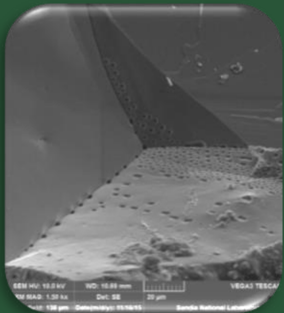
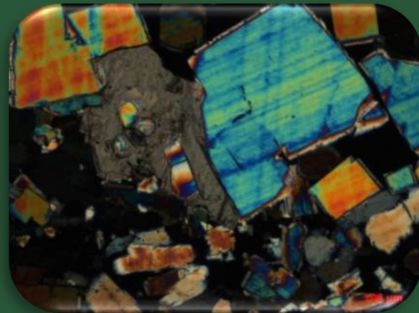
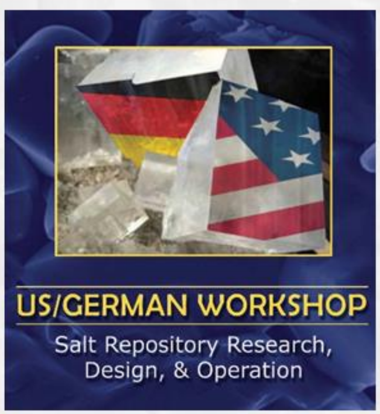



11th US/German Workshop on Salt Repository Research, Design, and Operation

UVERSTOFF – The Viscous Behavior of MgO-Concrete

Christian Lerch
Nina Müller-Hoeppe
BGE TECHNOLOGY GmbH

Part 4 of the online workshop
September 9, 2021



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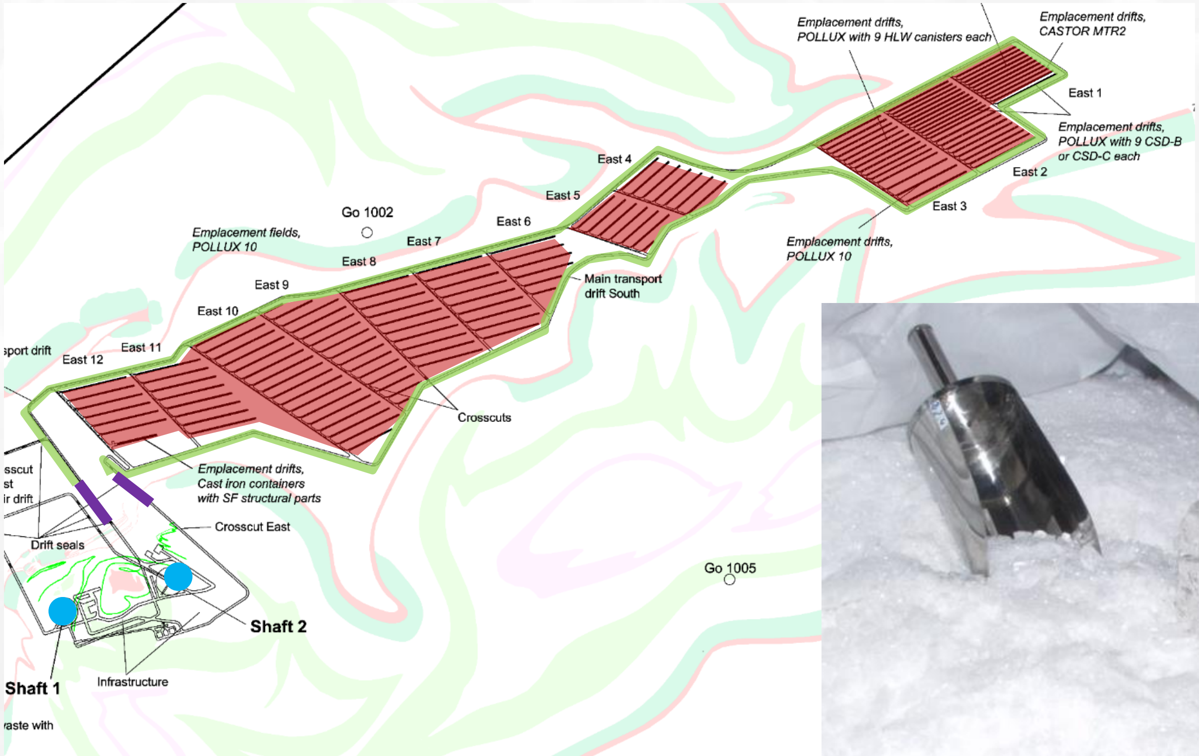
Isolation of Radwaste (BMU 2010) - VSG



