Tensiometer Development for High Suction Analysis in Laboratory Lysimeters

Cláudio Fernando Mahler and Abdoul Aziz Diene

COPPE/UFRJ – Cidade Universitário, Centro de Tecnologia, Programa de Engenharia Civil, Caixa Postal 68506, CEP 21945-970 RJ/RJ, Brazil
cfmahler@acd.ufrj.br, abdoulazizdiene@yahoo.com

Summary. This paper presents results when using a tensiometer designed in the Soil Mechanics Laboratory at COPPE/UFRJ, and several other instruments. This new instrument measures suction values up to 1500 kPa. In more typical tensiometers, the cavitation of the system hinders the measurement of suction with values over 100 kPa. Ridley and Burland (1993) designed a new model of tensiometer to measure suction of more than 100 kPa. Mahler et al. (2002) presented a new tensiometer with which suction values up to 350 kPa were measured. This paper introduces an updated model of a tensiometer, using a variation of the equipment proposed by Mahler et al. (2002). The updated model worked extremely well and cost little to build. The equipment used allows suction to be measured relatively quickly and, as previously stated, is economical to produce (about US$300). To date, the range of suction levels that can be measured reaches 1500 kPa with no difficulty. The tests were carried out in two boxes of $160 \times 50 \times 60$ cm under laboratory conditions. The equipment used included a 15 m.c.a. ceramic block pressure sensor, de-aerated water and a special acrylic tube specifically designed for this instrument. The results were compared to two simple automated tensiometers and equivalent tensiometers. In general very good results were obtained. The main final remarks so far are as follows:

- the high bubble air entry of the ceramic block inhibits the presence of air bubbles, but the response time is slower for suction values of more than 200 kPa;
- the saturation process used for the ceramic stone worked very well;
- as expected, the position of the equivalence tensiometer influences the value measured;
- the mini-lysimeter system proved to be a very good alternative for laboratory tests and for the development of instruments that measure suction;
- the new instrument presented herein proved to be a good and an economical alternative for measuring matrix suction in the soil.

Key words: suction, tensiometer, unsaturated soil, mini-lysimeter

1 Introduction

Tabor (1979) demonstrated theoretically that water resistance traction is around −500 MPa. On this hypothesis, Ridley (1993) and Ridley and Burland (1993) introduced the first equipment capable of measuring stress in soil of more than 1 MPa.

König et al. (1994) used a tensiometer for pore pressure in centrifugal Druck PDCR–81. This apparatus consists of an instrumented silicon diagram tied in an internal glass cylinder and connected at the porous elements by steel external box protector conform Fig. 1. Using a large-scale measuring device, with a porous stone of 15 bar of air entry, saturated at a pressure of 2000 kPa, Ridley (1993) was able to measure suctions of more or less 1370 kPa. He reported that the ample external strain of the diaphragm with broad negative pressure could compromise the integrity of the connection between the diaphragm and the glass cylinder support. Consequently, water is free to penetrate the cavities of the device, causing the suspect result of pressure measured for both negative and positive cases.

Ridley and Burland (1995) presented another prototype based on the principle of maximising the sustainable stress in tensiometers to measure high suctions in soil. This tensiometer makes it possible to measure onsite suctions of 1500 kPa. The equipment consists of an integrated strain-gauge diaphragm and a sealed ceramic porous element with a value of 15 bar of air entry, as shown in Fig. 2.

Guan and Fredlund (1997), likewise, introduced a tensiometer, which measured matrix suctions in soils of over 1250 kPa when saturated under a six-cycle pressure from 12000 kPa to −85 kPa (Guan and Fredlund 1997). The ceramic stone of high air entry value is sealed halfway in a box detachable from the device. Assembled in the water, the other half of the box acts as a compression element adjusting and sealing the commercial transducer in the water reservoir as showed in Fig. 3.

