Evaluation of suction-water content calibrations of filter paper

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ABSTRACT
The filter paper method (FPM) is probably the simplest of the methods available for estimating the capillary pressure (also known as soil matric suction, the reference being the atmospheric pressure) of an unsaturated soil. The FPM calculates soil suction indirectly by measuring the gravimetric water content of the filter paper at equilibrium that is related to soil suction through a predetermined calibration curve. A number of calibration functions for ash-less filter paper have been published in the literature. Significant discrepancy exists among the calibrations that are commonly used for estimating suction using the gravimetric water content of the filter paper data. This paper presents graphical and statistical comparisons of several calibration curves proposed at the literature for the Whatman 42 filter paper. A theoretical distribution (or model) to fit the data is proposed. Experimental errors induced by using a calibration curve that differ from those frequently used in the scientific community are presented and discussed. The simplicity and low cost of the FPM recommends it for preliminary studies of soil suctions in the unsaturated zone, but particular attention is required in the selection of suction-water content calibration for the estimation of soil suction using the method.

RÉSUMÉ
La succion du sol est une variable importante dans l'analyse du comportement hydromécanique des sols non saturés. La méthode du papier filtre (FPM) permet d'évaluer la succion du sol indirectement en mesurant la teneur en eau massique du papier filtre à l'équilibre, qui est liée à la succion de sol par une courbe d'étalonnage prédéterminée entre la teneur en eau du papier filtre et la succion. Cet article évalue l'utilisation de six fonctions de calibrage pour le papier filtre Whatman 42 pour la détermination indirecte de la succion d'un sable silteux compacté non saturé. L'évaluation de l'étalonnage du papier filtre a été effectuée en utilisant les résultats expérimentaux donnés par Fleureau et al. (2002), obtenus avec d'autres techniques employées pour mesurer ou contrôler la succion du sable vaseux compact. Les résultats prouvent que les succions déduites de la FPM dépendent de la fonction de calibrage utilisée. Une fonction de calibrage modifiée est proposée, qui donne une meilleure évaluation de la courbe de succion de sol. La FPM est une technique simple prometteuse pour la détermination de la succion du sol, à condition que d'utiliser une fonction d'étalonnage adaptée à la gamme de saturation du sol étudiée

1 INTRODUCTION

Knowledge of soil suction is essential to predicting and verifying the behavior of unsaturated soils in practical applications, including clay liners in waste containment and compacted clay cores in earth dams. The experimental techniques commonly used for measuring or controlling soil suctions vary widely in terms of cost, complexity, and measurement range. The soil suctions can be determined from previous calibration or can be measured directly. In comparison with direct measurements of soil suctions, the indirect methods of estimating soil suctions are attractive for their fast and simple use and low cost. These are the main reasons for their increasing use, mainly in spatial variability studies. On the other hand, it is known that their applicability is limited.

The filter paper method is probably the simplest of the methods available for estimating the suctions of an unsaturated soil. The method calculates soil suction indirectly by measuring the gravimetric water content of the filter paper at equilibrium that is related to soil suction through a predetermined calibration curve. A number of calibration functions for ash-less filter paper have been published in the literature. Significant discrepancy exists among the calibrations that are commonly used for estimating suction using the gravimetric water content of the filter paper data. This paper presents graphical and statistical comparisons of several calibration curves proposed at the literature for the Whatman No. 42 filter paper. A theoretical distribution (or model) to fit the data is proposed. Experimental errors induced by using a calibration curve that differ from those frequently used in the scientific community are presented and discussed.

2 FILTER PAPER TECHNIQUE

Filter paper technique was established for measuring soil suction by soil scientists and agronomists (e.g., Gardner 1937; Fawcett & Collis-George 1967; Al-Khafaf & Hanks 1974; and Hamblin 1981). In geotechnical engineering fields, many researchers have also used the technique as a routine method for suction measurement (e.g., McKeen 1980; Chandler & Gutierez 1986; Greacen et al. 1989; Chandler et al. 1992; Ridley 1993; Marinho 1994; Houston et al. 1994; and Marinho & Oliveira 2006).

