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Numerical simulation of cracking behavior in artificially designed rock models subjected to heating from a central borehole

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1. Introduction

Many countries concerned about the safe isolation of nuclear waste from the biosphere plan to dispose of nuclear waste in deep geological formations[1] because any leakage of nuclear waste into the biosphere can result in severe risks to human health and the natural environment. In a nuclear waste repository, the heat released due to nuclear radioactivity may increase the temperature in the surrounding rocks.[2,3] This temperature increase can result in buoyancy-driven convective pore-fluid flow, which has been extensively studied in recent years.[4]

Since the pore-fluid flow can affect the thermal field distribution through heat convection, it is strongly coupled with the thermal field in both geological and engineering length scales. More importantly, such pore-fluid flow in saturated porous rocks can result in the formation of large mineral deposits within the crustal rocks[4] and large geological cracks/faults.[5] In addition, thermal effects can also play an important role in geochemical reactions. However, the deformation of a porous rock can considerably change its porosity and permeability.[6] Both the physical and chemical dissolution of dissolvable materials in fluid-saturated porous rocks can significantly change the porosity and permeability of porous rocks and can therefore affect the pore-fluid flow through changes in the flow channels.[7] Therefore, chemical dissolution reactions are strongly coupled with the pore-fluid flow through porosity and permeability changes[8] and are indirectly coupled with the thermal field because the thermal field is strongly coupled with the pore-fluid flow. Therefore, fully coupled problems considering rock deformation, pore-fluid flow, heat transfer, mass transport and chemical reactions can be found in a wide range of scientific and engineering problems.[9] Thus, any improvement to the existing methods for predicting thermally induced cracks and porosity changes in fluid-saturated porous rocks may have both scientific and practical significance. In a broad sense, the outcome of such an improvement can enrich the emerging field of computational geoscience.[6]

Historically, thermal effects on host rocks have been widely studied by conducting heater tests in underground research laboratories, with complementary numerical analyses of coupled thermal-hydrological-mechanical (THM) problems since the beginning of the 1970s. Although they have neglected the effects of chemical reactions, these studies have all placed heaters along the axis of a tunnel in the host rock to simulate the effects of the heat produced by radioactive waste. Taking one of the largest heater tests, the Yucca Mountain drift scale test, as an example, a previous study found that fracture closure/opening caused by changes in the normal stress across fractures was the dominant mechanism for changes in the intrinsic permeability of the fractures induced by thermal stress.[10] Previous studies have also discussed the changes in rock porosity and permeability caused by both excavation deformation and thermal stress and have studied the mechanical behavior of the rock during a heating-cooling process.[2,11] In addition to the Yucca Mountain project, many heater tests have been conducted to investigate the distributions of stress, deformation and temperature fields in the host rock in Canada (Whiteshell), Sweden (Aspo), Switzerland (Grimsel) and Germany (Corleben).[12–14] In terms of numerical simulations, an international project called DECOVALEX has been conducted to improve our understanding of the coupled THM processes in rocks, and a number of benchmark tests have been performed over the course of this project. Artificially designed problems associated with the coupled THM processes have been considered to investigate the effects of length scales on waste repository

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performance.[15–18]

In general, coupled THM processes affect the initiation and propagation of cracks in a waste repository system. However, nuclear wastes are usually placed in relatively compact and intact rocks, for which the thermal effect is one of the most important factors for crack initiation in the early stages after placing nuclear storage containers in the rocks. Thus, as a fundamental problem for both nuclear waste disposal and induced pore-fluid flow, the thermal cracking process requires further research. In other words, both the coupled THM process and the coupled thermal-mechanical (TM) process require greater attention. To simplify the thermal cracking problems associated with nuclear waste disposal, a rock sample (heated from the central borehole) has been studied by conducting small length scale laboratory experiments and numerical simulations, and the conclusion was that a crack initiated from the outside of the specimen and then propagated toward the heater hole.[19–23] The model ultimately failed because of the maximum tensile tangential stress occurring at the outer boundary. However, when the specimen is sufficiently large, the heating front will not be able to reach the outer boundary of the model, resulting in the thermally induced maximum tensile stress occurring a certain distance away from the borehole. As shown in Fig. 1, there is a large tensile stress (approximately 3 MPa) near the borehole at approximately the 11th day, indicating that the thermal stress could result in tensile cracking around the borehole. However, such a problem has not been given sufficient attention because the previously studied thermal cracking problems mostly have small length scales. Therefore, it is necessary to conduct scientific investigations at different length scales.[24]

When the thermal stresses due to an inhomogeneous temperature field exceed the tensile strength of the rock, a crack can be initiated.[25] This paper presents the results of numerical simulations that were conducted to improve our understanding of thermal cracking in samples heated from a central borehole. In particular, these numerical simulations focus on the effect of length scale on thermal cracking by varying the sizes of artificially designed models from 300, 600, and 900 mm to the engineering length scale.

