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Estimation of Soil Water Characteristic Curves (SWCC) of mining sand using soil suction modelling

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Abstract. Soil water characteristic curve (SWCC) is widely known as the relationship between matric suction and water content. It is used as a tool to determine the hydraulic and mechanical behaviour of unsaturated soils and to predict soil water storage. Direct measurement is difficult and time-consuming. Many empirical models have been developed to represent SWCC. The objective of this study is to validate the Van Genuchten and Fredlund and Xing models. The SWCC was obtained from pressure plate tests for different soil gradations of mining tailing sand samples taken from Kuala Trong, Taiping, Perak, Malaysia. The results presented include moisture content and degree of saturation versus matric suction. The constructed SWCCs were fitted using the Van Genuchten and Fredlund and Xing equations, and the behaviour of the parameters analysed and discussed. The study found that this method is good for the SWCC for mining tailing sand, and that SWCC is greatly affected by initial water content and the grain size of the sample.

1. Introduction

In engineering practices, it is routinely to use the soil-water characteristic curves (SWCCs) for the estimation of unsaturated soil property functions [1]. The SWCCs have become essential to the implementation of unsaturated soil mechanics into geotechnical engineering practice. Generally, the estimation procedures for unsaturated soil property functions have been proposed for virtually every physical process where soils become unsaturated [2]. However, SWCCs have not proven to be a suitable tool for estimating in situ soil suctions, and their usage for this purpose has been discouraged [3].SWCC is generated by the relationship between the volumetric water content and soil suction. It is usually used to predict and determine engineering characteristics of unsaturated soil such as permeability, water volume changes and shear strength [4]. Volumetric water content or gravimetric water content, (Ө), is defined as the ratio of volume of water to the total volume of soil. The relationship between volumetric water content and matric suction in soil is observed from the SWCC [6]. In unsaturated soils, the quantitative measurements of the volumetric water content have been commonly carried out using the burette system during the SWCC tests. The burette system provides a continuous measurement of the soil water content, which is recommended to minimize errors in the identification of the SWCC [7]. The SWCC depends mainly on different factors such as soil types, grain size distribution, soil plasticity and initial void ratio [8]. The general behaviour of SWCC is hysteresis where the volumetric water content of the wetting process is often lower than that of the drying process in the same matric suction. Therefore, most of the SWCC is often generated for the

drying process due to the convenience of measurements [9].For a given soil, there are different methods to predict the SWCC which are broadly grouped into direct and indirect methods. Indirect methods use a measurement of water content or a physical property which is sensitive to the variations in water content [10]. On the other hand, direct methods measure pore water pressure or air pressure imposed into the soil include the use of pressure plates, bunchner funnels, tensiometers and pressure membranes. Of these methods, the conventional pressure plate extractor is widely used due to its reliability for measuring the SWCC behaviour of both coarse and fine grained soils. However, this method required long time for obtaining data. For instance, to obtain six to eight readable data points, the normal time required for soils such as sand or silt is between 6 and 8 days [11]. In other words, almost one day is required to obtain one data point for relatively coarse-grained soils. For fine-grained soils, such as silt and clay, longer periods of time are required [12].

In laboratory work, several tests are usually needed to develop a SWCC for a particular soil which is considered a time-consuming process and difficult to obtain all necessary information. To overcome this problem, several numerical models and empirical functions have been developed to predict SWCCs for different types of soil. The empirical models are classified as two curve fitting parameter and three curve fitting parameter SWCC models. These models are fit using least squares regression analysis [5]. Early empirical models consist of two curve fitting parameters, including Burdine,Brutsaert & Mualem. These models involve two curve fitting parameters to simulate the SWCC which are capable of describing SWCC. However, these models cannot provide a suitable fitting for data. This is due to the lack of a third parameter used to independently modify the curve shape. In that sense, the two curve fitting parameter models are insensitive to scatter data and resulted in the inability to accurately describe best fit curves and the trend of [13]. Some assumptions should be applied to mathematically describe a reverse sigmoidal curve like the SWCC [14] in a consistent manner.

After few years, Van Genuchten and Fredlund and Xing developed a three parameter equation which is capable of better simulation of the SWCC through the whole range of suction from 0 to 106 kPa. This was exhibited by Leong and Rahardjo, who evaluated the use of several published SWCC equations through a series of regression analysis to fit SWCC curves to experimental data from 12 different types of soil. Leong and Rahardjo concluded that, both Van Genuchten and Fredlund and Xing equations provided a better fit for a variety of soils than the two parameter models. Based on Leong and Rahardjo study, the Van Genuchten and Fredlund and Xing models are used in this study to fit the SWCC experimental data results. The main objective of this study is to produce soil water characteristic curves (SWCCs) using collected data from laboratory pressure plate extractor test, and mathematical models. The obtained results from pressure plate method were then used to estimate curves developed by mathematical models and correlations developed by Van Genuchten and Fredlund and Xing. The results of the measured soil water characteristic curves using pressure plates and mathematical models from three different samples of fine grained soils with different conditions are also presented and discussed.

