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Preparation of high capacity tensiometers for field application

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ABSTRACT: Monitoring suction variations within the construction materials of geotechnical infrastructure can provide essential information required to apply unsaturated soil mechanics to geotechnical problems related to climate risks. Such information can be useful in developing a strategy to mitigate climate risks at the design stage. Besides laboratory measurements, high capacity tensiometers can also be used for field measurements of suction. However, saturation, calibration, installation and long-term performance of these tensiometers need further consideration to ensure data accuracy. In this study, the response of tensiometers to pressurisation and cavitation cycles was investigated and the effect of the saturation time on the accuracy of the calibration was discussed. It was also found that temperature changes affect the tensiometer readings implying that temperature correction needs to be applied when tensiometers are installed in the field. A system was developed for field installation of tensiometers and measurement of suction in road subgrades. The installation system ensures occasional retrieving of the tensiometers when resaturation is required. The laboratory and field performances of the developed system showed that the accurate measurement of suction can be achieved.

RÉSUMÉ: La surveillance des variations d'aspiration dans les matériaux de construction des infrastructure géotechniques peut fournir les informations essentielles requises pour appliquer la mécanique des sols non saturés à des problèmes géotechniques liés aux risques climatiques. Ces informations peuvent être utiles pour élaborer une stratégie d'atténuation des risques climatiques au stade de la conception. Outre les mesures en laboratoire, des tensiomètres à haute capacité peuvent également être utilisés pour les mesures d'aspiration sur le terrain. Toutefois, la saturation, l’étalonnage, l’installation et les performances à long terme de ces tensiomètres doivent faire l’objet d’un examen approfondi pour assurer la précision des données. Dans cette étude, la réponse des tensiomètres aux cycles de pressurisation et de cavitation a été étudiée et l’effet du temps de saturation sur la précision de l’étalonnage a été discuté. Il a également été constaté que les variations de température affectaient les lectures du tensiomètre, ce qui impliquait que la correction de température devait être appliquée lorsque des tensiomètres étaient installés sur le terrain. Un système a été mis au point pour l’installation sur le terrain de tensiomètres et la mesure de l’aspiration dans les sous-sols routiers. Le système d'installation assure la récupération occasionnelle des tensiomètres lorsqu'une resaturation est requise. Les performances en laboratoire et sur le terrain du système développé ont montré que la mesure précise de l’aspiration peut être réalisée.

Keywords: Suction; tensiometer; field installation; low volume road

1 INTRODUCTION

The resilience and long-term performance of geotechnical infrastructure can be influenced by climate changes as the construction materials can undergo frequent wetting and drying cycles and suction changes due to soil-atmosphere interactions. Field measurements of suction can then be essential to gain the information needed to develop a strategy to mitigate climate-risks at the design stage of infrastructure provision.

Tensiometers are suitable instruments for suction measurements due to their rapid response, high accuracy and direct measurement of negative pore water pressure i.e. soil suction in natural conditions. High Capacity Tensiometers (HCT) are capable of measuring suction much higher than suction measured by commercial tensiometers. Lourenço et al. (2008) measured suction of 2.1 MPa and Tarantino and Mongiovì (2001) recorded suction of 2.5 MPa. A small size allows HCTs to be fitted to any device or to be easily transported. Nevertheless, only a few attempts have been made to use HCTs in the field, mainly due to challenges associated with their installation and long-term performance (Toll et al., 2013).

In this paper, saturation and calibration of high capacity tensiometers are discussed. The system developed for field installation of HCTs is introduced and the results of the laboratory and field performances of the system are presented. All tensiometers were developed at Durham University to be used for field measurements in the "Transport Africa" project which aims at investigating the sustainable use of local materials in road construction and the impacts of climate changes on transportation infrastructure in different African countries.

2 DURHAM TENSIOMETER

HCTs are commonly manufactured based on the design proposed by Ridley and Burland (1993). The tensiometer developed at Durham University is made of a stainless steel body hosting a ceramic porous stone with a thickness of 10 mm and an air entry value of 1.5 MPa. A ceramic transducer having a pressure capacity of 2 MPa is used for the measurement of the water pressure inside a reservoir which has a capacity of about 5 mm^3 (see details in Toll et al., 2011). The serviceability of high capacity tensiometers depends on preventing cavitation to take place either inside the reservoir or in the porous stone. The cavitation limits the maximum suction that can be measured by tensiometers.

