

NOTE / NOTE

Measurements of suction versus water content for bentonite–sand mixtures

Setianto Samingan Agus, Tom Schanz, and Delwyn G. Fredlund

Abstract: Compacted soils have been widely used as landfill barriers because of favorable characteristics such as low coefficient of permeability and high swelling. Compacted bentonite–sand mixtures are normally unsaturated and therefore suction can be used as a behavioral indicator in addition to generally used factors such as water content and dry density (or void ratio). This study focused on investigating suction characteristics of bentonite–sand mixtures. Suction was measured using various techniques for compacted bentonite–sand mixtures. The laboratory results were analyzed to provide an understanding of the suction concept in expansive soils. It was found that suction depends primarily on the water content and the bentonite content of the mixture, and suction in expansive soils changes with the time of hydration.

Key words: suction, suction components, suction measurements, bentonite–sand mixture, compaction, bentonite water content.

Résumé : Les sols compactés sont utilisés fréquemment comme barrière pour des dépotoirs en raison de leurs caractéristiques favorables, comme leur faible coefficient de perméabilité et de leur capacité de gonflement élevé. Les mélanges bentonite–sable sont normalement non saturés, et ainsi la succion peut servir d'indicateur du comportement, en plus des facteurs usuels comme la teneur en eau et la densité sèche (ou indice des vides). Cette étude vise à investiguer les caractéristiques de succion des mélanges bentonite–sable, à partir de mesures de succion faites avec différentes techniques. Les résultats de laboratoire ont été analysés dans le but de fournir une meilleure compréhension du concept de succion dans les sols expansifs. Il a été déterminé que la succion dépend principalement de la teneur en eau et du contenu en bentonite du mélange. L'étude a aussi permis de déterminer que la succion dans les sols expansifs varie selon le temps d'hydratation.

Mots-clés : succion, composantes de la succion, mesures de succion, mélange bentonite–sable, compaction, teneur en eau de la bentonite.

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Introduction

In landfill applications of compacted clay, one of the criteria commonly used for the performance of a landfill liner is the coefficient of permeability of the liner. The presence of clay material is therefore important. The addition of bentonite to granular material can change the performance of a highly permeable material and transform it to a material suitable for use as an engineered barrier for landfills. This type of mixture is often referred to as a bentonite-enhanced sand mixture with a low percentage of bentonite. Stewart et

al. (1999) indicated that an addition of 10% sodium-type bentonite (dry mass basis) is sufficient to reduce the coefficient of permeability of sand up to several of magnitudes. A further increase in the percentage of bentonite may not lead to a decrease in the coefficient of permeability of the mixture (Studds et al. 1998). For a less active bentonite such as a calcium-type bentonite, a higher percentage of bentonite, possibly with higher field compaction density, is required to achieve the same performance as a sodium-type bentonite – sand compacted mixtures.

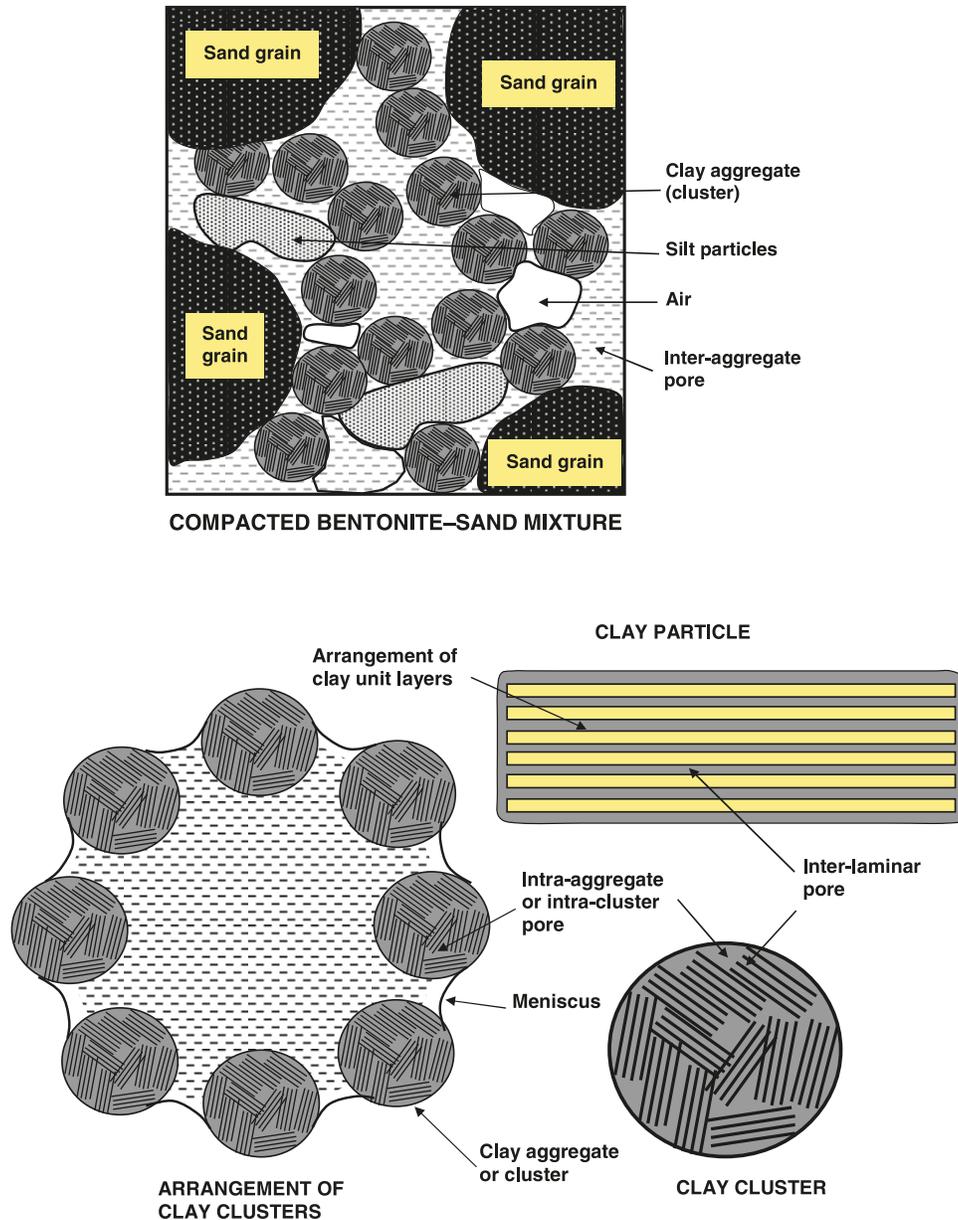
Compacted bentonite–sand mixtures are normally unsaturated (Fig. 1) and therefore suction can be used as a behavioral indicator in addition to generally used factors such as water content and dry density (or void ratio). The presence of suction in compacted bentonite–sand mixtures is often associated with the collapse behavior of compacted mixtures. However, there are also correlations between suction, collapse behavior, and the coefficient of permeability of the mixtures. A mixture that is compacted dry of optimum to an intermediate dry density has a relatively “low” degree of saturation and a high suction and tends to exhibit collapse under specific overburden pressures because of its meta-

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Fig. 1. Schematic representation of unsaturated bentonite–sand mixture (modified from Nagaraj and Srinivasa Murthy 1985).



stable flocculated structure. Therefore, the mixture can have a relatively “high” coefficient of permeability. On the contrary, the same mixture compacted close to its optimum water content and maximum dry density with the same compaction energy has a higher degree of saturation and lower suction. The mixture undergoes swelling when wetted at the same load and has a “lower” coefficient of permeability. The influence of suction on strength and stiffness of compacted sand–bentonite has been studied by Blatz et al. (2002). Strength and stiffness of a compacted bentonite–sand mixture generally increase with an increase in suction.

