

## Artigos

# Statistical comparison between the adjustment equations of the water retention curve in sanitary landfills coverage soil

## Comparaç o estat stica entre as equa es de ajuste da curva de reten o de  gua em solo de cobertura de aterro sanit rio

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### Abstract

Residual soils result from chemical weathering, so their characteristics depend on environmental factors, in addition to origin, topography, drainage and geological age. In the unsaturated condition, the behavior of soils is conditioned by suction, which refers to the state of the soil under reduced pressure. The aim of this study is to compare the water retention curve fitting equations in the study of tropical unsaturated soils through the filter paper technique and the analytical analysis of the data obtained in this test. By performing the analysis of the statistical evaluation parameters used in this study and the proximity of its values to the necessary boundary conditions defined for the equation to explain the soil suctioning behavior of the soil as it loses moisture naturally to the environment, it was verified that the Van Genuchten equation appeared to be the most suitable.

### Resumo

Os solos residuais resultam do intemperismo qu mico, logo suas caracter sticas dependem de fatores ambientais, al m de origem, topografia, drenagem e idade geol gica. Na condi o n o saturada, o comportamento dos solos   condicionado pela suc o, que se refere ao estado do solo sob press o reduzida. O objetivo deste estudo   comparar as equa es de ajuste da curva de reten o de  gua no estudo de solos tropicais insaturados atrav s da t cnica do papel filtro e a an lise anal tica dos dados obtidos neste ensaio. Ao realizar a an lise dos par metros de avalia o estat stica utilizados neste estudo e a proximidade de seus valores  s condi es de contorno necess rias definidas para a equa o para explicar o comportamento de suc o do solo   medida que ele perde umidade naturalmente para o meio ambiente, foi verificou que a equa o de Van Genuchten parecia ser a mais adequada.

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## 1. INTRODUCTION

Residual soils naturally found on all continents, especially in the tropical climate area, and formed in areas close to its parent rock, are due to constant erosion by physical and chemical processes. Das and Sivakugan (2016) stated that the effect of weathering varies widely depending on the climatic conditions in that area. The characteristics of the residual soil depend on its parent rock and vary along the depth towards the weathered rock.

The unsaturated or partially saturated condition, when associated with changes in the structure of the residual soils generates changes in the geotechnical and mechanical behavior of these soils, which are not well explained by the usual geotechnical parameters, thus making the description of the soils less consistent with reality (FREDLUND; RAHARDJO, 1993).

Lateritic soil is a highly weathered tropical soil. The water pre-

sent in the soil is responsible for solubilizing the ions adhered to the constituent materials of the soil and promotes the dissolution of the occluded gases in the pores. The presence of water in unsaturated soils, changes in moisture, due to climate change, modify properties such as capillarity and soil suction, interfering with their behavior (CAMAPUM DE CARVALHO *et al.*, 2015).

According to Fredlund and Rahardjo (1993), to distinguish saturated soils from unsaturated soils, it is necessary to know their characteristics regarding the environment in which the soil is located and its behavior in engineering constructions. Unsaturated soils can be divided into three phases: liquid (l), gaseous (g) and solid (s). The gas phase consists of dry air and water vapor, the liquid phase consists of liquid water and dissolved dry air, and the solid phase is composed of soil grains (S NCHEZ *et al.*, 2016; ABED; SOŁOWSKI, 2017; ZHENG *et al.*, 2020).

Fredlund and Morgenstern (1977) postulated the fourth phase for unsaturated soil, in addition to the air, water and solid phases. This additional phase, called the contractile skin or air-water interface, acts as an elastic membrane pulling soil particles through surface tension and influencing the soil's mechanical behavior (RAHARDJO; KIM; SATYANAGA, 2019).

The need for contractile skin to be recognized as a fourth phase can be visualized through the observation of volume changes that can occur, for example, due to the shrinkage imposed by the air-water interface during the drying of a soil (FREDLUND, 2016).

Due to the capillary effect on the soils, a movement of the water rise occurs, where it is raised above the level of the water table, against the action of gravity. The difference between air (atmospheric) and water pressures ( $u_{ar} - u_w$ ) is called soil suction. The suction present in unsaturated soils is always negative (CAMAPUM DE CARVALHO *et al.*, 2015).

In general, the total suction of a soil ( $\Psi_{Total}$ ) is usually divided into two components: the matric suction ( $\Psi_{Mat}$ ) and the osmotic suction ( $\Psi_{Osm}$ ). Therefore, the total suction is given by Equation (1):

$$\Psi_{Total} = \Psi_{Mat} + \Psi_{Osm} \quad (1)$$

The main methods of obtaining suction consider the direct or indirect interaction with soil, the direct interaction being that which measures the energy of the water in the pores, and the indirect interaction is the one in which are obtained parameters that can be related to the suction of the soil through a calibration.

