New insight into cavitation mechanisms in high capacity tensiometers based on high-speed photography

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Abstract

The high capacity tensiometer developed by Ridley and Burland (1993) is a milestone of experimental unsaturated soil mechanics. This device, which relies on development of tension in an enclosed water body, permits direct measurement of negative water potential. Many tensiometers have been built since 1993; all being based on the same principle although the design might slightly differ from the original one. In particular, the common characteristic is a very small water reservoir as this latter is believed to be the location of bubble nucleation, phenomenon referred to as cavitation that impedes the sensor from functioning properly. Many have studied cavitation and different explanations or cavitation mechanisms have been proposed. However, all the considerations put forward were derived without being in a position to capture what happened inside the water reservoir at cavitation. This is now achieved with the new tensiometer specifically designed to see inside the water reservoir during suction measurement. For the first time, cavitation has been captured via high-speed photography and the mechanisms of cavitation can be explained on physical evidence. The first outcome is that it is possible for a high capacity tensiometer to function to its full range with a large water reservoir. Then, the analysis of high-speed photographs revealed that the bubbles triggering cavitation are nucleated in the ceramic and make their way to the water reservoir. Cavitation occurs only when the air phase reaches the water reservoir.

Keywords: Cavitation, Tensiometer, High-speed cameras, Suction, Bubble

1) Introduction

Water potential, commonly called suction when in the negative range, is known to significantly affect the mechanical response and hydraulic behaviour of soils. This is one reason why measurement of water potential is a key aspect of experimental research in soil mechanics. While gaging positive water pressure is not problematic, measuring suction proves difficult. A broad range of techniques has been developed (see different techniques in Fredlund and Rahardjo, 1993) but the one retaining attention in this paper is the high capacity tensiometer developed by Ridley and Burland (1993). This device, depicted in Figure 1b of the next section, allows direct measurement of negative water potential since tension is developed in the water enclosed in the reservoir and the ceramic. Since 1993, many other models of tensiometers have been developed, all based on the same principle (Guan & Fredlund, 1997; Meilani et al., 2002; Tarantino and Mongiovì, 2002; Take and Bolton, 2003; Lourenço et al., 2008; Cui et al., 2008; among others). Although it is, on paper, a simple sensor to use, getting it to function to its full range can pose some issues. Indeed, water under tension is prone to cavitation, phenomenon first observed by Berthelot (1850) and that, when it occurs, prevents the sensor from working any longer.

According to the literature on the subject, cavitation can be delayed by adequate preparation of the sensor including use of de-aired water, application of vacuum, cycles of pressurization and even cycles of cavitation (e.g. Marinho and Chandler, 1994). There is also a general consensus on the fact that the design of the tensiometer itself has a role to play. In particular, the need to minimize the size of the water reservoir is regarded as fundamental: all high capacity tensiometers presented in the literature have a water reservoir less than about 10 mm^3. This special care comes from the perception that cavitation takes place in the reservoir due to heterogeneous nuclei as explained by Marinho et al. (2008).

However, Tarantino and Mongiovì (2001) put forward another cavitation mechanism where they suppose that water break down actually initiates in the ceramic, not in the reservoir. Today, there is still no clear answer as to where cavitation actually takes place because of a lack of experimental evidence. All conclusions tend to be drawn from analysis of the sensor response rather than direct observation of the cavitation mechanism inside the device (e.g. Lourenço et al., 2011).

This paper presents a tensiometer that was designed to observe cavitation inside the water reservoir during suction measurement. For the first time, cavitation has been captured via high-speed photography and the mechanisms of cavitation can be explained on physical evidence. Some results validating the new design are firstly presented, followed by the analysis of the sequence of high-speed photographs. The paper concludes with a model for cavitation in a tensiometer.

2) Experimental facilities

2.1) Details of the new tensiometer

FIGURE 1.

Two high capacity tensiometers were built at the laboratory of the Centre for Geotechnical and Materials Modelling of The University of Newcastle. The objective of the study being to visualize the cavitation within a tensiometer, a translucent perspex body was combined to a water reservoir far larger than the recommended volume. Indeed, the reservoir can hold 1100 mm^3 of water as opposed to less than about 10 mm^3 (Ridley and Burland, 1993; Guan and Fredlund, 1997; Meilani et al., 2002; Tarantino and Mongiovì, 2003; Lourenço et al., 2006). Two tensiometers were built, one with a 15 bar air entry value ceramic and one with a 5 bar ceramic. Both were equipped with the same type of pressure sensor (capacity 3.5 MPa, accuracy ± 10 kPa). The 5 bar tensiometer is shown in Figure 1a.