2. Studies of a small length scale model subjected to heating

2.1. Model description

The experiment conducted by Ishida et al.[19] is simulated using a numerical method to verify the numerical model. In the experiment, Ishida placed a heater in a central borehole, and the temperature, which was monitored by thermocouples, was progressively increased from 28 °C to 310 °C for three hours. The rock sample was a 300 mm cube, with a 28 mm diameter borehole at the center of the specimen. Thermal cracking was monitored by acoustic emission, and the breaking of the electro-conductive paste painted on the specimen was used to track the cracking time.

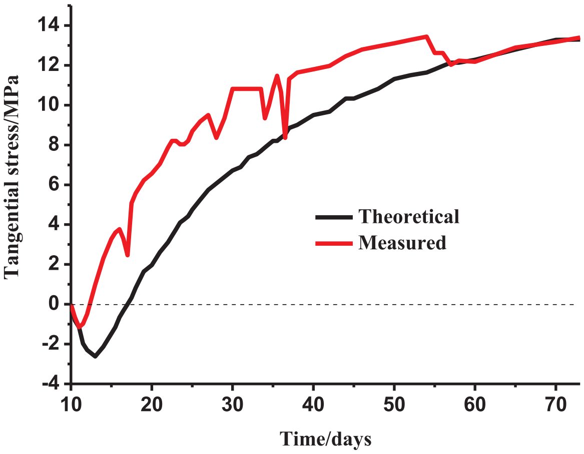

Fig. 1. Proof of the tensile stress generated around the borehole when a rock mass is subjected to heating from a central borehole.
Redrawn from Cook and Hood[40].

The experiments indicated that two cracks were initiated in the model. The first crack was initiated from the outer boundary and then propagated toward the inner borehole, whereas the second crack was initiated from the borehole and propagated toward the outer boundary. The second crack, which may have been caused by the high compressive stress around the borehole, is not discussed further in this paper.

Under such conditions, the thermal stresses can be theoretically calculated as

$$\sigma_\theta = \frac{\alpha E}{r^2}\left[\frac{r^2 + a^2}{b^2 - a^2}\int_a^b rTdr + \int_a^r rTdr - Tr^2\right] \tag{1}$$

$$\sigma_r = \frac{\alpha E}{r^2}\left[\frac{r^2 - a^2}{b^2 - a^2}\int_a^b rTdr - \int_a^r rTdr\right] \tag{2}$$

where σ_θ and σ_r are the tangential and radial normal stresses, respectively; E and α are the Young's modulus and coefficient of linear thermal expansion, respectively; a and b are the inner and outer diameters, respectively, assuming a cylindrical specimen; T is the temperature; and r is the distance to the model center.[26]

The calculations from Eqs. (1) and (2) showed that the maximum tangential tensile stress is formed at one boundary of the specimen. The experimental results also suggested that the tangential tensile stress at the outer boundary when the first crack initiated was approximately the same as the tensile strength of the specimen. In contrast, the maximum compressive stress produced at the borehole wall was considerably smaller than the compressive strength of the sample. Thus, when the temperature in the material is greater than the outside temperature, the outer surface is subjected to tensile stresses due to the inner part preventing the outer part from contracting.[27]

2.2. Numerical simulation

Although the particle simulation method has been widely used to simulate crack initiation and propagation problems in rocks at different length scales (e.g., from the laboratory length scale to the geological length scale),[28] a rock failure process analysis (RFPA) code is used in this paper. The theory of elastic damage mechanics is the basis of this code.[29] In the code, the rock-like materials are assumed to be composed of elements that are square in shape and have identical size, and the properties are assigned with a given Weibull distribution. This code has been successfully applied to the modeling of various fracturing problems combined with static and dynamic problems.[30–33] The module of thermal cracking in RFPA was developed by Tang, and a number of papers have been published on this topic.[34–36]

In this section, RFPA is used to simulate the initiation and propagation processes of cracks in an artificially designed rock model heated from a central borehole to simulate the experiment conducted by Ishida et al.[19] The rock sample in Ishida's experiment is simplified to an artificially designed numerical model, and the plane stress state is assumed in this paper.

Based on Ishida's experiment,[19] the temperature of the borehole wall is increased from 28 to 310 °C for three hours. However, because the initiation of the second crack in Ishida's experiment is not considered in this paper, the heating rate of the artificially designed numerical models corresponds to only that during the first two hours in the experiment (1.5 °C/min), when the first crack was generated. The outer boundaries of the models are all free from mechanical load, and the outer boundary temperature is kept constant at 28 °C.

The above boundary conditions are suitable for only the problems with finite computational domains, such as the artificially designed problem in this study. However, since most geoscience and