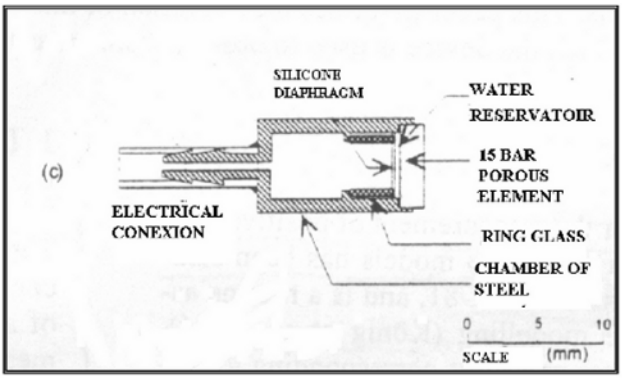


Fig. 1. Sketch of the tensiometer proposed by König et al. (1994)

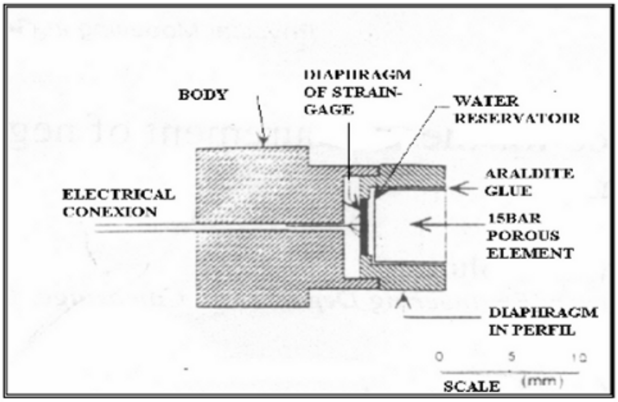


Fig. 2. Sketch of the Tensiometer proposed by Ridley (1995)

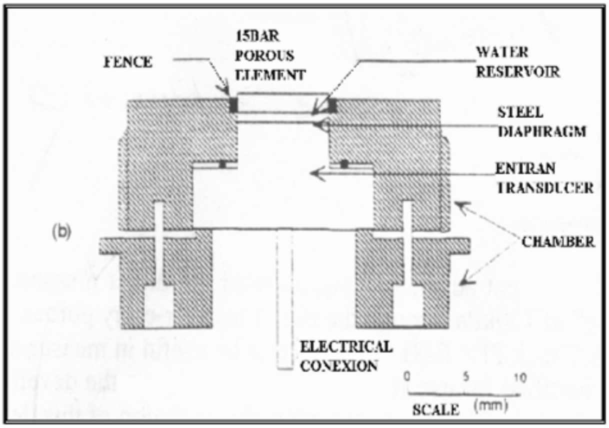


Fig. 3. Sketch of the Tensiometer proposed by Guan and Fredlund (1997)

Pacheco (2001) developed a low-cost tensiometer as shown in Fig. 4**a** and **b**, with measurements to even more than 3 atm without cavitation and concluded that: "the reduced water volume used in the transducer and porous stone interface of the new instrument and the saturation process inhibited the formation of air bubbles in the system, and permitted suction measurement up to 3 atm, with a time lag of a few seconds up to 1.5 atm."

Take and Bolton (2002) wanting to overcome the high loss of "Druck PDCR–81", conceived new more robust instruments for measuring negative pore pressure in centrifuge. They developed three prototypes introducing some format particularities for each. In common, the prototypes were fitted with an Entran (2000) EPB transducer with 7 bar air entry value and a porous stone of 15 bar, as shown in Fig. 5.

