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Experimental simulation of joint morphology

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Abstract

Desiccation experiments with starch–water mixtures whose dimensions and thickness are several centimeters produce a broad spectrum of tensile cracks. Their properties are remarkably similar to those of joints in rocks. This note concentrates on crack morphology in the form of plumose structures and fringe zones. Moreover, rupture velocity is determined from videos. After an initial, dynamic rupture phase with velocities of about 100 mm/s, which is restricted to a thin, strongly dried surface layer, the main rupture through the specimen is quasi-static with velocities of 10 mm/min and less. This phase is driven by the low supply of strain energy due to the ongoing desiccation. Quasi-static rupture produces plumose topographies, which range from simple to complex. From the similarity of plumose topography on joints in marine sedimentary rocks, it is hypothesized that these joints are generated by quasi-static rupture in an early stage of subsidence, compaction and diagenesis of water-bearing sediments. Rupture propagation in the fringe zone of cracks in starch, where topography is stronger than on the main crack, was slower than over the main crack. The same applies probably to fringe zones along bedding planes in sediments. © 2001 Elsevier Science Ltd. All rights reserved.

1. Introduction

The purpose of this note is to draw the attention of structural geologists to starch–water mixtures as a material for laboratory simulations of tensile cracks and joints through desiccation experiments. The crack spectrum of this material is surprisingly broad. Two topics have been studied so far, column formation like in cooling basaltic lava (Müller, 1998a,b) and tensile-crack morphology, similar to the morphology of rock joints (Müller and Dahm, 2000).

Müller (1998a) observed that there are two crack generations. The first-generation cracks in thicker specimens (like those in Figs. 1, 3 and 4 below) are generated 2–5 h after the beginning of desiccation. Water content decreases during this time from 50% to about 40%, i.e. most of the water is still present, and rupturing occurs in a material with a Poisson ratio close to 0.5, but with brittle properties. Further desiccation produces several hours later an irregular, small-scale pattern of second-generation cracks at the specimen's surface. This crack system grows vertically downward, and its cells develop a more and more polygonal form with a predominance of hexagons. The result are columns very similar to basalt columns (Müller, 1998a,b). When the front of the crack system has arrived at the bottom of the container after a few days, the starch is highly cracked and almost dry.

The main results of Müller and Dahm (2000), are the documentation of plumose structures on first-generation cracks and measurements of rupture velocity with photos and videos. The distribution of plumose structures on a rupture surface contains information on the distribution of rupture velocity. It is well known that their orthogonal trajectories are the rupture fronts and that by drawing them the evolution of the rupture can be visualized (e.g., Kulander et al., 1979; Kulander and Dean, 1985; DeGraff and Aydin, 1987; Weinberger, 1999). These relations were further developed in Müller and Dahm (2000), employing the analogy of plumose structures and seismic rays, of rupture fronts and seismic wave fronts, and of rupture velocity and seismic wave velocity. Well-developed quantitative methods from seismology can then be used, first, for the computation of plumose lines for given rupture velocities and, second, for the interpretation of measured plumose lines in terms of (relative) rupture velocity. Successful applications were given in Müller and Dahm (2000).

In this note, the results of Müller and Dahm (2000) are extended by new results for starch-crack morphology and by measurements of rupture velocity. Since starch-crack morphology is similar to the morphology of joints in rocks, in particular in sedimentary rocks (e.g., Bahat, 1991, figs. 3.10, 4.7, 5.9), and since there is a pronounced lack of model materials for laboratory simulation, it is rewarding to explore what starch experiments can contribute to the

