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Micro-scale Testing of Capillary Bridge Evolution due to Evaporation

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Abstract. Capillary bridge evolution between two fixed glass spheres during its natural convective evaporation is examined experimentally. For comparison extension tests were also carried out. The calibrated balance recording and digital image processing allow monitoring of a number of key variables of the process: the resultant capillary force, the water mass loss, radii of the bridge curvature. On that basis evaporating surface area, suction and surface tension force, interparticle force, axial stress vs (relative) volumetric mass loss are calculated. Testing shows a gradual decrease of suction within bridges down to zero and into a positive pressure range before a two step failure including a formation of a water thread according to a traditional Rayleigh instability pattern followed by a simultaneous rupture at two points of the lowest (negative) total (Gauss) curvatures of the bridge surface.

1 Introduction

The liquid loss from a porous (granular) material (*i.e.* soil) during evaporation plays a key role in the onset of drying cracks. Studies of desiccation shrinkage undertaken *i.e.* by Hu et al. [1], Kowalski and Mielniczuk [2], Peron et al. [3] revealed that the shrinkage in drying soil develops when soil is still saturated, while cracks appear shortly after the air entry, and formation and rupture of liquid bridges. On the other hand, the apparent cohesion of unsaturated soils is attributed to the generation of suction and capillary forces. Suction hardening and softening (wetting collapse) of granular materials are related to understanding of the evolution and rupture of liquid bridges.

To identify the mechanisms and critical variables that control evolution of the water body (liquid bonds) during evaporation we focus on the evolution and rupture of elementary liquid bridges between two, three and more particles. The important step of these studies is the analysis of the changes of the liquid bridge

geometry and interparticle (capillary) forces during desiccation of the smallest clusters of grains at the local scale. In this paper, capillary bridges are addressed between two grains only. Such systems are not only the most elementary ones, but also, it has been seen that more articulated systems break down eventually to a number of two-grain arrangements.

Most of the past studies were conducted in static conditions or during extension of the bridge with a fixed liquid volume [4-8]. Instead, in the present experiments, the driving force of the investigated response is evaporation in a constant relative humidity environment, and at a constant predetermined separation of grains.

2 Materials and Methods

Liquid bridge is produced by placing a 4 μl of distilled water between two glass spheres (radius $R=4\text{mm}$, grade 25), with the use of microsyringe. Next, the liquid bridges are exposed to evaporation at constant ambient conditions, at constant sphere separations D from 0.1 to 2.0 mm, or are stretched at a constant speed of 16 $\mu\text{m/s}$, at several constant water volumes, from 0.2 to 10 μl . The lower sphere is placed on a precision balance (with precision of 10^{-4} g). The upper sphere, attached to the micrometer, is suspended from the support, without any contact with the balance (Fig. 1a).

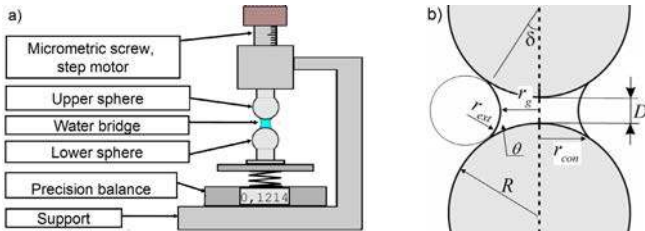


Fig. 1 a) Apparatus configuration to measure capillary force, b) Capillary bridge parameters

The attractive force between spheres is calculated as $F_C=(m_{dry}-m_{exp})\cdot g$, where m_{dry} is the mass of dry lower sphere, m_{exp} is a mass supported by the balance including the lower sphere and the liquid bridge during drying, g is the gravity. The evaporating mass of water is obtained in the same conditions, but also with the upper sphere supported by the balance. The changes in the bridge geometry were recorded by a photo camera with macro lens. The moment of the bridge rupture was recorded with a high-speed digital camera, with 27000 frames per second. Images were processed with Fiji and Matlab software, to determine gorge radius r_g and external radius r_{ext} (see Fig. 1b). It was hence possible to calculate via Laplace law suction and surface tension force components of the capillary force, and the average axial stress at the bridge neck.