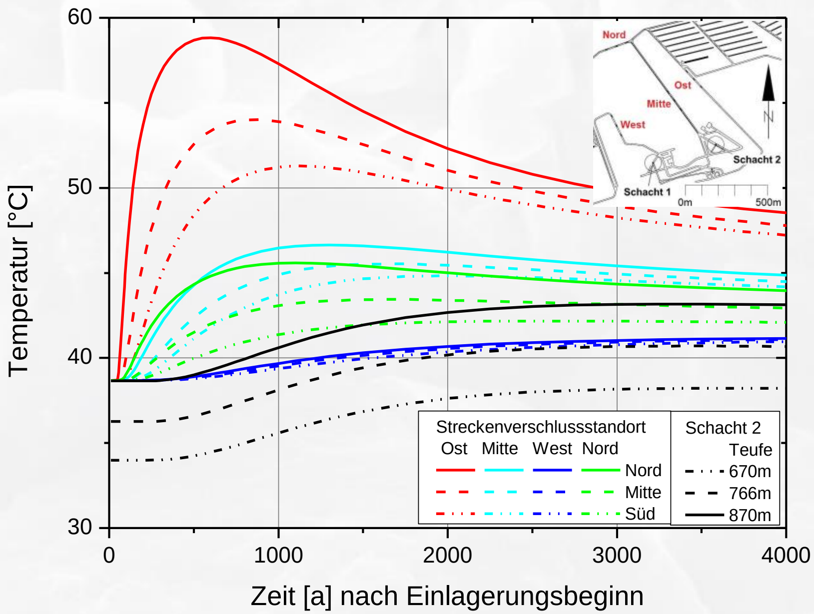
<u>Backfill and seals:</u>

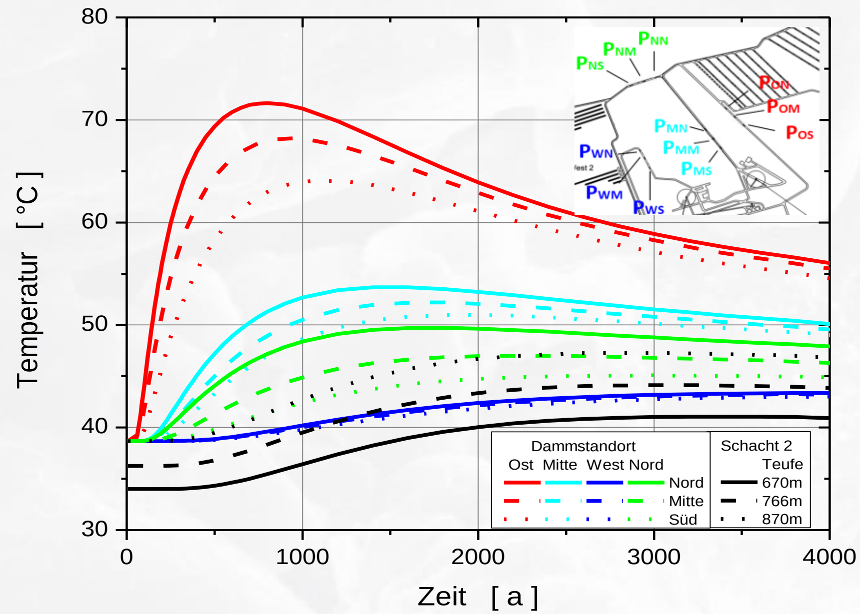
- Dry crushed salt in emplacement drifts and cross-cuts
- Humid crushed salt in access drifts
- Drift seals (made of MgO-concrete)
- Shaft seals include humid crushed salt sealing elements

… until crushed salt is sufficiently compacted shaft and **drift seals** guarantee safe confinement!

Drift Seals – Thermal Impact

- Drift seals are subjected to a long-lasting thermal impact/load
- The temperature maximum will appear after repository closure
- Question: Does the thermal impact affect drift seals´ functionality due to thermomechanical induced crack formation?

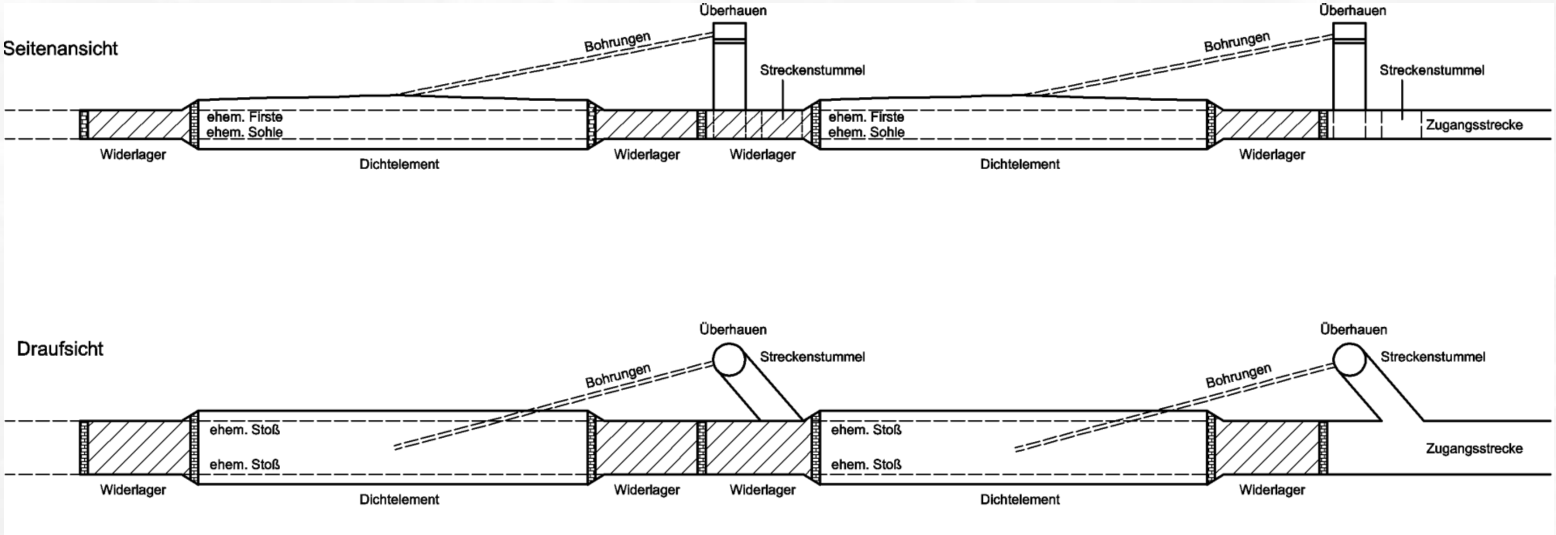




- Argumentation so far: The MgO-concrete structure was subjected to higher temperatures in its past
- However, the only significant thermal load considered is hydration heat at early age (mass concrete)
- Does this argumentation hold?

Structural Model – Material Model

- The geometry of a drift seal is simple
- ➢ Simple structural model



- The material behavior of concrete is complicated even in the case of conventional concrete
- So-called engineering models are used whose validness is restricted to special applications
- Question: But what about the material behavior of MgO-concrete with MgO constituting the binding agent and crushed salt the aggregate?