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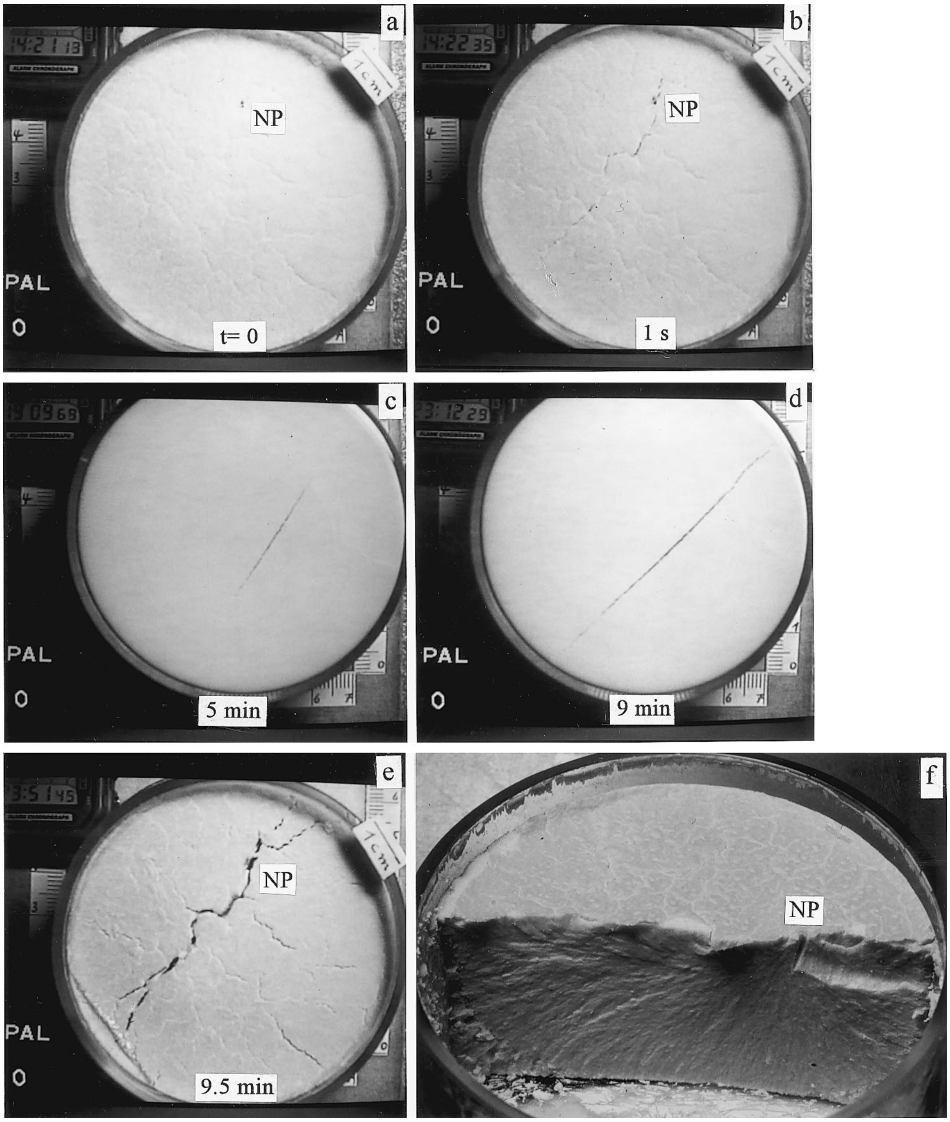

Fig. 1. Rupture process in a 32-mm-thick starch–water mixture. Desiccation by a hair drier. The first five photos were taken from a video. (a) Top side of specimen immediately after rupture start at an artificial nucleation point NP (time $t = 0$). (b) End of first, dynamic rupture phase in a thin, strongly dried surface layer, resulting in an irregular crack. Rupture duration was less than 1 s. (c, d) Bottom side of specimen after several minutes, showing that the second rupture phase was much slower and quasi-static. (e) Surface crack after the end of rupture. (f) Rupture surface with plumose structures, radiating from the nucleation point.

understanding of the generation, propagation and interaction of rock joints.

Starch as a substance, consisting mainly of glucose, is a less exotic material than one might think at first. Mixed with water it is an organic sediment with a pronounced granular structure and a simple, desiccation-related diagenesis of a few days which ends in a dry, brittle material (with many cracks of the second generation). As far as water content, structure and diagenesis are concerned, starch is similar to fine-grained marine sediments with end products such as sandstone, limestone or chalk (whose diagenesis, of course, is more complicated and takes much longer). Starch cracks are closest to subsidence or diagenesis joints in sedimentary rocks.

Rupture velocities of 200–300 mm/s and less, as they have been determined in Müller and Dahm (2000) in a larger number of experiments, cover the range from dynamic to quasi-static cracks. The highest values were observed for spontaneously nucleating cracks, which are clearly dynamic, i.e. the critical stress-intensity factor or fracture toughness was reached or exceeded. The lowest velocities, 1 mm/s and less, measured in Müller and Dahm (2000) and reported in this note, are 2–3 order of magnitude less than the highest and therefore quasi-static.