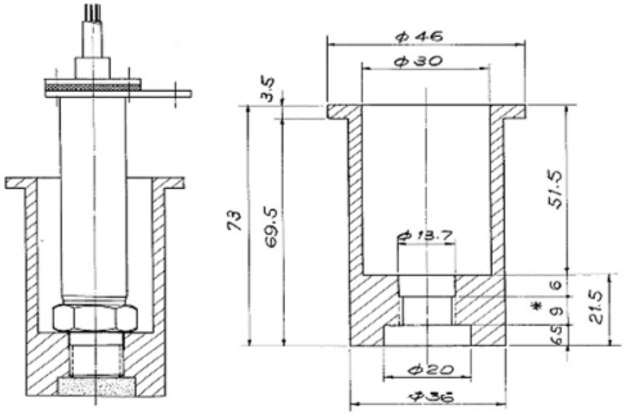


Fig. 4. Sketch of the First New Tensiometer (Pacheco 2001, Mahler et al. 2002)

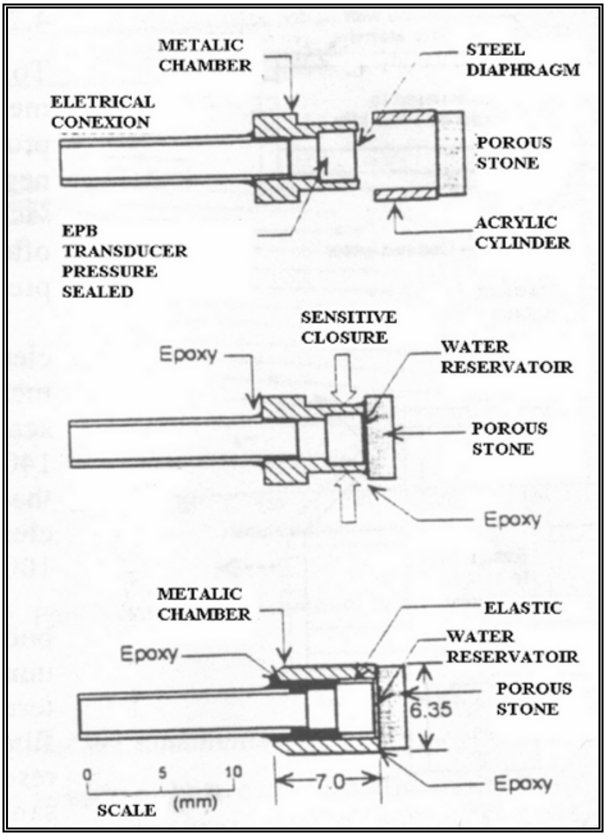


Fig. 5. Take and Bolton (2002) prototypes

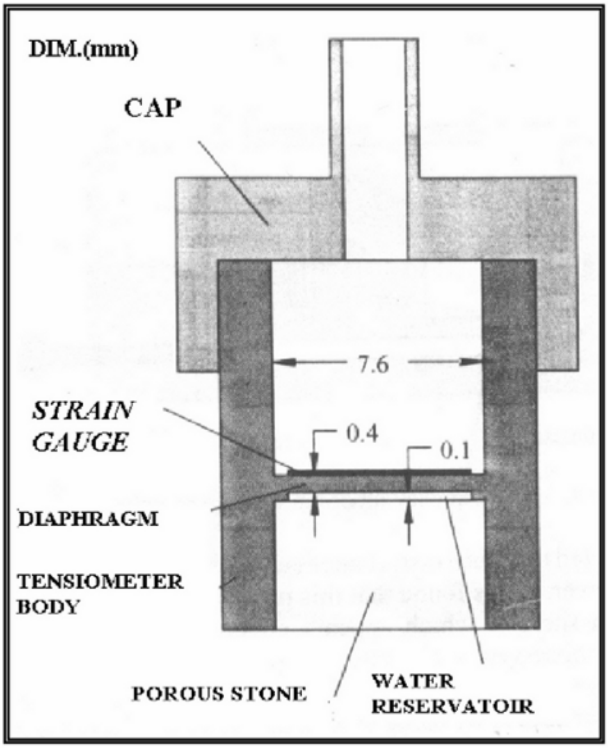


Fig. 6. Tarantino and Mongiovi (2002)

Tarantino and Mongiovi (2002) introduced a new tensiometer similar to the Ridley and Burland (1993) prototype, but with several modifications to the diaphragm diameter and thickness, to the water reservoir size and closing of the annular opening between the porous stone and tensiometer body (Fig. 6). This new equipment measured suction up to 1000 kPa for a period of time of more than 15 days and reached the maximum negative pressure of 2 MPa.