The filter paper method (FPM) calculates the soil suction indirectly from previous calibration. Basically, the filter paper comes to equilibrium with the soil either through vapour (total suction measurement) or liquid (matric suction measurement) flow. At equilibrium, the filter paper and the soil will have the same suction value. After equilibrium is established between the filter paper and the soil, the gravimetric water content of the filter paper disc is measured. The gravimetric water content of filter paper is converted to suction using a calibration curve for the type of paper used. This is the basic approach suggested by the American Society for Testing and Materials (ASTM) standard D5298 for the measurement of either matric suction using the contact filter paper technique or total suction using the non-contact filter paper technique. The ASTM D 5298 employs a single calibration curve that has been used to infer both total and matric suction measurements and recommends the filter papers to be initially oven-dried (16 h or overnight) and then allowed to cool to room temperature in a desiccator. The ASTM D 5298 calibration curve is a combination of both wetting and drying curves. However, because of the marked hysteresis on wetting and drying of the filter paper, the calibration curve for initially dry filter paper is different from that of the initially wet filter paper. Muñoz-Castelblanco et al. (2010) show that the gap between the drying and wetting filter paper calibration is more remarkable at higher levels of suction (> 100 kPa). Some publications presents calibration for the wetting path, with the paper initially air dry (Chandler & Gutierez 1986; Chandler et al. 1992; Ridley 1993; and Marinho 1994). Marinho & Oliveira (2006) show that the calibration for the particular type of paper is unique in relation to the type of suction (i.e., total or matric).

The contact filter paper technique is used for measuring matric suction of soils. In the contact filter paper technique, water content of an initially dry filter paper increases due to a flow of water in liquid form from the soil to the filter paper until both come into equilibrium. Therefore, a good contact between the filter paper and the soil has to be established. The contact filter paper method becomes inaccurate in high matric suction range since water transport is dominated by vapour transport (Fredlund et al., 1995).

2.1 FPM calibration curves

The calibration curve for the filter paper matric suction measurement is commonly established using a pressure plate apparatus (e.g., Al-Khafaf and Hanks 1974; Hamblin 1981; Greacen et al. 1989). It is important to note that only ash-less filter papers should be used in the filter paper technique. Although there are several ash-less filter papers available, only Whatman 42 and Sleicher and Schuell 59 (or SS 59) are commonly used.

A number of calibration functions for Whatman No. 42 filter papers have been published in the literature. The functions share a number of similarities, allowing them to be written in a general form as (Bicalho et al. 2009):

$$\text{Log}_{10}(\text{suction})\ (\text{kPa}) = A - B\, w\ (\%) \qquad [1]$$

where w is the gravimetric water content of the filter paper at equilibrium. Chandler and Gutierrez (1986) presented a calibration curve for Whatman No. 42 filter paper for suctions in the range of 80 kPa to 6000 kPa that included their own results and also those from Fawcett and Collis-George (1967) (i.e., A= 5.777 and B = 0.06) and Hamblin (1981) (i.e., A= 6.281 and B = 0.0822), therefore, the obtained calibration curves are similar with obtained A= 5.85 and B= 0.0622.

