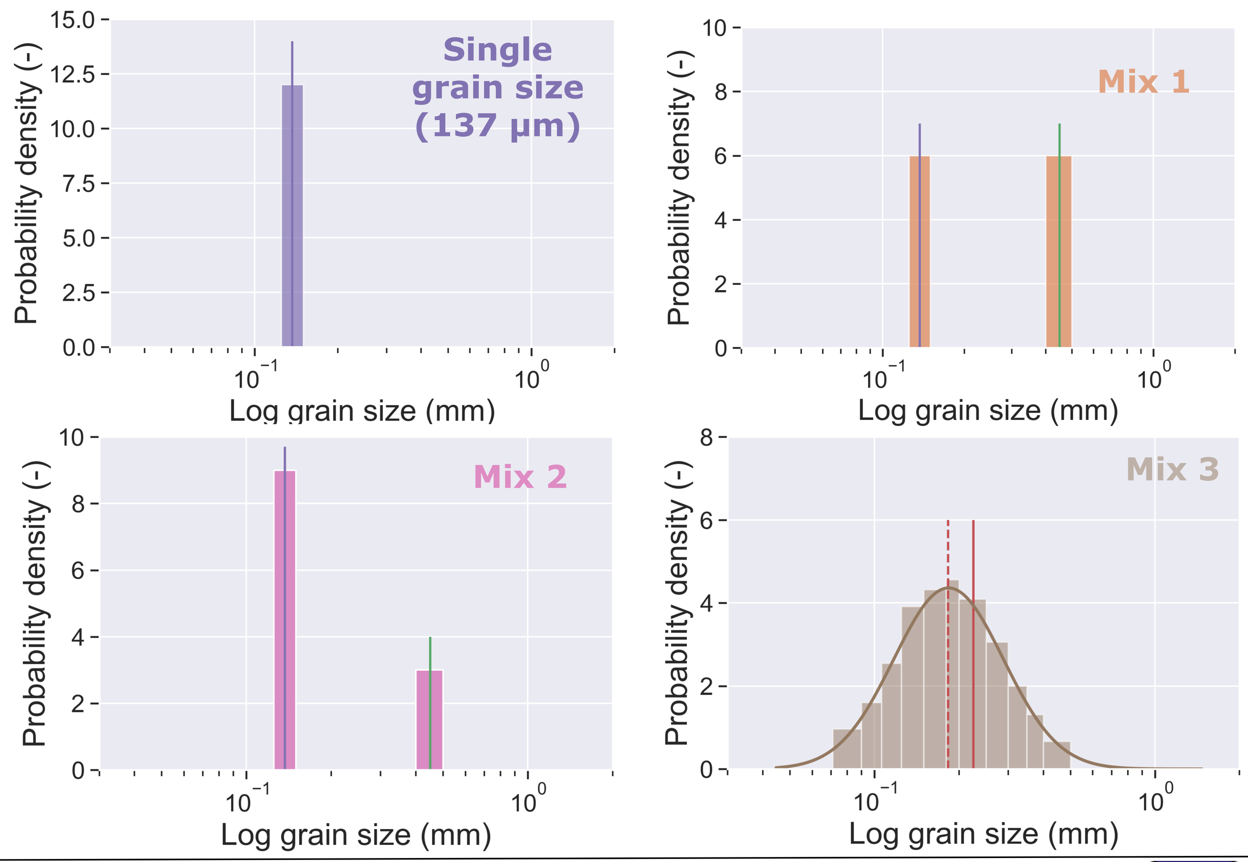


Figure 1
Overview of grain size mixtures used in this study. Note that the y-axis is the volume probability and not count probability. (a) single grain size of 137 µm ± 12.5 µm. (b) a 50%-50% mixture of 137 µm and 450 µm grains. (c) a 75%-25% mixture of 137 µm and 450 µm grains. (d) a log-normal volume distribution with a mean of 225 µm, mode of 183 µm and a standard deviation of 0.45