The objective of this study was to investigate the suction characteristics of bentonite–sand mixtures containing different proportions of bentonite. The scope of this study also included assessment of several available methods for measuring suction. Assessment of optimum bentonite content in the bentonite–sand mixtures in relation to the application in

landfills, however, is not within the scope of this paper. Although compacted mixtures may undergo changes in suction in the field due to environmentally induced wetting and drying cycles, the initial suction (or the as-compacted suction) plays an important role in the behavior of the compacted mixtures (Fredlund 1979; McKeen 1981, 1992; Dineen et al. 1999; Likos and Lu 2003). Several available methods for measuring suction were assessed, and errors encountered were analyzed and addressed accordingly.

Theoretical background of suction in expansive soils

The concept of suction was initially developed by soil physicists in the early 1900s (Fredlund and Rahardjo 1993). Generally, suction (or total suction, s_t) is considered to consist of two primary components, namely a matric component

(s_m) and an osmotic component (π). The matric suction component is associated with the air–water interface (or surface tension), thus giving rise to the capillary phenomenon. Matric suction is defined as the difference between the pore-air pressure (u_a) and the pore-water pressure (u_w) in the soil.

For nonexpansive soils (e.g., sands), osmotic suction can be generated by saturating the soil with a salt solution. By increasing u_a and maintaining u_w at a certain value, matric suction is applied and is associated with the difference between u_a and u_w (or $u_a - u_w$), provided there is no change in the soil-water composition.

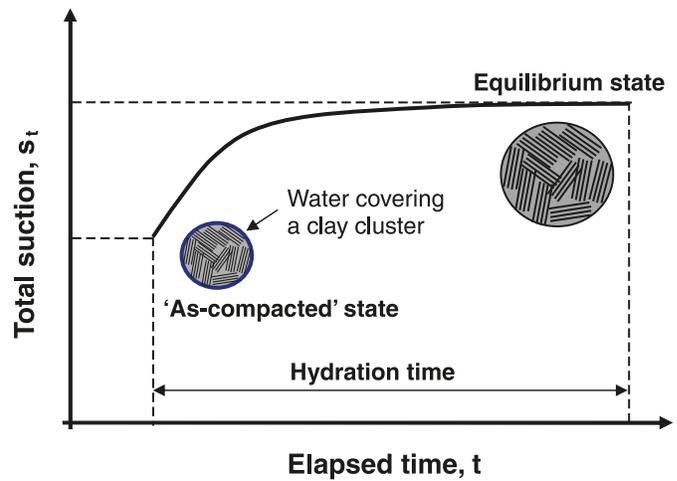
Hydration forces play an important role in controlling the suction characteristics of expansive soils, especially the matric component. When an expansive soil is relatively dry, hydration forces dominate because of unhydrated exchangeable cations near the clay surface. An increase in water content satisfies these forces and increases the interlayer separation distance to about three monolayers of water molecules or about 10 Å (1.0 nm); as a result, crystalline swelling occurs (Yong 1999). The hydration forces provide an additional driving force for water in a similar manner to capillary forces and osmotic suction. Besides the hydration forces, other contributing forces arise from van der Waals force fields. Both the hydration and the van der Waals forces are operative at a short range from clay particles and are called sorptive forces. Since sorptive forces dominate the matric component of suction, the presence of water menisci or capillary action is not necessary for soil to have matric potential or matric suction (Yong 1999).

In the “as-compacted” state, bentonite–sand mixtures may exhibit a nonuniform distribution of water potential or total suction due to incomplete hydration. At this state, the inter-aggregate pore water in the clay clusters appears to be held by capillary menisci. The potential in the intra-aggregate (or intra-cluster) pore water is different from that in the inter-laminar pore water. The total suction measured under this condition corresponds to the status of pore water under transient conditions and most likely represents the potential of pore water in the inter-aggregate pores. As time elapses, there is a redistribution of pore water where flow occurs under a potential gradient. Eventually, an internal equilibrium condition is achieved. Figure 2 shows the possible total-suction evolution associated with the internal redistribution of water in the pores. At this state, the total suction represents an equilibrium condition and is higher than that at the initial as-compacted state. The time to reach the equilibrium state depends on the size of the pores (or the coefficient of permeability) and the degree of interaction between the pore water and the clay unit layers (i.e., the chemistry of the pore fluid and the type of clay).

Materials and methods

Materials used in the investigation were mixtures of a calcium-type bentonite, named Calcigel and mined from southern Germany, and quartz sand. The bentonite used contained 60%–70% montmorillonite, about 8% quartz, and other materials such as feldspar, kaolinite, and mica. The quartz sand was a uniform sand consisting of about 95% quartz. The properties of the materials used are listed in Table 1, and Table 2 summarizes the chemical compositions

Fig. 2. Total-suction change with time due to pore-water redistribution.



of both materials. The exchangeable cations in the bentonite
Table 1. Basic properties of materials used.

	Bentonite	Sand
Specific gravity	2.65	2.65
Liquid limit (%)	130	na
Plastic limit (%)	33	na
Plasticity index (%)	97	na
Montmorillonite content (%)	65	na
Clay content (%)	83 *	0
Fines content (%)	100 *	0
D_{10} (mm)	—	0.25
D_{30} (mm)	—	0.40
D_{60} (mm)	—	0.70
External specific surface area (m^2/g)	69	0.25
Total specific surface area (m^2/g)*	493	0.25
Cation exchange capacity (mequiv./100 g) [†]	49	na
USCS classification	CH	SP

Note: D_{10} , D_{30} , and D_{60} are the grain sizes at which 10%, 30%, and 60% of the material by weight is finer, respectively; na, not applicable.

*Data from Schmidt et al. (1992).

[†]Data from Herbert and Moog (2002).

Table 2. Chemical compositions (%) of materials used.

	Bentonite	Sand
SiO ₂	53.2	96.7
Al ₂ O ₃	18.4	1.8
Fe ₂ O ₃	5.4	0.1
CaO	3.6	0.0
MgO	3.8	0.0
MnO	0.05	0.0
TiO ₂	0.32	0.02
K ₂ O	1.7	0.87
Na ₂ O	0.74	0.19
SO ₃	0.1	0.0
CO ₂	2.78	0.02
P ₂ O ₅	0.13	0.02
Organics	8.6	0.2

are mainly Ca^{2+} and Mg^{2+} , with a small amount of Na^+ . It was anticipated that the material would exhibit limited swelling under free-swell conditions and limited swelling-pressure development under constrained conditions in distilled water.