A problem common to all these items of equipment is the cavitation factor that is expressed when the transducer reading is interrupted, even momentarily. From the various models that explain water cavitation undergoing traction strain, the most acceptable is that proposed by Harvey et al. (1944): "it is supposed that cavitation arises from the non-dissolved gas nuclei in the space of the reservoir walls instead of in the free cavities of liquid;" this due to the fact that the spherical nucleus of free gas is generally unstable and tends to move into the liquid. On the contrary, the gas nucleus in the cavities of the container walls can remain indissoluble even under high water pressure. When the pressure decreases to negative values, these nuclei can expand and possibly cause cavitation. This process is controlled by gases spreading through the gas-liquid boundary and furtively moving into the solid-liquid-gas junction determined by moving forward and back (inward contact angle). Physicians using glass or steel in a Berthelot tube determine the stress tests for the water. This tube is initially almost completely filled with water and the remaining volume consists of a mixture of steam and air. The tube is heated to expand the liquid content and force the air into the solution. After cooling, the liquid sticks to the walls of the tube and undergoes gradual increasing stress until breaking at the start of cavitation.

In order to inhibit the cavitation in the equipment, various solutions were proposed by a number of authors, which was summarised in procedures applied to assembly or saturation, or their calibration. these proposals gave rise to some conclusions on how to prevent cavitation. Ridley (1993) assumed that the maximum tension sustainable by the tensiometer is also a function of the air entry value of the porous element. "If the difference in pressure between the water volume reservoir and the measured pressure in the soil exceeds the air entry value, the air can be drawn into the water reservoir; a variation of external pressures that operate in the device will result in expansion or contraction of the air bubbles and the measured pressure is potentially detached from reality." Marinho and Chandler (1995) assigned the use of a small water volume in the suction measurement system as responsible for the non-occurrence of cavitation, and that the minimum volume possible is limited by the transducer diaphragm. The pre-pressurisation of water was considered essential for the saturation of tensiometers by Ridley and Burland (1993) and Guan and Fredlund (1997).

Some differences however do exist between the two pre-pressurisation methodologies.

Guan and Fredlund (1997) apply several pre-pressurisation cycles first under a vacuum of −85 kPa followed by higher positive pressures until 12 000 kPa. In fact, it was suggested that the rupture tension is initially affected by the number of cycles and magnitude of applied positive pressure (Guan and Fredlund 1997). Ridley and Burland (1993) affirmed that the pre-pressurisation procedure is less important. These authors proposed that a tensiometer be saturated by applying constant pressure of 4000 kPa maintained for at least 24 hours. Tarantino et al. (2000) made suction measurements higher than the air entry value of the porous element without cavitation and concluded that "cavitation may occur before the soil-equipment system equalizes, causing the interruption of the test and pre-saturation of the instrument; the knowledge of conditions that address cavitation is, therefore, essentially based on optimising the instrument's design and on determining a suitable experimental process."

Cavitation does not occur if the system is free from cavitation nuclei, which in short means the use of pure clean "de-aerated" water, extremely clean smooth surfaces, undergoing the vacuum system, cyclical application of positive and negative pressures and pre-pressurising the system at high pressures to dissolve the free air.

2 Description of the Equipment – Tensiometer

A traditional tensiometer usually consists of a porous stone in contact with the soil, a body containing the porous stone, de-aerated water and a transducer (in this case). The soil matrix suction is measured by excitation of the transducer.

The problems referring to cavitation that generally occur at approximately 80 kPa are very common to the traditional tensiometers mentioned above. Such problems were solved in this new form of building tensiometers due to:

- the use of porous stone with a high air entry value;
- the use of "de-aerated" water throughout the saturation process and assembly;
- the use of acrylic in constructing the tensiometer because of its smooth surface that prevents the formation of micro air bubbles during the saturation process of the system;
- the process of assembly, saturation and calibration of the prototype.