2.2) Preparation and testing

The tensiometers were prepared by following the typical steps evoked in the literature (e.g. Marinho and Chandler, 1994): use of de-aired water, application of vacuum, saturation and cycles of pressurization. Different pressurization values were used, as per Table 1. As for testing the tensiometers, it simply consisted of exposing the device to air-drying, which is referred to as a “pulling test”.

Cavitation is characterised by apparition of air bubbles in a liquid phase, a phenomenon that takes place quickly. For example, micro bubbles have been observed to appear within microseconds (Vincent et al., 2012). Preliminary testing with the new tensiometers showed that the bubbles accompanying cavitation were visible at the naked eye in the large water reservoir. Consequently, high-speed cameras (Optronis, CR600) were deemed sufficient to capture the apparition of air bubbles in the water reservoir during testing. A low frame rate was initially used (50 frames per second or fps) but this was progressively increased to 7000 fps. Most of the tests were done at 2000 fps, the reason being that the higher the frame rate, the lower the accuracy and the lower the recording time. 2000 fps was found be an acceptable compromise. Table 1 summarizes the different frame rates used throughout the testing.

For tests 1 to 10, suction was recorded via a data logger DT80 with a relatively low sampling rate (1 data point every 3 seconds).

The objective of the last test (#11) was to verify the concomitance of bubble appearance in the water reservoir and cavitation, which requires synchronisation of suction measurements and high-speed photographs. For that purpose, a high rate logger capable of recording 2000 data per second (USB Compact DAQ system from National Instruments 9234) was preferred to the DT80. The National Instruments logger was only used for the last test because of the noise generated when combined to the tensiometer: the accuracy in suction measurement dropped to about ± 90 kPa.

For test 11, synchronisation of data was achieved via a LED, the status of which (on/off) can be detected from the logger (voltage) and from the high-speed cameras (light). Exact matching was later confirmed through the internal clock of the logger and the high-speed cameras.

One pulling test was performed on the 15 bar tensiometer in order to demonstrate that the sensor can work to its full capacity despite the large reservoir. This test did not require use of high-speed cameras. The actual study on cavitation was done on the 5 bar tensiometer only in order to minimize the damage to the tensiometer. Indeed, the 5 bar tensiometer requires lower magnitude of pressure to achieve saturation meaning that its perspex body is less likely to crack under the cycles of pressurization and multiple testing.

TABLE 1.

Note that the calibration of the tensiometers (performed in the positive range) was checked before each test.

3) Results and discussion

3.1) Validation of the new design

Figure 2 shows the sharp decrease in pressure recorded by the tensiometers HCTP2 and HCTP3 when exposed to air. The first noticeable result of this study is that the maximum suction sustained by both tensiometers is equal or greater than the nominal air entry value of the ceramics: about 920 kPa for HCTP2 and 1520 kPa for HCTP3 (Figure 2). The possibility for suction to exceed the nominal air entry value of the ceramic has already been observed (e.g. Tarantino and Mongiovi, 2001; Marinho and Chandler, 1994) and is explained by successive cycles of pressurization and cavitation (Tarantino and Mongiovi, 2001).

The results here obtained demonstrate that the perception held by the community regarding the size of the water reservoir is somehow incorrect: high capacity tensiometers can function to their full range with a large reservoir provided the preparation of the sensor is adequate. This finding considerably simplifies the manufacturing process of tensiometers and provides the opportunity to observe possible changes in the water reservoir during or following cavitation.

Note that the large volume is not significantly detrimental to the saturation time of the tensiometers. From a totally dry state, it takes about three days under 2 MPa of pressure to be in a position to measure 1 MPa of suction and an extra five days under 3.45 MPa of pressure allowed to reach 1.5 MPa. Any subsequent use requires only about a day of pressurization.

FIGURE 2.

3.2) High-speed photographs of cavitation

All the photographs presented in the following were taken with the tensiometer placed horizontally, which was the position of test. The slight angle visible on some photographs actually reflects a slightly inclined

position of the camera. The horizontal position was chosen to avoid any preferential direction from or towards the ceramics due to gravity. Note that the final location of the bubbles in the reservoir has little influence on the overall results.

Figure 3 shows all the results obtained with tensiometer HCTP2 (5 bar). For test 8, the sharp decrease of suction is interrupted by cavitation at a value lower than the air entry of the ceramic. In the light of all the tests performed, this cavitation is attributed to the presence of gas nuclei in the water reservoir (dissolved in the water or on crevices of the reservoir walls) that the pressurization procedure did not suffice to get rid of.

Although this type of cavitation is possible in case of inadequate sensor preparation, it is not the scope of the paper. Attention is herein focused on the cavitation occurring after suction has reached or exceeded the nominal air entry value of the ceramic, which is illustrated in Figure 3 for all other tests but test 8.

FIGURE 3.

The evolution of suction in time in Figure 3 is quite peculiar: the peak value of suction is not followed by straight cavitation nor by a plateau but by a slight relaxation during a variable time (up to 8 minutes) before cavitation occurs. Some explanations about this behaviour will be provided in a later section.

