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High Capacity Tensiometers: performance and behaviours

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Abstract. High capacity tensiometers (HCT) allow the direct measurement of soil matric suction, and their major limitation is the occurrence of cavitation. In this paper HCT designs using different ceramic filters with varied air entry values (AEV), varied reservoir sizes, and different pressure transducers are assessed as to determine the impact that each component may have in the HCT performance. Moreover, the effectiveness of first saturation and resaturation processes is discussed in relation to the time required to prepare/recover HCTs. The results obtained with the different designs show that the measuring range is directly linked to the AEV of the ceramic filter and that the choice of materials used for the various components may affect the reliability of measurements in field installations if the thermal performance is not accounted for in the calibration procedure. The use of a 1hr high vacuum pre-stage followed by overnight water pressurisation at pressures equal or above the AEV of the ceramic filter was found to be the quickest process to fully saturate an HCT for the first time. While resaturation time for an HCT can be reduced to as little as a few minutes if the HCT is resaturated immediately after cavitation has occurred.

1 Introduction

Soil suction (negative pore water pressure) is a crucial parameter for the study of the hydro-mechanical behaviour of unsaturated soils. Various techniques have been developed in the past for measuring and monitoring soil suction. Currently, however, the only sensors that allow the direct measurement of soil suction are conventional and high capacity tensiometers (HCT). Although the measuring principle of conventional tensiometers and HCTs is the same (the soil pore water pressure is measured via a pressure transducer), the former sensors are limited to a suction measuring range of 0.1 MPa (0 MPa of absolute pressure) while the latter ones have a measuring range that extends well beyond 1 MPa owing to the use of special ceramic filters. HCTs were initially developed in the 90's at Imperial College, London by Ridley and Burland [1]. This transformative development allowed, for the first time, the direct measurement of suction to values up to 1.5 MPa. The basic design of the Imperial College HCT is shown in Fig. 1 and comprises a porous ceramic filter with a nominal air entry value (AEV) of 1.5 MPa, a 3 mm^3 water reservoir and a 3.5 MPa ENTRAN Ltd EPX series electronic pressure transducer. Since then, other HCTs with similar design have emerged, such as those described in [2-8] among others.

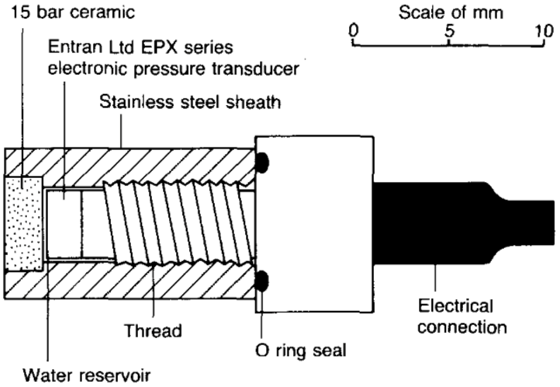

Fig. 1. High capacity tensiometer developed at Imperial College, after [1].

The measurement of soil suction beyond 0.1 MPa is only made possible due to the high AEV of the porous ceramic filter. The AEV is the pressure at which air starts to permeate through and is also related to the maximum difference in pressure that can exist between the two sides of the ceramic filter (i.e., the pore water pressure in the soil pores and the water pressure in the reservoir of the HCT). Assuming that the porous ceramic filter and water reservoir are fully saturated when the HCT is placed in contact with the soil, the pressure inside the water reservoir will reduce to reach equilibrium with the soil pore water pressure (suction). In general, if the difference in pressure is smaller than the AEV of the ceramic filter, then the water reservoir

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will remain fully saturated and an equilibrium between the pore water pressure in the soil and the water pressure in the reservoir will be reached. However, if the difference is greater than the AEV of the ceramic filter, cavitation within the water reservoir may occur rendering the HCT inoperable. Cavitation in HCTs occurs when gas bubbles emerge inside the water reservoir, thus breaking water continuity. It is still unclear whether these gas bubbles are made of diffused air from outside the HCT or entrapped air in the ceramic filter or vapour from water cavitation or a combination of the aforementioned. Cavitation is easily identifiable as it is marked by an almost immediate increase and levelling out of pressure readings at about -0.1 MPa (0 MPa of absolute pressure at sea level).