2.1 Saturation

Seven HCTs were kept in a saturation vessel and saturated as described in Table 1. Except T05, all tensiometers were subjected to vacuum of -100 kPa for about 20 min, followed by flushing deaired water through the chamber under vacuum for a few seconds. Next, T01 and T02 were pressurised to 1 MPa whereas the other tensiometers were pressurised to 2 MPa in order to study the impact of the pressurisation magnitude on the saturation process. The pressure (P) was periodically decreased to zero and increased again to the initial pressure. T01, T03, T05 and T06 were frequently subjected to the pressurisation cycles (4-5 times every 24h) whereas the pressure applied to T02 and T04 was changed every 48h. T07 was continuously subjected to 2 MPa so no pressurisation cycles were imposed.

Table 1. Saturation stages applied to tensiometers

HCT	Vacuum kPa	P (MPa)	P Cycles
T01	-100	1	frequent
T02	-100	1	every 48
T03	-100	2	frequent
T04	-100	2	every 48
T05	-	2	frequent
T06	-100	2	frequent
T07	-100	2	-

Figure 1 shows the first six days of the saturation stage of T01 and T04. The readings showed a gradual pressure increase following the pressurisation stage. When the imposed pressure was reduced to zero, a residual pressure was maintained due to the capillary force in the porous stone. The residual pressure dissipated with time due to progressive saturation (Tarantino et al. 2016). It can be observed that the residual pressure of T04 dissipated faster than T01 which means that the saturation process of T04 was shorter.

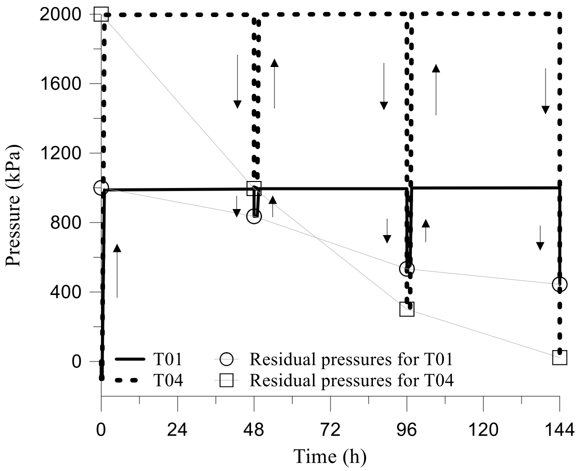


Figure 1. The saturation process of T01 and T04

Figure 2(a) shows the dissipation of the residual pressures with time. The dissipation and saturation took place faster when the higher pressure (2 MPa) was applied. The frequent pressurisation cycles had no significant effect on the saturation time of tensiometers subjected to 2 MPa but slightly accelerate the saturation when T01 and T02 were pressurised to 1MPa. The delayed saturation of T05, as compared to T03, T04 and T06, suggests that applying vacuum before pressurisation may influence the saturation and speed up the process.

When the residual pressure dissipated completely, the cavitation limit was then measured by exposing the tensiometers to the environment air and monitoring suction until cavitation takes place (Figure 2(b)). Tensiometers were pressurised immediately after cavitation and left to be resaturated at least for 48h. The cavitation limit was improved with cavitation cycles, even after the residual pressure was completely dissipated, except for T07. The maximum suction was also measured after fewer cycles when tensiometers were pressurised to 2 MPa.