As detailed previously, sequences of high-speed photographs were taken for all these tests, some of which are presented below to elaborate the discussion. Firstly, Figure 4 presents a sequence occurring inside the water reservoir for test 4 at 2000 fps. A bubble emerges from the ceramics within 0.5 ms (Figure 4b) and makes it way to the highest point of the reservoir (Figure 4c). At the end of the process (about 4s, Figure 4d), a large number of bubbles have accumulated. These do not come from the ceramics but from air that was dissolved in the water reservoir.

FIGURE 4.

This mechanism, which was similarly observed for tests 2 and 3, suggests that cavitation could be driven by the ceramic since the first bubble to appear in the reservoir comes from the stone. However, it is not trivial to assess from Figure 4 whether the bubble has formed from a nucleus lodged on the surface of the ceramic surface or inside the ceramic.

Sequences of photographs obtained for tests 5, 6, 7 and 9 at 2000 fps (not shown here for the sake of brevity) suggest that the phenomenon might actually be due to nuclei located on the surface of the reservoir walls, including the surface of the ceramic. Indeed, the photographs reveal bubbles appearing, at the same time, from both the ceramic side and the sensor side of the reservoir.

On one hand, this would be consistent with the crevice model depicted by Marinho et al. (2008) but on the other hand, one question remains unanswered: why, in Figure 2, can suction be maintained during a certain time after having reached a peak?

The frame rate was further increased up to 7000 fps in order to provide elements of answer.

Figure 5 (test 10) reveals an interesting mechanism that was not visible at 2000 fps: a bubble first emerges from the ceramic in 0.14 ms (bottom right corner, Figure 5b) but this latter largely disappears back in the ceramic in the next frame (Figure 5c at t=0.28ms). In the meantime, some change in colour suggests nucleation of a bubble close to the tip of the pressure sensor. The reason why the initial bubble would partly be drawn backwards in the ceramic is still unknown. Then, two bubbles can be seen: one from the pressure sensor (where the change in colour was observed) and one from the ceramic, located at a higher position than where the first bubble appeared. This occurred at 0.43 ms but the photograph at t = 2.57 ms that is of better quality is showed here (Figure 5d).

This sequence suggests that concomitant occurrence of bubbles from the two sides of the reservoir, as observed for tests 5, 6, 7 and 9 at 2000 fps is likely, in fact, to be preceded by the arrival of a bubble from the ceramic.

FIGURE 5.

This observation corroborates the view of Tarantino and Mongiovì (2001) who stated that bubbles start to form within the ceramic. Indeed, pressurizing the nuclei in water is easier than in the ceramic where a three-phase interaction prevails. Consequently, nuclei in the ceramic are likely to be bigger than those in the reservoir, and bubbles would grow preferably in the porous stone. However, Figure 11 in Tarantino and Mongiovì (2001), and the related discussion, suggest that the cavitation mechanism takes place only in the stone, which is contradicted by the upcoming results.

A final test (number 11), conducted with synchronization of high speed cameras at 2000 fps and high rate logger (2000 data/s) via a LED (visible in Figure 6), showed that although bubbles might initially appear in the ceramic, it is only when the air phase reaches the reservoir that cavitation occurs. Evidence is shown in Figure 6 where values of suction are given for each frame. The abrupt drop in suction coincides with the appearance of a bubble in the water reservoir. In addition, it is interesting to see that the maximum value of suction has been sustained for at least 13.75 seconds before cavitation occurred, meaning that the peak suction was reached without occurrence of a bubble in the water reservoir.

FIGURE 6.

Following from the analysis of the high-speed photographs, a mechanism for cavitation is proposed: as per Tarantino and Mongiovì (2001), it is considered that some convex air-water interface exist during pressurization (Figure 7a). As suction is applied, menisci turn concave and the air cavities progressively grow without significant interaction (Figure 7b). Then it can be hypothesised that, at some stage, the different cavities start interacting and joining together creating some re-adjustment in pressure or relaxation, as they do not necessarily all have the same menisci curvature. The air cavity eventually reaches the interface between water reservoir and the ceramic (Figure 7c) at which stage small bubbles appear in the reservoir triggering cavitation (Figure 7d). Quite quickly, small bubbles gather into larger ones (Figure 7e). According to the mechanism described, the time between peak suction and cavitation, observed in Figure 2, is the time required for the agglomerated air cavities within the ceramic to reach the water reservoir. A sharp response with no plateau or relaxation might be observed if the air cavities start to form close to the water reservoir.

While high-speed cameras are useful to visualize the chain of events taking place in the water reservoir, considerations about mechanisms inside the ceramic are only speculative. At this stage, it is still difficult to capture the microstructure of the ceramic with the three-phase interaction.