Figure 1 shows some calibrations (wetting paths) presented in the literature for the filter paper Whatman. 42 with an inflection point occurring at a filter paper gravimetric water content value somewhere between 33 and 47% (corresponding 115 kPa > suction > 60 kPa). The calibration curves proposed by Chandler et al. (1992), ASTM Standard D 5298 and Leong et al. (2002)-Matric suctions are similar with A in Eq. (1) ranging from 4.842 (Chandler et al 2002) to 5.327 (ASTM D5298) and B ranging from 0.0622 (Chandler et al. 1992) to 0.0779 (ASTM D5298). A similar agreement can be seen in the suctions derived using the curves proposed by Chandler et al. (1992), ASTM D 5298 and Leong et al. (2002)-Matric suctions. Considerable variability is observed between their results and those of Fawcett and Collis-George (1967), Hamblin (1981) and Chandler and Gutierrez (1986) (which seem to overestimate the values of suction). Although Leong et al. (2002) suggested the use of different calibration curves for matric and total suction, caution is recommended when using published total suction calibration curves since such curves are expected to be valid only for the equalization time used during the corresponding calibration. If the equilibrium between the filter paper and the soil has not yet been achieved, the total suction calibration curve might give total suction estimations smaller than corresponding matric suction estimations, yielding an unrealistic negative value of osmotic suctions. Marinho & Oliveira (2006) show that the filter paper calibration is unique in relation to the type of suction (i.e., total or matric).

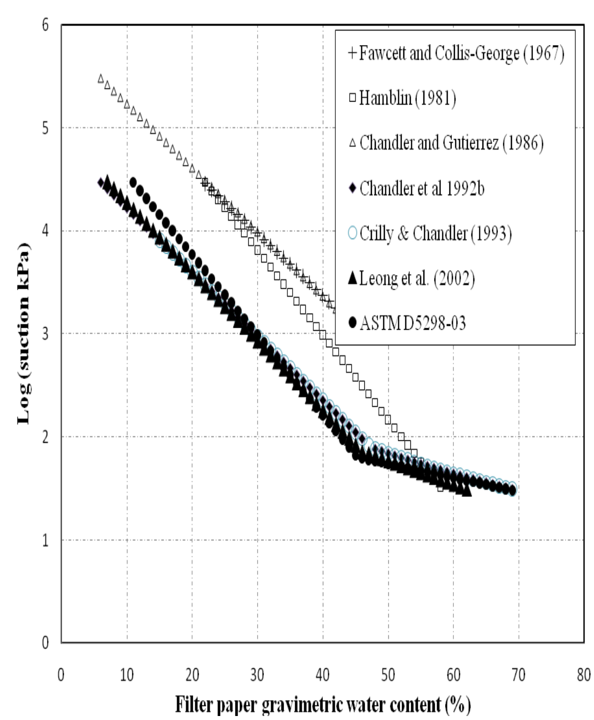

Figure 1. Evaluated calibration curves for Whatman 42 filter paper

Even though, Hamblin (1981) did not observed significant difference between batches of filter paper produced at different times, Likos & Lu (2002) and Marinho & Oliveira (2006) have shown that the filter paper calibration curves can significantly vary among the same type of filter paper from one “batch” or “lot” to another. They recommend batch-specific calibrations.

The non-contact filter paper technique for estimating total suctions must be performed with extra cares to avoid suction errors induced by temperature gradient, relative humidity error, and equilibrium time. It is recommended to allow the filter papers to equilibrate for a sufficient time period. Liquid phase equilibration is fairly rapid in the wet range (high potential) and generally requires only a few days. In contrast, vapour equilibration is slow in the wet range because a large amount of water needs to be transferred. Thermal equilibration is also important. Temperature gradients in the sample can result in liquid flow. In addition, temperature gradients can result in large errors when vapour exchange is used for equilibration.

3 EXPERIMENTAL RESULTS

Tests were performed on a residual silty sand, hereafter called Perafita sand, resulting from weathered granite, which has been used as a building material for a road in the north of Portugal. It contains about 20% of grains smaller than 80 μm, with a layered structure similar to that of clay particles. The liquid limit of the Perafita sand is 32.6 %, the plastic limit is 25 %, clay fraction is 2.5%, specific gravity is 2.66, standard Proctor optimum water content is 17.6% and the corresponding dry density is 16.8 kN/m^3, modified Proctor optimum water content is 13.2% and the corresponding dry density is 18.6 kN/m^3. The preparation procedure of samples is the same for all the tests: the soil is sieved to avoid the presence of coarse grains (maximum size 4.75 mm), then it is mixed up with the right quantity of water; after that, it is placed in a sealed plastic bag for 24 hours to allow the hydric equilibrium to establish. The contact filter paper tests were carried out on soil specimens compacted to the Modified Proctor Optimum water content (13.2%) and nearly maximum density (18.6 kN/m^3). The compacted soil specimen sizes were 102 mm in diameter and 23.35 mm high.