2. Soil Water Characteristic Curves methods

2.1 Van Genuchten (1980)
Van Genuchten used models proposed by Burdine and Mualem's theory to develop soil water content pressure head curve equation that produced three independent parameters to determine hydraulic conductivity. Equation (1) determines the soil permeability based on information obtained from SWCC [15].

$$K_r = \theta^{1/2} = \left[\int_0^\theta \frac{1}{h(x)} \, dx . \left(\int_0^1 \frac{1}{h(x)} - 1 \right)^{-1} \right]^2 \tag{1}$$

where h is the pressure head and water content, Θ is a dimensionless function of h.

$$\theta = \frac{\theta - \theta_r}{\theta_s - \theta_r} \tag{2}$$

where r and s represent the residual and saturated water contents, respectively. Water content is shown corresponding to the SWCC based on the following relationship:

$$\theta = \left[\frac{1}{1+(\alpha h)^n}\right]^m \tag{3}$$

where α, m, and n are parameters determined from the soil water retention curve. Combining equation (2) and (3), the following model was proposed:

$$\theta = \theta_r + \frac{(\theta_s - \theta_r)}{[1+(\alpha h)^n]^m} \tag{4}$$

From the SWCC, four parameters were estimated, α, n, θ_s, and θ_r. Saturated water content, θ_s, can be determined based on the water content of saturated soil samples. Residual water content, θ_r, can be obtained from SWCC or determined by measurement of water content in dry soil samples. The slope of the curve, (S), is evaluated at the midway point of the curve ($\theta = 1/2$). The halfway point on the moisture retention curve is denoted by subscript P in equation (5). Parameter m can be determined by evaluating S_p(6).

$$m = 1 - e^{(.8sp)}\left(0 < S_p \leq 1\right) \tag{5}$$

$$m = 1 - \frac{.5755}{S_p} + \frac{.1}{S_p^2} + \frac{.025}{S_p^3}\left(S_p > 1\right) \tag{6}$$

The parameters m and α were determined from the following two relationships:

$$m = 1 - \frac{1}{n} \tag{7}$$

and,

$$\alpha = \frac{1}{h}\left(\theta^{1/m} - 1\right)^{1/n} \tag{8}$$

2.2   Fredlund and Xing (1994)

The Fredlund and Xing model for the SWCC is determined based on the equation derived from pore size distribution of the soil. The Fredlund and Xing equation is expressed as:

$$\theta_w = c(\psi) \frac{\theta s}{[\ln(\exp(1)+(\Psi/a)^n)]^m} \tag{9}$$

Where:

$$c\left(\psi\right) = 1 - \frac{ln\left(1+(\frac{\Psi}{\Psi_r})\right)}{ln\left(1+(\frac{10^6}{\Psi_r})\right)} \tag{10}$$

Correction factor (Ψ_r) is the suction which is correlated with the residual water content. Value (*a*) is a related parameter the fits with air-entry value (AEV) of the soil measure in (kPa). Values *n* and *m* also fit the parameters, but *n* is related to the slope of the SWCC, while *m* is related to the residual water content of the soil, and *e* is the Euler number (2.71828) [16].

3. Materials and methods

In this study, mining sand were collected from Kampung Kuala Trong, Perak, Malaysia and several samples were tested to investigate the physical properties, including moisture content, particle size distribution, Atterberg limit, and specific gravity. Unified Soils Classification System (USCS) and the American Association of State Highway and Transportation Officials (AASTHO) were used for soil classification. Figure 1 shows the particle size distribution of mining sand and Ottawa sand. The result of particle size distribution for Ottawa sand is obtained from Li Xudong. The basic physical properties for sand are presented in Table 1. In this study, SWCC test with three different particle sizes of sand will be used, including the mining sand, 2mm mining sand, the mining sand without 2mm size sand and Ottawa sand were performed to characterize the properties of the SWCC.

Table 1 The **physical** properties of mining and Ottawa sands.