Mixture preparation and compaction curves

Pure bentonite and three different mixtures of bentonite and sand were used, namely 30:70, 50:50, and 70:30 bentonite–sand (on a dry mass basis). Quartz sand was sieved through a 2 mm sieve prior to mixing. The two materials were mixed at an initial water content, and an adequate amount of water was subsequently added using a water sprayer to reach the target water content. The composition of bentonite in the mixtures was prepared to obtain different materials with different degrees of plasticity, and in which suction is expected to differ. The mixtures were subsequently cured in a two layered plastic bag for 2 weeks to allow for a homogeneous water-content distribution. Full hydration of the bentonite may not have been reached even at the end of curing.

Two different compaction curves were obtained by dynamically compacting the mixture using the standard and enhanced Proctor methods (compaction energy of 600 and 1000 kN·m/m³, respectively) following the American Society for Testing and Materials test standard D698-91 (ASTM 1997a).

Four different techniques were used to measure suction, namely the filter paper (FP), psychrometer (PSY), dew point sensor (DP), and chilled-mirror hygrometer (CMH) techniques. The first three techniques can possibly be used for field measurement, whereas the last technique is only applicable for laboratory total-suction measurements. The FP technique was used to measure both matric suction and total suction, whereas the three other techniques only measure total suction. The measurement of suction was performed on specimens of differing mixtures along the respective compaction curves. Small, statically compacted specimens were used for the CMH technique, whereas measurements of total suction via the PSY and DP techniques were performed directly on the ASTM standard-sized (i.e., 10.16 cm in diameter and 11.64 cm in height) (ASTM 1997b), dynamically compacted specimens. The total-suction measurement using the FP technique was performed on both the standard-sized, dynamically compacted specimens and the small-sized, statically compacted specimens (i.e., 5 cm in diameter and 2 cm in height). It was anticipated that there might be differences in measurements as a result of different compaction methods. Both compaction methods appear to produce a similar open soil structure for specimens compacted dry of optimum. The dynamic compaction method tends to break down the flocculated fabric. The static compaction method for specimens compacted wet of optimum generally results in a more “dispersed” structure (Mitchell 1993). The methods of suction measurement performed in this study are summarized in Table 3.

Filter paper technique

Measurements were performed using Whatman No. 42 filter paper disks. Although calibration curves for the Whatman filter paper are available in the literature, it is desirable

to have a calibration curve for each study involving different filter paper lots. The calibration curve of the Whatman filter paper was measured using a pressure-plate apparatus for suctions less than 1500 kPa and the vapor-equilibrium technique for suctions greater than 2000 kPa.

The following equations were calculated from a best-fit regression analysis of the calibration data and are of the form proposed for the soil-water characteristic curve (SWCC) for soils by Fredlund and Xing (1994). For total suction

$$[1] \quad s_t = 2223 \left[\exp \left(\frac{235.57}{w_{fp}} \right)^{0.129} - \exp(1) \right]^{3.822}$$

$$r^2 = 0.904$$

and for matric suction

$$[2] \quad s_m = 93.82 \left[\exp \left(\frac{299.93}{w_{fp}} \right)^{0.148} - \exp(1) \right]^{5.235}$$

$$r^2 = 0.99$$

where r^2 is the regression coefficient, s_t and s_m are in kPa, and w_{fp} is the filter paper water content in percent.

The mixtures were statically compacted in two layers in a stainless steel ring with a diameter of 50 mm. The targeted dry densities were based on the compaction curves. After the first layer was compacted, a 25 mm diameter filter paper was sandwiched between two larger diameter filter papers (i.e., 35 mm diameter) for the measurement of matric suction. The second layer was subsequently compacted to produce specimens with a height of 15 mm. For total-suction measurements, a 25 mm diameter filter paper was mounted on a stainless steel wire mesh and placed directly on the upper surface of the specimen. Larger diameter protective filter paper was placed on the measuring filter paper to avoid direct contact between the measuring paper and the container lid. The entire specimen was subsequently placed in a sealed air-tight container that was almost the same size as the soil specimen. The container was immersed in a constant-temperature water bath for 5 weeks, significantly longer than the 2 week minimum equilibration time specified in ASTM standard D5298-94 (ASTM 1997b). At the end of the test, the water content of each specimen was measured, as it might differ from the compaction water content. No significant differences in water content were observed.

Psychrometer technique

Ten thermocouple psychrometers precalibrated using standard salt solutions were used in this study. Two holes were drilled in each dynamically compacted soil specimen to bury two psychrometers. The compacted mixtures and the psychrometers were subsequently wrapped with plastic and aluminum foil to avoid moisture loss. The wrapped compacted sample was placed in a water-tight container, and the container was immersed in the water bath to attain constant temperatures during measurement. An additional temperature sensor was placed over the water surface in the bath to ensure temperature equilibrium between the bath and the soil specimen. An equilibration time of 1 day was used

Table 3. Summary of suction measurement techniques used in the study for the different mixtures and pure bentonite.

Specimen conditions	Matric suction				
	FP	FP	PSY	DP	CMH
Bentonite 30%, sand 70%					
Loose	No	No	No	No	No
Dynamically compacted (standard)	Yes	Yes	Yes	Yes	No
Dynamically compacted (enhanced)	Yes	Yes	Yes	Yes	No
Statically compacted (standard)	Yes	Yes	No	No	Yes
Statically compacted (enhanced)	Yes	Yes	No	No	Yes
Bentonite 50%, sand 50%					
Loose	No	No	No	No	No
Dynamically compacted (standard)	Yes	Yes	Yes	Yes	No
Dynamically compacted (enhanced)	Yes	Yes	Yes	Yes	No
Statically compacted (standard)	Yes	Yes	No	No	Yes
Statically compacted (enhanced)	Yes	Yes	No	No	Yes
Bentonite 70%, sand 30%					
Loose	No	No	No	No	No
Dynamically compacted (standard)	Yes	Yes	Yes	Yes	No
Dynamically compacted (enhanced)	Yes	Yes	Yes	Yes	No
Statically compacted (standard)	Yes	Yes	No	No	Yes
Statically compacted (enhanced)	Yes	Yes	No	No	Yes
Pure bentonite					
Loose	No	No	No	No	No
Dynamically compacted (standard)	Yes	Yes	Yes	Yes	No
Dynamically compacted (enhanced)	Yes	Yes	Yes	Yes	No
Statically compacted (standard)	Yes	Yes	No	No	Yes
Statically compacted (enhanced)	Yes	Yes	No	No	Yes

Note: CMH, chilled-mirror hygrometer; DP, dew point sensor; FP, filter paper; PSY, psychrometer.

throughout the study. Measurements were performed when the temperature of the system was about the same as that of the soil specimen as measured by the psychrometers.

Dew point sensor

The dew point sensor used in this study was a polymer capacitance sensor with a warmed head and is commonly used in meteorological applications. Literature reviews on this technique and its applicability have been provided by Leong et al. (2003) and Agus and Schanz (2003). The warming function keeps the sensor head dry when excessive condensation is detected, thus the sensor can measure low total suctions (or high relative humidities) without condensation problems. The sensor measures the dew point and temperature in the vapor space in and above the soil specimen, and the measured relative humidity (RH) is shown in the digital display. Total suction is computed from the RH value and temperature using Kelvin’s law.