Model

Single grain size

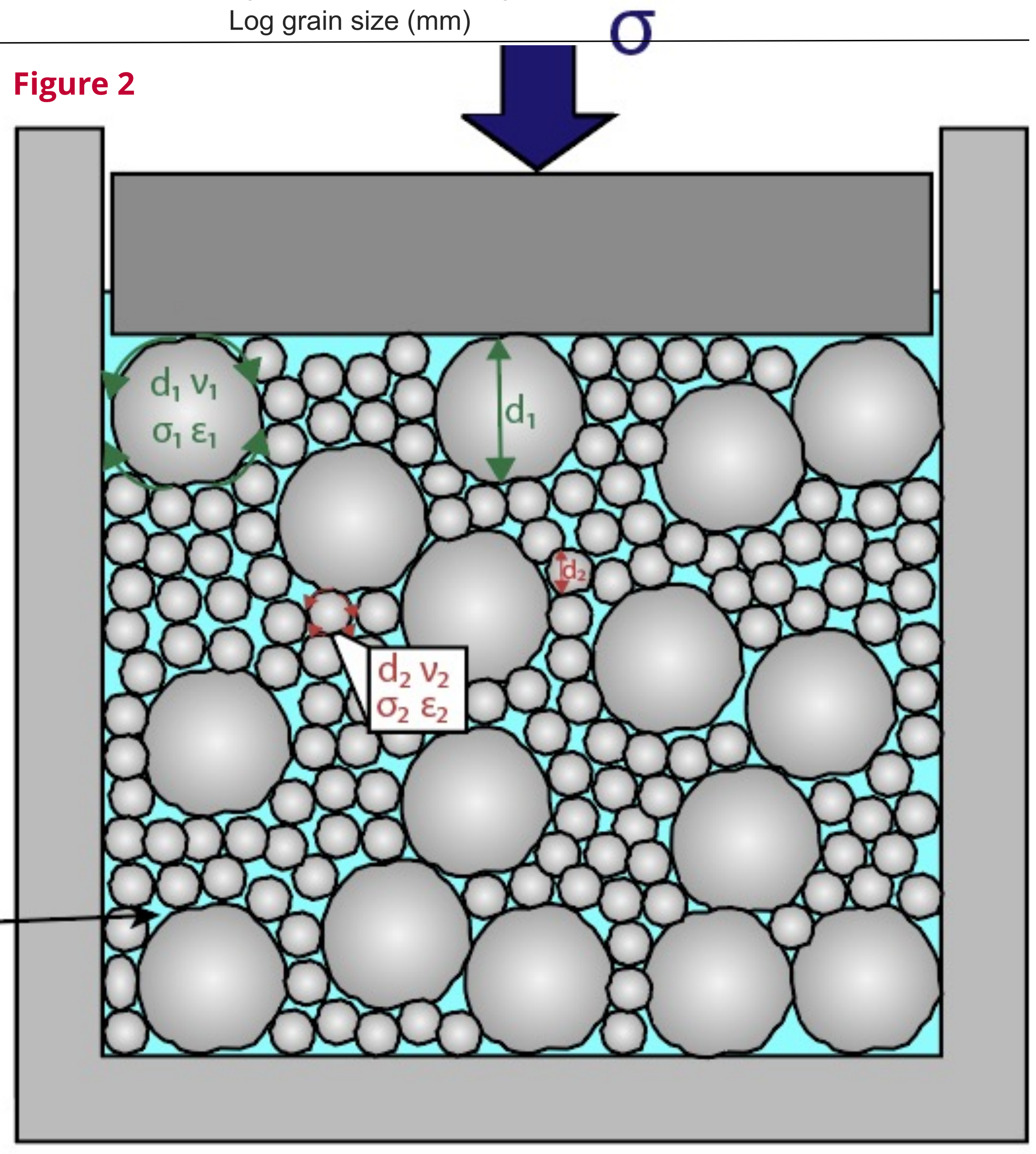
- Compaction rate is described by:
- $\dot{\varepsilon} = A\frac{\sigma_e}{d^3}f(\phi) = 1.1\cdot 10^{-19}\frac{\sigma_e}{d^3}\cdot 4.1\cdot 10^{-3}\phi^{2.594}$ (Eq. 1)
- in which, $\dot{\varepsilon}$ is the strain rate (s^{-1}), σ_e is the stress (MPa), d is the grain size (m) and ϕ is the porosity (%).

