Proceedings of the 3rd World Congress on Civil, Structural, and Environmental Engineering (CSEE'18)
Budapest, Hungary – April 8 - 10, 2018
Paper No. ICGRE XXX (The number assigned by the OpenConf System)
DOI: TBA

Investigation of Bentonite qualities on Water Retention Characteristic Curve

Abhijit Deka[1], Sreedeep Sekharan[2]

[1]Department of Civil Engineering, Central Institute of Technology, Kokrajhar Assam, India. Email: a.deka@cit.ac.in
[2]Department of Civil Engineering, Indian Institute of Technology Guwahati, Assam, India. Email: srees@iitg.ernet.in

Abstract- Bentonites are known for its high volume change behavior when it interacts with water. Bentonite and its mixes with specific geo-materials like sand, fly ash etc. are the most widely used materials for the construction of hydraulic barriers such as liners and covers due to its low hydraulic conductivity (< 10^{-9} m/s). It is very much useful in waste containment application for storing the high and low level waste all over the world. Under such condition of applications, the material under goes different interaction with water and other harmful contaminants present in the leachate. Due to this fact, the material remains in unsaturated state and hence its study is essential for getting a systematic understanding of the unsaturated mechanism. Numerous studies have been conducted by researchers on this geomaterial bentonite to understand its unsaturated mechanism. However, there is still a lack in the database where the unsaturated condition of the geomaterial has been properly addressed for different qualities of bentonite. The effect of different qualities of bentonite on WRCC and its implication on WRCC parameterization need to be investigated in detail. This study was particularly carried out to measure and compare the water retention characteristics curve (WRCC) of different types of commercially available bentonite and to get a proper way of representing the WRCC to correctly do the interpretation of water content and suction. Total suction was measured using WP4 dew point potentiometer technique. It was found that volumetric water content (θ) with total suction (Ψ) gives an accurate representation of WRCC for different bentonites. Again, the WRCC for the different bentonites were found comparable. A study of different WRCC parameters of the bentonites shows that Fredlund and Xing (FX) WRCC parameters can be well compared for all the bentonites than the van Genuchten (vG) WRCC parameters.

Keywords: Suction, bentonite, water retention characteristic curve (WRCC), dew point potentiometer, air entry value (AEV).

1. Introduction

Bentonite has been the most popularly used soil in waste containment system such as landfill liner due to its intrinsic property of low hydraulic conductivity (< 10^{-9} m/s) for water and many harmful contaminants [1, 2, 3, 4]. It is very much useful in waste containment application for storing the high and low level waste all over the world. In these applications, the material under goes different interaction with water and other harmful contaminants present in the leachate. Due to this fact, the material remains in unsaturated state and hence its study is essential for getting a systematic understanding of the unsaturated mechanism. The unsaturated state of the soil is characterized by its water retention characteristic curve (WRCC), which is the variation in negative pore water pressure (or suction) with water content [5, 6] Suction is divided in to two types namely matric suction and osmotic suction which together can be expressed as total suction. Matric suction is due to adsorptive and/or capillary forces existing in the soil matrix whereas osmotic suction is due to the presence of salts or contaminants presents in the pore water [7]. Water content can also be expressed as either gravimetric or volumetric based on the area of study.

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2. Measurement of Suction

The suction measurement was carried out using a dew point sensor called "WP4 dew point potentiometer" [8]. The instrument works on the principle of chilled-mirror dew point technique [8, 9]. WP4 measurements are considered to be inaccurate for suction less than 1 MPa [10]. It essentially consists of a sealed block chamber in which the soil sample can be placed in a 15 cc Polyurethane sampling cup. The geomaterial with particular water content induce a specific relative humidity in the head space of sealed block chamber. Based on the relative humidity of air in the headspace of the block chamber ψ can be estimated with the help of Kelvin's equation and as given by Eq. 1 below [11]. The instrument has limitation in measuring low suction range < 1 MPa [8].

$$\psi = \frac{R.T}{\chi} \ln\left(\frac{p}{p_o}\right) \quad \textbf{(1)}$$

where, R is the universal gas constant (=8.31 J/mol.K), T is the temperature of the sample in K, χ is the molecular mass of water (=18.016 kg/kmol), p is the vapour pressure of air and p_0 is the saturation vapour pressure. The block chamber consists of a mirror, dew point sensor, which is a photoelectric cell, a temperature sensor, which is a thermocouple, an infrared thermometer (optical sensor) and a fan. The details of working of the instrument has been shown in the literature [10, 8].

3. Experimental Investigation

The materials used in this study consist of four types of commercially available bentonite (B1 to B4) selected based on different ranges of liquid limit (L.L.). All the bentonite has been characterized for its specific gravity [12, 13, 14, 15]. The specific surface area has been obtained by EGME method [16]. This method measures the total surface area of the soil mass, and hence it is suitable for high swelling expansive soils like bentonite. The details of these characterizations are tabulated in Table 1.