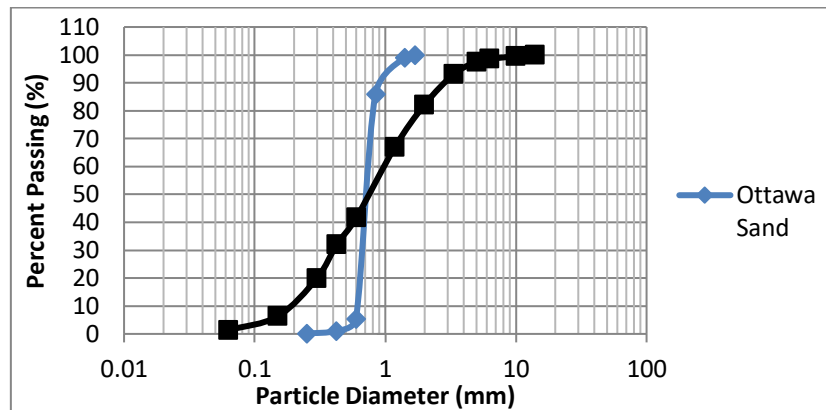| Properties	Unit	Mine tailing sands	Ottawa sand
Natural water content	(%)	5.474	-
Particle size distribution	Gravel (%)	2.41	-
	Sand (%)	91.31	75
	Fines (%)	6.286	25
	D_{10} (mm)	0.19	0.5
	D_{30} (mm)	0.4	0.68
	D_{60} (mm)	1	0.76
	Cu	5.263	18.3
	Cc	0.842	1.18
Plastic limit	(%)	NA	-
Liquid limit	(%)	23.5	-
Plasticity index		23.5	-
Specific gravity		2.641	2.65
USCS		SP	SP
AASTHO		A-2-6	-

Figure 1. Particle size distribution of mining sand & Ottawa sand.

From the physical properties test, both studied sand is classified as poorly graded sand with little or no fines. Both soil has similar specific gravity and is characterized in a same group of SP for USCS. Both are classified as poorly graded sands, gravelly sands, with little or no fines.

3.1   Methods

In this research, the SWCC have been produced and investigated using pressure plate apparatus (figure 2). The pressure plate apparatus is most the commonly used among other SWCC test methods because it allows direct measurement of water content under the applied matric suction acted on a specimen [8]. The pressure plate apparatus is comprised of a porous plate and a sealed pressure cell [17]. Each ceramic pressure plate cell is covered by a thin neoprene diaphragm on one side and is made of a porous ceramic plate (figure 3). Water flows through an internal screen between the plate and the diaphragm. The passage is connected to an outlet stem running through the plate to an outflow tube fitting, which connects to the atmosphere outside the extractor [18].
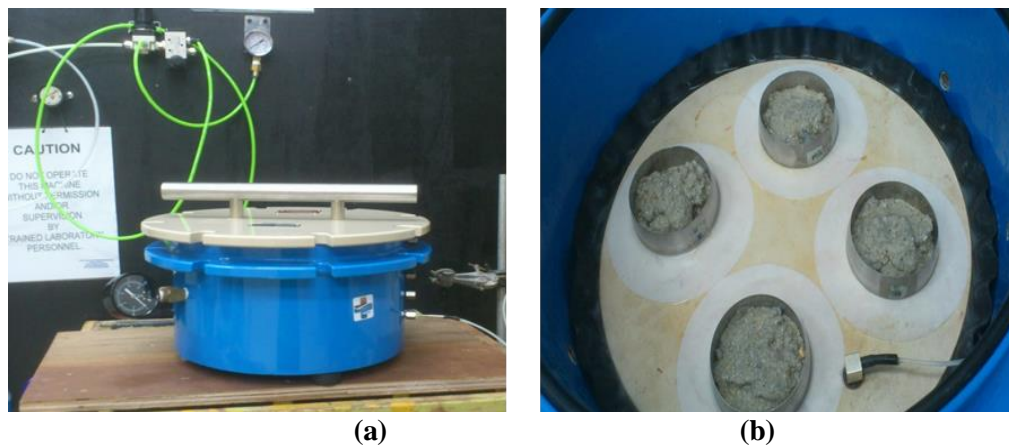

(a)   **(b)**

Figure 2. (a) Pressure plate apparatus (**b**) Experimental test set up.
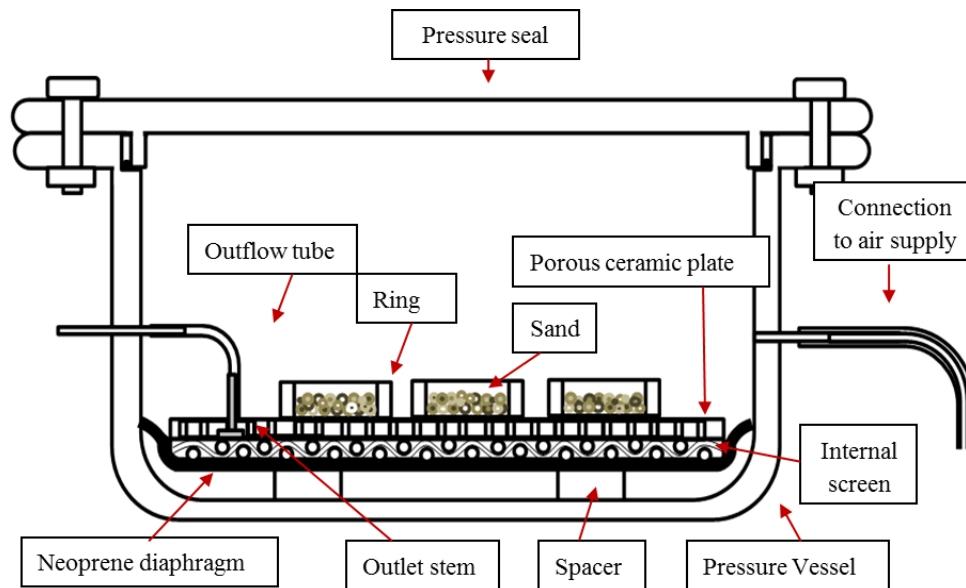
Figure 3. Cross section view of testing using pressure plate apparatus.