2. Tensile cracks in starch, their morphology and rupture velocity

The experiments for this paper were performed with

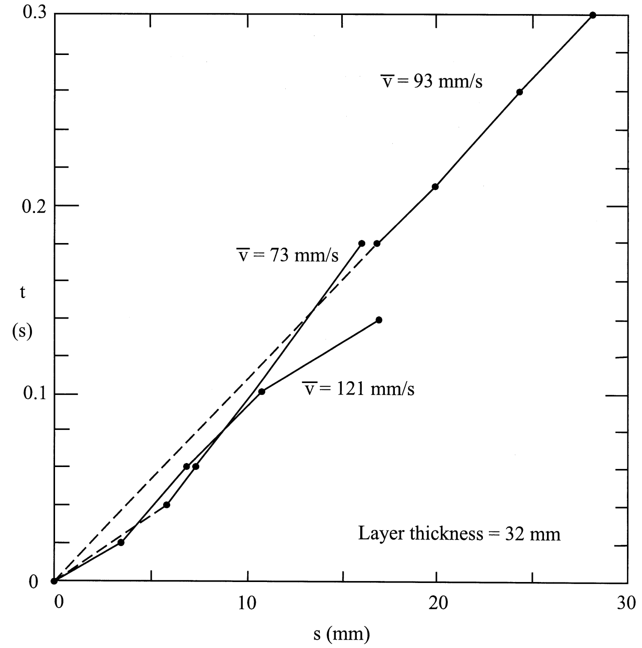

Fig. 2. Travel-time curves of the crack tip in the first, dynamic rupture phase of the specimen in Fig. 1 and of two more specimens. Along the dashed parts the tip could not be followed because of the irregular crack form (see Fig. 1b). $\bar{v}$ is the average rupture velocity along the continuous parts ($\bar{v} = 93$ mm/s: case of Fig. 1).

mixtures of corn starch and water, having a mass ratio of about 1. Circular and rectangular layers with dimensions of 60–80 mm and thicknesses of 30–40 mm in glass vessels were dried from above with a hair drier (oblique distance about 50 cm) or a lamp (vertical distance 3–5 cm). It took 2–5 h of water diffusion to the surface and evaporation, until a first-generation crack appeared, generated by contraction. Such cracks usually originate at the surface at an artificial or spontaneous nucleation-point and propagate from there over an essentially vertical rupture surface downward and to the sides. Rupture morphology varies from simple to complex and consists almost exclusively of plumose structures or lines (crests, grooves, steps), giving the local rupture direction. Conchoidal structures, orthogonal to the plumose structures, are rare and, if present, related to a fringe zone, limiting the rupture surface.

The peculiarity of the rupture process in relatively thick layers, with a thickness-to-diameter ratio of about 0.5, is that in a first phase a thin layer at the surface of a specimen ruptures dynamically, followed in a second phase by slow, quasi-static rupture over the rest of the vertical rupture surface. (In thin layers with thickness-to-diameter ratios of 0.2 and less, which were mainly studied in Müller and Dahm (2000), rupture is one process with horizontal propagation and only little delay at the bottom compared to the top). A description of the two-phase rupture process has already been given in Müller and Dahm (2000), documentation and details follow now.

Fig. 1 demonstrates the rupture process with photos, most of them taken from a video and covering about 10 min until rupture was complete. In the first phase, dynamic rupture of a strongly dried surface layer, less than 1 mm thick (Fig. 1f), generated a very rugged crack in less than 1 s (Fig. 1b). Average rupture velocities of 70–120 mm/s could be determined from the travel-time curves of the crack tip in this and two further experiments (Fig. 2).

During the second rupture phase the specimen was briefly turned a few times bottomside up to document the slowly expanding crack trace; hair-drier desiccation continued. From the times given in Fig. 1c,d, it is evident that this phase had rupture velocities of 10 mm/min and less and was, therefore, 2–3 orders of magnitude slower than the initial rupture at the surface. This quasi-static rupture continued the surface crack and was driven by the ongoing desiccation, with slow accumulation of strain energy.

The plumose structures in Fig. 1f start at the nucleation point and are straight or slightly curved. In other cases, partly shown later and in Müller and Dahm (2000), they are more complicated, both in their directions and in the topographic variations perpendicular to them. Plumose structures are generated when an originally smooth rupture expands and interacts with stress concentrations at heterogeneities in the form of larger starch granules and air bubbles (due to mixing of starch powder and water) and, in particular, at surface heterogeneities due to the pre-existing rugged crack of the first rupture phase. The process zone of the expanding rupture itself may contribute through microcracks of variable orientation. The stress-field changes produce, mainly behind heterogeneities, local changes in the direction of maximum principal (tensile) stress and corresponding local deviations of the rupture surface from its original form.

