MICROCRACK GROWING AND LONG-TERM MECHANICAL STABILITY IN A HLW DEEP-BOREHOLE REPOSITORY IN GRANITE

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ABSTRACT

The longterm host rock integrity assessment of a deep borehole emplacement for HLW in granite has been addressed with a detailed new constitutive model considering temperature and pressure effects on microscale phenomena (as microcracking) under repository conditions. The results of these finite element calculations have been compared with results obtained using conventional, state of the art constitutive modelling. While the results of conventional modelling did suggest the existence of an important safety margin before failure, the improved calculations with the new model predict a thin but very long region of degradated host rock along the waste canister column. The results obtained up to now may well be considered as safety relevant, because they suggest that the actual long-term granite strength lies well below the conventionally determined failure limits, thus challenging the barrier properties of this host rock if the actual strength is not properly considered in the repository design.

INTRODUCTION

For a number of countries with a small nuclear power plant program the final disposal of radwastes in deep boreholes in granite is a meaningful alternative to the much more expensive disposal in mined repositories. In a deep borehole repository special attention must be payed to the long-term host rock integrity assessment, since the rock itself is the main barrier for preventing nuclide migration, because the adequate emplacement of engineered barriers in a deep borehole and its quality assurance (except for the waste package itself) can not be ensured.

An evaluation of available constitutive equations for the longterm thermomechanical modelling of granite under HLW-repository conditions (high temperature and pressure) has recently been carried out [1]. This evaluation clearly shows, that important aspects, as for example nonlinearities, microcrack growing and static fatigue remain unconsidered thus challenging seriously the reliability of long-term model predictions.

To overcome these shortages as well as for improving the confidence degree of long-term model predictions the necessity of new constitutive equations was recognized. These new equations should reproduce as far as possible the microscale phenomena occurring inside the granite under high temperatures and heavy loading rather than being of empirical, curve-fitting type, in order to ensure reliable long-term extrapolation.

THE NEW CONSTITUTIVE MODEL

As a first step towards this goal an extensive literature study was carried out in order to identify the main microscale mechanisms responsible for the well known laboratory behaviour of granite. Microcrack opening and closing was found to be responsible for the nonlinearities in the reversible part of granite load-defomation behaviour. Microcrack growing accounts for all the irreversible phenomena as dilatancy, static fatigue and strain rate dependent failure.

In a second step, a new constitutive model for granite has been developped. This new model takes into account both the temperature and pressure dependency of the elastic (reversible) part of the load-deformation behaviour. For the irreversible deformations, which arise for granite after exceeding about one half of the short-term failure strength, a microcrack growth model including load, memory and temperature effects has been established. On the basis of failure mechanics considerations a "damage surface" (analogous to a yield surface in viscoplasticity) has been derived to describe the onset of microcrack growth after achieving certain stress conditions. By combining failure mechanics concepts with some ideas of viscoplasticity, it has been possible to state relations for the suitable description of crack growth rates in the microscale, as well as for the macroscopic irreversible strain rates resulting from microcrack growth i.e. the well known volumetric dilatancy shown by granite and other cristalline rocks under heavy deviatoric loading. These relations accurately reproduce laboratory results, as for example dilatancy and temperature effects (Fig. 1). Finally, a single failure criterion which soundly reproduces the temperature dependence of short-term strength and the strain rate dependence of failure strength in the long term (also known as delayed failure or static fatigue, Fig. 2) results straightfor wardly from the theoretical background under the model assumptions. The details of this new constitutive model, of it's derivation and the theoretical background can be found in a previous work of one of the authors [1].

The constitutive model has been incorporated into the well established finite element code MAUS [2], a special purpose program developped by the authors at Aachen University of Technology in Germany, for thermomechanical assessment of HLW repositories. By numerical modelling of several different laboratory experiments (mainly on

Stripa granite, see Figs. 1 and 2) the constitutive equations have been successfully verified and validated.

CALCULATION RESULTS

With the mentioned calculation tools a single deep-borehole of a final repository has been analyzed using assumptions corresponding to the conditions in a country with a small nuclear power program, Argentina, i.e. with high level wastes arising from reprocessing of PHWR or CANDU fuel elements. Besides the new developped constitutive equations, also conventional, state of the art granite constitutive modelling was used in the finite element calculations.