The ceramic pressure plate cell is designed to fit one or more soil samples and contains a porous ceramic surface to hold samples. The porous ceramic surface is supported by a retaining ring. The samples including the porous ceramic plate are saturated with water. After being completely saturated, the cell is ready to use and filled with air pressure. The air pressure is used to extract moisture samples under controlled conditions. Pressure is applied using an Airtac 4H: Hand Lever Air Valve model 4H210-08 air compressor, and when the pressure in the chamber rises above atmospheric pressure, excess water flows out of the outlet stem through the microscopic pores. Since the pores are fully saturated, the high-pressure air will not flow through the pores in the ceramic plate [19][20]. The test is considered complete and in equilibrium when the pores in the plate are the same as the effective curvature of the water films throughout the soil. Water content is then determined when the samples are removed. This is equivalent to the soil suction, and therefore a relationship can be made between air pressure in the extractor and the soil suction at equilibrium.

4. Results and Discussions

4.1 *Plate Test Results*
The soil water characteristic curves were measured for all samples of mining sand. The results of the SWCC for mining sands were compared to SWCC for Ottawa sand were obtained from Li (2008). As shown in Figure 4, it is clear that the particle size distribution of sand has effect on SWCC. Table 2 shows a summary of obtained experimental data of the studied soil. At the given matric suction, moisture content of mining sand and 2mm mining sand has been compared, and it was found that mining sand shows higher moisture content than 2mm sizes mining sand, which was 24.07% and 2.05%, respectively. An inverse relationship was found between the matric suction and moisture content of soils. For mining sand without 2mm and 2mm mining sand, after reaching 10kPa (matric suction), moisture content become constant. Mining sand takes 50 kPa (matric suction) for moisture content to become constant.

Table 2 Experimental data.

Matric suction (kPa)	Moisture content (%)		
	Mining sand	Mining sand without 2mm size	2mm mining sand
0.1	24.07	23.46	2.05
0.5	23.57	23.2	2.05
1	20.79	22.14	1.998
2	11.23	15.6	1.81
3	7.92	5	1.43
10	4.05	3.62	1.36
50	2.83	3.1	1.34
100	2.67	3	1.34

Table 3 shows the SWCC parameters obtained from the experimental data. It shows that 2mm mining sand has the highest AEV and *m*. Meanwhile, mining sand without 2mm sand shows the lowest AEV and *m*. It can be conclude that air entry value and the amount retained water at low matric potential decrease with the increase of a gravel content. This is because the suction of volumetric water content increases as the soil type becomes progressively finer [21].

Table 3 SWCC parameters from experimental data.

Soil	AEV (kPa)	a (kPa)	m	n	θs	θr
Mining sand	0.9	1	0.25	1.334	0.401	0.06
Mining sand without 2mm	0.9	1.1	0.182	1.222	0.398	0.034
2mm mining sand	0.7	1	0.692	0.591	0.042	0.034