The equipment presented here consists only of these three elements – porous stone, transducer and acrylic body.

This is extremely simple equipment. It uses the stone and transducer in its original dimension. So this tensiometer can be tailor-made for each case.

Figures 7 and 8 presents respectively photographs of the prototypes designed and used in this research and the acrylic capsule design with different dimensions for each tensiometer used.

In the development of the current tensiometer prototypes, the following porous stone and transducers were used (Table 1).

All prototypes presented satisfactory behaviour, the time-lag variation in seconds, not significantly enough to negatively influence its use in laboratory or field.

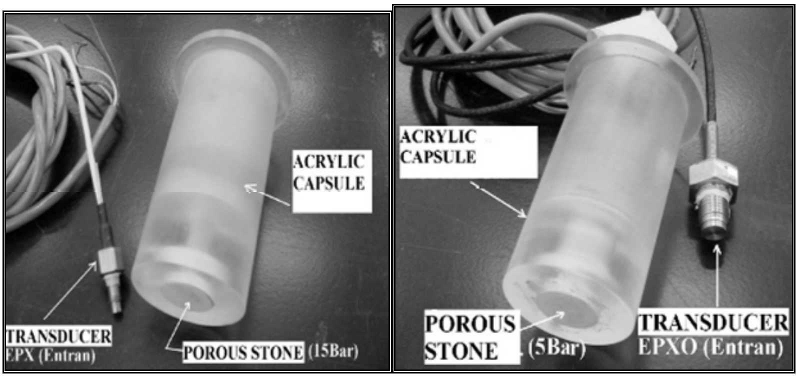
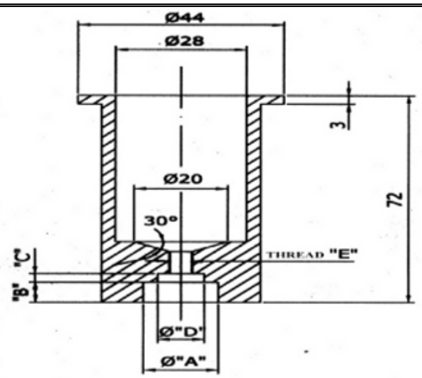


Fig. 7. Example of developed tensiometers – Tense EPX and Tense EPXO (Diene 2004)



PIECES	Ø"A" x "B"	Ø"D" x "C"	THREAD "E"
EPX 1	15.85 X 7.55	4.40 X 0.35	3/8" x 24fpp
ASH 1	15.60 X 7.05	6.98 X 3.00	NPT 1/4"
EPXO 1	29.00 X 7.20	9.00 X 0.20	M5 x 0.8
ASH 2	29.00 X 7.20	5.50 X 3.00	NPT 1/4"

(DIMENSIONS IN mm)

Fig. 8. Design of the acrylic capsule prototype (Diene 2004)

Table 1. Dimensions and characteristics of the components of tensiometers (Diene 2004)

Tensiometer	Tense-EPX.1		Tense-ASH.1		Tense-EPXO.1		Tense-ASH.2	
	Diam.	Thickn.	Diam.	Thickn.	Diam.	Thickn.	Diam.	Thickn.
Stone	test		test		test		test	
Diam./Thickn. (mm)	15.85	7.55	15.6	7.05	29	7.20	29	7.20
Pressure (kPa)	1500		1500		500		500	

In this research, other equipment for control and monitoring, such as TDR and equitensiometers were used together with the tensiometers.

The equivalence tensiometer or equitensiometer consists of a Theta probe and acrylic body, as shown in Fig. 9.

The equitensiometer sensor consists of a Theta probe built in a special projected porous material (Fig. 9). The water content of this material enters into equilibrium with the matrix potential of the soil involved, where it is detected by the Theta probe, when absorbed. This operation is based on the equivalence of the matrix potential between the soil material and instrument's body.