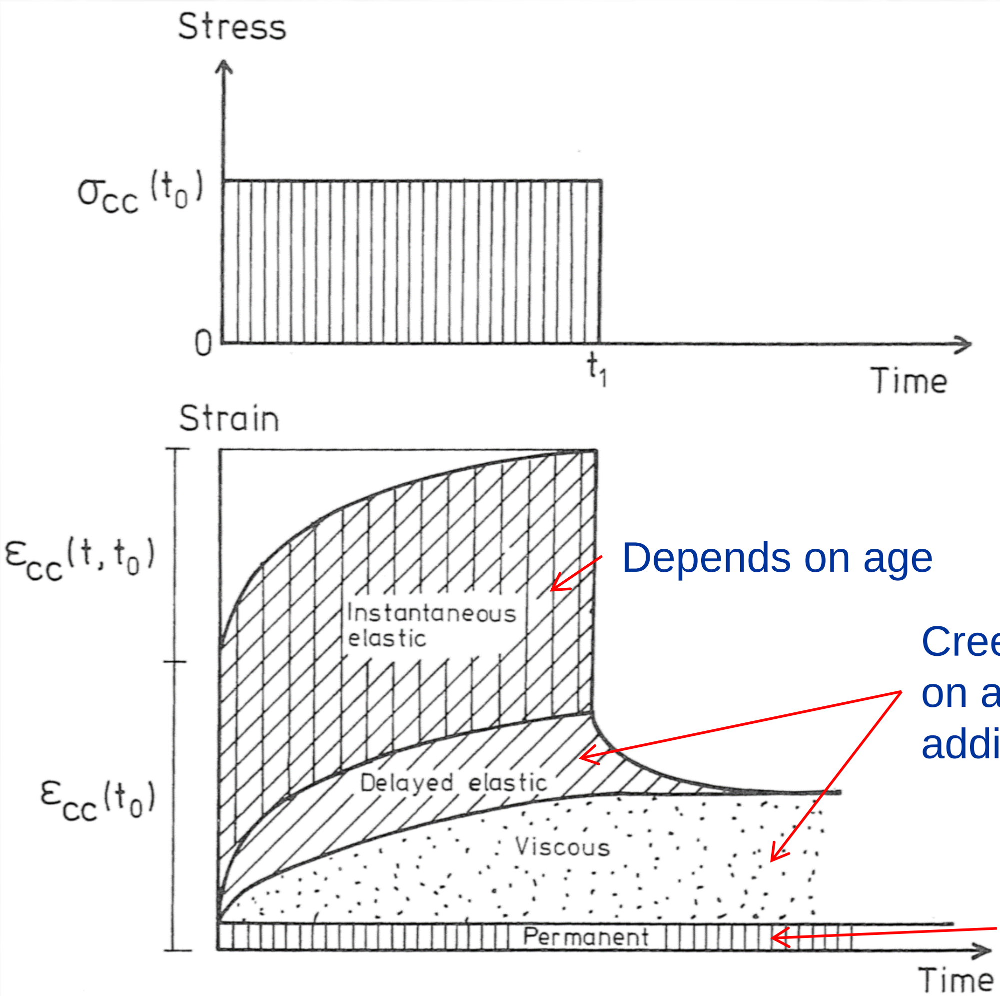
Starting Point: Conventional Concrete

Knowledge on material behavior of conventional mass concrete

- Heat release due to hydration process and coupling of concrete age to temperature history
- Evolution of elastic material properties depending on concrete age
- Evolution of mechanical strength depending on concrete age
- Evolution of shrinking/swelling depending on concrete age and hygric state
- Evolution of viscous behavior depending on concrete age and additional factors
    - Distinguishing two* types of creep behavior
    - Basic creep (long term creep/viscous flow)
    - Transient creep (short term creep/delayed elastic)

* The existence of one or two types of creep was frequently discussed in the past and the scientific discussion is ongoing. Presently, the discussion tends to two parts.

Conventional Concrete – Decomposition of Strains



Depends on age

Creep depends on age and additional factors

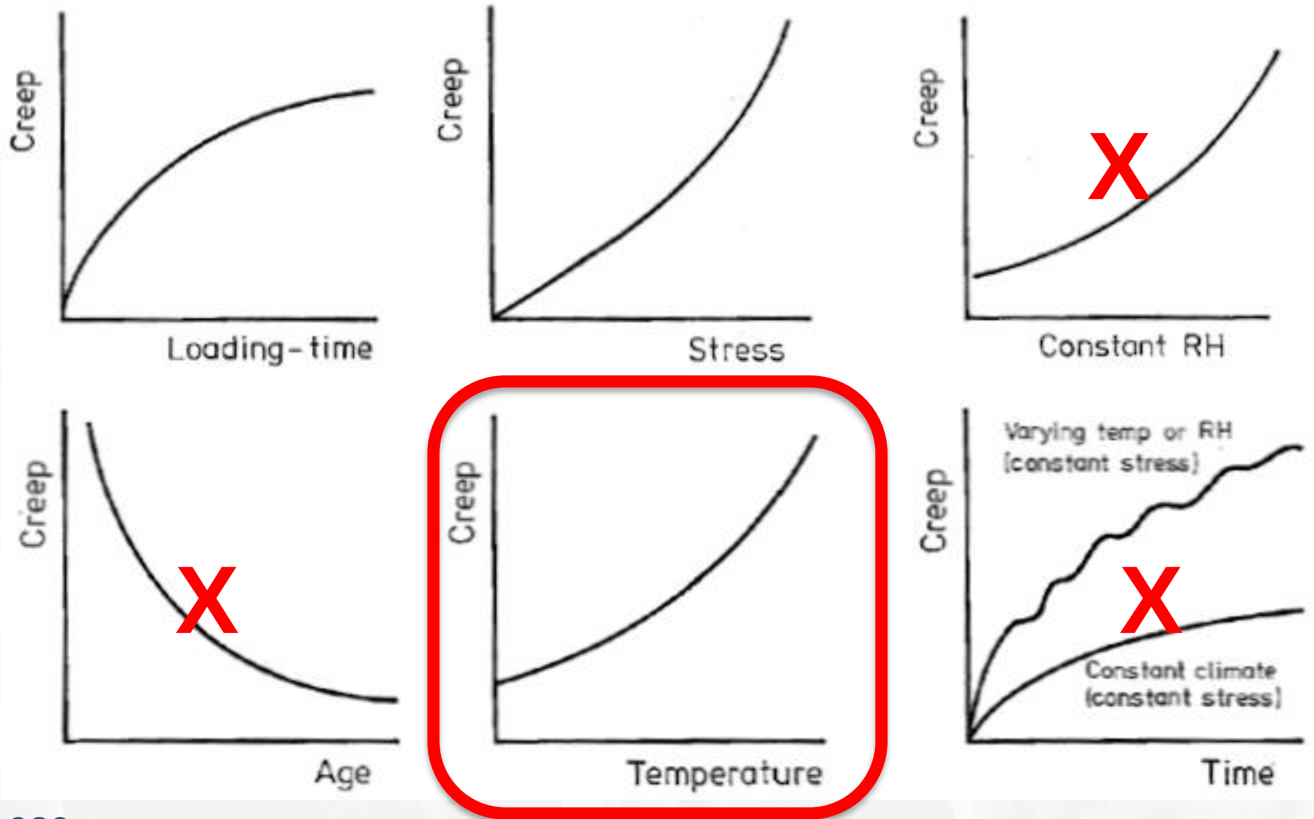
In the case of very early loading

Byfors 1980

Conventional Concrete - Creep Influencing Factors

Under repository conditions thermal impact occurs at

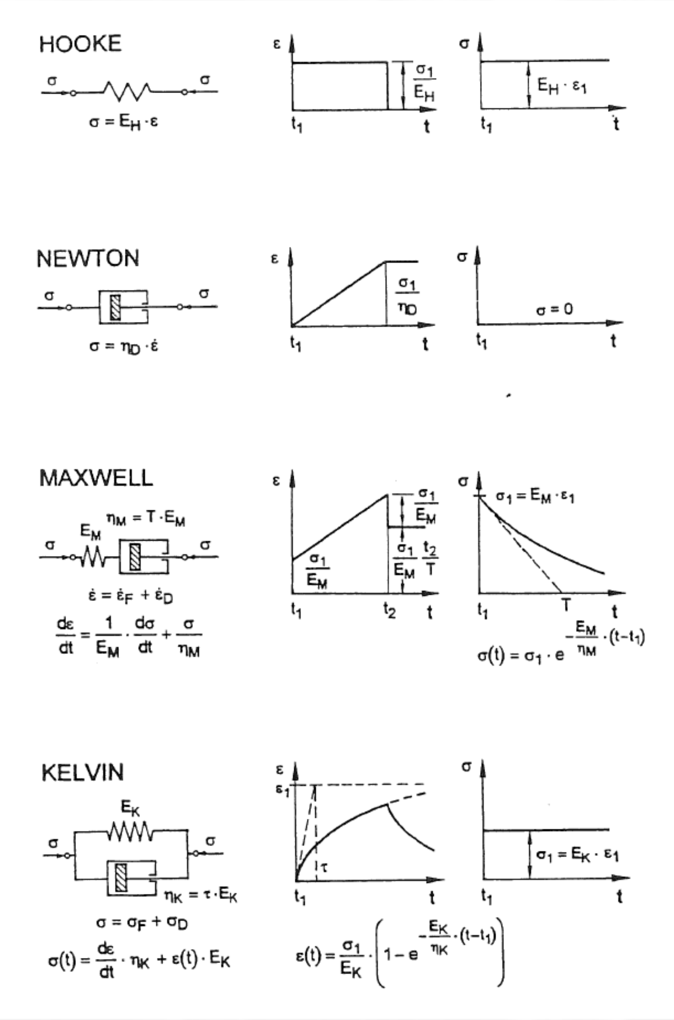
- High concrete age
- Dry constant climate (expected repository conditions)
- One long-lasting thermal impact
- ➢ Some influencing factors could be neglected