Figure 4 (a) shows that the SWCC for mining sand has a steeper curve compared to mining sand without 2mm size and 2mm size sand. This observation was due to the increasing of fines which in turn leads to the increasing of water content retained at certain matric suction. For mining sand, the pore size distribution was considered uniform. When more water is absorbed, matric suction will increase, and the resulting moisture will decrease gradually. Figure 4 (b) shows that when the matric suction increases up to 10 kPa, SWCC starts to fall gradually. This observation can be explained by the shape of the SWCC which is mainly influenced by soil structure, especially in the low-suction range. At very low suctions, it depends primarily on capillary surface tension effects, and hence on the pore size distribution and soil structure. At higher suction (lower moisture contents); water retention is increasingly due to adsorption which is influenced more by the texture and the specific surface of the material [22]. It is known that soil pores are typically large and only low water content will remain after the large pores are forced to be emptied. SWCC behaviour largely depends on the pore size distribution of the soil, while pore size distribution is completely related to the grain size distribution of the soil. The larger D_{10} of the coarser grained soils have bigger voids and hence, air can easily absorb into the soil skeleton (small AEV) [23].
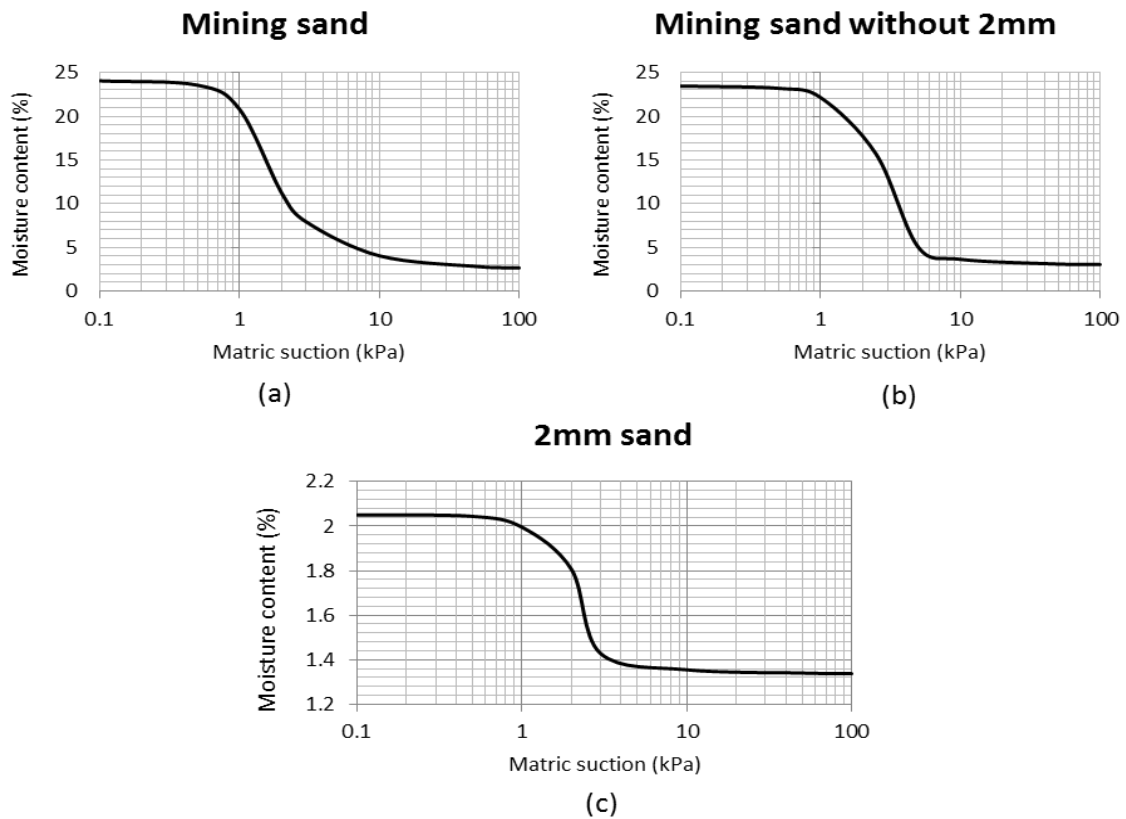
Figure 4. (a) Result of SWCC on mining sand **(b)** Result of SWCC on mining sand without 2mm sand size **(c)** Result of SWCC on 2mm sand size.
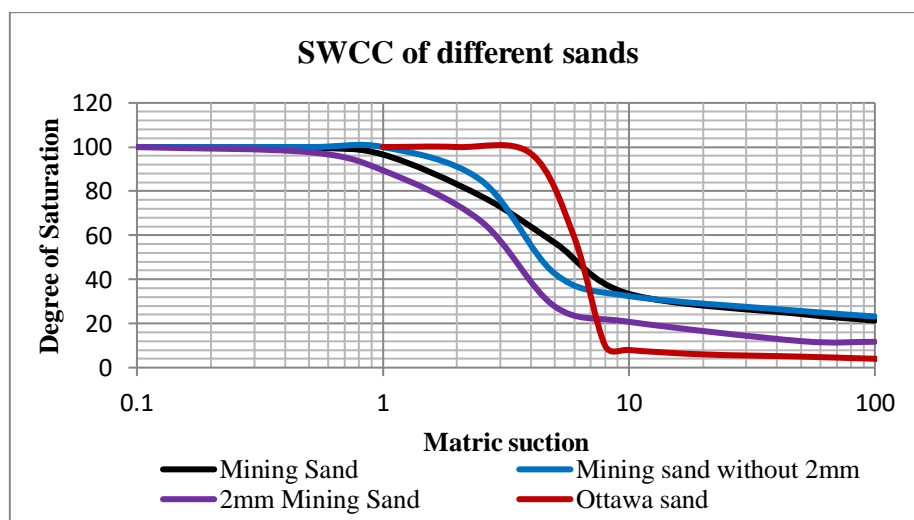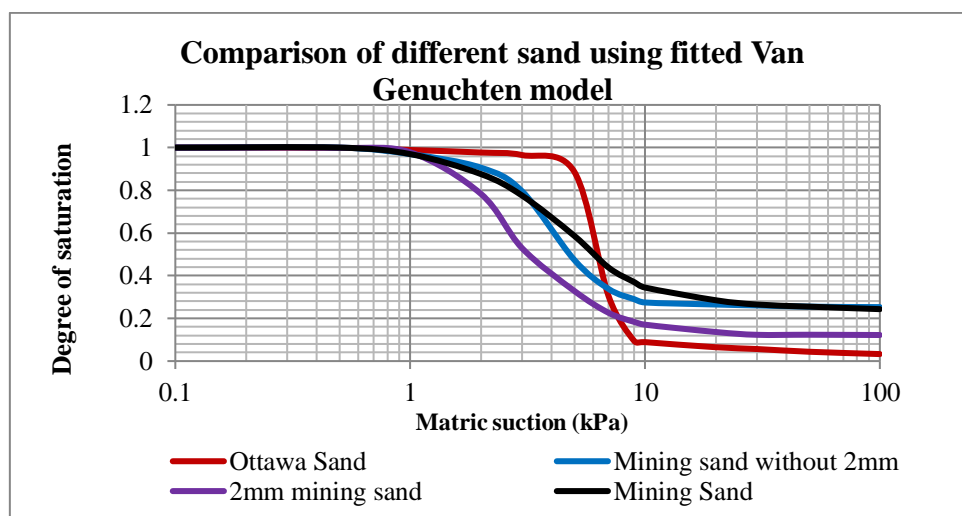