Two 8 cm deep holes, one 2 cm in diameter and one 1 cm in diameter, were drilled in each dynamically compacted specimen. The holes were separated by 4 cm for the insertion of the main RH sensor and the additional temperature sensor. The larger diameter hole was for the RH sensor, and the smaller hole was for embedding the temperature sensor. The clearance between the two sensors must be sufficient to prevent the temperature sensor from being heated by the RH

sensor during measurement. A perforated PVC pipe was inserted into the larger diameter hole to accommodate the RH sensor and to prevent direct contact between the sensor and the compacted mixture. Procedures similar to those used for the psychrometers were adopted to prevent moisture loss and to maintain a constant temperature during measurement. The measurement of RH was carried out immediately after compaction and terminated after stable RH and temperature readings were attained. Typically, 20–30 min was required to measure total suction in the compacted bentonite–sand mixtures.

Chilled-mirror hygrometer technique

The CMH technique was first introduced to measure the RH of food products and pharmaceuticals. Literature reviews on the use of this technique in soil science and geotechnical engineering fields can be found in Gee et al. (1992), Leong et al. (2003), and Schanz et al. (2004).

For loose soil specimens, a special measuring chamber was half filled with the cured mixture. In the case of compacted specimens, small pieces were cut from the statically as-compacted specimen and placed in the sealed chamber (also about half capacity). Extra care was taken when cutting the compacted specimens with a high sand content because the cutting might introduce structural disturbance to the specimens. The measurement of total suction using this

technique was started by placing the chamber with the soil specimen in the CMH device. The soil was allowed to reach isothermal equilibrium, which was defined as the difference between the temperature of the vapor space and that of the specimen. The device displayed the difference in temperature between the space above the soil specimen and the mirror. The mirror temperature should be set slightly higher than that of the vapor space, particularly when measuring high RHs (or low total suctions), as condensation might occur on the mirror. The chamber was subsequently closed and, after reaching thermal equilibrium, the RH and temperature in the vapor space were displayed. An average equilibration time of 3 min was required for the total-suction measurement.

Accuracy of the techniques used

Good contact between the filter paper and the soil specimen is necessary to accurately measure matric suction using the FP technique. Accurate matric suction measurement can be more readily obtained in the low matric suction range. The contact between the filter paper and the specimen diminishes in the higher matric suction range, and hence its accuracy reduces as transfer of water from the soil specimen to the filter paper becomes more difficult (Fredlund et al. 1995).

The accuracy of the techniques used for measuring total suction depends on isothermal equilibrium between the specimen and the vapor space in the closed system. The CMH technique appears to have the best accuracy, since it provides the greatest possibility of maintaining isothermal equilibrium between the specimen and the vapor space. Agus and Schanz (2005) used this technique to estimate the possible thermal gradient that exists in the psychrometer and the dew point total-suction measurements. A statistical analysis of the measured data presented therein indicates that the CMH technique produces the most consistent results among other total-suction measurement methods assessed.

Results and discussion

This section presents a comparison of the suction measurements performed in this study. It is important to note that the suction versus water-content curve cannot be regarded as a true soil-water characteristic curve (SWCC). The presented suction versus water-content information represents the status of pore water at a certain state as a function of water content. In general, the testing procedure for SWCC requires that the soils be saturated prior to the start of the test. The presented results show the relationship between the as-compacted water content and soil suction.

The standard and enhanced compaction curves for the four mixtures are shown in Figs. 3*a–3d*. Data points corresponding to the specimens used for suction measurements are also plotted. The data points used for determination of the compaction curves are similar to those used for the measurement of total suction using a dew point sensor denoted as DP (dynamic) in the figures. The optimum water contents and maximum dry densities for the mixtures are listed in Table 4. The degrees of saturation corresponding to the optimum water content conditions and maximum dry densities are different for the different mixtures. Generally,

the higher the bentonite content, the closer the optimum water content conditions are to the zero air void (ZAV) line.

Comparison of different methods of measuring total suction

Figures 4*a–4d* show a comparison of the four different methods used to measure total suction of the compacted bentonite–sand mixtures. The data obtained for the standard Proctor densities cannot be distinguished from those obtained for the enhanced Proctor compaction. The best-fit curves for the data obtained from the FP and PSY techniques are indicated in each figure as solid and a dashed lines, respectively; and those for the data obtained from the DP and CMH techniques as dash-dot and dotted lines, respectively. The CMH technique appears to be the most accurate of the four methods presented and is thus used as a benchmark for assessing the other three methods.

Data obtained from the PSY method are more scattered. This is most obvious for the case of the compacted 70% bentonite – 30% sand mixture and the compacted pure bentonite at low total-suction measurements (i.e., less than 1000 kPa). Generally, lower total suctions were obtained when using the PSY technique (as compared with the readings obtained using the CMH technique). The difference is attributed to possible condensation of water vapor on the measuring junction of the psychrometer. Although excessive condensation can be dissipated by heating the psychrometer before the measurement, the water evaporated from the junction will most probably condense on the nearest surface (i.e., thermocouple mount or inner wall of the psychrometer cup) instead of being dissipated into the soil specimen. It is felt that the prolonged equilibration period may cause excessive condensation of water vapor on the measuring junction of the psychrometers.

The data obtained from the DP measurements show the least scatter. The plots show that the DP consistently gives higher total-suction values than those measured by the PSY and CMH. The difference in the readings obtained from the dew point sensor is likely attributable to thermal gradients between the vapor space (i.e., the specimen hole) and the overall specimen. There may also be some contribution from heterogeneity in the water-content distribution in the large dynamically compacted specimens. The total suctions measured using the DP show the total suctions at the point of measurement and are not representative of the specimen as a whole due to heterogeneity in the water-content distribution.

Total-suction measurement results obtained using the FP technique and those determined using the CMH technique for the compacted 50% bentonite – 50% sand mixture specimens and the compacted pure bentonite specimens are compared in Figs. 5*a* and 5*b*, respectively. The results obtained using the two methods clearly show a systematic difference, with higher suctions being measured by the FP technique. The small filter paper for total-suction measurement was suspended in a narrow vapor space above a much larger soil specimen, and the fluctuations in temperature were minimized by immersion in the water bath. There should be little difference between the results obtained using the FP technique and those determined via the CMH technique. The effect of extra water-vapor condensation on the FP tech-

Fig. 3. Compaction curves of the four mixtures investigated: (a) 30:70 bentonite–sand mixture; (b) 50:50 bentonite–sand mixture; (c) 70:30 bentonite–sand mixture; and (d) pure bentonite. S_r , degree of saturation.