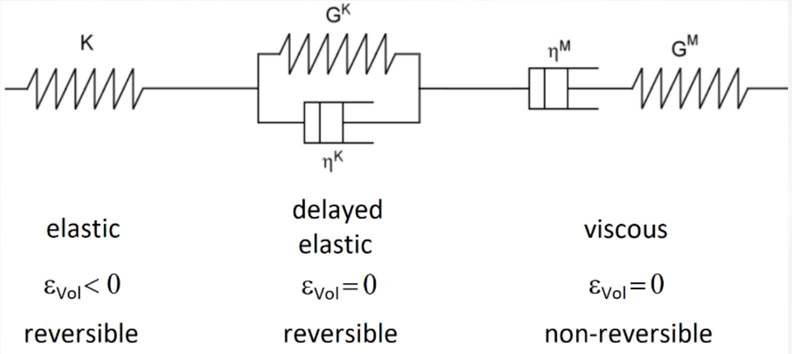
Byfors 1980

Selection of Rheological Model

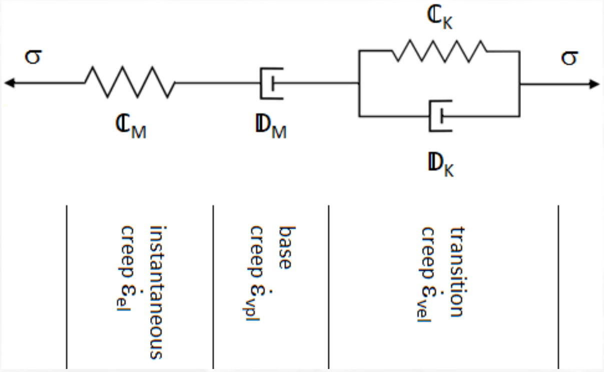
- Basic rheological models used for concrete



- Rheological model used for salt



- First choice of rheological model for MgO-concrete with crushed salt aggregate

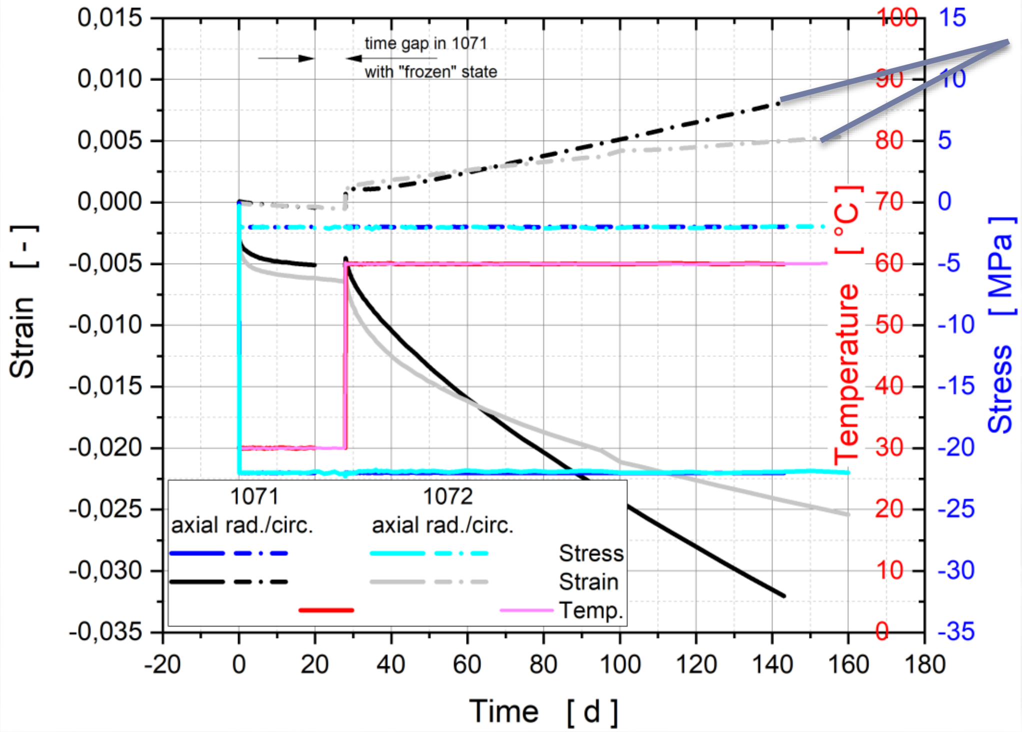


MgO-Concrete - Laboratory Investigations

- Challenge: Test specimens of high concrete age kept at constant climate
  - Availability of test specimens of MgO-concrete that were produced in the context of the building of flow barriers in the Asse mine

- Definition of the load-temperature conditions of laboratory tests conjointly with GRS taking into account conditions of the VSG drift seals
  - Triaxial tests starting at 30 ^{o}C heating up to 60 ^{o}C, loading condition 22 MPa axial stress and 2 MPa radial stress but well below MgO-concrete´s strength
  - Triaxial tests were performed twice under nearly similar conditions to control the reproducibility of test results