The test procedure involves placing a piece of initially air dry filter paper against the compacted soil specimen whose matric suction is required and sealing the whole to prevent evaporation. The filter paper then wets up to a water content in equilibrium with the magnitude of the soil matric suction, and careful measurement of the water content of the filter-paper enables the soil matric suction to be obtained from a previously established correlation. This provides a measure of the matric suction, which is assumed to be the same numerically as the capillary pressure (the reference being the atmospheric pressure).The Whatman 42 filter paper was used in all tests.

The other techniques (i.e., tensiometers, and the osmotic technique) used to measure or control the negative pore water pressure in the compacted soil specimens are not discussed in this paper since the purpose herein is to discuss the filter paper technique only. Details of the experimental techniques are given in Fleureau et al. (2002).

4 STATISTICAL ANALYSIS

The suctions inferred from filter paper measurements depend on the used calibration function, and there is a variability and uncertainty associated with the used calibration. In practice, an engineer is unlikely to evaluate the several calibrations functions proposed in the literature. Therefore, it may be conveninent to know what error can be expected from chosing one of the many proposed calibration functions for Whatman No. 42 filter paper.

In this paper, a regression line (known as the *least squares line*) is used to examine the linear k-Log_{10} (suction) relationship (Eq. 1) and to quantify the variability around the best estimate calibration function. Initially, two best fitted calibration functions that "minimizes the squared residuals" is defined for all data points obtained from the evaluated seven calibration functions. It is assumed an inflection point occurring at a filter paper gravimetric water content value of 47% (see Figure 2). Since the regression model is usually not a perfect predictor, there is also an error term in the Eq. (1). The coefficient of determination (r-squared, R^2) is the square of the correlation coefficient. Its value may vary from zero to one. The resulted functions based on the correlation coefficient criterion are:

for $w \leq 47\%$

$$Log_{10}\,(\text{suction})\ (\text{kPa}) = 5{,}201 - 0.062\,w \qquad [2a]$$

for $w > 47\%$

$$Log_{10}\,(\text{suction})\ (\text{kPa}) = 2{,}909 - 0{,}021\,w \qquad [2b]$$

Figure 2 shows a large discontinued data in the ordinates (y) represented by suction values in logarithmic scale such as: if the filter paper gravimetric water content (w) is near 47%, the corresponding suction lies between 84kPa (Eq. 2b) and 194 kPa (Eq. 2a). Therefore, only one best fitted calibration function that "minimizes the squared residuals" is defined for all data points (i.e., suction values between 30 e 30000 kPa) obtained from the seven calibration functions previouly discussed and presented in Figure 1. The resulted function based on the correlation coefficient criterion (R^2 = 0.837) is given by (see Figure 3):