FIGURE 7.

Conclusions

High capacity tensiometers have been developed to allow direct measurement of suction. Since the initial design from Ridley and Burland (1993) many tensiometers have been proposed, although all based on the same principle. In particular, the scientific community agrees on the need to minimize the volume of the water reservoir in order to measure suction close to the air entry of the ceramic. Also, discussions have arisen in the literature about cavitation mechanisms but, so far, conclusions were based on the response of the sensor rather than actual observation of the cavitation inside the water reservoir. For the first time, in this study, high capacity tensiometers were built of translucent perspex with water reservoirs at least 100 times larger than the typical recommended volume. This combination permits to visualize the cavitation inside the tensiometer, phenomenon that was captured by high-speed cameras. The following conclusions can be drawn from this study:

- It is possible for a high capacity tensiometer to function to its full range with a large water reservoir, provided that the preparation procedure is adequate (de-aired water, vacuum, cycles of pressurization).
- Sequence of high-speed photographs revealed that, when suction reaches or exceeds the nominal air entry value of the ceramic, cavitation is due to the appearance of bubble(s) into the water reservoir.
- The bubbles triggering cavitation are nucleated in the ceramic and make their way to the water reservoir. Indeed, the crevice model applied to the ceramic wall does not explain the time gap between the peak suction and cavitation.
- A mechanism for cavitation has been proposed based on the understanding gained from the high-speed photographs.

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List of Captions

TABLE 1: Details of the tests performed: pressurization values and high-speed camera frame rate.

FIGURE 1: (a) Tensiometer developed by Ridley and Burland (1993) at Imperial College. (b) Perspex tensiometer built at The University of Newcastle, 5 bars ceramics, 3.5 MPa sensor, 1100 mm^3 water reservoir.

FIGURE 2: Tests 1 and 2: Evolution of suction measured by HCTP2 (5 bar AEV) and HCTP3 (15 bar AEV) in time as the tensiometers are exposed to air. Maximum sustained suctions of about 920 kPa and 1520 kPa.

FIGURE 3: Tests 2, 4, 5, 8 and 10: Evolution of suction measured by HCTP2 (5bar) in time as the tensiometer is exposed to air-drying. The time between peak suction and cavitation (visible on tests 4 and 10) is referred to as delay.

FIGURE 4: Sequence of high speed photographs for test 4 (2000 fps).

FIGURE 5: Sequence of high-speed photographs for test 10 (7000 fps).

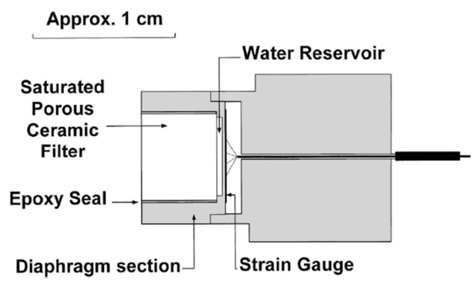
FIGURE 6: a) to d) Sequence of high-speed photographs for test 11 (2000 fps). e): Measurement of suction at time of cavitation.

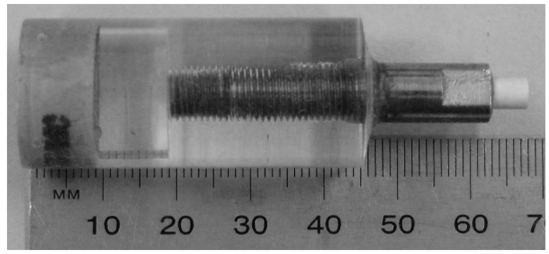
FIGURE 7: Mechanism for cavitation in a high capacity tensiometer. The sketch represents the water reservoir (with the back wall) and the ceramic (not to scale). In white is the air phase, light grey is the water and dark grey are the solid particles (referred to as S.P) constituting the ceramic. The dotted circle is a close-up of an idealised crevice. (a): Air-water interface exist during pressurization; (b): Agglomeration/expansion of the cavities under suction application; (c): Air cavities reach the water reservoir; (d): Small bubbles form in the reservoir triggering cavitation; (e): small bubbles gather into larger ones.

Table 1: Details of the tests performed: pressurization values and high-speed camera frame rate.