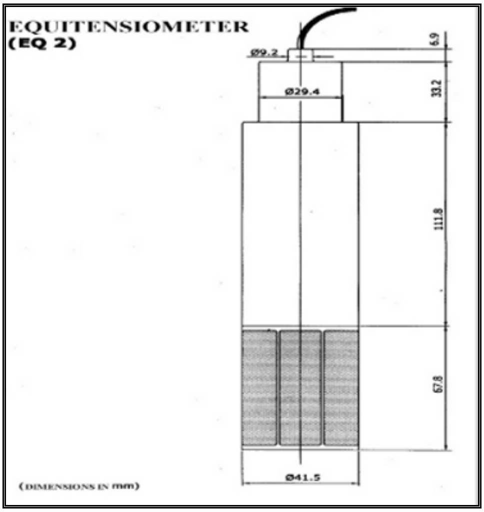


Fig. 9. Equivalence Tensiometer – Equitensiometer EQ2 (Diene 2004)

In principle, the EQ2 instrument response varies in a band from 0 to −1000 kPa. The best precision occurs between −100 kPa and −1000 kPa, with ± 5% error. Its reading precision in suctions from 0 to −100 kPa is ± 10 kPa.

Calibration and Saturation Process

The saturation and calibration process comprised the following actions and equipment (Fig. 10):

1. Check the inclusion of the porous stone in the acrylic body by applying three water pressure cycles, to check the water tightness of the contact (porous stone-acrylic);
2. The porous stone was saturated by applying a vacuum in the calibration chamber, which has no water content inside it for longer than 15 hours. Later, "air bubble free" water is introduced in the chamber (maintaining the vacuum application) until the water covers the porous element. The vacuum in the system should be maintained for another two hours;
3. Transfer the assembled set to the calibration/saturation chamber and apply pressure cycles varying from zero to 600 kPa, following the value of the bubbling pressure of the porous stone used to generate a water flow into the stone and remove any bubbles;
4. Install the pressure transducer in the system by screwing it to the acrylic body in "air bubble free" water and re-apply a vacuum to the system for three to four hours;
5. Calibrate the prototype using pots of mercury in three loading and unloading stages, with water pressure values until it reaches the calibration

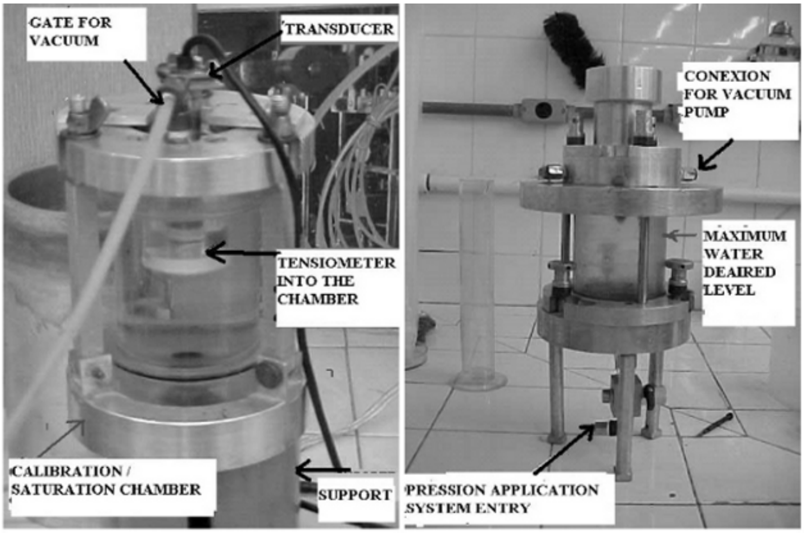


Fig. 10. Calibration/saturation chamber and porous stone saturation chamber (Diene 2004)

linear curve (these water pressure values vary according to the installed prototype).

3 Results

Figures 11 and 12 showed some of the results obtained in lysimeter laboratory tests (Diene 2004), compared with other automatic tensiometers and different suction measuring systems such as equitensiometers.