$$Log_{10}\,(\text{suction})\ (\text{kPa}) = 5{,}1078 - 0.0594\,w \qquad [3]$$

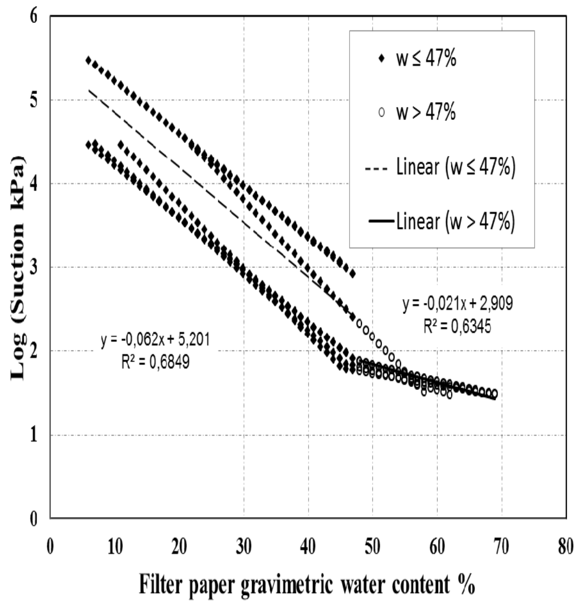

Figure 2. Two linear calibration functions resulted from the seven evaluated calibration curves for Whatman 42 filter paper

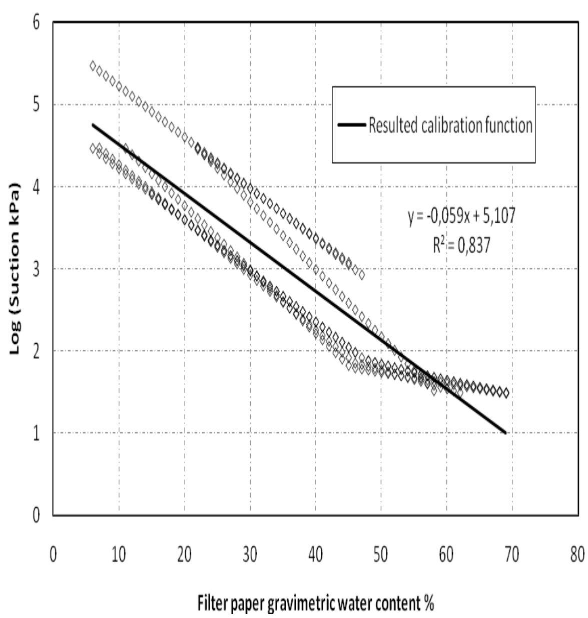

Figure 3. Resulted calibration function from the seven evaluated calibration curves for Whatman 42 filter paper

To quantify the variability around the best estimate calibration function defined by Eq. (3), the predicted suctions obtained by each evaluated calibration function were compared with the suction values from the best fitted defined by Eq. (3) for each level of w. The variability is evaluated by using the mean error (ME) and the root mean squared error (RMSE) defined by:

$$ME = \frac{1}{N}\sum_{i=1}^{N}(\hat{Y} - Y_M)$$

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(\hat{Y} - Y_M)^2}$$

where $\hat{Y}$ is the Log (suction) obtained by Eq. (3) and Y_M is the Log (suction) of each evaluated calibration function for the corresponding w, and N is the number of data points. The results are presented in Table 1.

When comparing regression models that use the same dependent variable and the same estimation period, the RMSE goes down as adjusted R^2 goes up. Hence, the calibration function proposed by Chandler et al. (1992) has the lowest RMSE, and, therefore it is the one that best adjust the resulted calibration function defined by Eq. (3) (see Table 1). The results of ME indicated that the ASTM is the best adjusted calibration function. Considerable variability is observed between the best fitted calibration function´s results and those of Fawcett and Collis-George (1967) and Chandler and Gutierrez (1986) that present the highest RMSE and ME values.

Therefore, it is also determined a best fitted calibration function that "minimizes the squared residuals" defined for all data points (i.e., suction values between 30 e 30000 kPa) obtained from the calibration functions proposed by Chandler et al. (1992), ASTM Standard D 5298 and Leong et al. (2002) called here local calibration function. The local calibration function based on the correlation coefficient criterion (R^2 = 0.9523) is given by (see Figure 4):

$$\text{Log}_{10}\,(\text{suction})\ (\text{kPa}) = 4{,}6412 - 0.0534\ w \qquad [4]$$

Table 2 presents the obtained RMSE and ME values for the three evaluated calibration functions compared to Eq. (4). The RMSE and ME values goes down indicating small variability among the calibration functions proposed by Chandler et al. (1992), ASTM Standard D 5298 and Leong et al. (2002) and Eq. (4). In Figure 4, the solid line represents the predicted equation 4 corresponding to the best adjusted function to the three evaluated calibration functions for Whatman 42 filter paper.