This paper presents a study where the performance of distinct HCT designs is assessed using different ceramic filters with varied AEVs (namely, 1.5 and 3.5 MPa), reservoir sizes (namely, 4, 40, 50, 430 and 800 mm^3), pressure transducers and sheath materials. The aim is to determine the impact that each HCT component may have on the measuring range, especially in field applications. Moreover, the effectiveness of first saturation (involving the application of pressurised deaired water above the AEV with high vacuum pre-stage) and resaturation processes (involving the application of pressurised deaired water above the AEV) is discussed in relation to the time required to fully saturate and resaturate HCTs.

2 HCT designs

The HCT designs presented in this paper follow that of Imperial College London (Fig. 1). To assess the performance of each component (ceramic filter, water reservoir size, pressure transducer, and sheath), eight different HCT designs were developed, the details of which are presented in Table 1. Each HCT design was named according to the format VV–WW–XX(YY)–ZZ. Where, VV indicates the AEV of the ceramic filter in MPa (1.5 or 3.5), WW indicates the size of the water reservoir in mm^3 (4, 40, 50, 430 or 800), XX(YY) indicates the pressure range in MPa (2, 3.5 or 6.8) and material (AL – alumina, BC – beryllium copper or SS – stainless steel) of the pressure transducer, and ZZ indicates the material of the sheath (AL – alumina, SS – stainless steel or P – perspex). Further details for each specific HCT design can be found in the references of Table 1.

2.1 Ceramic filter

As mentioned before, the AEV of the ceramic filter defines the upper limit of the measuring range of HCTs [11] and can be estimated from the size of the largest pore in the ceramic filter. Where, a smaller size of the largest pore corresponds to a greater AEV and, therefore, to a greater suction measuring range.

Apart from 3.5-50-6.8(SS)-SS, all HCTs were assembled with a common ceramic filter having an AEV of 1.5 MPa. This filter is composed of a mixture of ball clays fired on a ceramic body with a largest pore size of 165-220 nm, as shown in Fig 2, with the microstructure and texture shown in Fig. 3a. The 3.5 MPa AEV ceramic filter is instead composed of 99.9% alumina pellets with a largest pore size of 75-92 nm, as shown in Fig. 2, with the microstructure and texture shown in Fig. 3b.

2.2 Water reservoir and sheath

The water reservoir of a HCT allows the pressure transducer sensing face to deflect inward (into the water reservoir) when exposed to negative pressure. The sheath in most designs protects and encapsulates the ceramic filter, water reservoir and pressure transducer.

Different water reservoir sizes have been used in distinct designs (Table 1) from less than 50mm^3 (1.5-4-3.5(BC)-SS, 1.5-40-2(AL)-SS, 1.5-40-2(AL)-AL, 1.5-50-2(SS)-SS and 3.5-50-6.8(SS)-SS) to more than 400mm^3 (1.5-800-3.5(BC)-P, 1.5-430-2(AL)-SS and 1.5-430-2(AL)-AL).

In most of the designs studied in this paper, the water reservoir is part of the sheath, which includes a gap to separate the ceramic filter and pressure transducer (Fig. 1). The only exceptions are 1.5-430-2(AL)-SS and 1.5-430-2(AL)-AL, in which the water reservoir coincides with the cavity of the monolithic pressure transducer.

2.3 Pressure transducer

All HCT designs presented in Table 1 share the same principle of converting the enacting pressure on the sensing face to voltage using a strain gauge. The sensing face of the pressure transducer should ideally be symmetrical, allowing the calibration obtained in the positive pressure range to be extrapolated to the negative pressure range (suction). Three different pressure transducer designs were here considered: flush mount, threaded flush mount, and monolithic. Flush mount and threaded flush mount are very similar in design as the sensing face is fully exposed, differing only in the

Table 1. HCT design configurations.