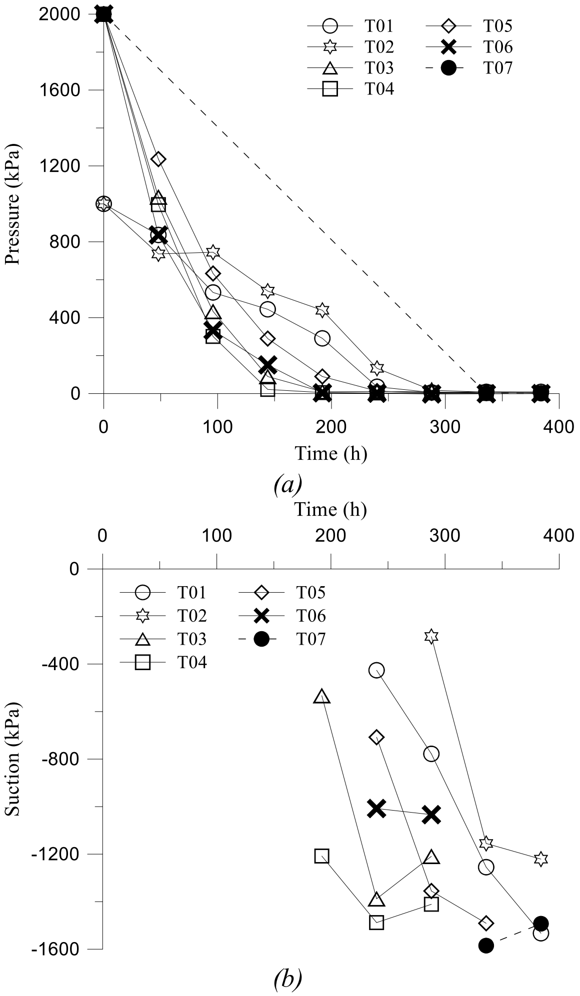


Figure 2. (a) Dissipation of the residual pressurse (b) changes in cavition limits with time

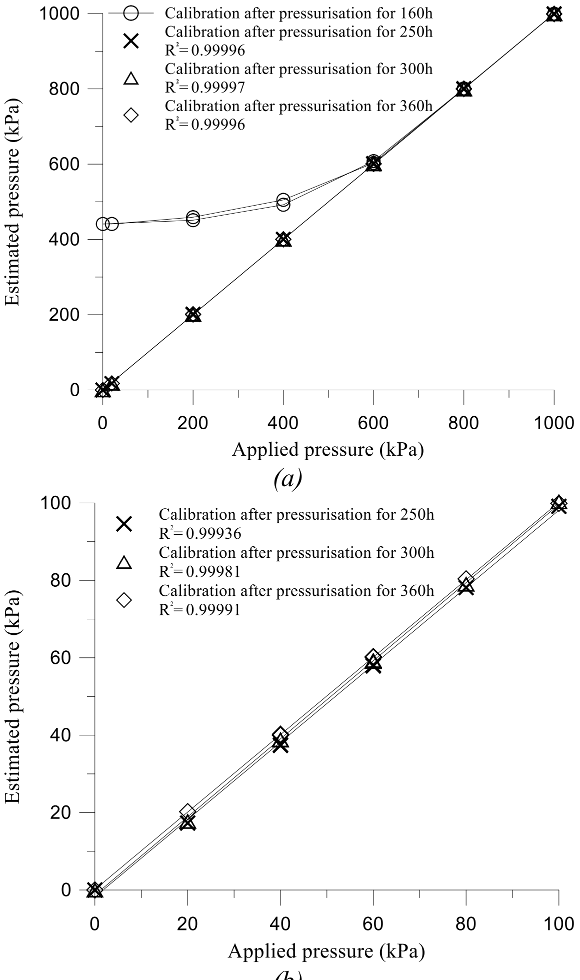
The results showed that the application of positive pressures even lower than the air entry value of the porous stone was sufficient to saturate the tensiometers but applying a higher pressure (2 MPa) reduced the saturation time substantially. Nonetheless, the pressure magnitude may not influence the measured suction range. Indeed, a direct relationship linking pressurisation magnitude to the cavitation limit is unlikely to be achieved since both saturation and cavitation are influenced by other factors than the magnitude of pressurisation.

2.2 Calibration

HCTs are generally calibrated by applying positive pressure steps while a linear extrapolation of the calibration equation is assumed to apply to the negative range. This procedure was reported to be sufficiently accurate (Lourenço et al, 2008). The tensiometers were calibrated periodically during the saturation process and the linear relationship between the output voltage and the applied pressure was detected using a least-squares regression technique. Figure 3(a) shows the relationship between the applied pressures (P_a) and the pressures obtained from the calibration equations of T01. The curves were found to diverge from the straight line in the first calibration attempts at low-pressure ranges due to the residual pressure, but approach a straight line with time and increasing the saturation degree. Tensiometers are generally assumed to be saturated when a linear regression fitted the pressure values well, approved by a high R-squared value. $R^2 = 0.99996$ was found for T01 when the residual pressure was completely dissipated after 240h.