The Tense-ASH1 and 2 tensiometers behaved in a similar manner until reaching suction values of over −800 kPa, at which point a loss of pressure in the Tense-ASH2 tensiometer was observed. This loss of pressure is due to the fact that this tensiometer, with a porous stone of 500 kPa, reached the air entry pressure, and the system achieved the air entry value limit. Consequently, bubble air nuclei formation causes cavitation (Fig. 11). In this case, cavitation might also be called maximum water-ceramic adhesion stress.

The Tense-EPXO1 tensiometer measured soil suction values with sufficient precision and continuously until reaching higher values than air entry value of 500 kPa of the porous stone attached to it.

The Tense-EPX1 tensiometer inserted to 30 cm in depth measured quite similar suction values to those measured by the Tense-EPXO1 installed at a depth of 15 cm. The tensiometer measured suction values of up to −1465 kPa and when correlated to the Tense-EPXO inserted at a depth of 15 cm, showed a difference of decreasing pressure of 15 to 25 kPa (Fig. 12).

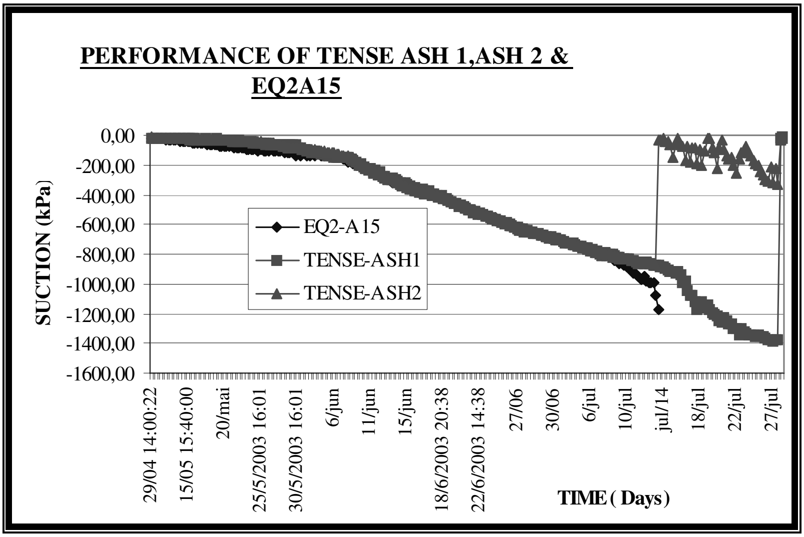


Fig. 11. Results of high suction tensiometers correlated with the equivalence tensiometer tested in lysimeters (Tank A) (Diene 2004)

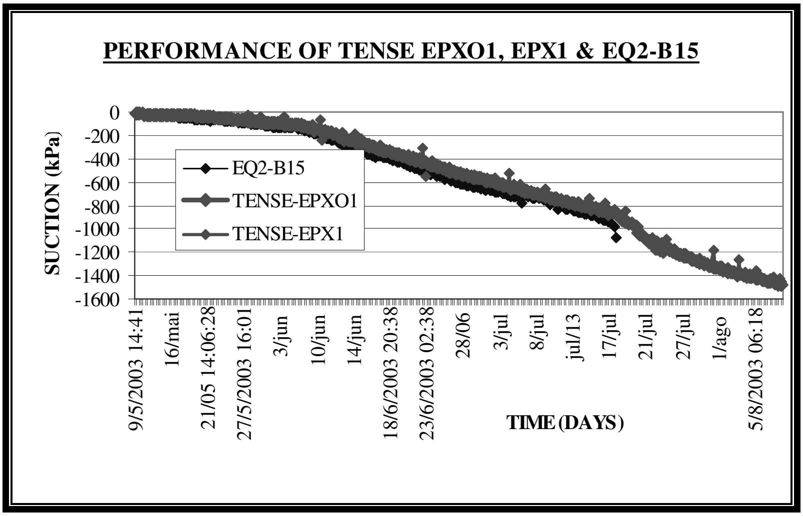


Fig. 12. Results of high suctions tensiometers correlated to the equivalence tensiometer tested in the lysimeter (Tank B) (Diene 2004)