From the two rupture phases of the starch experiments, the first appears to be relatively special, occurring in nature perhaps for cracks in mud, but not in subsiding marine sediments. The second rupture phase, with quasi-static expansion of the rupture surface and plumose topography, is probably more typical, both for quickly drying muddy sediments (Weinberger, 1999) and for marine sediments.

3. Extreme rupture velocities and fringe zones

Fig. 3a is an example of plumose topography with pronounced step-like structures, running from the nucleation point to the sides, and with low amplitudes along more vertical directions. Such a topography has been observed several times. The rupture fronts are concentric circles around the nucleation point with good approximation, which implies constant (quasi-static) rupture velocity along each front. Plumose topography, however, varies strongly along the rupture fronts.

Soon after the photo in Fig. 3a was taken, a deep stitch was produced behind the rupture surface, and by pulling horizontally at the needle a new rupture was generated

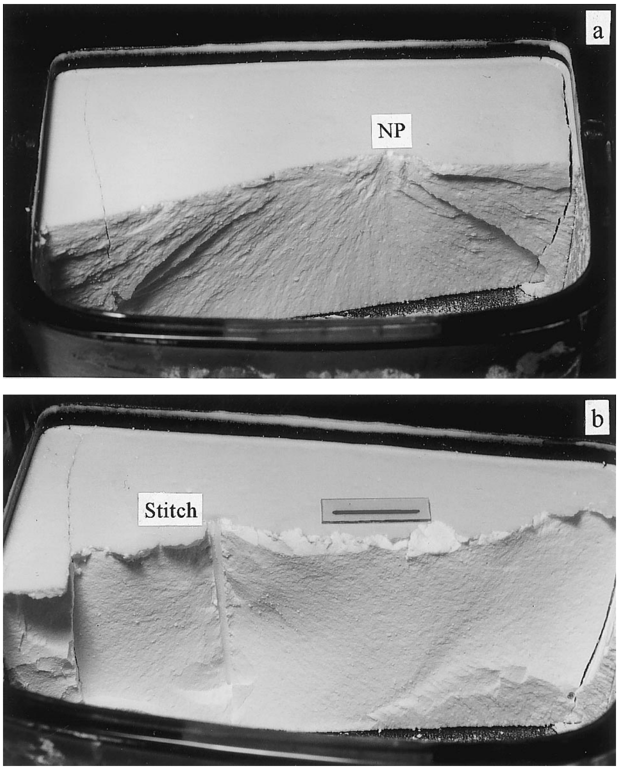

Fig. 3. (a) Radial plumose structure from a spontaneous nucleation point in a lamp-dried specimen. Plumose topography due to slow, quasi-static rupture is very pronounced. (b) Rupture surface, produced behind the rupture surface of (a) by a deep stitch and by pulling at the needle. Fast, dynamic rupture left a smooth crack face without plumose structure (see text). The bar is 1 cm long.

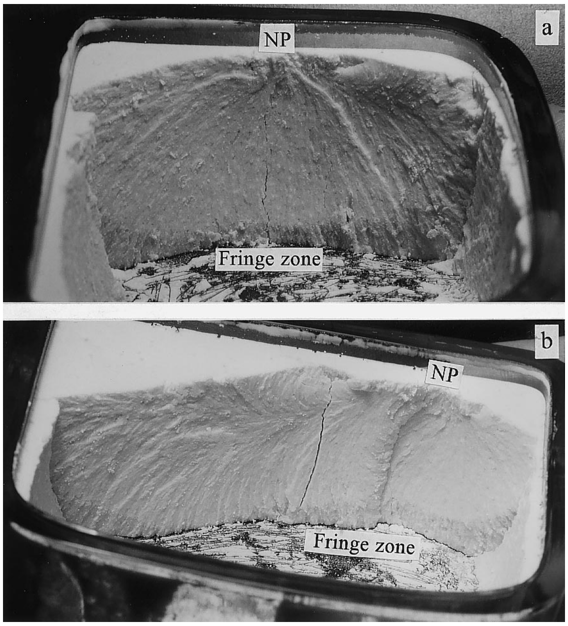

Fig. 4. Two examples of a fringe zone, limiting the rupture surface close to the glass. Topography is stronger than on the main part of rupture. Because of the clear relation to the rigid boundary at the glass, it is evident that rupture slows down in the fringe zone (see text). The dark cracks in (a) and (b) occurred later than the main crack. Long dimension of container is 8 cm.