One of the main methods of obtaining suction indirectly is by means of the filter paper technique. Filter paper is considered an indirect method of suction evaluation, since calibration equations are used to determine the suction values, where moisture is transferred from the unsaturated material to the dry filter paper, after an equilibrium period (KUCHIISHI *et al.*, 2019).

Basically, there are two techniques using filter paper to assess suction: non-contact and with contact. In the non-contact technique, the transfer of moisture from the soil to the paper takes place in the vapor phase above the specimen, since the filter

paper is suspended above the sample. In the contact technique, the filter papers are placed in direct contact with the soil sample. Consequently, adsorption forces control the transfer of moisture from the soil to the paper. In both techniques, equilibrium suction and equilibrium soil moisture are determined by the amount of water adsorbed by the papers and by the paper's calibration curve. (GARAKANI *et al.*, 2018).

One way to evaluate the suction of a soil is by means of the water retention curve, which consists of the graphical presentation of the relation between the matric or total suction and the moisture (gravimetric or volumetric) or degree of saturation. By means of this curve, parameters describing the behavior of the unsaturated soil can be estimated. These parameters can be verified by means of the retention curves of each type of soil (ARAUJO, 2017).

The retention curves are calibrated by equations of the filter paper itself and by curve fitting equations.

On the other hand, the curve fitting equations relate intrinsic parameters such as residual volumetric moisture ( $\theta_{Res}$ ), volumetric moisture saturation ( $\theta_{Sat}$ ), matric suction ( $\Psi_{Mat}$ ), as well as parameters dependent on soil type (CAMAPUM DE CARVALHO *et al.*, 2015). Normal volumetric moisture ( $\theta_{Nor}$ ) and soil volumetric moisture ( $\theta$ ) can be determined by Equation (2).

$$\theta_{Nor} = \frac{\theta - \theta_{Res}}{\theta_{Sat} - \theta_{Res}} \quad (2)$$

Being,  $\theta_{Nor}$  = normalized volumetric moisture;  $\theta$  = soil volumetric moisture;  $\theta_{Res}$  = residual volumetric moisture;  $\theta_{Sat}$  = volumetric moisture saturation.

That being said, the aim of this study is to compare the water retention curve fitting equations in the study of tropical unsaturated soils through the filter paper technique and the analytical analysis of the data obtained in this test.

## 2. MATERIALS AND METHODS

### 2.1. Soil characterization

For the physical characterization, the tests presented in Table 1 were carried out in order to identify the type of soil and its properties.

**Table 1** - Soil characterization tests

Test	Norm
Soil samples - Preparation for compactation and characterization tests	ABNT (2016a)
Grain size analysis	ABNT (2016e)
Liquid limit	ABNT (2016c)
Plasticity limit	ABNT (2016d)
Soil water permeability	ABNT (2000)
Specific gravity of the Soil	ABNT (2016b)
Compaction test	ABNT (2016f)

## 2.2. Preparation of test specimens

In order to perform the filter paper test, specimens were molded using the Marshall compactor. It used cylindrical molds with 0.10 m of height and 0.10 m of diameter, according to DNIT (1995). The process consisted of mechanically striking soil samples inserted into the mold to the normal Proctor energy at its optimum moisture and maximum dry apparent density (Figure 2).

Then, using a press, metal rings 0.07 m in diameter and 0.02 m in height were screwed onto the specimen (S) in order to extract samples with the same dimensions (Figure 3 and Figure 4).

All samples were compacted at the optimum moisture content of the soil, identified as 12%, determined by the Proctor compaction test. After the preparation of the samples, the moisture content of the specimen was varied to values of  $\pm 2\%$  and  $\pm 4\%$  of the optimum soil compaction moisture.

The process of increase and decrease of the moisture content of the samples was based on the method proposed by Scariot (2018), where the samples were submitted to the water spraying process or drying through the use of a dryer until test specimens were obtained, approximately, in the defined moistures (Figure 3 and Figure 4).

**Figure 2** - Insertion of the soil in the compaction mold



**Figure 3** - Sprinkling water to the sample



**Figure 4** - Drying of the sample



### 2.3. Paper Filter Method

After the molding procedure of the specimens with the increase and decrease of their moisture contents, two filter paper (Whatman N°. 42) of 0.07 m in diameter were placed. The first was placed in direct contact with the soil of the mold in order to obtain the matric suction; while the second paper, was placed on a plastic screen that separated it from direct contact with the soil, in order to obtain the total suction of the soil. Thereafter, the ensemble was wrapped with several layers of

PVC film and a layer of foil in order to avoid moisture loss and interference from the external environment. Each specimen was labeled and remained for 15 (fifteen) days at rest inside a thermal box for the purpose of thermodynamic equilibrium (exchange of moisture and temperature equilibrium).