Name	AEV [MPa]	Reservoir size [mm^3]	Pressure transducer		Sheath Material	Reference
			Range [MPa]	Material		
1.5-4-3.5(BC)-SS	1.5	4	3.5	Beryllium Copper	Stainless Steel	[9]
1.5-800-3.5(BC)-P		800			Perspex	
1.5-40-2(AL)-SS	1.5	40	2	Alumina	Stainless Steel	[10]
1.5-40-2(AL)-AL					Alumina	
1.5-430-2(AL)-SS		430			Stainless Steel	
1.5-430-2(AL)-AL					Alumina	
1.5-50-2(SS)-SS	1.5	50	2	Stainless Steel	Stainless Steel	[11]
3.5-50-6.8(SS)-SS	3.5		6.8			

presence or absence of a thread in the transducer body. In the monolithic one, the sensing face is instead placed at the bottom of a cavity in the pressure transducer body. The designs 1.5-4-3.5(BC)-SS, 1.5-800-3.5(BC)-P, 1.5-50-2(SS)-SS, and 3.5-50-6.8(SS)-SS were assembled with threaded flush mount pressure transducers, the designs 1.5-40-2(AL)-SS and 1.5-40-2(AL)-AL were assembled with flush mount pressure transducers, and the designs 1.5-430-2(AL)-SS and 1.5-430-2(AL)-AL were assembled with monolithic pressure transducers.

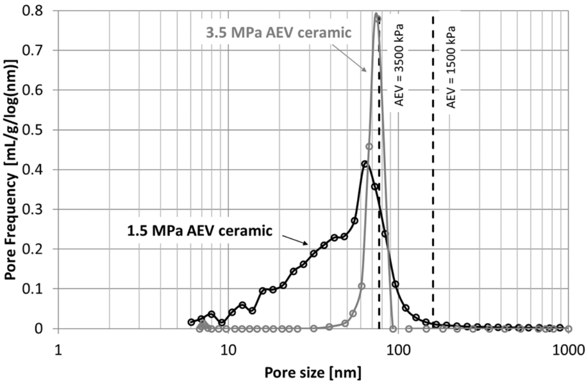
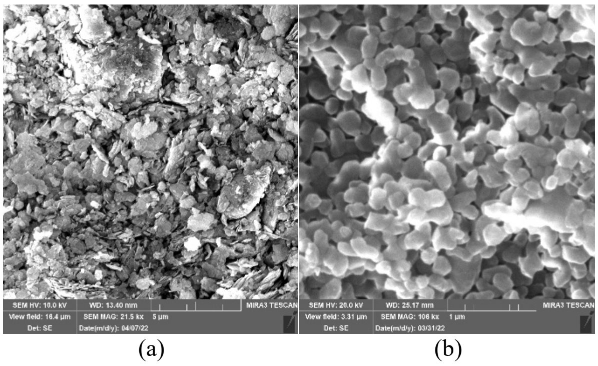


Fig 2. Ceramic filters pore size distribution measured by means of mercury intrusion porosimetry (after [11]).



(a) (b)

Fig 3. Texture and microstructure of a) 1.5 MPa AEV and b) 3.5 MPa AEV ceramic filters captured by scanning electron microscopy.

3 First saturation, calibration and resaturation

Prior to measurement, the ceramic filter and water reservoir of a HCT need to be fully saturated with deaired deionised water. In this study, two different saturation procedures are considered: "first saturation" and "resaturation".

First saturation has been identified as critical to ensure good measuring performance [12] and is applied to HCTs that are fully dried (for example, after assembly). The first saturation procedure adopted in this work consists of the three stages of high-vacuum, zero-pressure and water pressurisation.

High vacuum is applied to minimise the amount of entrapped air inside both the ceramic filter and water reservoir prior to flooding with deaired deionised water. The zero-pressure stage brings the pressure inside the saturation vessel from negative to atmospheric. During this stage, the empty volume inside the saturation vessel must be quickly filled with deionised deaired water as to minimise the amount of entrapped air inside the saturation vessel before the water pressurization stage. In the water pressurisation stage, the HCTs are subjected to relatively high positive water pressures to dissolve any remaining gas pocket and ensure proper saturation of the small pores of the ceramic filter and water reservoir.