MgO-Concrete – Laboratory Test Results

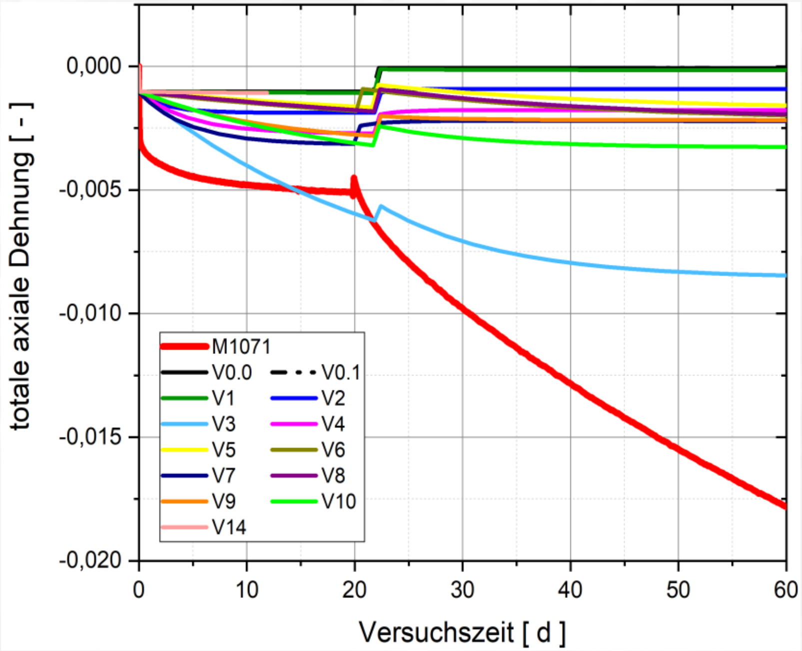


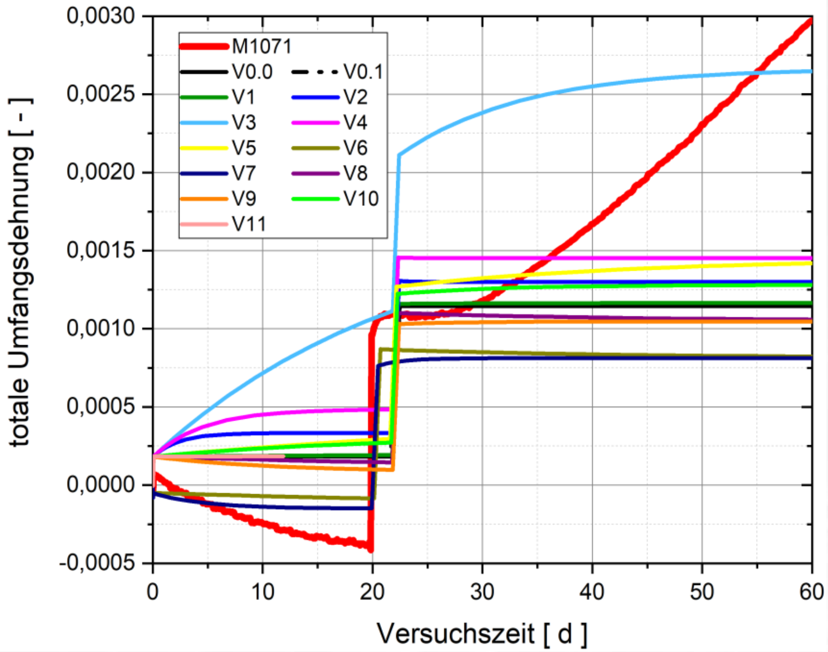
Different trends

- The two tests were not sufficient
- GRS performed two additional tests
- Application of the recent test concept to distinguish mainly deviatoric and mainly spherical stress conditions

Experimental Results and Numerical Adjustments

Some numerical adjustments to available tests in the waiting period for additional test results



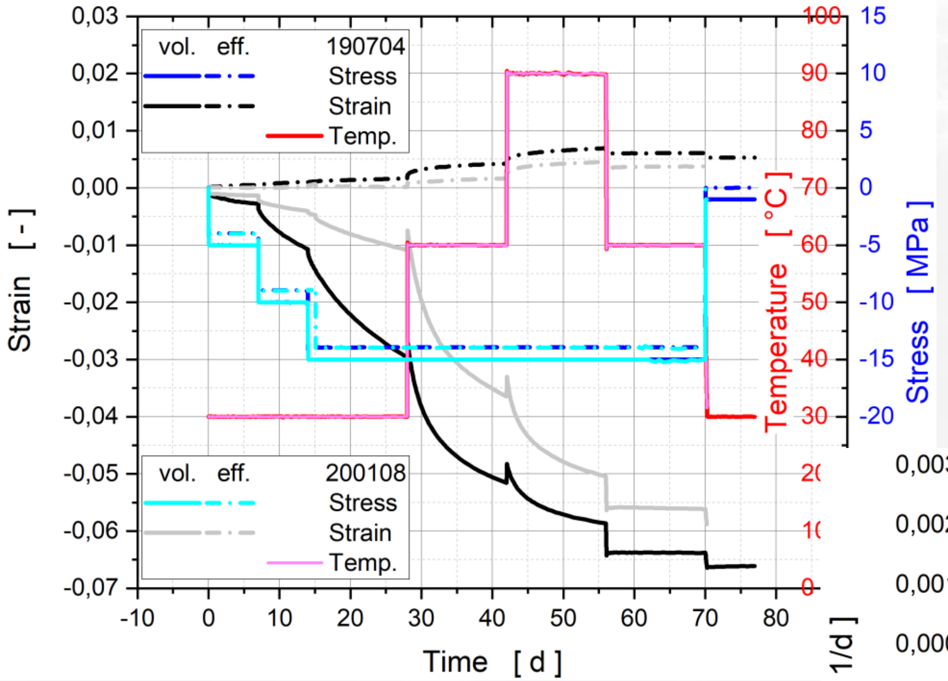


- Hein´s crushed salt approach for the Maxwell element supplemented by an Arrhenius term
- Linear Kelvin element with constant elastic module and constant viscosity supplemented by an Arrhenius term
- Accompanying checks whether parameter values remained within reasonable limits