Table 1: Physical properties of bentonite

Property	Bentonite			
	B1	B2	B3	B4
Specific gravity, *G*	2.71	2.8	2.71	2.76
Particle size characteristics (%)				
Coarse sand (4.75-2mm)	0	0	0	0
Medium sand (2-0.425mm)	0	0	3	0
Fine sand (0.425-0.075mm)	5	2.2	0.6	2.9
Silt size (0.075-0.002mm)	31	42.8	48	40.6
Clay size (<0.002mm)	64	55	51.4	56.5
Maximum dry density, (kN/m^3)				
Optimum moisture content (%)				
Liquid limit (%)	300	310	433	244
Plastic limit (%)	53	48.1	54.61	61.86
Shrinkage limit (%)	26.4	29.53	21.26	35.26
USCS classification	CH	CH	CH	CH
Total SSA (m^2/g)-EGME method	601	244	428	215

For suction measurement using WP4 dew point potentiometer technique, all the bentonite samples were mixed with sufficient water to attain slurry state since it is already reported in the literature that dry unit weight has negligible influence on WRCC [17, 18]. The sample cup with the specimen was placed inside the block chamber of WP4 for ψ measurement. After each ψ measurement the specimen was taken out of the WP4 chamber and the weight of the sample cup along with specimen was recorded using a high precision balance. The volume changes of the specimen were also measured at each stage of suction measurement by measuring diameter and thickness of the samples using vernnier calipers. The cup with the sample was then left for air-drying till the next measurement was taken. This process was repeated several times till a near dry state of the sample was attained ($\psi \approx 300$ MPa). At the end of the test, the sample cup with the soil specimen was placed in an oven to determine its dry weight. Using the dry and wet weights of the specimen, the gravimetric water content, w, corresponding to each ψ measurement was back calculated. The gravimetric water content (w) thus obtained has been used to obtain the volumetric water content using the formula θ (= w.(γ_d/γ_w)) where γ_d and γ_w are dry unit weight of the specimen at different stages of measurement and unit weight of water, respectively. Before using the WP4, its calibration was ensured by measuring ψ_o of the measuring standard (0.5 M KCl solution) [8].The WRCC of each bentonite has been mathematically quantified by fitting Fredlund and Xing (1994) and van Genuchten (1980) WRCC equations to the experimental data [19, 20]. Eqs. (2) and (3) represents Fredlund and Xing and van Genuchten model equations, respectively.

$$\theta(\psi) = \theta_s \left[1 - \frac{\ln\left[1 + \frac{\psi}{h_r}\right]}{\ln\left[1 + \frac{10^6}{h_r}\right]} \right] \mathrm{X} \left[\left[\ln\left[\exp(1) + \left(\frac{\psi}{a_f}\right)^{n_f} \right] \right]^{m_f} \right]^{-1} \tag{2}$$

$$\theta(\psi) = \theta_r + (\theta_s - \theta_r)\mathrm{X}\left[\left[1 + (a_{vg}\psi)^{n_{vg}}\right]^{m_{vg}}\right]^{-1} \tag{3}$$

where $\theta(\psi)$ is the volumetric water content at any suction, ψ; θ_r is the residual volumetric water content; θ_s is the volumetric water content at saturation; a_{vg} and a_f are fitting parameters primarily dependent on the air entry value (AEV); n_{vg} and n_f are fitting parameters that are dependent on the rate of extraction of water from the soil; m_{vg} and m_f are fitting parameters which depend on θ_r; h_r is the suction (in kPa) corresponding to residual state.

4. Result and discussion

Figures 1-2 show the general trend of the drying behaviour of bentonite used in this study. The plot presents the water retention characteristics curve in terms of gravimetric water content (w) and volumetric water content (θ). The measurement were carried out from a slurried soil in order to cover a wide range of water content and suction change in the soil specimen as mentioned above.

It is observed that the WRCC of all the bentonites shows similar trend for all the representation of WRCC. The θ-Ψ representation (Fig. 2) gives the desaturation portion clearly while the horizontal near saturation portion and the residual portion is absent. The w-Ψ representation of WRCC shows clearly the desaturation and residual portion while the horizontal near saturation portion is absent in this case. It was observed that the θ-Ψ plot of all the bentonites shows a flatter slope than the w-Ψ plot. The volumetric water content (θ) decreases with the increase in suction. This relationship can be regarded as a unimodal curve between the saturated and dry state of the sample. On the other hand, the gravimetric water content (w) for all the bentonites shows a sharp fall at a suction <1000 kPa. This is shown by dotted line in the figures. Below this water content the WRCC almost become a horizontal line with further increase in suction. Hence the WRCC in this case can be considered as a bimodal plot consisting of desaturation and residual flat portion. The sharp fall in the gravimetric water content at the initial stage of measurement as seen in w-Ψ plot is due to the evaporation of water from the pores of the bentonite sample producing cracks on it.