3 Results

Variations of bridge volume (evaporation) or bridge length (extension) are the main factors affecting the radii of the meniscus surface. During evaporation the profile of drying bridge evolves with the receding lateral meniscus surface of revolution, following the classical sequence of Plateau, from the surface of the negative unduloid, through catenoid to negative nodoid (Fig. 2) [9]. Measured value of r_g decreases smoothly as a convex parabola, and external radius r_{ext} decreases proportionally with the decreasing liquid volume. The r_g for the bridge in extension decreases as a concave parabola with the increasing separation, with almost constant r_{ext} (see [10] for details). The duration of the process till the bridge rupture varies from 9 to 67 min for evaporation and up to 150 seconds for extension.

Most notable is a relatively slow change of the bridge shape from a catenoid into a nodoid, which then developing into a very thin water wire. The wire ruptures simultaneously near both ends within 0.3-0.9 msec and then transitions into a small droplet of water, which next free-falls in the gravity field. Eventually the mass of water is separated into two drops attached to each of the spheres (Fig. 2).

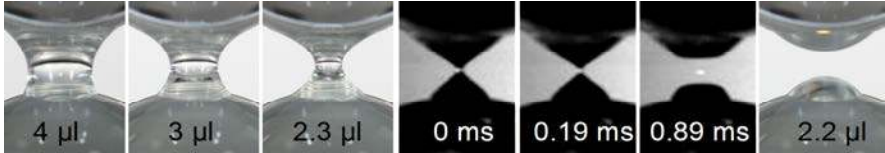


Fig. 2 Evolution of evaporating capillary bridge between two spheres at separation of 1.3mm with the initial total water volume 4 μl , at decreasing water volume (in μl), detail of the rupture process (fast camera, time in milliseconds)

The bridge evolution due to evaporation at $D= 1.3$ mm is shown in Fig. 2. The bridge ruptures at the water volume $V= 2.28$ μl ., with the water wire 90 μm in diameter, and 130 μm in length (see [11] for details).

Based on the measured evolution of the meniscus radii it is possible to estimate capillary forces, as a sum of a vertical resultant of the surface tension acting at the perimeter of the neck and the Laplace pressure Δp (difference between ambient and internal bridge pressure) expressed as $\Delta p = \gamma(r_g^{-1} - r_{ext}^{-1})$ acting at the cross-section of the neck, $F_C = 2\pi r_g \gamma - \pi r_g^2 \Delta p$ [4, 6, 8], where $\gamma = 0.0496$ N/m is the experimentally determined surface tension of the actual water. At our calculations hydrostatic pressure of water bridge acting at the neck level is also considered.

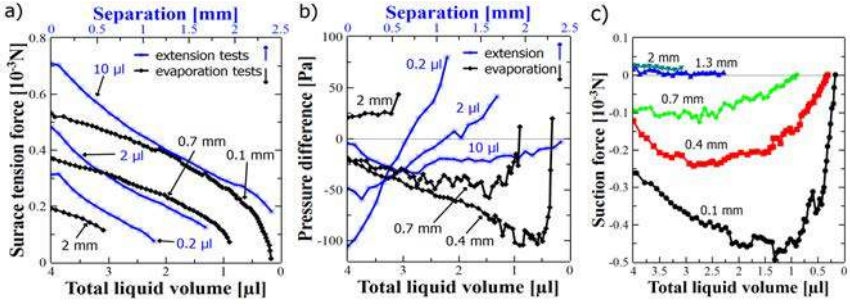


Fig. 3 a) Surface tension force for evaporation and extension tests, b) Laplace pressure changes for both experiments, c) Resultant suction force for evaporation

The surface tension force is positive and decays gradually following the neck perimeter length with volume loss or increasing separation. Its initial value is the highest at small separations and large volumes, as shown on Fig. 3a.