For a sound comparison of the calculation results obtained with both material models, suitable, problem oriented measures of the "distance to failure" or "safety margin" have to be defined. Obviously, these measures should include in some direct or indirect manner the predicted thermomechanical loads as well as the predicted host rock load-bearing capacities. Furthermore, because we are concerned mainly with the tightness of the host rock surrounding the radwaste emplacement, the appearance of macrofractures will compromise seriously its function as a barrier to prevent nuclide migration independently of furthergoing mechanical effects. Thus, the arising of fractures must be considered as the limiting condition to avoid, even in the case that the fracturing did not challenge the overall mechanical integrity of the repository itself.

The failure criterion of the new constitutive model predicts accurately the arising of macrofractures because just this condition has been considered during its development as the definition of "failure". As a suitable measure of the safety margin at a given time for the new constitutive model we use therefore a relation including the actual "mean microcrack length" and the "critical microcrack length". This relation yields values near "1" for the undisturbed, intact granite and "0" at failure. The used mean microcrack length is not only a measure of the actual loading and temperaure at a given time but also a measure of the load and temperature history of the granite. The critical microcrack length is the one which under the given conditions of temperature and mean stress will lead to the onset of macrocracking and therefore to failure.

Conventional constitutive modelling of granite's strength did not include any time or temperature dependant phenomena. As a measure of the safety margin under given stress conditions we hence used one of the usual approaches, namely the Drucker-Prager failure criterion suitably normalized to yield "1" under hydrostatic loading conditions (undisturbed, intact granite) and "0" at the onset of failure.

An example of the calculation results ist shown in Fig. 3. It shows both safety margin measures near the wall of the borehole one year after the emplacement of the heat generating wastes. This example was choosen because to this time the temperature maximum in the host rock (that has been limited to 200° C for this calculation) has been just achieved and it is coincident with the maximal mechanical loading of the granite.

Conventional modelling yields a safety margin of at least 33% of the initial value at a given depth before sinking the borehole. Most of the safety margin reduction is but a result of the stress rearrangement due to borehole sinking, as can be seen at the top (at 2000 m depth) and at the bottom (at 3000 m depth) of the waste column. About 50 m above and below the waste column heat effects are negligible at this time, and the safety margin did not depart from the value obtained inmediately after sinking the hole. Furthermore, it can be derived from Fig. 3 that the temperature rise did not challenge host rock strength substantially, for the departure from the initial value is only of a few per cents.

The results obtained with the new model are in sharp contrast with this. One year after emplacement of the heat generating wastes the granite is fractured around the wastes along the whole waste column. A few days after waste emplacement an anular fractured zone builds up near the column's bottom and rapidly propagates until the top. The temperature increase in the inmediate vicinity of the borehole wall does induce rapid microcrack growing in a zone of about 10 cm thickness around the hole leading to the appearance of macrocracks.

CONCLUSIONS

1) Because of its ability to reproduce much more better the laboratory material behaviour of granite in the long and in the short term and under mechanical and thermal loading (including irreversible phenomena, see Figs. 1 and 2), it is obvious that the calculation results obtained with the new constitutive model must be considered as much more reliable than the results of conventional constitutive modelling. In order to obtain high quality, reliable long term predictions of the host rock behaviour in a HLW repository in granite the here presented or a similar, sofisticated constitutive model should be used.
2) Although the fractured zone predicted with the new model is very thin, it can eventually compromise the repository safety. For any water inflow through local, natural fissures (wich are always present in granite but has not been modelled here) will lead to the whole waste column being submerged in hot water and therefore submitted to corrosion. Furthermore, the long, vertical fractured zone will be very favourable to the formation of an hydrothermal convection cell, eventually improving in an unconvenient manner the radionuclide transport from the bottom area of the waste column to the neighbourhood of the top.
3) It must be pointed out, that the formation of a fractured zone arround the waste canisters can be reliably prevented with simple engineered means or through a reduction of the host rock thermal load, thus ensuring granite integrity. In spite of this, the most important conclusion of our research work is that more attention must be payed to the question of host rock integrity, and that conventional constitutive modelling does lead to non-conservative predictions, suggesting the presence