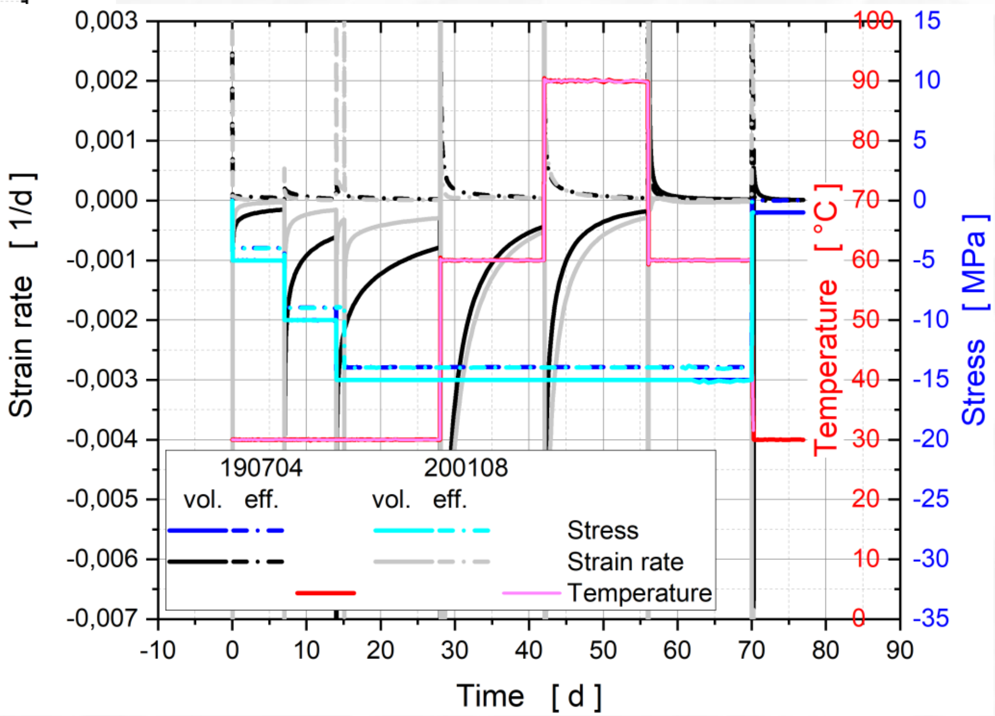
➢ Numerical adjustments were too stiff

➢ The increasing trend in the lab test was assumed not to be plausible

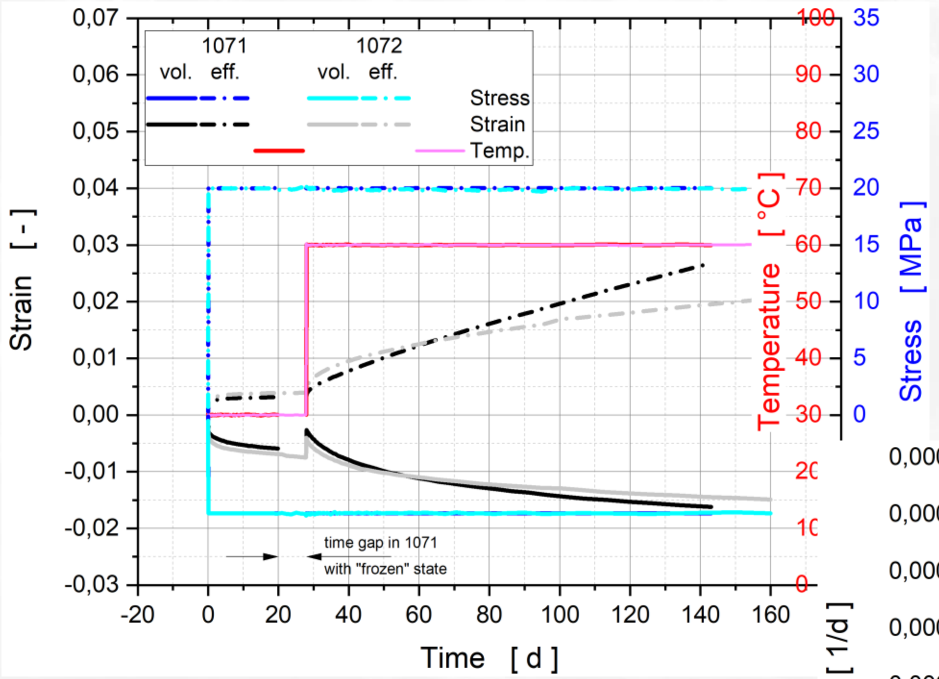
Results from (Additional) Mainly Spherical Tests



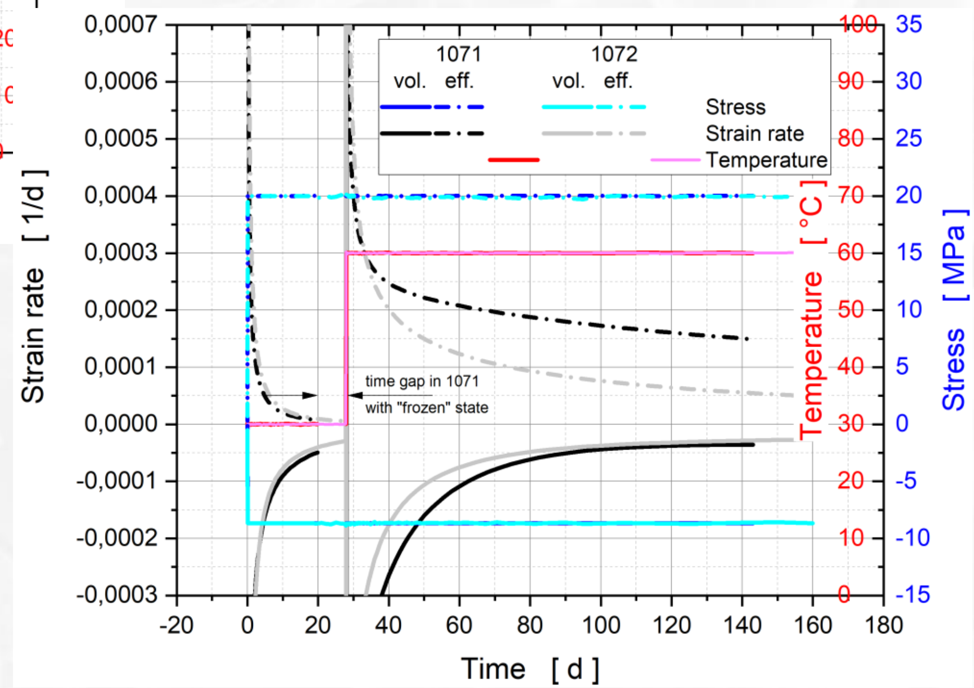
Decomposition of test regime in mainly spherical and mainly deviatoric tests utilizes the mathematical orthogonality of spherical tensor and deviator in the material model