The regression line was also used to fit low pressures (0-100 kPa) as shown in Figure 3(b). The results show that the R-squared value in this range can slightly increase even when there is no change in the residual pressures or the regression line fitted the whole applied pressures well. This was observed for T01 and T05 accompanied with an evident improvement of their cavitation limits. This may suggest that further saturation degree might be achieved even after dissipation of the residual pressure.

T07 was pressurised to 2 MPa for two weeks without any pressurisation and cavitation cycles. The R-squared value of 0.99999 was obtained for both regression lines fitted to the low and the whole pressure range. The first cavitation occurred at -1.41 MPa and the second cavitation took place at -1.37 MPa indicating that the maximum measured suction was achieved.



(a)

(b)

Figure 3. (a) Caliration over the whole pressure range (b) caliration between 0 and 100 kPa

It was found that the dissipation of the residual pressure or the well-fitted linear regression line over the whole pressure range can not assure achieving the maximum cavitation limit. The high accuracy of the regression line fitted to low-pressure ranges may help to assess the saturation levels further. Once full saturation is achieved, the maximum suction that can be measured by the tensiometers is expected without any pressurisation or cavitation cycles. Tarantino et al. (2016) and Mendes et al. (2018) applied pressures two times higher than the air entry value of the porous stone and achieved the maximum measured suction in the first cavitation test.

2.3 Temperature sensitivity

Tensiometers are temperature sensitive and this may lead to significant errors in suction measurements in the field with temperatures substantially higher than the temperature in the laboratory where the tensiometers are calibrated.

The effect of temperature (T) on two tensiometers was studied while they were kept in the saturation vessel and submerged in a temperature-controlled water bath (Figure 4). The temperature was changed between 17°C and 40°C while tensiometers were subjected to 300 kPa, 500 kPa or 800 kPa. The tensiometers were calibrated after each heating-cooling cycle to detect any impact on the calibration equation.

Figure 4. Tensiometers submerged in the temperature-controlled water bath

Figure 5(a) shows the apparent tensiometer reading based on the calibration at 20 °C while a constant pressure of 300 kPa was imposed. The reading increased with temperature and decreased when cooling, with no significant hysteresis effect. Figure 5(b) shows that the difference between the tensiometer readings and the applied pressure (P_r-P_a) varies with the difference between T and the reference temperature T_R = 20 °C at the average rate of about 1.2 kPa/°C for T02 and 1.6 kPa/°C for T04.

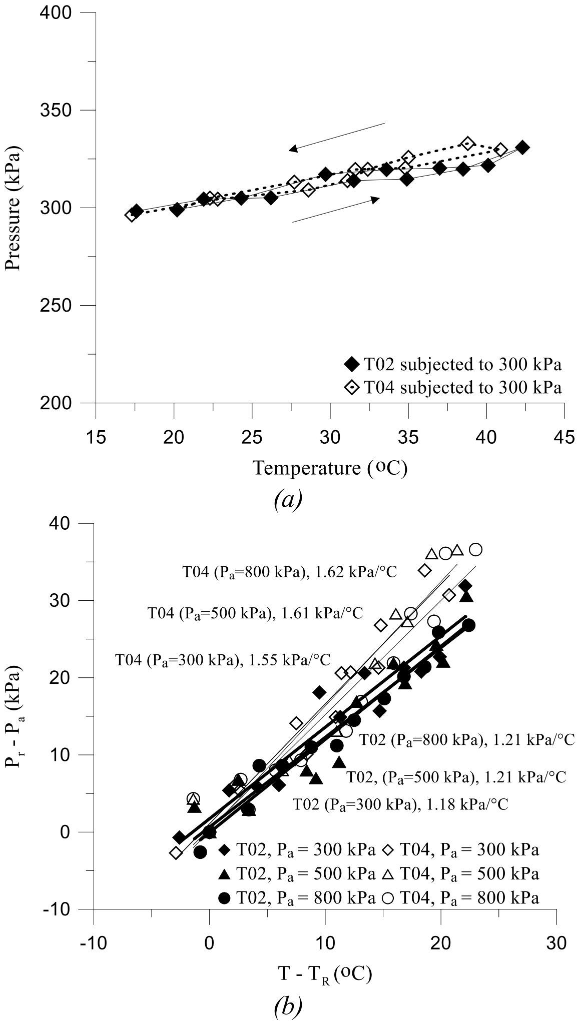


Figure 5. The effect of temperature changes at (a) the pressure of 300 kPa (b) different pressures 300kPa, 500kPa and 800kPa