4 Final Comments

The following conclusions can be made from the developed prototypes and their results:

1. With the manufacturing progress of porous stones and transducers there are no longer problems in developing tensiometers to measure high suction values;
2. The acrylic should be as smooth as possible, in order to prevent the accommodation of any micro-bubbles in irregularities of the walls;
3. The variation band of suction measurement to be achieved will be determined by the (air entry pressure) porous stone used and transducer capacity;
4. The obtained results show that the developed prototype may be employed in onsite measurements or in the laboratory with its adjustment, for example, to the cells of triaxial tests or odometer;
5. This is robust equipment. It is able to use the porous stone and transducer separately in other installations due to the easy handling of the proposed procedure.

Acknowledgements

The authors thank the National Research Council (CNPq), CAPES, Foundation Volkswagen and the Institute for Environmental System Research of the University of Osnabrück, Professor M. Matthies, for their constant support and interchange. They thank Ms. Elvyn Marshall for the revision of the English text.

References

Diene AA (2004) Tensiometers development for high suction measurement in laboratory lysimeters. MSc Thesis, Coppe-UFRJ, 173 pp (in Portuguese)

Entran® Pressure Sensors (2000) EPX Miniature Threaded Pressure Sensors, `www.entran.com`

Guan Y, Fredlund DG (1997) Direct measurement of high soil suction. In: Simpósio solos não saturados brasileiro, 3, Rio de Janeiro, 2:543–550

Harvey EN, Barnes DK, McElroy WD, Whiteley AH, Pease DC, Cooper KW (1944) Bubble formation in animals. I. Physical factors, J Cell Comp Physiol 24(1):1–22.

König D, Jessberger HL, Bolton MD, Phillips R, Bagge G, Renzi R, Garnier J (1994) Pore pressure measurement during centrifuge model test: experience of five laboratories. In: Leung, Lee, Tan (eds) Centrifuge'94. Balkema, Rotterdam:101–108

Mahler CF, Pacheco AC, Souza HG (2002) Development of an automatic tensiometer in laboratory using a Mini-Lysimeter. In: 3rd Int Conf on Unsaturated Soils, REcife, Brazil

Marinho FAM, Chandler RJ (1995) Cavitation and the Direct Measurement of Soil Suction. In: First Int Conf on Unsaturated Soils, Paris, France 2:623–630

Pacheco AC (2001) Development of a new tensiometer to measure suctions higher than one Atm. MSc Thesis, Coppe-UFRJ 93 pp (in Portuguese)

Ridley AM (1993) The measurement of soil moisture suction. PhD Thesis, University of London, Civil Eng Dept

Ridley AM (1995) Strength–suction–moisture content relationship for kaolin under normal atmospheric conditions. In: First Int Conf on Unsaturated Soils Unsat'95, Paris 2:645–651

Ridley AM, Burland JB (1993) A new instrument for measuring soil moisture suction. In: Technical Note, Geotechnique 43(2):321–324

Ridley AM, Burland JB (1995) Mesasurement of suction in materials which swell, Appl Mech Rev 48(10):727–732

Tabor D (1979) Gases, liquids and solids, 2nd ed. Cambridge University Press

Take WA, Bolton MD (2002) A Negative Devices for the Measurements of Negative Pore Water Pressure in Centrifuge Models, Physical Modeling On Geotecnics: 89–94

Tarantino A, Bosco G, Mongiovi L (2000) Response of the IC Tensiometer With Respect to Cavitation. Unsaturated Soils for Asia:309–313

Tarantino A, Mongiovi L (2002) Design and Construction of a Tensiometer for Direct Measurement of Matric Suction. Unsaturated Soils:319–334