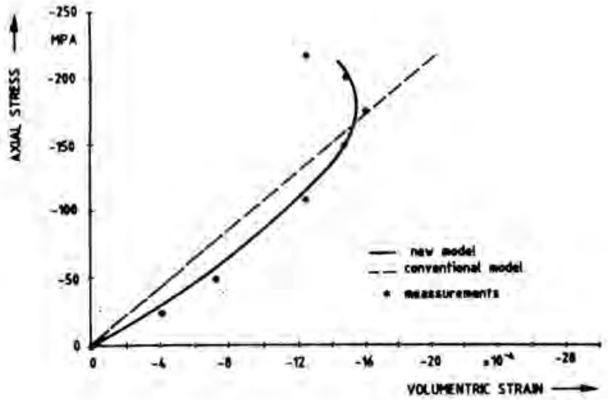

Fig. 1. Uniaxial Stress-Strain Behavior of Granite.

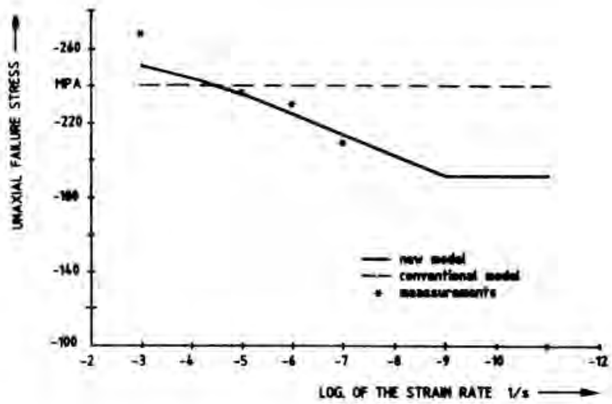

Fig. 2. Strain Rate Dependency of Granite Failure Strength.

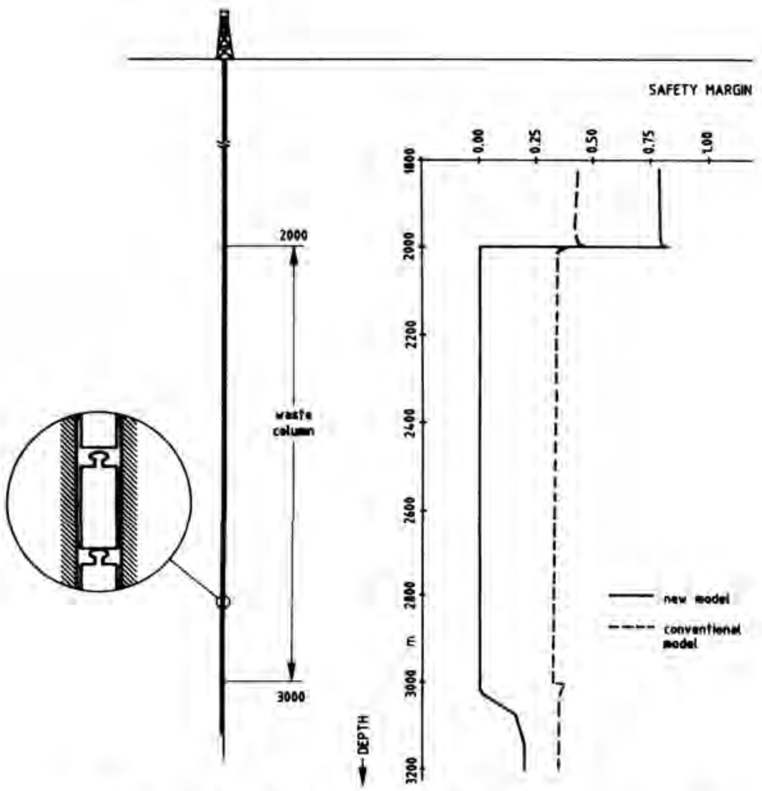

Fig. 3. Safety Margin as a Function of Borehole Depth.

of significant safety margins befor failure that actually did not exist.

4) Although at present no calculations with the new constitutive model have been performed for a mined repository, it can be assumed by analogy, that also in such repositories unexpected integrity problems may arise. And because the stress rearrangements in the vicinity of large cavities involves a substantially larger volume of rock than in the neighbourhood of a 40 cm diameter borehole, the potentially damaged host rock zone will be presumably much more larger than in a deep-borehole repository.

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