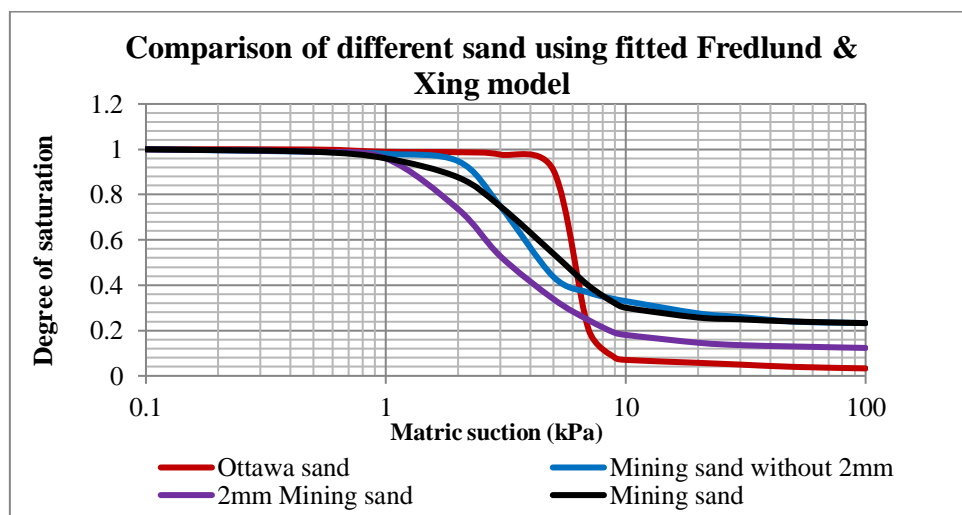**Figure 5.** Soil water characteristic curves for the four different types of soil.

Figure 5 shows the comparison of studied experimental data and data obtained using Tempe cell for Ottawa sand by Li [24]. The SWCC of different types of soil show similar behaviour due to the particle size distribution.

4.2. Comparison of laboratory experiments results with Mathematical Model Van Genuchten (1980) and Fredlund and Xing (1994).

Figure 6(a-b) shows a set of constructed SWCCs after applying the Van Genuchten and Fredlund and Xing models. The analysis was performed as degree of saturation versus matric suction. The water content versus matric suction data was obtained on initially saturated soil samples. Table 4 shows the obtained parameters. Figure 6 shows the results of suction values below 100 kPa for all types of sand. The SWCC of the studied soil shows low AEV and suction. The results appear to be comparable; there were no significant differences due to the similarity in grain size distribution curves of mining and Ottawa sand. It can be summarized that the both model provides a better fit of the experimental data.

(a)

(b)

Figure. 6 (**a**) The comparison of soil water characteristic curves for four different types of soils after applying the Van Genuchten model (**b**) The comparison of soil water characteristic curves for four different types of soils after applying the Fredlund& Xing model.