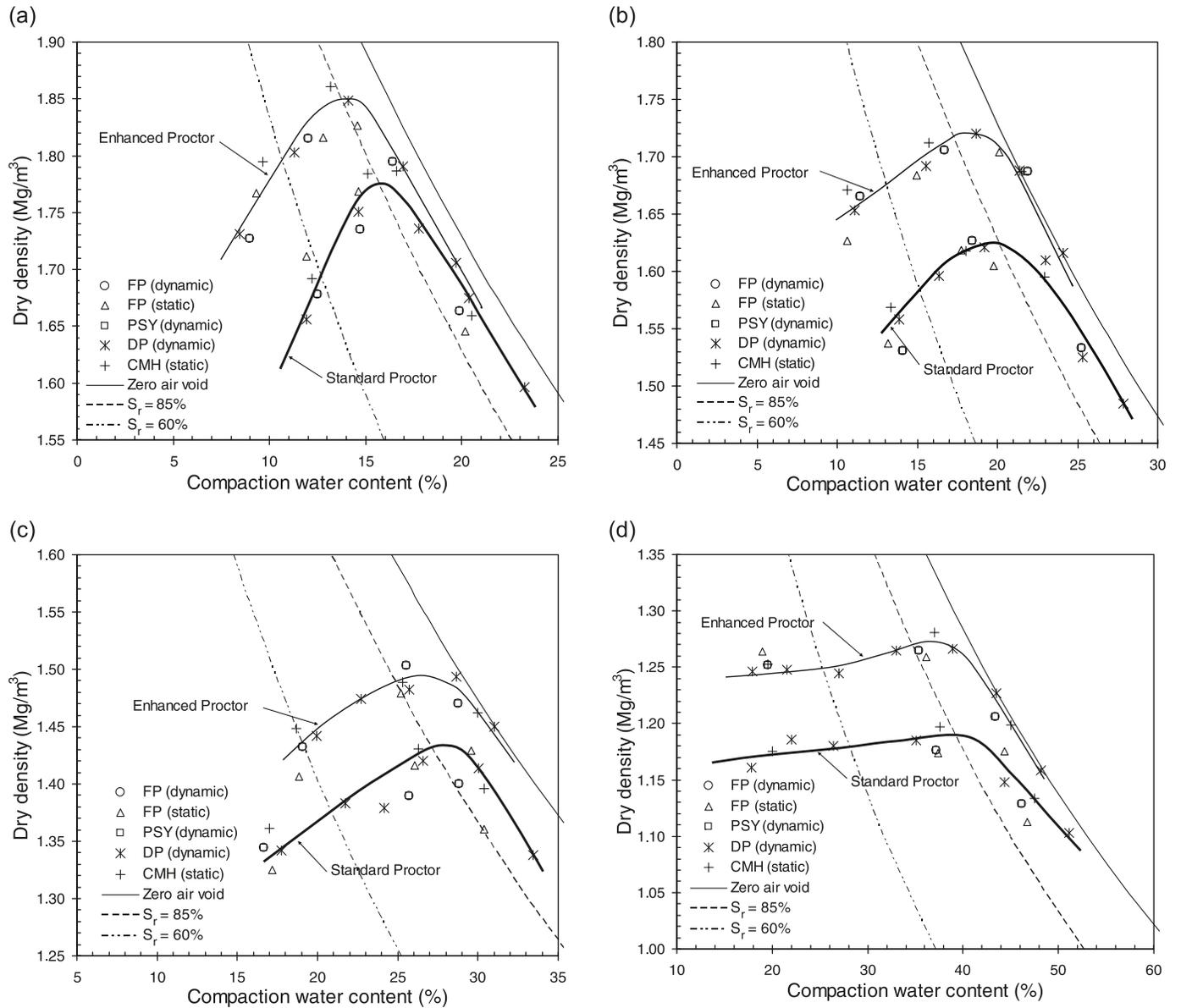


Table 4. Optimum water contents and maximum dry densities of the mixtures.

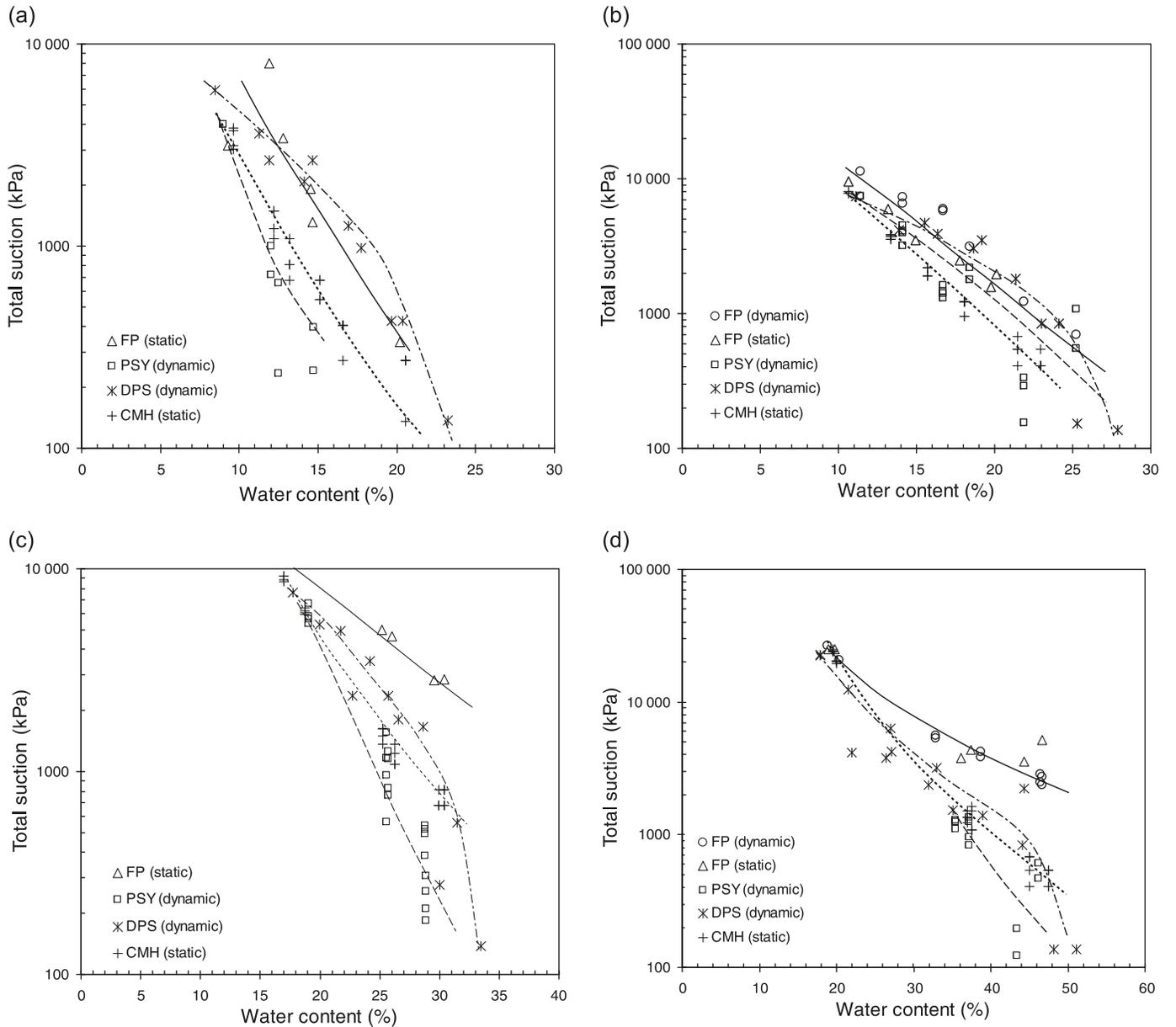
Proctor	Optimum water content, w_{opt} (%)	Maximum dry density, $\rho_{d max}$ (Mg/m ³)
Bentonite 30%, sand 70%		
Standard	16	1.775
Enhanced	14	1.850
Bentonite 50%, sand 50%		
Standard	20	1.625
Enhanced	18.6	1.720
Bentonite 70%, sand 30%		
Standard	28	1.435
Enhanced	26.8	1.495
Pure bentonite		
Standard	40	1.189
Enhanced	37	1.275

nique should not have been significant due to the method of maintaining a constant temperature.