Test No.	Sensor	AEV (bars)	Saturation pressure (kPa)	Camera Frame rate (Fps)
1	HCTP3	15	3450	None
2	HCTP2	5	750	50
3	HCTP2	5	750	500
4	HCTP2	5	750	2000
5	HCTP2	5	2000	6000
6	HCTP2	5	2000	2000
7	HCTP2	5	2000	2000
8	HCTP2	5	0*	2000
9	HCTP2	5	2000	2000
10	HCTP2	5	2000	7000
11	HCTP2	5	2000	2000

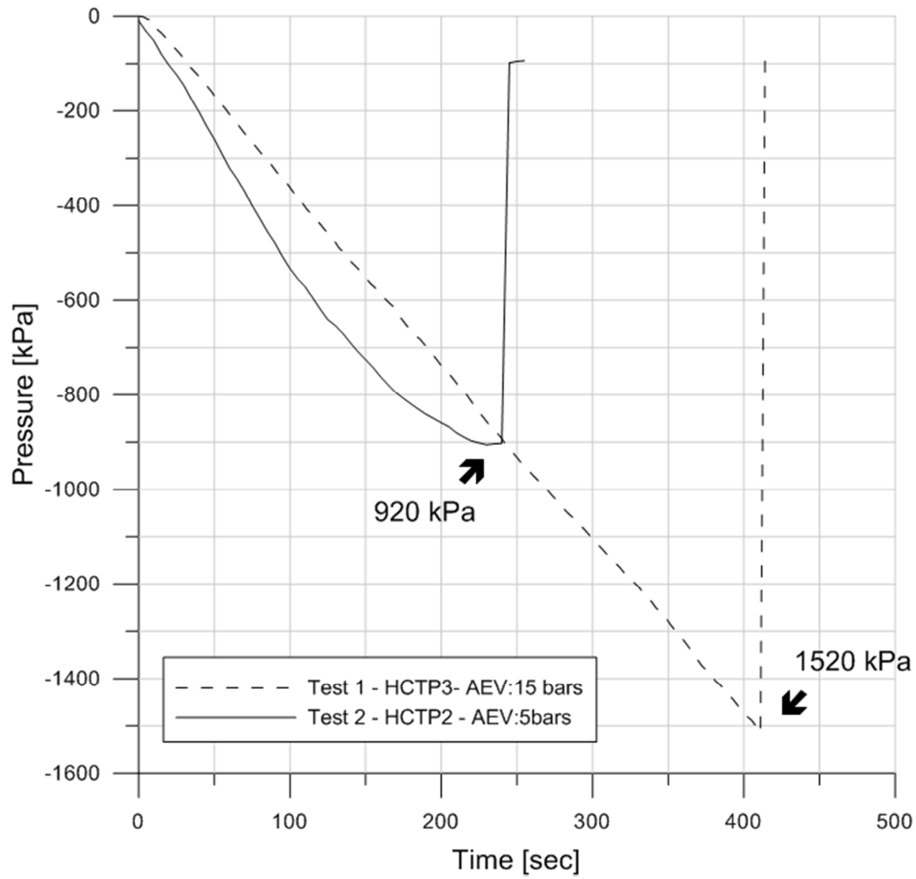
* - tensiometer was saturated, cavitated and immersed in water without further pressurisation.





(a) (b)

Figure 1: (a) Tensiometer developed by Ridley and Burland (1993) at Imperial College. (b) Perspex tensiometer built at The University of Newcastle, 5 bars ceramics, 3.5 MPa sensor, 1100 mm^3 water reservoir.