This observation implies that the suction measured in the field needs to be corrected based on the temperature measured by using other sensors installed in the ground. Changes in suction with temperature can be obtained from the output voltage (V):

$$s = a_T.V + b_T \quad (1)$$

As stated by Hoffman et al. (2008) and Lourenço et al. (2011), changes in the slope (a_T) of the calibration line might be negligible but the intercept (b_T) seemed to change notably with temperature. Assuming a_T is equal to the slope of the calibration line at the reference temperature a_R,

$$s = a_R.V + b_R - \beta(T - T_R) \quad (2)$$

where b_R is the intercept of the calibration line at the reference temperature and β is the rate of pressure changes with temperature (kPa/°C).

In order to assess the impact of temperature on the tensiometer readings in the negative pressure range, a vacuum of -100 kPa was applied to T02 and T04 and the temperature was changed as shown in Figure 6. The equation (2) was used, assuming β is 1.2 for T02 and 1.6 for T04, to predict the suction changes with temperature. The results showed a good prediction of suction can be obtained using the temperature effects measured in the positive pressure range.

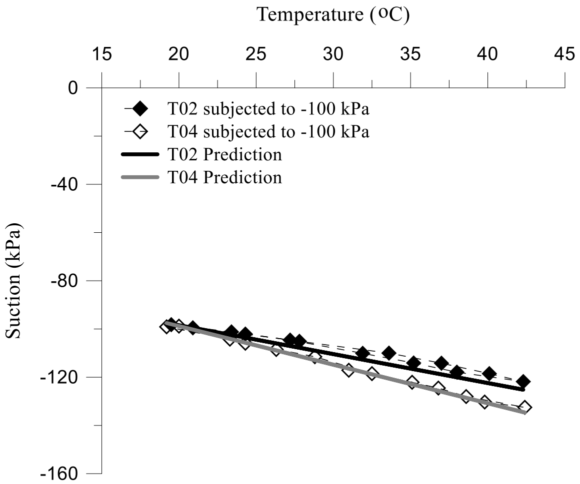


Figure 6. The effect of temperature at suction of -100 kPa

The calibration carried out at the end of each cycle confirmed that there was no significant effect on the slope of the calibration equation implying that the temperature impact was reversible. The slope remained 0.0666 for T03 and 0.0635 for T04. The intercept was found to increase from 8.2 to 11.1 for T02 and from 27.8 to 31.1 for T04 after the first cycle while remained constant for the following cycles. This may only cause less than 4 kPa errors in suction readings.

3 INSTALLATION TOOL

There are two challenges that make field installation of HCTs difficult. First, making a good contact between the tensiometer and soil in deep holes is imperative to get genuine readings but is not easy to implement. Second, HCTs can cavitate if subjected to high suctions so any installation technique should allow HCTs to be removed from the ground when resaturation is needed. Only a few attempts have been made to install tensiometers in the field for long-term measurements (Cui et al., 2008; Mendes et al., 2008).

In the “Transport Africa” project, the tensiometers are needed to be installed within subgrades of low volume roads. Any installation device present on the road surface may obstruct the free passage of traffic. Accordingly, it was decided to access the subgrade under the pavement through inclined boreholes drilled from the road shoulders. As shown in Figure 7, an installation device was developed in order to insert HCTs in the inclined boreholes. It consists of a PVC tube having an external diameter (40 mm) slightly smaller than the borehole and an internal diameter (15 mm) slightly larger than the tensiometer. Each tube was made with a length of 50 cm. The tubes can then be screwed together to supply the required length. For some tubes, a rotary rubber seal was fitted at the lower end to support the HCT. The tubes with the rubber seals are to be placed at the bottom of the boreholes where a contact between the tensiometer and the soil is made. A nylon tube attached to the tensiometer supports the cable and allows pushing the tensiometer inside the PVC tubes during installation or pulling out during removal. A support was designed to be placed on the ground to prevent any displacement of the PVC tubes. A top cap was also installed at the top end of the tube to hold the nylon tube and to prevent any water infiltration during rainfalls. The designed system ensures periodical retrieving of the tensiometer without disturbing the surrounding soil.