Several additional total-suction measurements were performed using the CMH technique on the compacted specimens of 30% bentonite – 70% sand that had been kept for 5 weeks in air-tight containers in a manner similar to that used in the FP technique. The specimens were subjected to the same conditions as those used in the FP total-suction measurements. Figure 6 shows the results of the additional tests, and it appears that the results from both methods essentially fall along a single curve. This indicates that the difference in the water content versus total-suction curves of the specimens at two different conditions (i.e., the as-compact and aged conditions) as shown in Figs. 5a and 5b was not due to different accuracies associated with the two methods.

The results shown in Figs. 5a, 5b, and 6 suggest that

Fig. 4. Comparison of results from different techniques used for measuring total suction of compacted specimens: (a) 30:70 bentonite–sand mixture; (b) 50:50 bentonite–sand mixture; (c) 70:30 bentonite–sand mixture; and (d) pure bentonite.



5 weeks are required to equilibrate the bentonite–sand mixtures to a quasiequilibrium state where both the CMH and FP techniques should give comparable measurement results. However, it must be noted that the true equilibrium state may not be reached at 5 weeks. The time to reach the true equilibrium depends on the physicochemical characteristics of the bentonite and the permeability of the mixture at the micro and macro levels. The phenomenon of pore-water redistribution as reflected in the magnitude of total suction of a specimen at different ages may be correlated with the effects of aging on the swelling pressure and swelling potential of compacted expansive soils as described, for instance, in Subba Rao and Tripathy (2003). The rearrangement of clay particles during the aging process causes changes in

the swelling pressure and swelling potential of the soil. The rearrangement of clay particles may be the result of the water redistribution process. Further studies are required.

The age of the specimens used for the measurements varied significantly (i.e., 5 weeks for the FP technique and a few minutes for the CMH technique). The difference in time may be due to the redistribution of pore water, as described earlier. The measurement of total suction in the as-compacted specimens provides values corresponding to a transient state. Redistribution of water is believed to occur as time elapses. The moisture redistribution results in a difference in total suction between the inter-aggregate pores and the intra-aggregate and intra-laminar pores. Similar to the results from the other three techniques, the results ob-

Fig. 5. Total suction determined using the FP and CMH techniques on compacted specimens: (a) 50% bentonite – 50% sand mixture; (b) pure bentonite.

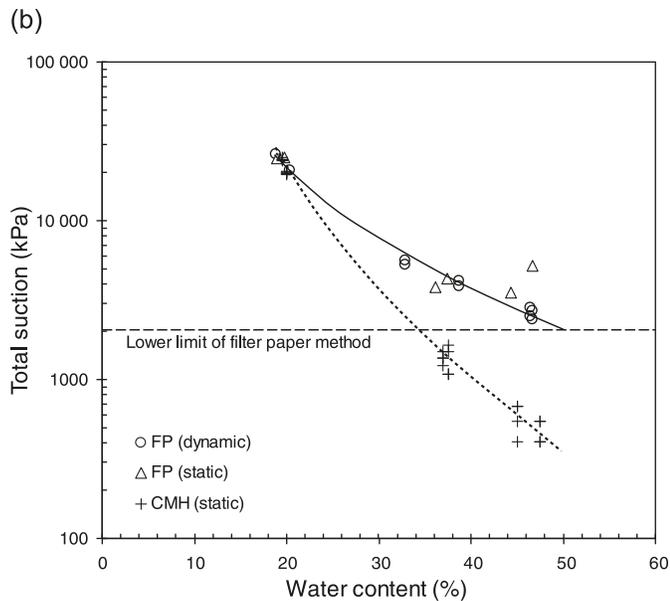
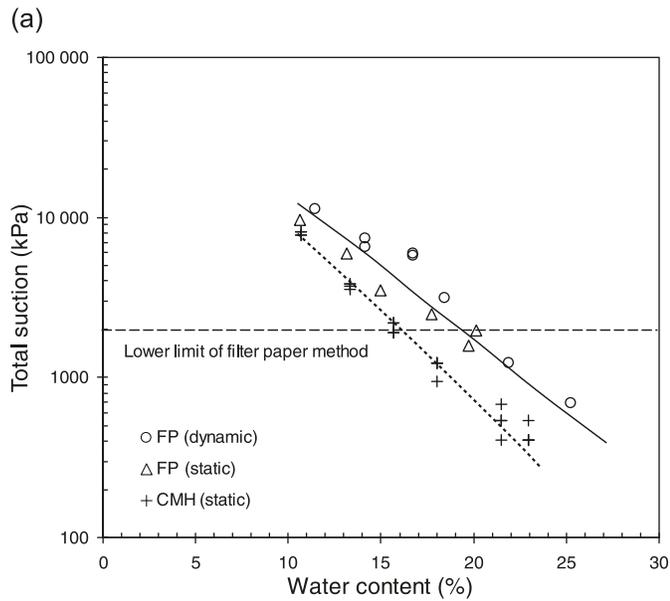


Fig. 6. Comparison of total-suction measurements using the FP and CMH techniques on compacted specimens aged for 5 weeks.