The models fitting parameters proposed by Van Genuchten and Fredlund and Xing are compared with experimental data in Figure 7-10 for five types of soil with different textures. Van Genuchten and Fredlund and Xing models use three parameters (a, *n*, and *m*). Table 3 presents the obtained parameters and R^2 values for all the studied soils. These parameters were obtained by nonlinear regression, and the Van Genuchten and Fredlund and Xing models fit adequately over the entire range of available experimental data. These models predict almost identical SWCCs. The calibrated Van Genuchten and Fredlund and Xing models have shown a good fit with experimental results. The fitted SWCCs plots show the Van Genuchten and Fredlund and Xing models succeed well in the optimization procedure. In terms of the coefficient of determination (R^2), it can be observed that the fitted curves of most of the tested soil score a higher R^2 value.

Table 4 SWCC parameters from fitted SWCC experimental data.

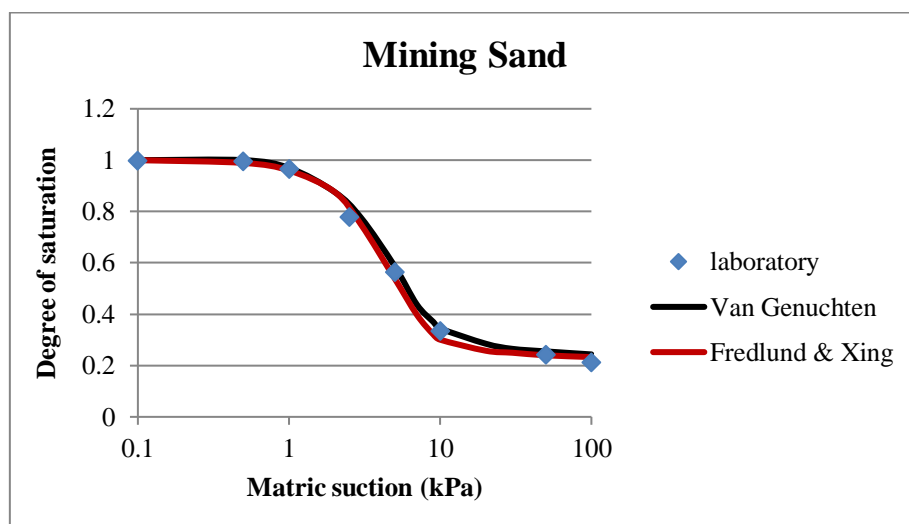| Soil		Mining Sand	2mm Mining Sand	Mining sand without 2mm	Ottawa Sand
Parameter					
Van Genuchten (1980)	θ_s	1.0006	0.97601	0.99691	0.99314
	θ_r	0.21130	0.12251	0.25783	0.049226
	α	0.34623	0.41766	0.31064	0.16428
	m	0.5709	0.6606	0.7425	0.909
	n	2.3307	2.9417	3.8840	10.979
	R^2	0.99814	0.99509	0.99701	0.99914
Fredlund & Xing (1994)	θ_s	1.0101	0.98349	0.99337	0.98996
	θ_r	0.22098	0.11974	0.11594	0.022917
	a	5.2819	2.9018	2.4492	5.9373
	m	3.4038	2.4514	0.57549	0.60779
	n	1.6865	2.4010	8.5382	10.81
	R^2	0.99878	0.99612	0.99964	0.99961

 Figure. 7 Comparison of SWCC experimental data with Van Genuchten (1980) and Fredlund & Xing (1994) of Mining sand.
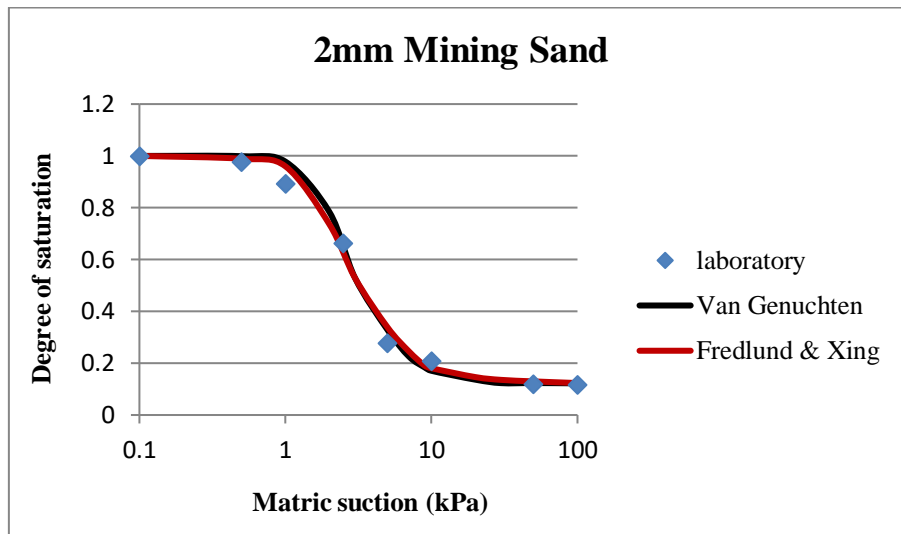
Figure. 8 Comparison of SWCC experimental data with Van Genuchten (1980) and Fredlund & Xing (1994) of 2 mm Mining sand.
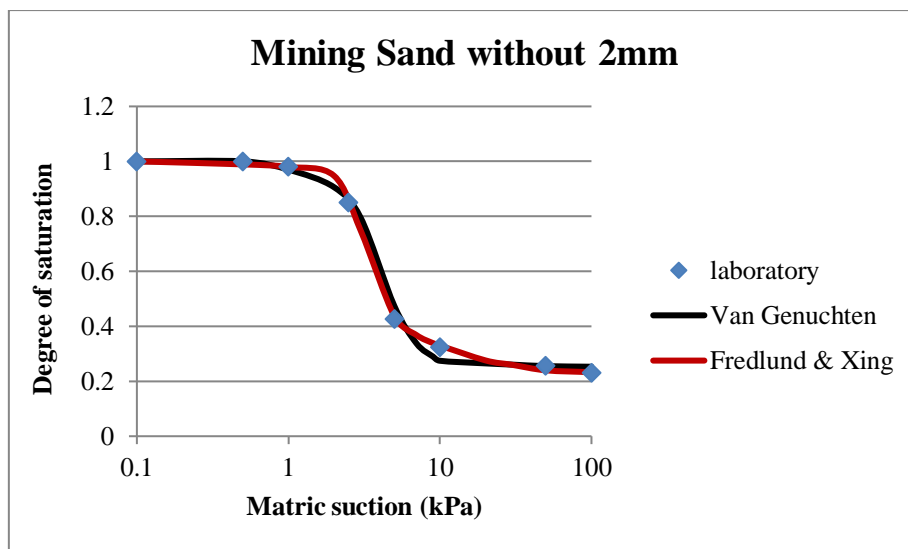