This crack expands with time resulting further removal of water from the sample. This decrease in water content results in an equal decrease in the volume of the sample. The dry density of the sample also gets decreased and hence the decrease in θ is not so drastic as compared to w. It is now clear from this observation that θ-Ψ representation of WRCC for bentonite gives an accurate picture of the suction water content relationship while studying its unsaturated properties. This result also proves that the WRCC of high volume change soil like bentonite is not unique when expressed in θ and w form.

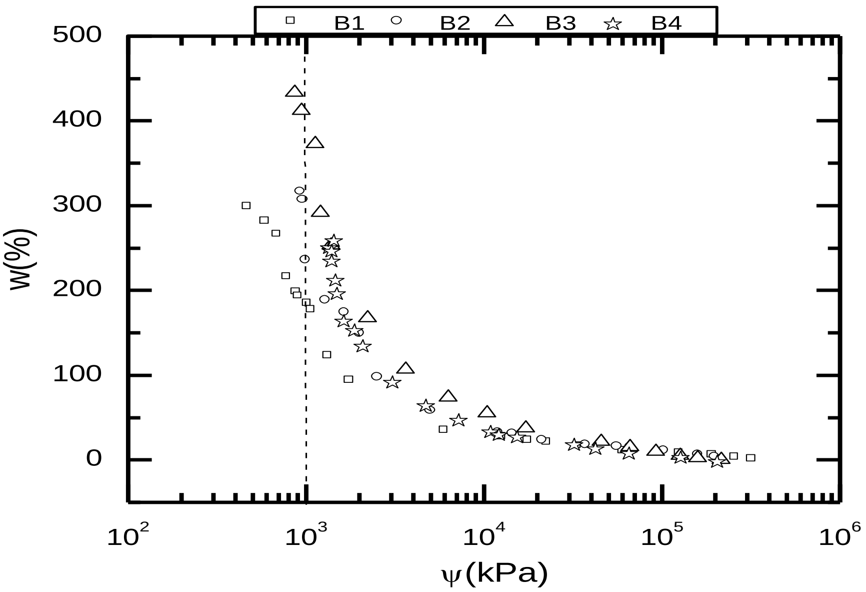

Fig. 1: Comparison of WRCC of bentonites in terms of W-Ψ representation.

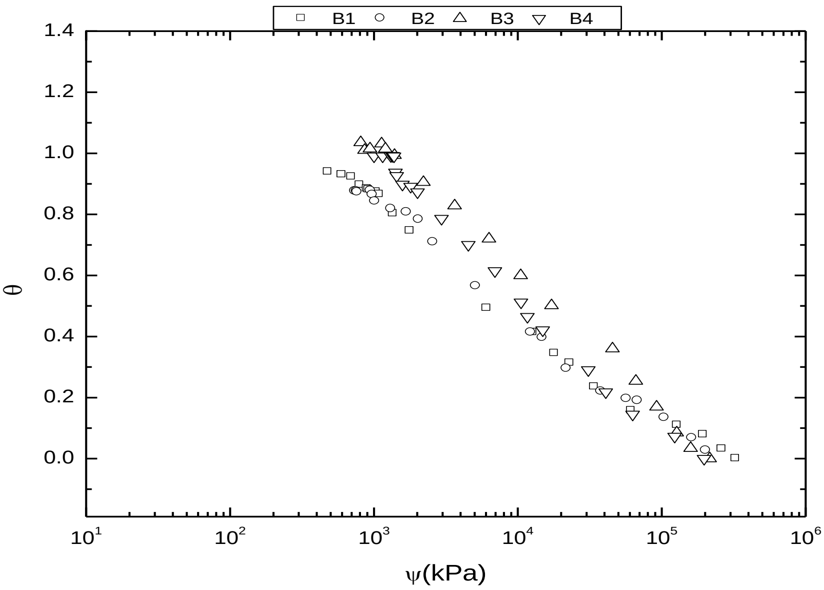

Fig. 2: Comparison of WRCC of bentonites in terms of θ-Ψ representation.

Figure 2 shows that the B1 bentonite measures the minimum suction of around 400 kPa while all other bentonite has a minimum suction of around 700 kPa. It is clear from the figure that WRCC for B1 and B2 merges completely. The WRCC of B3 bentonite falls above all the plots. WRCC for B4 falls below B3 and above B1 and B2. This shows that for a particular water content, B1 and B2 gives the same suction, while the suction is higher for B4 and B3. However, above 10^4 kPa suction all the three plots of B1, B2 and B4 merges together. All the plots merges to a common point at 10^5 kPa. It is understood from this observation that higher the liquid limit of bentonite higher is the total suction. The higher suction measured by B3 bentonite may be attributed due to its high liquid limit

(433%) as compared to other bentonites B1, B2 and B4. It is also clear from this plots that for a variation of liquid limit from 244% to 310%, the variation in the WRCC is very marginal.