The fully dry HCTs were secured in saturation vessels where they were subjected to high vacuum using pumps delivering an ultimate absolute pressure of at least 3.10^{-7} MPa for about one hour. This was followed by the zero-pressure stage, rapidly flooding the saturation vessel with deionised deaired water at atmospheric pressure. In the water pressurisation stage, the water pressure inside the saturation vessel was increased to values above the AEV of the ceramic filter but kept lower than the burst pressure of the pressure transducer using pressure/volume controllers. This meant that the applied water pressure varied from 2.99 MPa for the 1.5-40-2(AL)-SS, 1.5-40-2(AL)-AL, 1.5-430-2(AL)-SS and 1.5-430-2(AL)-AL to 3.45 MPa for the 1.5-4-3.5(BC)-SS and 1.5-800-3.5(BC)-P until 4 MPa for the 1.5-50-6.8(SS)-SS and 3.5-50-6.8(SS)-SS. While a pressurization time between 12 and 24 hours was found to be sufficient to saturate all HCTs with a small reservoir size (<50 mm^3), for the HCT designs with large water reservoir size (>400 mm^3), a longer pressurisation stage was required consisting of 96 hrs for 1.5-430-2(AL)-SS and 1.5-430-2(AL)-AL and almost 2 weeks for 1.5-800-3.5(BC)-P.

HCT calibration is typically performed after first saturation. Due to insufficient accuracy in the control of negative pressures, HCT calibration is performed in the positive pressure range and then extrapolated to the negative range [13]. All HCTs used in this work were calibrated inside saturation vessels where they were subjected to a pressure cycle in the positive range using pressure/volume controllers. Because of the different measuring range of the transducers, the pressure cycle varied from 3.45MPa→0.05MPa→3.45MPa for the 1.5-4-3.5(BC)-SS and 1.5-800-3.5(BC)-P, 2.99MPa→0.05MPa→2.99MPa for the 1.5-40-2(AL)-SS, 1.5-40-2(AL)-AL, 1.5-430-2(AL)-SS and 1.5-40-2(AL)-AL and 3.5MPa →0.025MPa→3.5MPa for the 1.5-50-2(SS)-SS and 6.8-50-2(SS)-SS. Further details regarding the pressure cycle for each HCT design can be found in the references cited in Table 1.

The resaturation procedure is applied to an HCT that has experienced cavitation during suction measurement leading to the formation of gas bubbles inside the ceramic filter and water reservoir. These gas bubbles must be eliminated to restore the sensor ability to record soil suction.

The resaturation procedure adopted in this work consists in subjecting the HCTs to a pressurisation stage as in the first saturation, with the exception of high vacuum. The application of high vacuum is not recommended and, in fact, should be avoided to prevent damage to the ceramic filter. After cavitation, the level of saturation of the ceramic filter remains close to 100% and the application of high vacuum for the same period of time as during first saturation may cause water to freeze inside the ceramic filter and potentially result in the formation of cracks, endangering the ability of the HCT to measure suction. The resaturation procedure typically lasts for approximately 12hrs but, if the HCTs are placed in water immediately after cavitation as shown in [11] and [14], this time can be reduced to as little as 10 minutes for HCTs with small size reservoirs (<50 mm^3). If the HCT is left exposed to atmospheric pressure after cavitation, the resaturation time increases significantly. This means that a short resaturation may be sufficient when performing point measurements of suction in both laboratory and field where the HCT can be placed under water pressure relatively quickly after cavitation. However, during long term monitoring, even if the HCT is placed in the saturation vessel immediately after cavitation, it is still recommended that the resaturation procedure should last for at least 12hrs (overnight) to ensure that the gas bubbles inside the ceramic filter are dissolved in water. If the readings of the HCT have levelled at about -0.1 MPa of relative pressure, a resaturation period of at least 12hrs (overnight) should be sufficient. This is because the gas bubbles that have formed after cavitation are still localised in the water reservoir and the ceramic filter is still fully saturated. Instead, if the readings of the HCT approach a relative pressure of 0 MPa (atmospheric pressure), the HCT should undergo a first saturation procedure. This is because the HCT starts to approach dry conditions as the ceramic filter is rapidly desaturating, with the formation of air channels between the atmosphere and the water reservoir, and the water reservoir itself is mostly dry.