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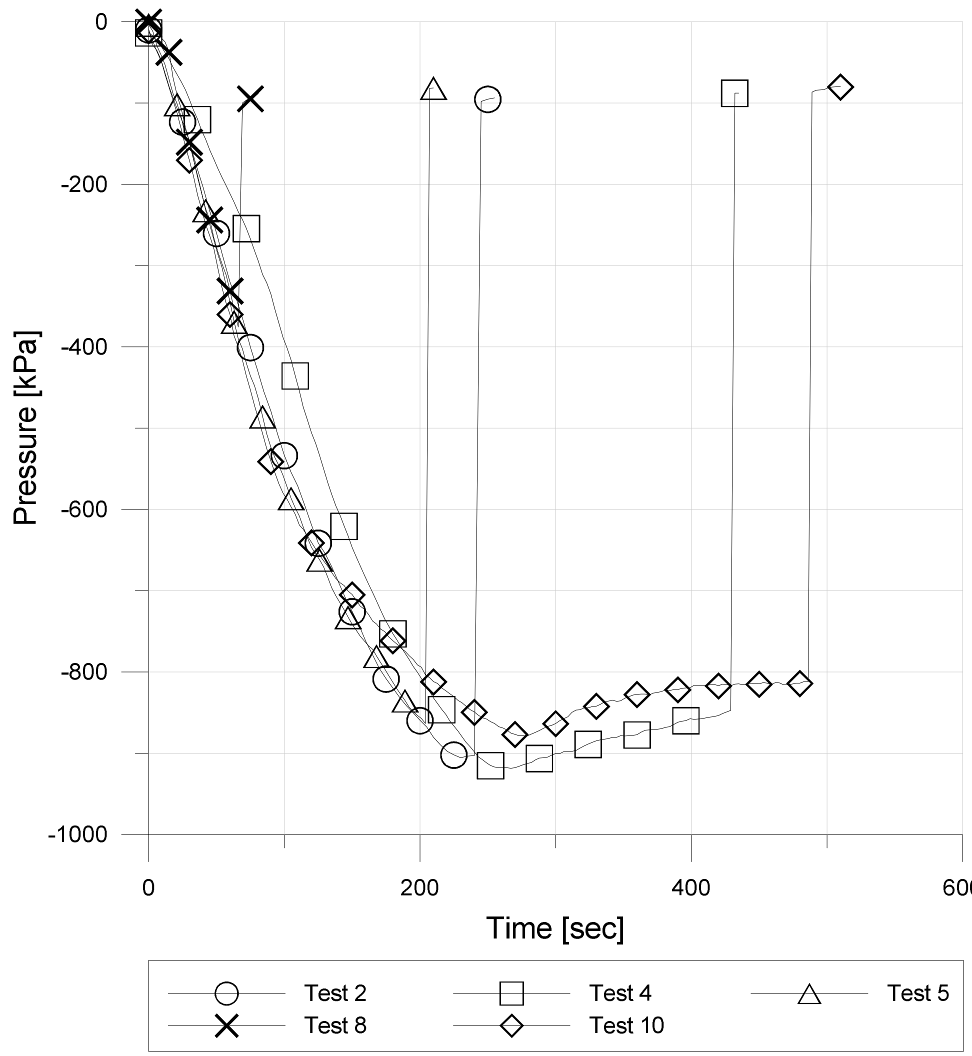
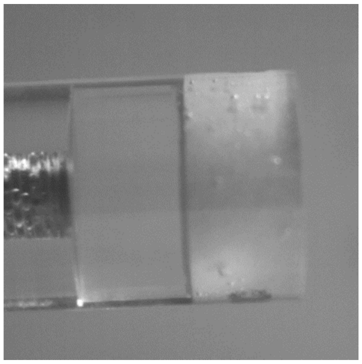
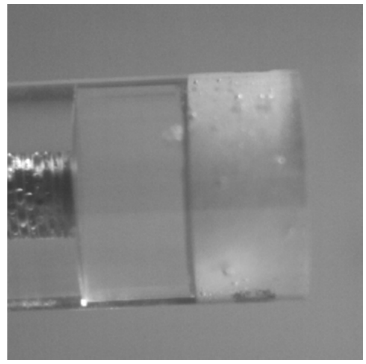


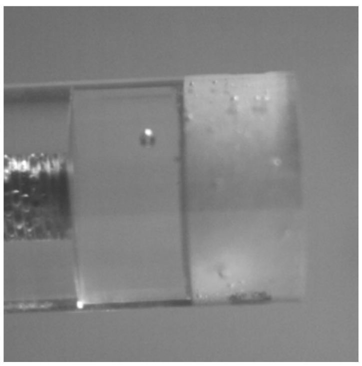
Figure 3: Tests 2, 4, 5, 8 and 10: Evolution of suction measured by HCTP2 (5bar) in time as the tensiometer is exposed to air-drying. The time between peak suction and cavitation (visible on tests 4 and 10) is referred to as delay.



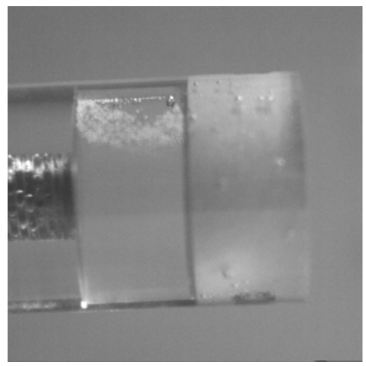
a) Initial state, t=0s



b) Small bubbles emerging from the ceramic, t=0.5 ms

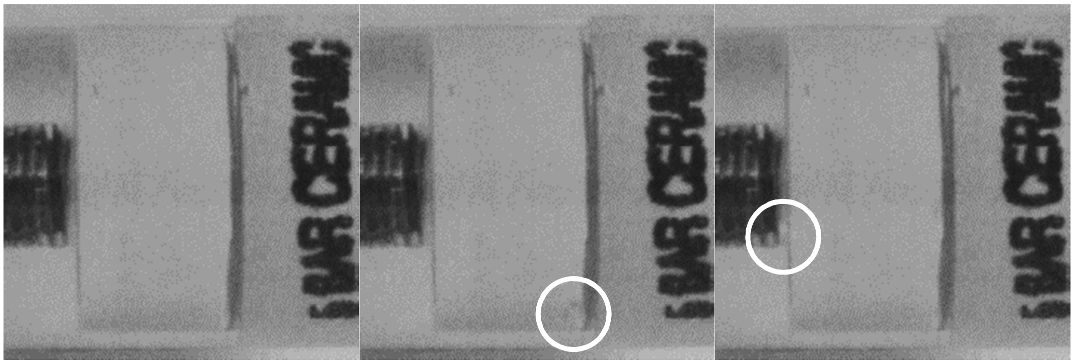


c) Small bubbles have agglomerated into a large bubble, t=5.5 ms.