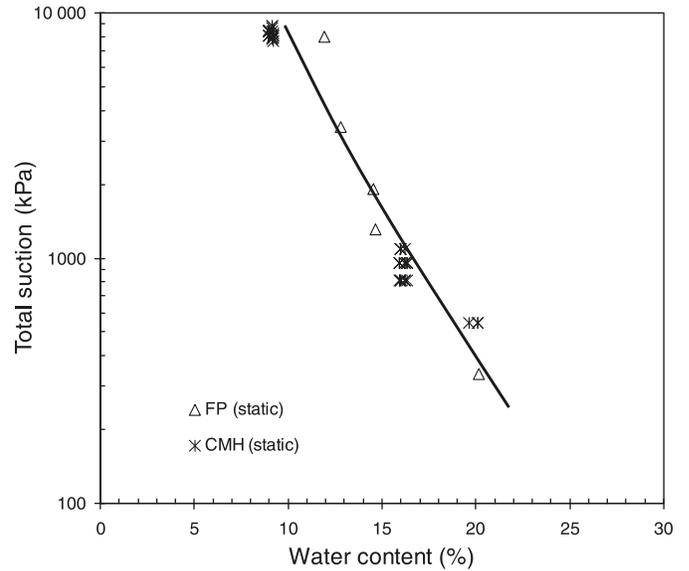
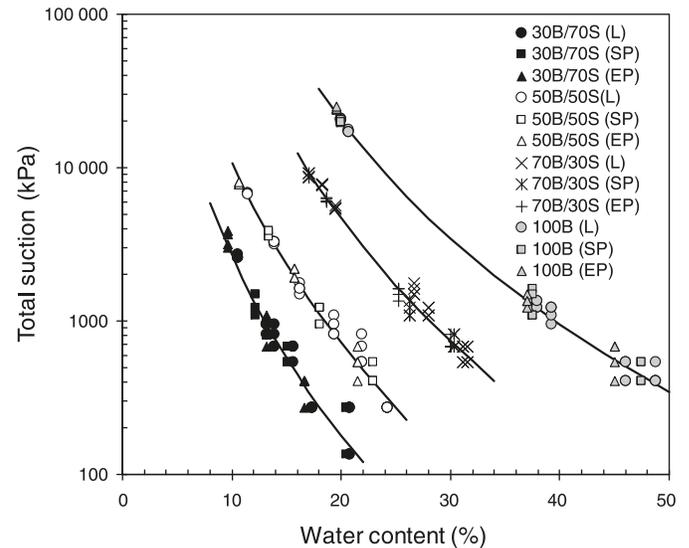


Fig. 7. Total suction versus water content of the four mixtures at different states. The mixtures are given as ratios (e.g., 30B/70S denotes 30% bentonite and 70% sand). L, loose; SP, standard Proctor; EP, enhanced Proctor.



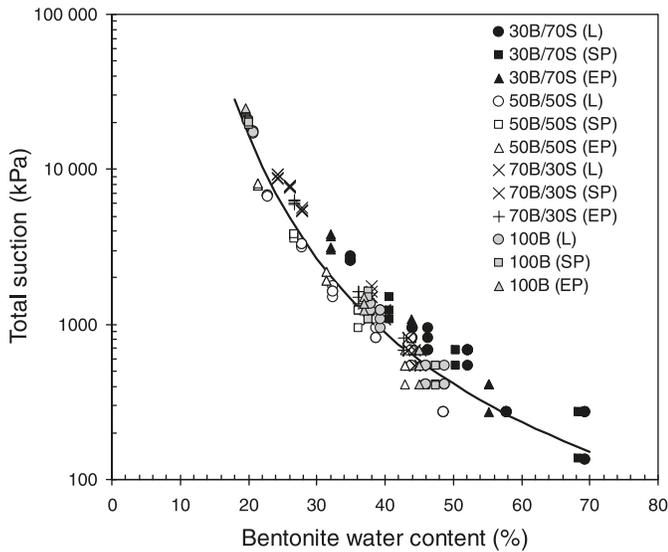
tained from the FP technique show that the compaction technique plays no significant role in the magnitude of total suction for the compacted bentonite–sand mixtures.

Total suction of loose and compacted specimens

Figure 7 shows a comparison between total suctions measured using the CMH technique for the small, statically compacted specimens and those obtained under loose conditions (powder form) for the four bentonite–sand mixtures. Total suctions for both the as-compact specimens and the loose specimens were measured at almost the same time. The results clearly show that compaction had no significant impact on the magnitude of total suction, as indicated by the

results for the three specimen states (i.e., loose, standard Proctor compaction, and enhanced Proctor compaction) falling essentially on a single curve. Total suction is shown to be primarily a function of water content and bentonite content. The higher the percentage of bentonite in the mixture, the higher the total suction for the same water content. The bentonite minerals possess surface electric charges; in addition, at the same water content, a mixture with a higher percentage of bentonite is expected to have greater osmotic and sorptive forces. Consequently, there appears to be a less significant contribution due to capillary phenomena. A higher total suction is expected in the mixture with a higher bentonite content.

Fig. 8. Total suction versus bentonite water content of the four mixtures at different states.



The results also show that, in addition to the percentage of bentonite, the availability of water in the bentonite plays a significant role in controlling the magnitude of total suction. The specific surface area of bentonite is much higher than that of sand, and therefore any addition of water will mostly be absorbed by the clay, even for mixtures with a small percentage of bentonite. It is reasonable to assume that water is only absorbed by the bentonite, and the void ratio of the mixture can be regarded as the bentonite void ratio. Using this as an assumption, the bentonite water content w_b (%) can be computed according to eq. [3] with w_m (%) as the water content of the mixture and β (%) as the bentonite content in the mixture, and the corresponding bentonite density ρ_{db} (Mg/m^3) can be expressed as eq. [4], with ρ_m (Mg/m^3) and G_{ss} as the mixture density and specific gravity of the sand, respectively:

$$[3] \quad w_b = \frac{100 w_m}{\beta}$$

$$[4] \quad \rho_{db} = \frac{(\beta/100)\rho_m G_{ss}}{G_{ss}(1 + w_m/100) - \rho_m(1 - \beta/100)}$$

Figure 8 is a semilogarithmic plot of total suction versus bentonite water content for different mixtures at the three different states (i.e., loose, standard Proctor compaction, and enhanced Proctor compaction). The plot indicates that the suction versus water-content curves for the four different mixtures appear to merge into a single curve. These results support the suggestion that total suction is strongly controlled by water content and bentonite content, or collectively by the bentonite water content. The influence of fabric on the magnitude of total suction (or in the suction characteristic curve) is insignificant, which is different from the results observed for the SWCC. Stoicescu et al. (1998) observed that the SWCC changed from a unimodal to a bimodal curve when bentonite was added to a sandy soil.

The suction concepts and the microstructural view of suction as described in the previous sections help explain how

the presence of bentonite can increase the total suction (or total water potential) of soils. The difference in the total suction for different mixtures (or bentonite contents) at the same mixture water content is believed to be due to the difference in the sum of osmotic suction and sorptive forces, whereas surface tension or capillary action has an insignificant influence. When water is added to a dry bentonite-sand mixture in a loose form, most of the water will be adsorbed on the surfaces of clay clusters, and an insignificant amount will be left to wet the sand grains.

The increase in degree of saturation is caused by a reduction in the amount of air in the inter-aggregate pores due to compaction of the mixtures from the loose state. Compaction reduces the size of the inter-aggregate pores, whereas the cation concentration of water in these pores remains unchanged. The lack of apparent change in total suction due to compaction may indicate an insignificant contribution of the capillary phenomenon. There will be an apparent change in total suction due to a change in osmotic suction only if the specimen is further compressed so that some pore water is squeezed out.