Results from Mainly Deviatoric Tests

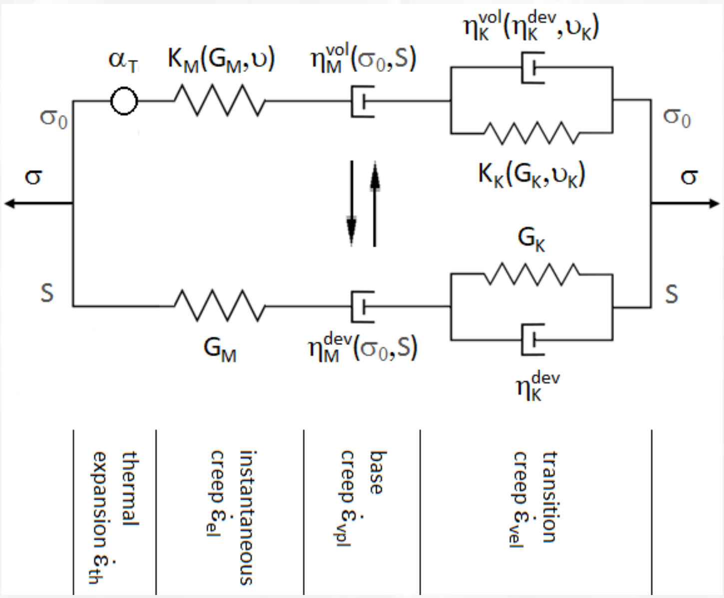


Test results were also displayed and re-analyzed in the decomposed way



Material Model for high aged MgO-concrete

Initial state

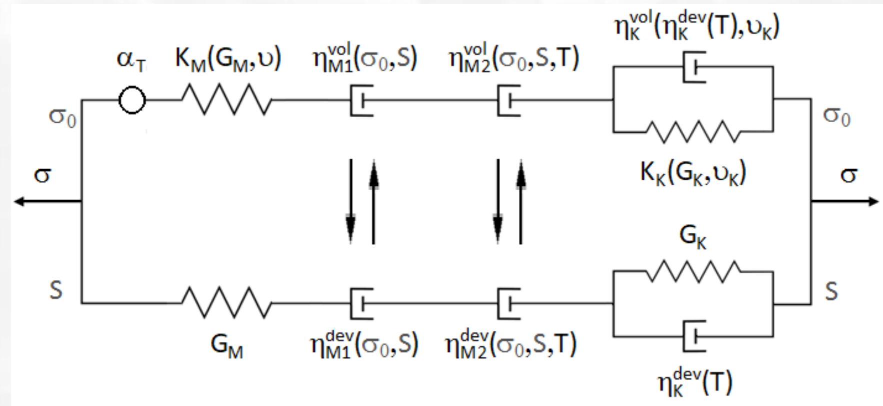


$$\dot{\boldsymbol{\varepsilon}}_{th} = \alpha_{th}\dot{T}\,\boldsymbol{I} \qquad \dot{\boldsymbol{\varepsilon}}_{el} = \mathbb{C}^{-1}\dot{\boldsymbol{\sigma}}$$

$$\dot{\boldsymbol{\varepsilon}}_{vpl} = A\,F(\sigma_0,\hat{\sigma})\,\frac{\partial F}{\partial \boldsymbol{\sigma}}\;; F = m|\sigma_0| + n\hat{\sigma}$$

$$\dot{\boldsymbol{\varepsilon}}_{vel} = \mathbf{D}^{-1}\boldsymbol{\sigma} - \mathbf{D}^{-1}\mathbb{C}\,\boldsymbol{\varepsilon}_{vel}$$

Current state



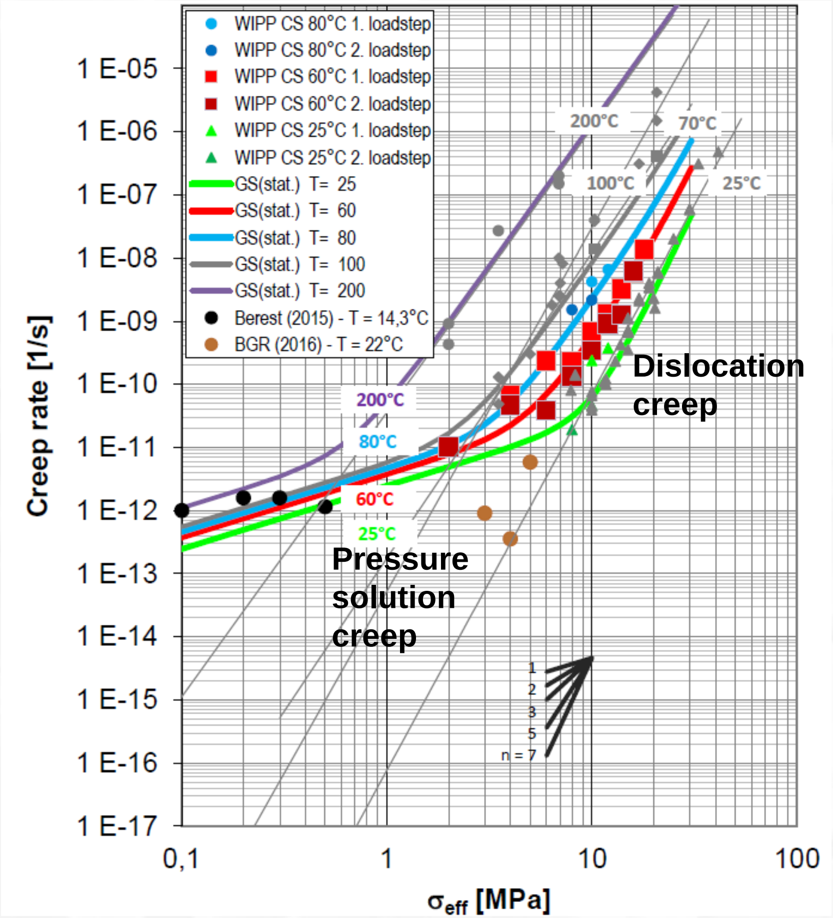
$$\dot{\boldsymbol{\varepsilon}}_{th} = \alpha_{th}\dot{T}\,\boldsymbol{I} \qquad \dot{\boldsymbol{\varepsilon}}_{el} = \mathbb{C}^{-1}\dot{\boldsymbol{\sigma}}$$

$$\dot{\boldsymbol{\varepsilon}}_{vpl} = \sum_{i=1}^{2} A_i e^{-\frac{Q_{M,i}}{RT}}\,F_i^q(\sigma_0,\hat{\sigma})\,\frac{\partial F_i}{\partial \boldsymbol{\sigma}}\;; F_i = m_i|\sigma_0|^{p_i} + n_i\hat{\sigma}^{p_i}$$

$$\dot{\boldsymbol{\varepsilon}}_{vel} = e^{-\frac{Q_K}{RT}}\,\mathbf{D}^{-1}(\boldsymbol{\sigma} - \mathbb{C}\,\boldsymbol{\varepsilon}_{vel})$$

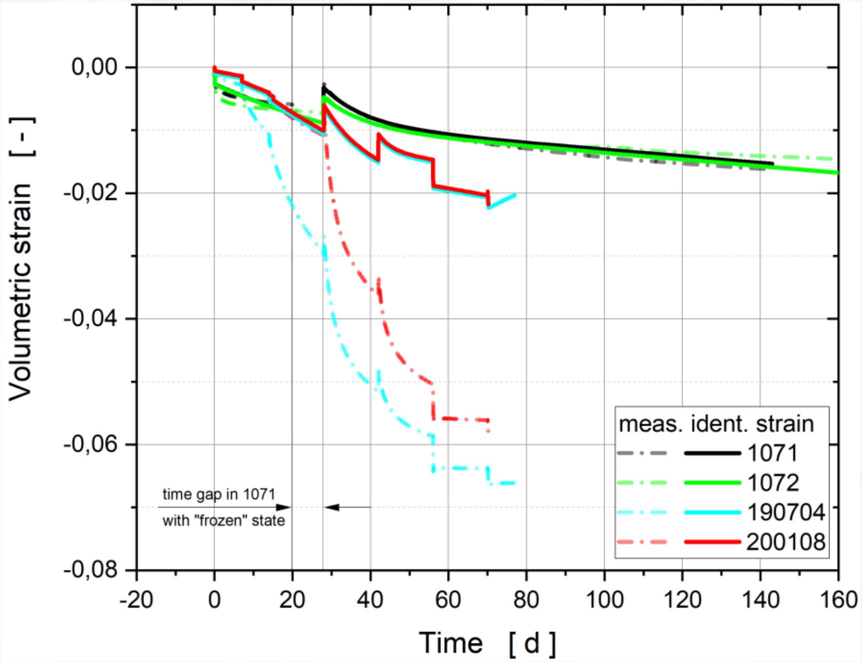
Maxwell Element and Successive Parameter Identification