A confidence interval gives an estimated range of values which is likely to include an unknown population parameter, the estimated range being calculated from a given set of sample data. The level C of a confidence interval gives the probability that the interval produced by the method employed includes the true value of the parameter.

Figure 5 shows a pair of 80% confidence intervals (upper and lower limits) calculated from each calibration line, but varies from calibration line to calibration line, although obtained under the same experimental conditions. The results presented in Figure 5 are the estimated suctions determined by the contact filter paper tests using the calibration functions proposed by Equation 4 and ASTM D5298 and the measured suctions of compacted Perafita sand specimens resulting from several methods used by Fleureau et al. (2002). Although it was observed a general agreement between the FPM test results using the calibration curves ASTM D 5298 and proposed by this paper (Eq. 4) and other techniques used to measure or control suctions in the compacted soil specimens for 100 kPa < suction < 300 KPa, the calibration curves overestimated the suctions for suction > 300 kPa (Figure 5). Similar results are observed in Figure 6 that show a pair of 80% confidence intervals (upper and lower limits) calculated from the calibration functions proposed by Chandler et al. (1992) and ASTM D 5298. The calibration functions proposed by Fawcett and Collis-George (1967), Hamblin (1981) and Chandler & Gutierrez (1986) overestimated the known suctions, therefore they are not included in Figures 5 and 6.

Table 1. Values of RMSE and ME for the evaluated calibration functions compared to Eq. (3).

References	RMSE	ME
Fawcett and Collis-George (1967)	0,649	-0,649
Hamblin (1981)	0,357	-0,261
Chandler and Gutierrez (1986)	0,669	-0,668
Chandler et al (1992b)	0,315	0,206
Crilly and Chandler (1993)	0,322	0,196
Leong et al. (2002)	0,354	0,326
ASTM D5298-03	0,341	0,200

Table 2. Values of RMSE and ME for the evaluated calibration functions compared to Eq. (4).

References	RMSE	ME
Chandler et al. (1992b)	0,182	-0,036
Leong et al. (2002)	0,169	0,066
ASTM D5298-03	0,263	-0,026

It can be observed from Figure 5 that at higher suctions (suctions > 1000 kPa) the best fit line (Eq. 4) gives over-estimated suction values, therefore more data should be collected before anything very definite can be said about the calibration function defined by Eq. (4) and the linear considered calibration form expressed by Eq. (1). A non linear calibration function should be investigated showing that the suction may increase less rapidly with decreasing filter paper gravimetric water content.

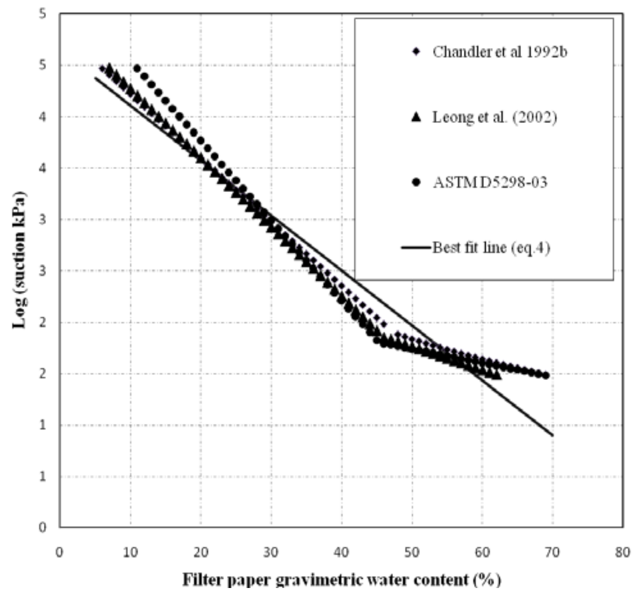

Figure 4. Best fit line resulted from the three evaluated calibration curves for Whatman 42 filter paper