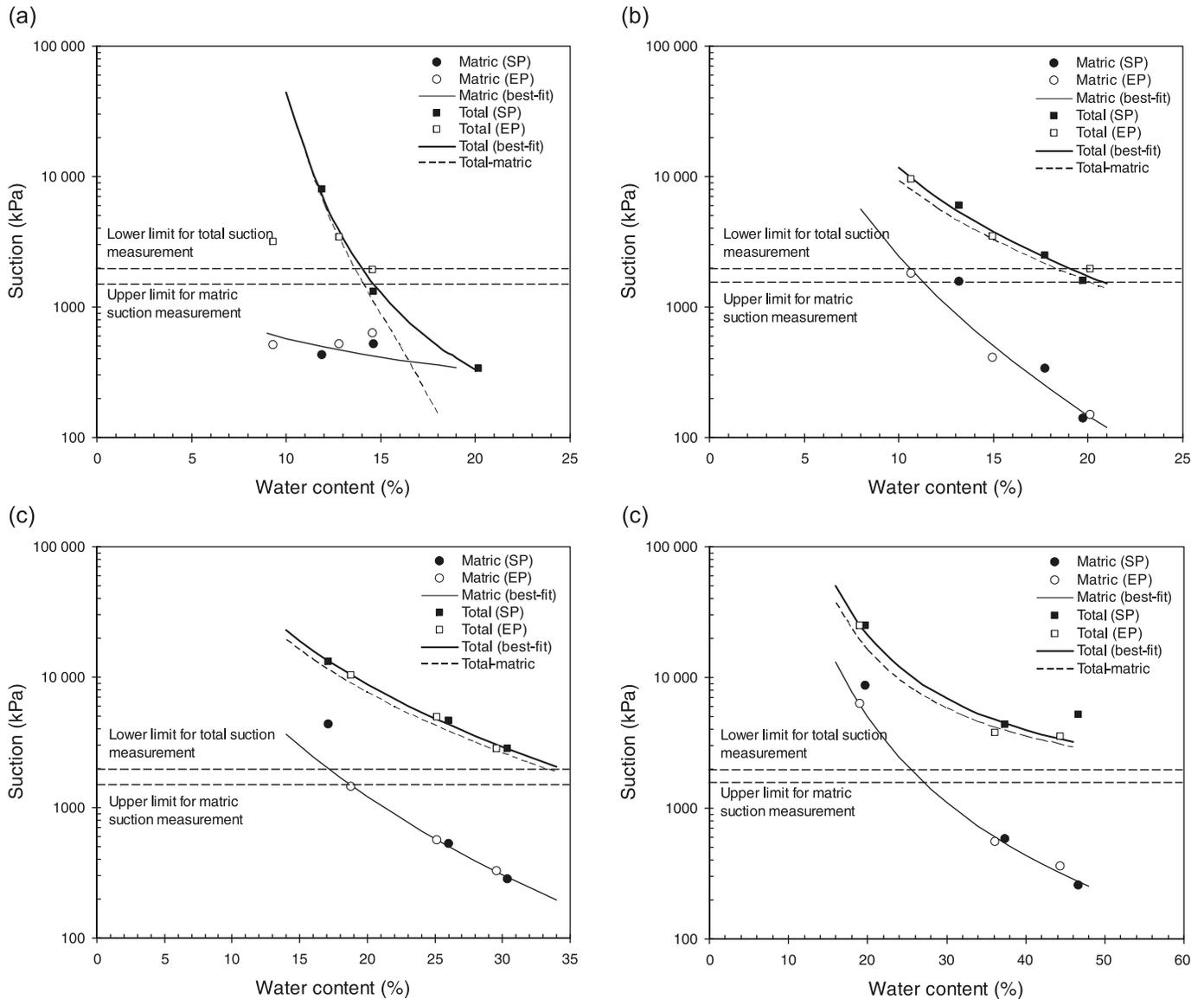
Total and matric suction of compacted mixtures

Figures 9a–9d show semilogarithmic plots of matric and total suction versus water content for the compacted mixtures obtained using the FP technique. The best-fit curves for matric and total suction are also given as thin and thick solid lines, respectively, and the total suction minus matric suction curve is shown in each figure as a thin broken line. The matric suctions of the compacted 30% bentonite – 70% sand specimens are essentially constant up to a certain water content and then tend to cross the corresponding total-suction curve in the high water content range. The results indicate that there is a significant contribution of matric suction to the total suction of the 30% bentonite – 70% sand mixtures at high water contents. The geometry of the pores influences the magnitude of total suction more dominantly than the properties of the clay minerals. However, the curve should remain below the total-suction curve, as matric suction is always less than total suction. The matric suction ranges from 300 to 700 kPa for a range of water contents between 7% and 15%. In this range, the total suction minus matric suction curve tends to separate away from the total-suction curve.

On the other hand, the total suction minus matric suction curves for the other three compacted mixtures closely follow the shape and magnitude of the total-suction curves, indicating an insignificant contribution of matric suction.

Filter paper is not a true semipermeable membrane, and therefore the effect of salt is bypassed in the measurement of matric suction. The results appear to provide values of the capillary component. Hence, the total suction minus matric suction as shown in Fig. 9 constitutes the effects of osmotic suction and the contribution due to sorptive forces. The range of capillary component of suction is 300–700 kPa for water contents between 7% and 15% in the 30% bentonite – 70% sand mixture, 100–1500 kPa for water contents between 10% and 20% in the 50% bentonite – 50% sand mixture, 300–1500 kPa for water contents between 18% and 30% in the 70% bentonite – 30% sand mixture, and 300–1500 kPa for water contents between 25% and

Fig. 9. Matrix and total suction versus water content using the FP technique on compacted specimens: (a) 30:70 bentonite–sand mixture; (b) 50:50 bentonite–sand mixture; (c) 70:30 bentonite–sand mixture; (d) pure bentonite.



48% in the pure bentonite. For all mixtures, the capillary component of suction measured higher than 1500 kPa should not be considered, since the FP technique tends to measure total suction at this higher range.

Conclusion

The following conclusion are drawn based on the results of this study on suction in bentonite–sand mixtures.

- (1) The assessment of suction measurement techniques indicates that the chilled-mirror hygrometer technique appears to provide the most accurate means of measuring total suction in the suction range encountered in the bentonite–sand mixtures used in this study (200–30 000 kPa). This technique is deemed to be the most accurate and thus is recommended in the study of suction characteristics of bentonite–sand mixtures.
- (2) The total suction of bentonite–sand mixtures is primarily

a function of water content and bentonite content or collectively a function of bentonite water content. There appear to be no apparent effects of void ratio (or pore geometry or fabric), and thus an insignificant contribution of the capillary component of suction. For the bentonite used in the study, total suction varies from 100 to 30 000 kPa for bentonite water contents ranging from 20% to 70%.

- (3) The total suction of specimens in the as-compacted state does not represent the true total suction at equilibrium. Redistribution of water occurs after compaction because of a difference in total suction (or water potential) in the different levels of the pores (i.e., the inter-aggregate, intra-aggregate, and inter-laminar pores). After 5 weeks, a quasiequilibrium state of water distribution is reached where both the chilled-mirror hygrometer and noncontact filter paper techniques give reasonably similar results.
- (4) The incontact filter paper technique appears to measure

the capillary matric suction component. The component due to the action of sorptive forces is not measured using this technique. This technique should only be used to measure a capillary suction component of less than 1500 kPa.

- (5) The noncontact filter paper technique measures total suction but is not suitable for measuring as-compacted total suction of bentonite–sand mixtures due to its long equilibration time. At the time of suction measurement (or the filter paper water-content measurement), the total suction measured no longer corresponds to the as-compacted total suction of the specimen.

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