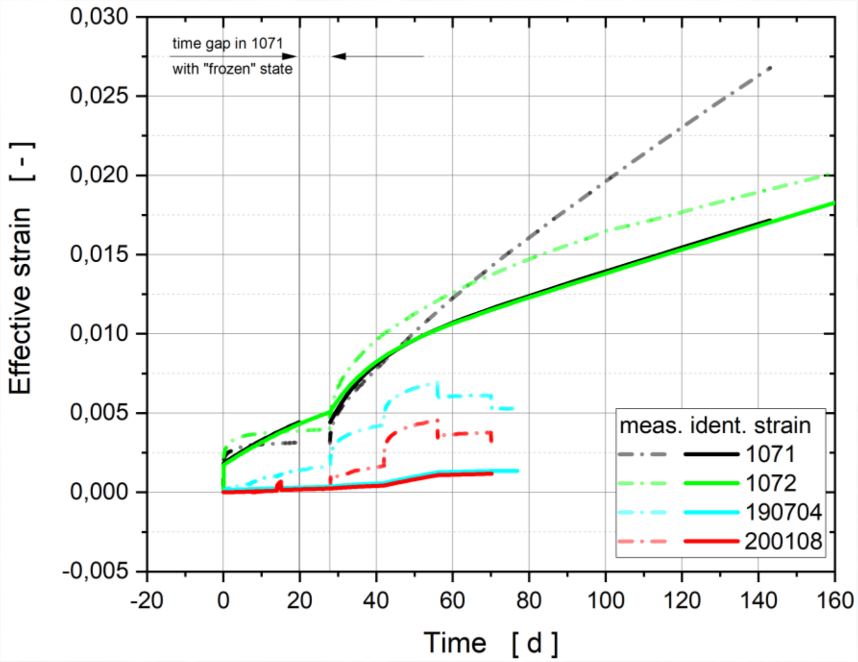
- Parameter values and their explanation:
- Exponents: 1 - 3
- Indicating main influence of pressure solution creep
- Spherical activation energy shows negligible dependency on temperature
- Deviatoric activation energy shows dependency on temperature in the range of salt



Salt

Kelvin Element and Parameter Identification

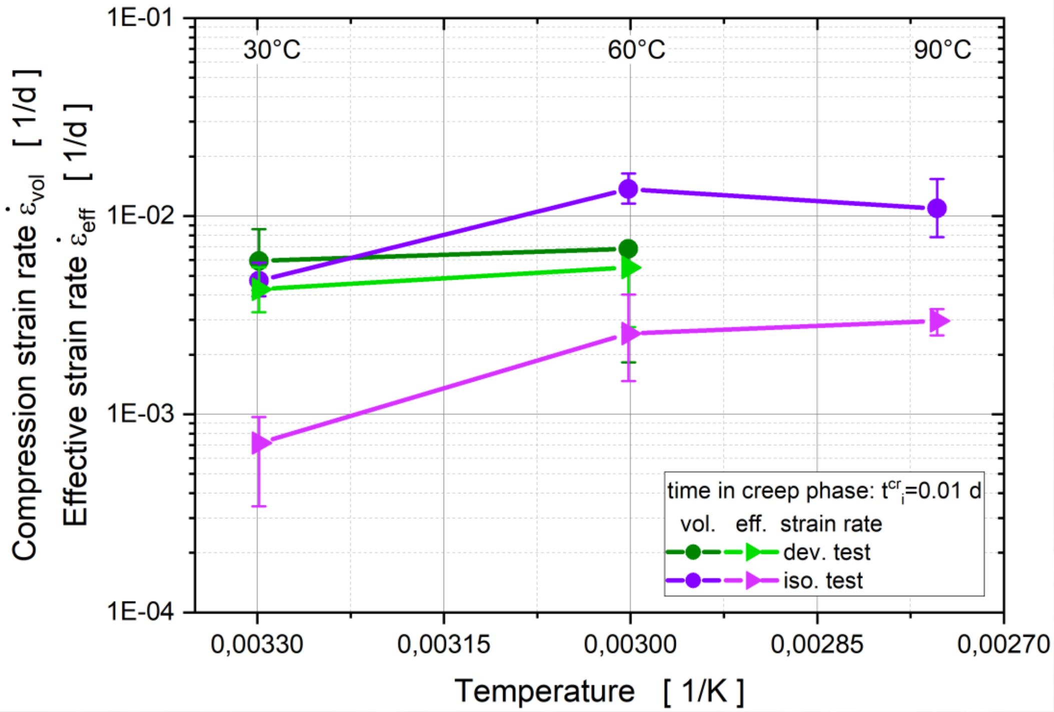




- Requiring that all experiments should be captured by the same set of parameters the identified parameter set is unsatisfactory as the Kelvin element remains too stiff
- Typically, thermal activation plays a role of „softening“ the material
- ➢ Consequently, temperature dependency of strain rate immediately after mechanical/thermal load step was investigated in detail (assuming that in this time period the Kelvin element dominates the strain rate)

Influence of Temperature

Temperature dependency of strain rate decomposed in deviatoric and spherical part shortly after temperature rise



- Result: None or very low temperature dependency

Process Understanding and Conclusions

- The short term process seems to be governed by viscoelasticity (like concrete)
  - Due to the limitations of engineering concrete models further applications of viscoelasticity were considered
- Literature from modeling of polymers was included
  - The finding: The viscoelastic behavior of polymers is described by a spectrum
  - This issue is explained by the internal structure of the polymers being composed of different molecular chains
- This argumentation also holds for concrete being a multi-aggregate material
  - The argumentation explains the stiff behavior of one Kelvin element (missing internal degrees of freedom to represent the spectrum)
  - The Maxwell and Kelvin chains applied in concrete models on a semi-empirical basis are an adequate approach, the parameters of the chains, however, are not independent (as they treated) but belong to a spectrum
  - The parameters of the spectrum must be identified, experimentally
  - The mathematics to describe these relationships is non-standard

Summary and Outlook

- A material model for MgO-concrete was established consisting of rheological elements - Maxwell and Kelvin type - and being able to capture thermal activation
- Experimental results gained from complex experiments formed the basis for parameter identification
- The Maxwell element shows thermally activated behavior and seems to capture mainly the salt aggregate´s influence
  - The range of exponents identified indicates the dominance of pressure solution creep
- The Kelvin element did not agree well with the experimental results – too stiff
- Surprisingly, the Kelvin element shows low temperature dependency indicating that a different (unexpected) type of process is acting
- Based on further information the conclusion is drawn that an internal "dynamic" process may act that is characterized by a spectrum
  - Due to the "dynamics" of the process potentially it might be neglected in long-lasting processes with small changes on the time scale

US/GERMAN WORKSHOP
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Casting of MgO-Concrete

PTKA
Projektträger Karlsruhe
Karlsruher Institut für Technologie

Supported by:

Federal Ministry for Economic Affairs and Energy

on the basis of a decision by the German Bundestag