within a fraction of a second. Rupture velocity was much higher than quasi-static, because loading by the experimenter was fast and more strain energy was available than in the other cases. The crack face of this dynamic rupture is smoothly curved and without plumose topography (Fig. 3b). This appears to be an extreme case: dynamic rupture in thin starch layers was studied in detail in Müller and Dahm (2000), and plumose structures of characteristic, downward curved form were observed. Measured rupture velocities were below 200–250 mm/s. The rupture of Fig. 3b may have been faster.

In Fig. 4 two examples of a fringe zone along the rim of a rupture surface, close to the bottom and the walls of the glass vessel, are shown. Topographic amplitudes are larger than on more central parts of the rupture surface, and the transition is abrupt. Fringe zones were observed in roughly 20–30% of the experiments with thick layers, and sometimes they were restricted to the vertical walls or even to the bottom corners of the rupture surface. A plausible explanation of fringe zones is that rupture senses the stiff or rigid wall and is slowed down, perhaps after temporary arrest at the beginning of the fringe zone. A theoretical argument in support of slowing rupture, based on considerations of strain energy of two welded half-spaces with a crack approaching the interface vertically, can be found in Pollard and Aydin (1988) or Helgeson and Aydin (1991); see also Müller and Dahm (2000). However, the abrupt transition at the inner boundary of the fringe zone is not explained.

Fringe zones quite similar to those in Fig. 4 are familiar from joints in rocks, in particular along layer boundaries in sediments (e.g., Suppe, 1985; Bahat, 1991). Often they also start abruptly, at a so-called shoulder. Opinions about rupture velocity in fringe zones, whether it is higher or lower than on the parent crack, appear to be divided (e.g., Bahat, 1991, pp. 193–195). The starch experiments point to lower values.

More generally, the usual view that slow rupture produces smooth and fast rupture rugged crack faces (e.g., Engelder and Fischer, 1996, pp. 259–261) is not confirmed by starch experiments. They rather point to the opposite (Müller and Dahm, 2000) p. 734).

4. Discussion and conclusions

Cracks and crack patterns in drying starch–water mixtures are remarkably similar to cracks and joints in rocks. In this note the focus was on first-generation cracks in thick starch layers, their morphology and rupture velocity. The main phase of crack formation is quasi-static and slow, with rupture velocities of 10 mm/min and less, and connected with various forms of plumose topography, from simple to complex. The cracks in muddy sediments studied by Weinberger (1999) have similar properties. In both cases, energy supply is due to the ongoing desiccation and hence slow. Because plumose topography on joints in marine sediments is similar, they may have formed under similar low-energy, quasi-static conditions in soft, water-bearing material, i.e. in an early stage of subsidence, compaction and diagenesis. Dynamic cracks are not excluded (Müller and Dahm, 2000), but their energy requirements are definitely higher.

The initial phase of crack formation in thick starch layers is dynamic, although of a special form, namely rupture of a strongly dried, thin surface layer of the specimens. This is not typical for sediments, but also in their case a dynamic rupture start at a stress concentration could rather be the rule than the exception.

In starch, the relation between rupture velocity and plumose topography does not follow the traditional view, which connects smooth (rough) topography and slow (fast) rupture. This view depends largely on dynamic-fracture observations in glass, and it may not be as general as currently assumed. More controlled laboratory experiments and field observations on cracks and joints in earth materials are highly desirable.

The starch specimens and cracks, investigated in this note and in Müller and Dahm (2000), have dimensions in the centimeter range, whereas those of rock joints usually are decimeters to meters. A plausible modelling rule is that starch cracks should be geometrically similar to rock joints, and this rule can roughly be adhered to. Modelling of stress distributions and rupture initiation is close to impossible, however, and the stress-free and rigid boundary conditions of starch specimens do not always reflect the conditions in rocks, which undergo jointing. Desiccation experiments in starch fit well into the long suite of laboratory experiments in structural geology, which model processes such as shearing, rifting, diapirism etc. in a qualitative rather than in a one-to-one, quantitative sense, but which nevertheless contribute to the understanding of these processes. Successful computer simulation of processes is sometimes the end of experimental simulation, but it will take a while until this applies to crack and joint morphology.

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