The variations of measured WRCC has been mathematically quantified by comparing the Fredlund and Xing (1994) (FX) and van Genuchten (1980) (vG) equation parameters. To determine the WRCC fitting parameters only the θ-Ψ plot of all the soil has been considered. The fitting parameters were obtained by using the Soil Vision 2009 [21]. The WRCC equations fitted to the measured results of all the bentonites as discussed above is depicted in Figure 3. The fitting parameters obtained are listed in Table 2. Figure 3 shows that FX & vG WRCC equation were fitted well with the measured data of all the bentonites. Although, the initial near saturation portion is absent in all the WRCC's, the minimum θ was fixed as the saturated θ_s for both the fitting function. As shown in the Table 2, the regression coefficient (R^2) is close to unity which indicates a good fit to the measured data.

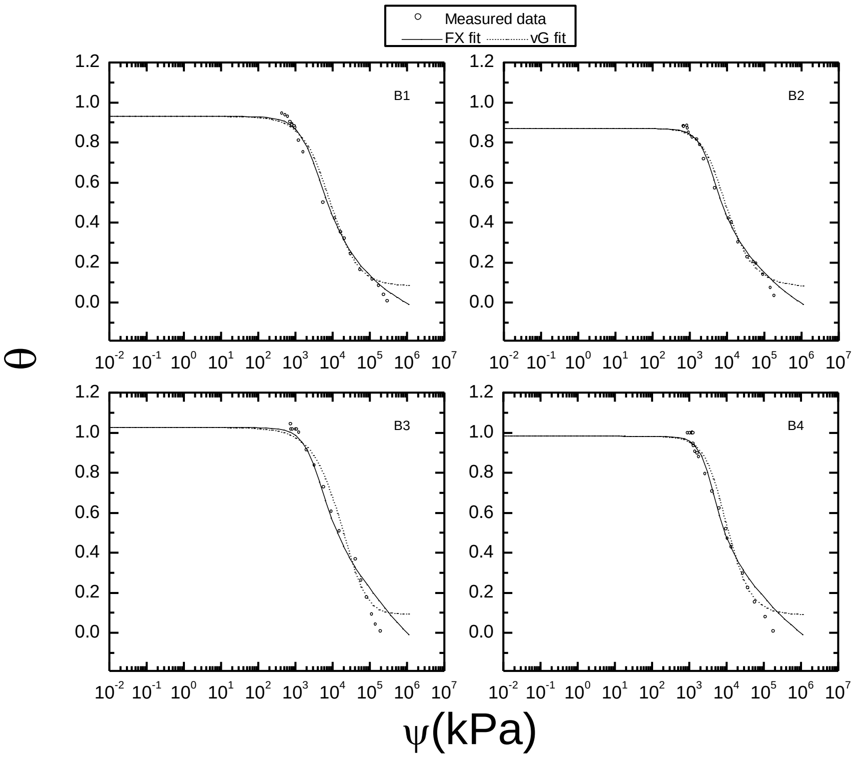

Fig. 3: Comparison of FX & vG fitting to the measured data of bentonites.

Table 2: WRCC fitting parameters of bentonite for Θ-ψ representation

Fitting function	Parameter	Material			
		B1	B2	B3	B4
Fredlund and Xing (1994)	a_f(kPa)	2286.98	2499.96	2499.98	2499.97
	n_f	1.54	2.13	1.85	2.38
	m_f	0.76	0.57	0.58	0.55
	AEV(kPa)	1017	1412	1354	1490
	R^2	0.9941	0.9934	0.9694	0.9782
van Genuchten (1980)	a_{vg} (x10^{-5} kPa^{-1})	11.92	18.6	2.71	14.16
	n_{vg}	1.11	1.46	1.00	1.52
	m_{vg}	1.10	0.628	2.2	0.78
	AEV (kPa)	1284	1721	2561	2086
	R^2	0.9857	0.9898	0.9794	0.9833

5. Conclusion

The water retention characteristics curve (WRCC) of different qualities bentonite has been measured and compared in this study. The study established WRCC in terms of gravimetric water content w and volumetric water content θ. It was found that volumetric water content (θ) with total suction (Ψ) gives an accurate representation of WRCC for different bentonites. Again, the WRCC for the different bentonites were found comparable. A study of different WRCC parameters of the bentonites shows that Fredlund and Xing (FX) WRCC parameters can be well compared for all the bentonites than the van Genuchten (vG) WRCC parameters.

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