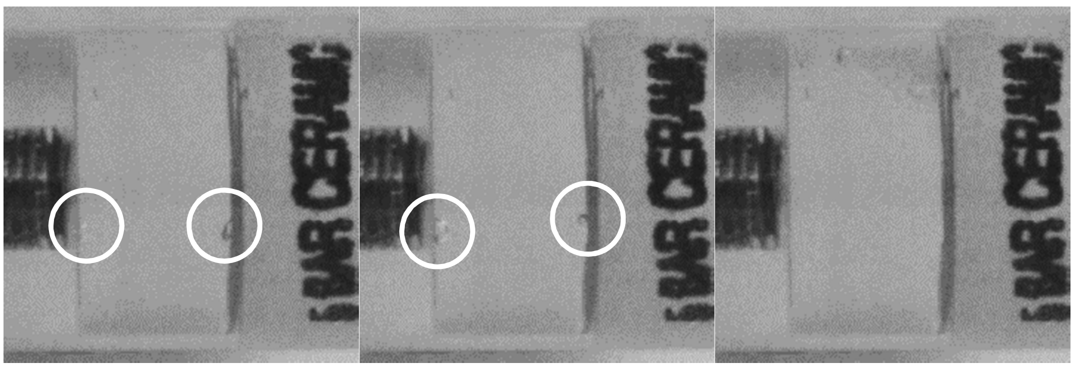


e) Final state after more bubbles have formed, t=4.4s

Figure 4: Sequence of high speed photographs for test 4 (2000 fps).

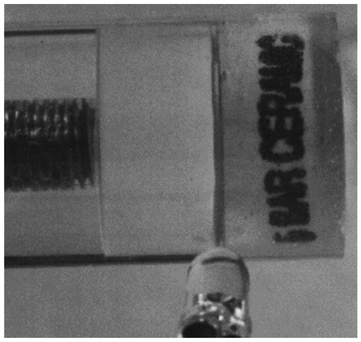


a) t = 0ms b) t = 0.14ms c) t = 0.28ms

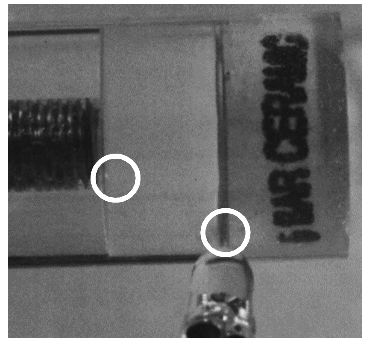


d) t = 2.57ms e) t = 4.43ms f) t = 2.343 s

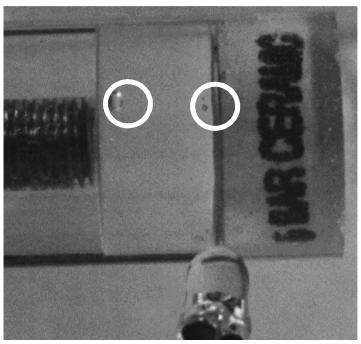
Figure 5: Sequence of high-speed photographs for test 10 (7000 fps).



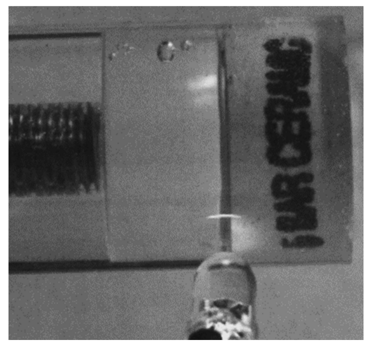
a) Initial state pre cavitation
t= 0 s or t_{log}=13.7585s
suction ≈ 800 kPa



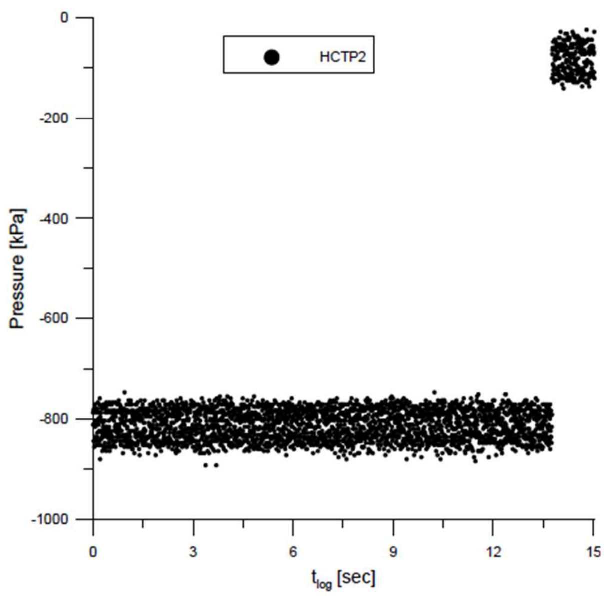
b) Bubble emerging from the ceramics and crevice
t = 0.5 ms or t_{log}=13.7590s
suction ≈ 100 kPa



c) Bubbles that emerged from ceramics and crevice
t = 22.5 ms or t_{log}=13.7610s
suction ≈ 100 kPa.