4 Measuring range – evaporation test

A simple method to determine the measuring range of an HCT is to perform an evaporation test after saturation. In an evaporation test, the HCTs are removed from the saturation vessel and exposed to atmospheric conditions, allowing the water in the ceramic filter to slowly evaporate. As water evaporates, due to the continuity of water between the ceramic filter and the water reservoir, the sensing face of the pressure transducer will be pulled inward. If the HCT is properly saturated, the pressure readings will decrease with time. Because HCTs are currently unable to sustain pressures equivalent to a relative humidity below 98%, cavitation eventually occurs. The occurrence of cavitation in an HCT is easily observed as the pressure readings suddenly increase to -0.1 MPa.

The typical behaviour of the HCTs tested in this work during evaporation tests is presented in Fig. 4. Independent of reservoir size, pressure transducer or sheath material, all HCTs were able to attain a pressure similar to the nominal AEV of the ceramic filter before cavitation. More importantly, the results show that the AEV of the ceramic filter has the highest influence on the measuring range. Some HCT designs incorporating 1.5 MPa AEV ceramic filters attained pressure values of -2.25 MPa before cavitation, which was however still about 1 MPa less than the value of -3.4 MPa recorded by the 3.5-50-6.8(SS)-SS HCT (assembled with the 3.5 MPa AEV ceramic filter).

From Fig. 4, it is also apparent that the water reservoir size somewhat influences the measuring range of HCTs. However, it is not clear if this happened because the HCTs were not given sufficient time to be properly saturated or because the AEVs of the corresponding ceramic filters were close to the nominal value of 1.5 MPa provided by the manufacturer. Note that the readings before cavitation of the HCTs with large reservoir size were -1.79 MPa for the 1.5-430-2(AL)-SS, -1.65 MPa for the 1.5-430-2(AL)-AL and -1.51 MPa for the 1.5-800-3.5(BC)-P, which were all above the nominal AEV of the ceramic filter. Nevertheless, large water reservoir sizes should be avoided, if possible, simply because they require times of days/weeks for first saturation.

A close analysis of Fig. 4 also suggests that the response time of the HCTs during evaporation tests was

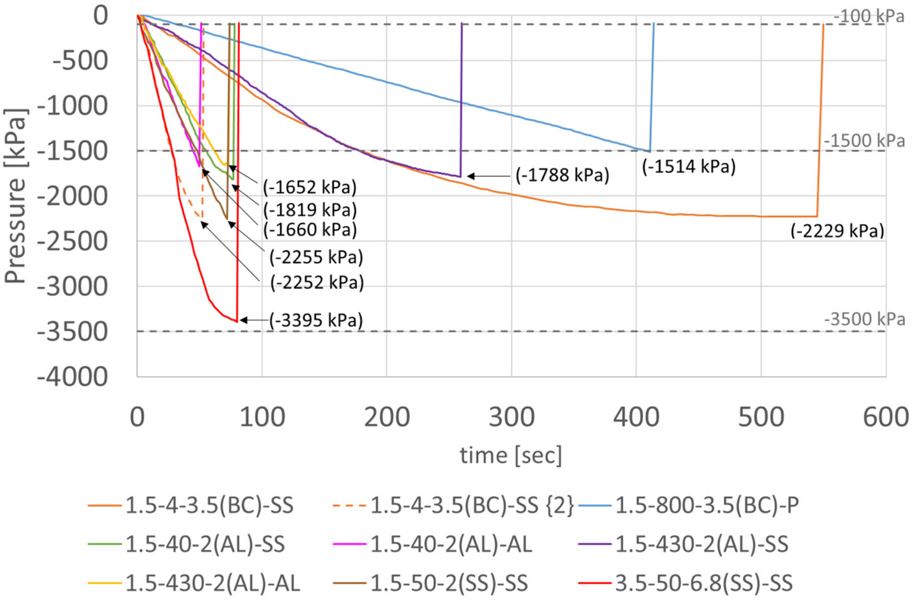


Fig 4. Typical HCTs behaviour during evaporation tests.