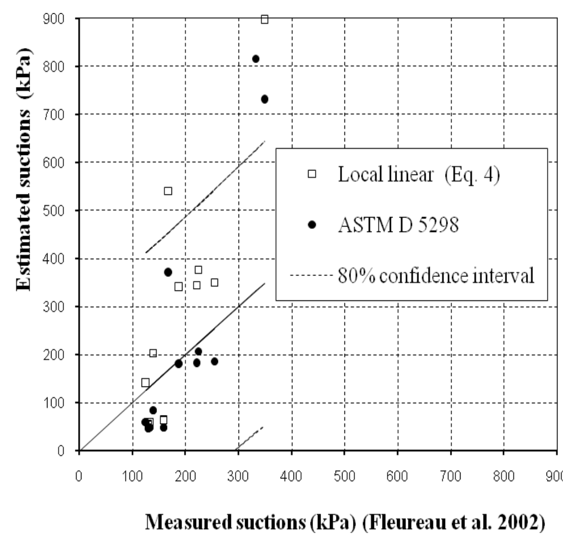

Figure 5. A pair of 80% confidence intervals (upper and lower limits) calculated from Eq (4) and ASTM calibration function

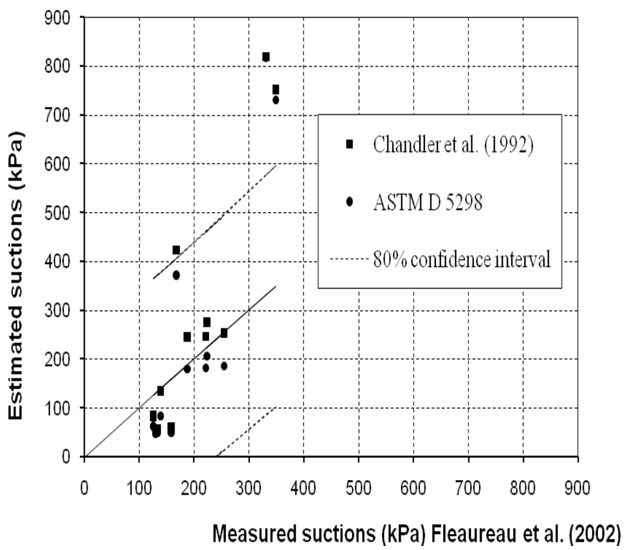

Figure 6. A pair of 80% confidence intervals (upper and lower limits) calculated from two calibration functions

5 CONCLUSIONS

An evaluation of using different filter paper calibrations in the contact filter paper test for measurement of soil suction was conducted in this paper. The method offers a simple technique for the determination of soil suction, provided that an adequate calibration curve is used. It is always recommended to verify if the calibration can be used without causing significant errors in the suction values to be determined. A similar agreement can be seen in the suctions derived using the calibration functions for Whatman No. 42 filter papers (wetting path) proposed by Chandler et al. (1992), ASTM D 5298 and Leong et al. (2002)-Matric suctions. Although it was observed a general agreement between the FPM test results using these calibration curves and other techniques used to measure or control suctions in the compacted soil specimens for 100 kPa < suction < 300 kPa, the calibration curves overestimated the suctions for suction > 300 kPa. Considerable variability is observed between their results (Chandler et al. (1992), ASTM D 5298 and Leong et al. (2002)-Matric suctions) and those of Fawcett and Collis-George (1967), Hamblin (1981) and Chandler and Gutierrez (1986) which seem to overestimate the values of suction.

A non linear calibration curve for Whatman No. 42 filter paper should be investigated showing that the suction may increase less rapidly with decreasing filter paper gravimetric water content.

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