Laplace pressure arises as a consequence of the total bridge curvature, which can be either positive or negative, depending on gorge (neck) and external radii (Fig. 2). It is initially negative (suction) at small separations, but it may be positive at large separations (Fig. 3b). Such cases are described by Kralchevski and Nagayama [12]. Most notable is the evolution of suction during both evaporation and extension showing a consistent decrease until zero, and becoming eventually a positive pressure. Hence, pressure at bridge rupture is positive in all cases (except for the largest volume extension). The resultant suction force however remains attractive (due to surface area factor), for small separations, while reaching negligible positive values (repulsion) near rupture (see Fig. 3c). At large distances the resultant force is consistently repulsive.

The total capillary force (Fig. 4a) decreases consistently in both processes. For evaporation at large separations the force decreases almost linearly with an early sudden jump to zero at the bridge rupture. At separations D smaller than 0.7 mm there is an initial increase of F_C up to a maximum, followed by a decay to zero. At separation $D=2$ mm the maximum (initial) force value $F_C=0.14 \cdot 10^{-3}$ N (0.14 mN), with force jump of 0.09 mN at 23% of water loss. At $D=0.1$ mm the maximum force $F_C=0.85$ mN at 33% of water loss, and at rupture the force jump is 0.02 mN, at 96% of water loss.

Also during extension the total capillary force F_C decreases to zero, with a slight initial increase at higher volumes.

Based on the capillary force it was possible to visualize stress evolution for both tests, as presented in Fig. 4b. The values of tensile stress in water in both processes are of the same order of magnitude, with rupture occurring between 200 and 600 Pa, depending on separation D and total liquid volume V .

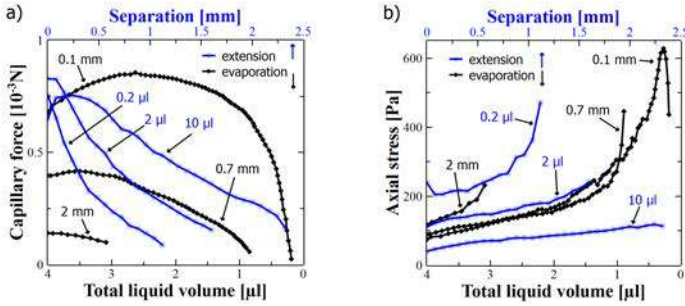


Fig. 4 a) Capillary force evolution during evaporation and extension tests, b) Axial stress vs decreasing volume for evaporation, vs increasing separation for extension tests

The tensile stress at rupture at $D=1.3$ mm ($V=2.28$ μl) caused by evaporation is 220 Pa. For an ad hoc extension test performed at this particular liquid volume, the bridge ruptures at $D=1.76$ mm, with tensile stress of 243 Pa. Notably, the axial stress at rupture is different for every test.

4 Conclusions

The behavior of an evaporating liquid bridge resembles tensile failure of a ductile steel rod, while no external tensile force is applied to the system. The process is controlled by a decreasing volume of the liquid bridge (at constant separation). The moment of rupture is dependent on separation of spheres. For larger separations the bridge rupture alters a smooth desiccation process early, whereas for very small separations, the rupture blends with the vanishing of all the liquid mass.

Notable findings concern the evolution of liquid suction, which monotonically decreases during evaporation (and extension) to zero, and becomes a positive pressure prior to rupture. The total capillary force between the grains remains attractive due to the surface tension effect. However, it also has a decreasing trend and approaches very small values near rupture.

The intergranular bridge rupture is a two-stage process. The first stage includes a formation of a water thread in the central part of the bridge according to a traditional Plateau-Rayleigh instability pattern, followed by a rupture at simultaneously two points of the lowest (negative) total (Gauss) curvatures of the bridge surface. The later subject is pursued in Mielniczuk et al. [13]. The rupture of the bridge is critically important as it marks the end of suction controlled strengthening of unsaturated granular media. As seen it may occur very early in the process of evaporation in a loose medium with large grain separation. It also determines how much of water is left out after the process of bridge formation and rupture. Notably, the stage where two-grain bridges dry in isolation is the last stage of earlier processes when suction growth plays a crucial role in the removal of water from the porous medium (Hu et al., [1]).

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