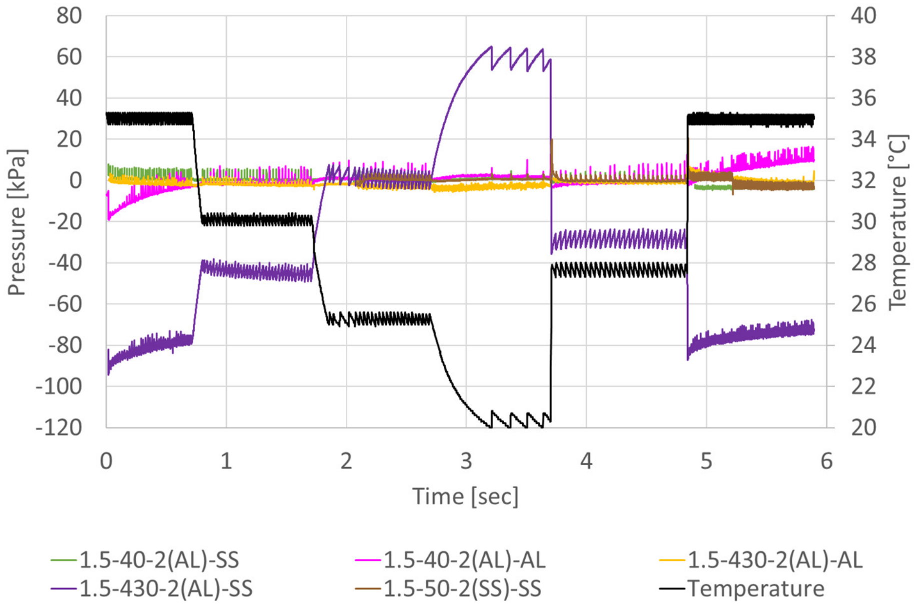


Fig 5. Temperature regulated water bath test results for different HCT designs.

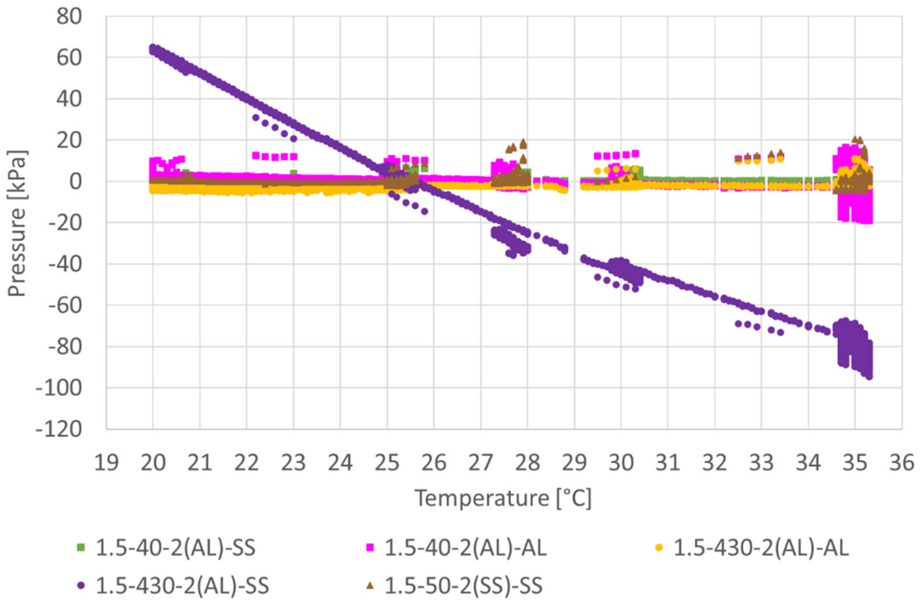


Fig 6. Temperature regulated water bath test results: temperature vs pressure.