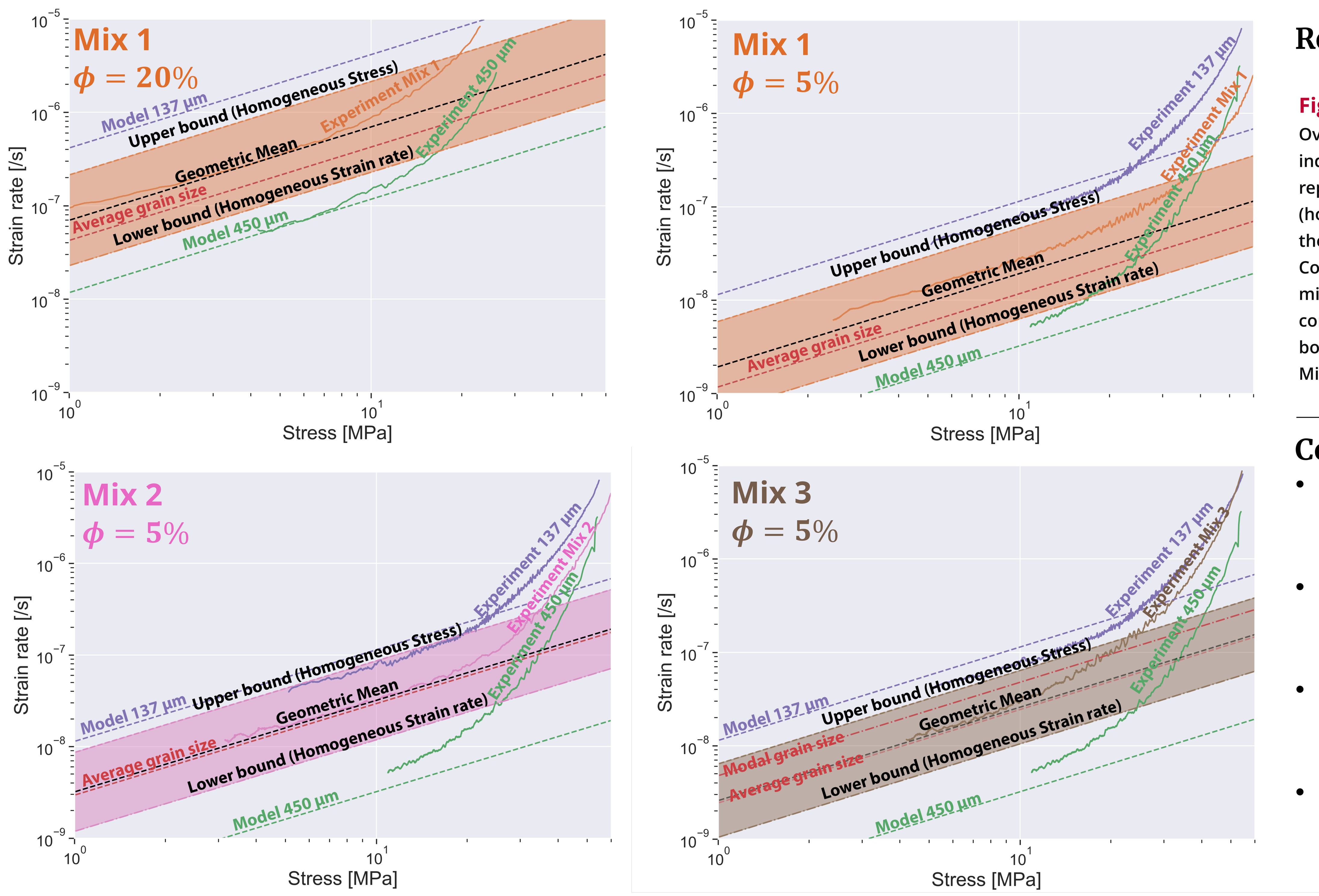
Mixture (see Figure 2)

Upper bound:
- Stress is distributed homogeneous, strain rates can be calculated for each grain, using Eq. 1
- Using the volume probability (v_1, v_2, …, v_i) of each grain size, the strain rate can be calculated using:
- $\dot{\varepsilon} = \frac{\Sigma\left[A\frac{\sigma_e}{d_i^3}f(\phi)\right]v_i}{\Sigma v_i}$

Lower bound:
- Strain rate is distributed homogeneous, stresses can be calculated for each grain, by rewriting Eq. 1
- Using the volume probability (v_1, v_2, …, v_i) of each grain size, the stress can be calculated using:
- $\sigma_e = \frac{\Sigma\left[A\dot{\varepsilon}d_i^3 f(\phi)\right]v_i}{\Sigma v_i}$

Figure 2





Results

Figure 3
Overview of compaction rates in experiments (solid lines) and model fits (dotted lines) for the two individual grain sizes (shown in all plots) and the three different mixtures. The highlighted areas represent the range between the upper bound (homogeneous stress) and lower bound (homogeneous strain rate). The geometric mean of the upper and lower bound is shown in black and the average and modal grain size are shown in red. (a) Compaction rates of mixture 1 at 20%, (b) Compaction rates of mixture 1 at 5%, (c) Compaction rates of mixture 2 at 5%, (d) Compaction rate of mixture 3 at 5%. The geometric mean of the upper and lower bound is a good indicator for the compaction rate of each of these three mixtures. Compaction rates are generally closer to the upper bound at low porosity (See figure 3b vs 3a) and when there is a larger percentage of small grains (e.g. Mixture 2).

Conclusion

- Compaction rates of mixtures can vary by up to one order of magnitude depending on distribution of stress/strain rate.
- The geometric mean of the upper and lower bound gives a reasonable prediction of the compaction rate of a mixture.
- At high porosities, compaction rates are relatively slower (e.g. more towards the lower bound).
- In mixtures with a large percentage of small grains (e.g. Mix 2), compaction rates move towards the upper bound.

References
1. Spiers et al. 1990
2. Zhang et al. 2007
3. Krohn et al. 2017
4. Ter Heege et al. 2004
5. Czaikowski et al. 2020

Acknowledgements
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