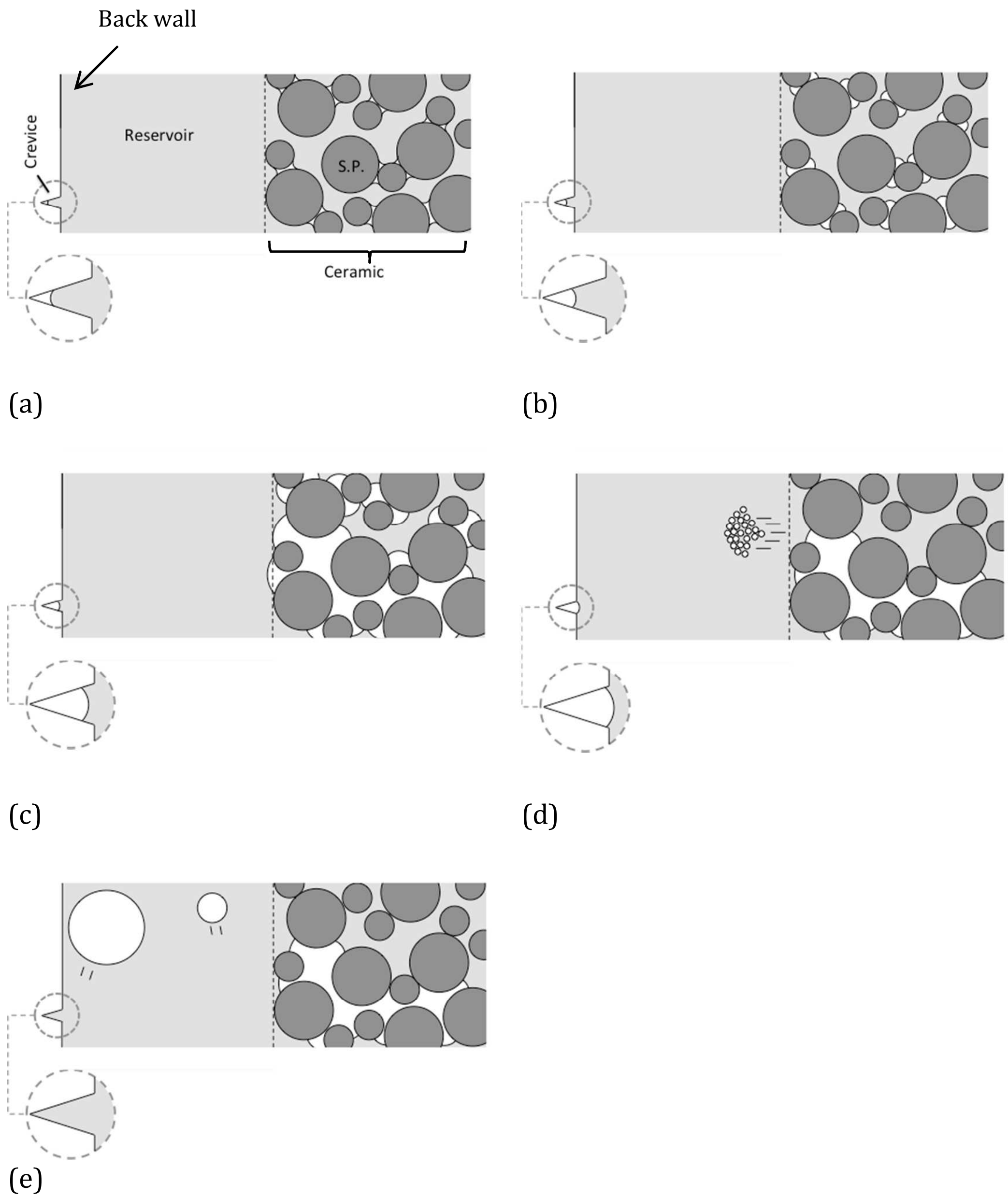


d) Final state
t = 0.64s or t_{log}=14.3990s
suction ≈ 100 kPa



e)

Figure 6: a) to d) Sequence of high-speed photographs for test 11 (2000 fps). e): Measurement of suction at time of cavitation.



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