not significantly influenced by the design components (ceramic filter, water reservoir, pressure transducer and sheath), but rather by the type of epoxy resin used during assembly. The designs 1.5-800-3.5(BC)-P and 1.5-430-2(AL)-SS were assembled with an epoxy resin typically used to preserve organic matter (such as animal/human bones), named herein E1, while the designs 1.5-40-2(AL)-SS, 1.5-40-2(AL)-AL, 1.5-430-2(AL)-AL, 1.5-50-2(SS)-SS and 3.5-50-6.8(SS)-SS were assembled with an epoxy resin specifically designed for bonding ceramic and metals, named herein E2. The design 1.5-4-3.5(BC)-SS was the only one for which both types of epoxies were used. In this case, the results from evaporation tests are presented in Fig. 4 as 1.5-4-3.5(BC)-SS for the HCT assembled with E1 and as 1.5-4-3.5(BC)-SS {2} for the HCT assembled with E2. The HCT assembled with E2 responded faster, reaching their peak within the first 90 seconds. In contrast, the HCT assembled with E1 was much slower to respond, reaching their peak after 250 seconds. Comparing the response time of designs 1.5-430-2(AL)-SS and 1.5-430-2(AL)-AL (both with large water reservoirs but respectively assembled with epoxies E1 and E2), it is also evident that the response of 1.5-430-2(AL)-AL was faster and comparable to that of designs with smaller water reservoirs.

5 Thermal behaviour – temperature regulated water bath test

Laboratory tests on unsaturated soils are commonly performed in temperature-controlled environments so that the effect of temperature on the performance of HCTs can be neglected. In the field, however, the temperature can vary significantly, whose effect on readings may be noticeable due to the different thermal expansion/contraction of the distinct materials making the HCTs.

To study the effect of temperature on readings, different HCTs were placed inside a beaker with deaired deionised water that was, in turn, submerged in a temperature regulated bath. During this test, the temperature in the water bath was cycled as follows 35ºC →30ºC →25ºC →20ºC →27.5ºC →35ºC. At each temperature stage, the temperature in the water bath was kept constant for 24hrs. The effect of temperature was evaluated for HCT designs with large size reservoirs (1.5-430-2(AL)-SS and 1.5-430-2(AL)-AL), small size reservoirs (1.5-40-2(AL)-SS and 1.5-40-2(AL)-AL) and small size reservoirs and temperature compensated pressure transducer (1.5-50-2(SS)-SS).

The overall results are shown in Fig. 5 and Fig.6 where it can be observed that the adopted combination of materials can have a significant impact on the HCT performance. The design most affected by temperature changes was that incorporating an alumina pressure transducer and large reservoir size inside a stainless steel sheath (1.5-430-2(AL)-SS), for which a calibration drift of 10kPa/ºC was observed. This was in stark contrast with the behaviour of 1.5-430-2(AL)-AL, differing only in the sheath material (in this case alumina), for which a calibration drift of 0.25 kPa/ºC was observed. For HCT designs with a small size reservoir, the influence of temperature on calibration was also found to be dependent on the chosen materials, i.e. 0.65 kPa/ºC for 1.5-40-2(AL)-SS and 0.29 kPa/ºC for the 1.5-40-2(AL)-AL. Finally, for the design 1.5-50-2(SS)-SS incorporating a temperature compensated pressure transducer, the effect of temperature on calibration was the smallest and equal to 0.15 kPa/ºC.

Therefore, when designing HCTs for field applications, it is recommended to use similar materials for the different HCT components and, if possible, a temperature compensated pressure transducer. In addition, HCTs should still be calibrated for temperature effects after assembly.

6 Conclusions

This paper compared the performance of distinct HCT designs with different ceramic AEVs, reservoir sizes, pressure transducers and sheath materials. The impact that each design component may have on the measuring range of HCTs, especially in field applications, was assessed. Results show that the measuring range is affected only by the AEV of the ceramic filter. The AEV is inversely related to the largest pore size within the ceramic filter, where smaller pore sizes generate higher AEVs and, therefore, larger measuring ranges. The water reservoir, pressure transducer and sheath do not directly affect the measuring range of HCTs. However, when used in environments with variable temperatures, such as during field applications, the choice of materials will influence the calibration owing to thermal expansion. The use of distinct materials (with distinct thermal expansion/contraction coefficients) for different design components will introduce a thermal drift of the sensor calibration. Thus, it is recommended to perform a temperature calibration of each individual HCT, even if the pressure transducer is thermally compensated.

Moreover, the application of a 1hr high vacuum pre-stage followed by overnight water pressurisation above the AEV of the ceramic filter was found to be the quickest process to fully saturate an HCT for the first time. Resaturation time can instead be as little as a few minutes if the HCT is pressurised above the AEV immediately after cavitation.

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