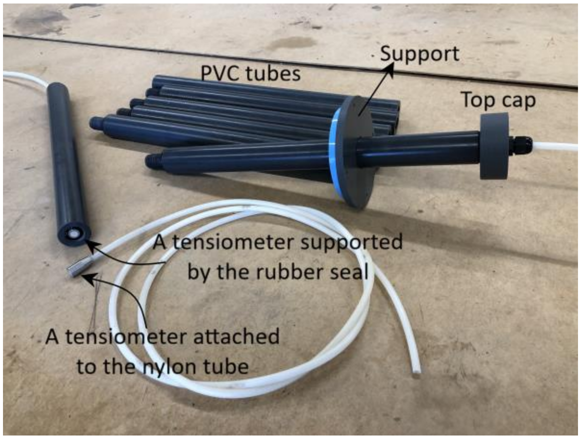
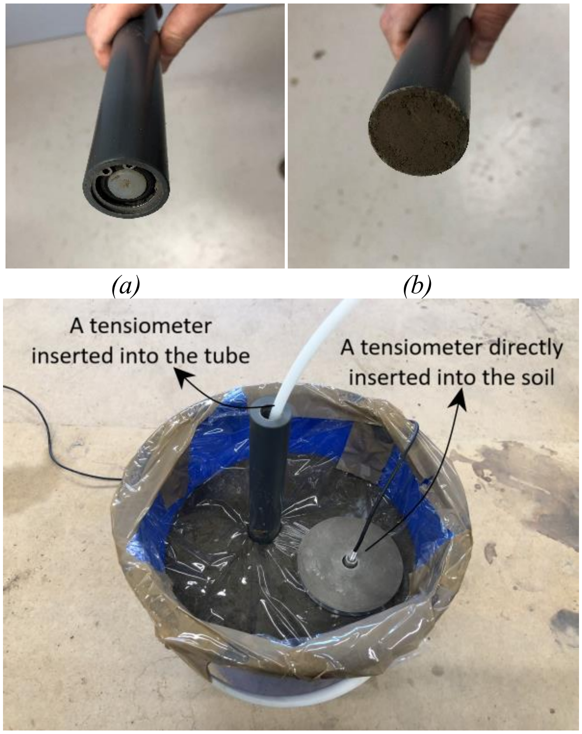


Figure 7. The tensiometer and installation system

4 LABORATORY PERFORMANCE

A smaller tube (with an external diameter of 20 mm and a height of 20 cm) was also built to assess the efficiency of the system in the laboratory before attempting installation in the field. A clayey soil was compacted inside a container at 20% of water content. The sample was held in a relative humidity/temperature-controlled room for seven days to ensure water content equilibration. A small hole was drilled to a depth of 100 mm. Before placing the tube in the hole, a plug was held inside the rotary rubber seal (Figure 8(a)) and a soil paste was packed in front of the plug (Figure 8(b)). After lowering the tube in the hole, the plug was replaced by a tensiometer. Another tensiometer was also inserted directly to the depth of 20 mm while supported by a disk on the surface as shown in Figure 8(c). The sample surface was sealed by a plastic cover to reduce the evaporation rate.



(a) *(b)*

(c)

Figure 8. (a) The plug supported by the seal (b) coating soil paste (c) two tensiometers installed

Figure 9 shows the suction measurement of these two tensiometers (T05 inserted into the tube and T07 inserted directly into the soil). T05 measured a positive pressure initially due to the force applied during installation. Both tensiometers showed reductions in suction although it was quicker in T07. The suction readings in T07 were delayed only due to the low permeability of the porous stone whereas the soil paste used at the bottom of the tube also delayed the suction equilibrium in T05. However, both tensiometers measured almost the same suction of about -100 kPa after 35h. The results indicate a consistency between the readings of the two tensiometers and therefore assure achieving accurate results if the developed system is properly installed in the field.