Figure. 9 Comparison of SWCC experimental data with Van Genuchten (1980) and Fredlund & Xing (1994) of Mining sand without 2mm size of sand.
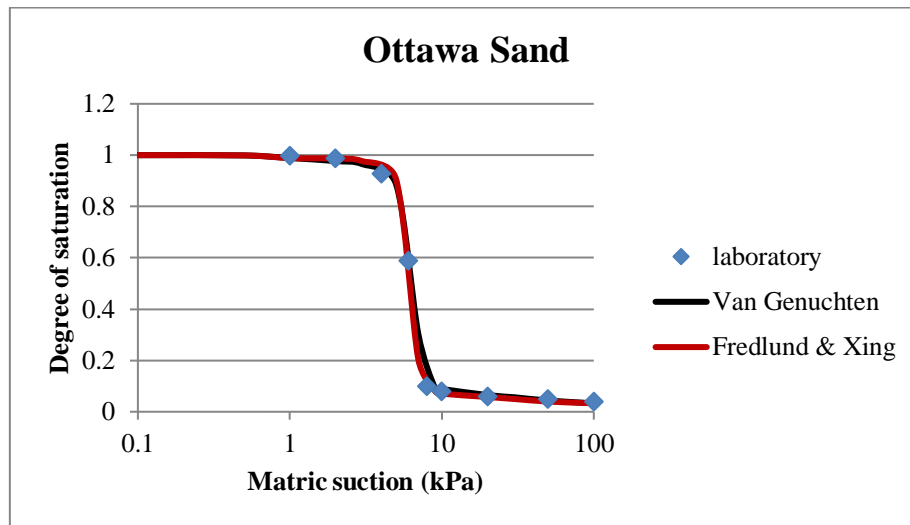
Figure. 10 Comparison of SWCC experimental data with Van Genuchten (1980) and Fredlund & Xing (1994) of Ottawa sand.

It can be clearly observed that the efficiency of this model is accurate in predicting SWCC. The reason for most accurate prediction is because it divides the whole particle size distribution curve into many small parts of uniform and homogeneous particles and SWCC corresponding to that part is estimated. Interesting agreements were obtained between the prediction by the models and the experimental data. The Van Genuchten and Fredlund & Xing model fit the experimental data and it was also found to be the suitable model for the SWCC of the mining sand.

5. Conclusions

The SWCCs of mining sand with different size distribution were produced using pressure plate apparatus and compared to SWCC of Ottawa sand obtained by Li (2008) using the Tempe cell. The SWCC for the studied soil show similarities due to their similar physical properties. The experimental results were compared to the mathematical models proposed by Van Genuchten (1980) and Fredlund and Xing (1994). Results show that the 2mm mining sand has a lower AEV and residual suction than mining sand and mining sand without 2mm sand.The comparisons show that the Van Genuchten (1980) and Fredlund and Xing (1994) models using three fitting parameters and based on pore size distributions provide almost identical results except at high suction values and yields a good fit with the experimental data. In addition, both models produced almost identical results to the laboratory data. It could be used to predict permeability coefficients and SWCCs for the mining sand.

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