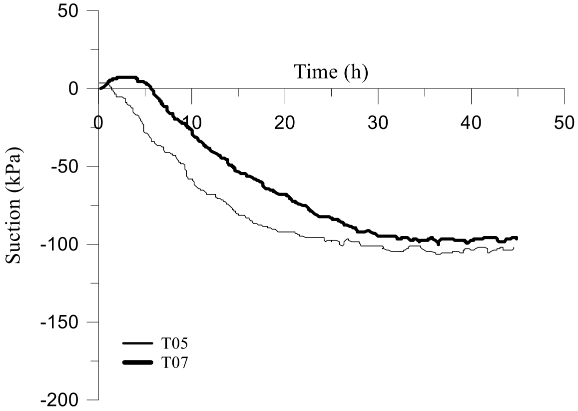


Figure 9. Suction measurments in the laboratory

5 FIELD PERFORMANCE

Different low volume roads located in Ghana and Tanzania have been selected for instrumentation in the “Transport Africa” project. A road section from the Bago-Talawanda road in Tanzania was selected to evaluate the efficiency of the developed system. Two boreholes were drilled in the shoulder to access the subgrade layer of the road and the developed systems were installed (Figure 10). Another borehole was drilled and used to install a potentiometer (known as MPS6). This sensor provides an indirect measurement of suction and temperature. A soil taken from the site was mixed with water, packed around the potentiometer to form a soil ball and then inserted in the borehole. The borehole was then backfilled by compacting the removed soil.

Figure 11 shows the suction measurements obtained by the instruments installed after temperature corrections. The tensiometer no. 1 measured an increase in suction until it reached about -120 kPa after a few weeks whereas the other tensiometer measured very high suction values from the beginning. The readings of the tensiometer no. 2 seem incorrect likely due to poor saturation of this tensiometer so it was removed and transported to the laboratory for resaturation. The potentiometer initially measured a very high suction due to the suction in the soil packed around the sensor. The suction measured by the potentiometer decreased approaching the same suction that the tensiometer no. 1 measured. The result showed that one of the two tensiometers was successfully installed and performed well.

Figure 10. The study road in Tanzania and the installation devices

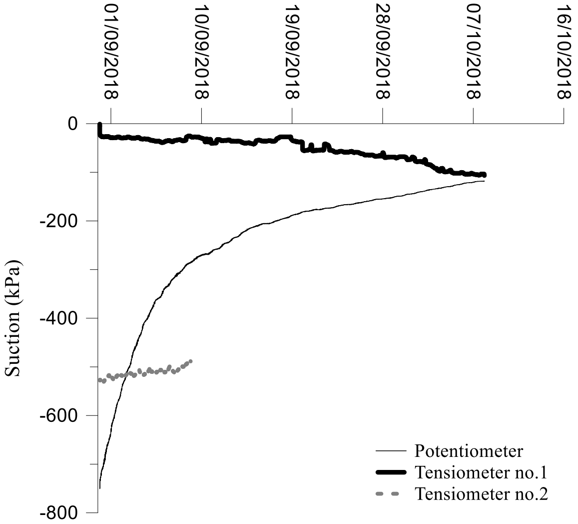


Figure 11. Suction measurements in the field

6 CONCLUSIONS

High capacity tensiometers are the most suitable instrument for suction measurements due to the direct measurement of negative pore water pressures. However, the performance and reliability of these tensiometers critically depend on sufficient saturation and accurate calibration.

Different saturation processes were applied to the tensiometers developed at Durham University. It was found that applying pressures higher than the air entry value of the porous stone can substantially accelerate the saturation process although no significant changes took place in the maximum measured suction. Once full saturation is obtained, the maximum suction that can be measured by the tensiometers is expected even without any pressurisation or cavitation cycles. The temperature changes were also observed to influence the tensiometer readings implying that temperature correction needs to be applied when tensiometers are installed in the field.

An installation system was developed which allows using the tensiometers for suction measurements in road subgrades. The system allows periodical retrieving of tensiometers when resaturation is required. The efficiency of the system was assessed in the laboratory and in the field and assured achieving reliable data if properly installed.

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