After the resting time of 15 (fifteen) days had elapsed, then these papers were placed in capsules and taken to the oven for 24 hours at a temperature of  $100 \pm 5$  °C. (Figure 5).

**Figure 5** - Filter paper weighing



With the moisture content of the filter papers, the experimental data was calibrated in the equations of Chandler *et al.* (1992) and ASTM (2010), Table 2.

## 2.4. Curve Adjustment Equations

The equations proposed by Gardner (1956), Van Genuchten (1980) and Fredlund and Xing (1994) were used to adjust soil water retention curves obtained by calibration of the filter paper, since according to Gerscovich and Sayão (2002), represent the best adjustments for Brazilian soils.

**Table 2** - Filter paper calibration equations

Reference	Type of suction	Equations	Requirements
Chandler <i>et al.</i> (1992)	Not defined	$\Psi = 10^{(4.84 - 0.0622 \times W_{pf})}$ $\Psi = 10^{(6.05 - 2.48 \times \text{Log}W_{pf})}$	$W_{pf} \leq 47\%$ $W_{pf} > 47\%$
D5298 (ASTM, 2010)	Not defined	$\Psi = 10^{(5.327 - 0.0779 \times W_{pf})}$ $\Psi = 10^{(2.413 - 0.0135 \times W_{pf})}$	$W_{pf} < 45.3$ $W_{pf} > 45.3$

Source: Adapted from Araujo (2017).

## 3. RESULTS AND DISCUSSION

This research was developed in the city of Campina Grande-PB, located in the Agreste region of Paraíba and inserted in the Brazilian Semiarid Region, where it has an average temperature of 22.7 °C, annual evaporation of 1417.4 mm and average annual rainfall of 802.7 mm/year, which represents conditions typical of semi-arid zones and tropical latitudes (AES, 2017).

The experimental field of this research is the sanitary landfill located at Fazenda Logradouro II in the municipality of Campina Grande-PB, located at kilometer 10 of the PB-138 that connects the city of Campina Grande to the district of Catolé de Boa Vista.

The landfill has been in operation since the month of July 2015 occupying a total area of 80 ha, with 39,384 ha destined for the construction of municipal solid waste cells. Designed to initially receive 350 tons of waste per day, for a useful life of 25 years, it now receives 500 tons of waste/day from the municipality of Campina Grande as well as contributions from other municipalities.

As material for covering the waste, a clayey soil from the bed of an empty reservoir (earth dam) in the landfill region is used. The collection of the soil to carry out the tests proceeded in

## 2.5. Statistical analysis

The software STATISTICA 12.0 was used for the treatment of the experimental data in order to adjust the parameters of the equation to the experimental data. From the Gauss-Newton interactive process, it was established a maximum number of interactions of 100, a convergence criterion of 10<sup>-6</sup> and a significance level  $\alpha = 5.0\%$ , obtaining the values of the parameters of the analyzed equations.

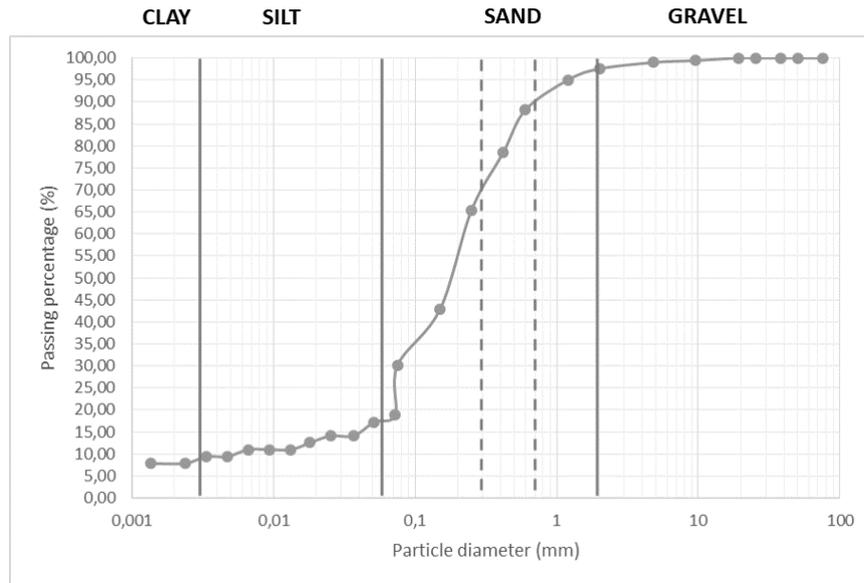
compliance with the ABNT NBR 9604/2016 standard, where the samples were packed in plastic bags and taken to carry out the tests as deformed samples.

In the laboratory, the soil was spread out in the open air for prior drying until near hygroscopic moisture, following the procedures described in ABNT NBR 6457/2016. After drying, the clods of soil were dismantled, taking care not to break the grains. Then, the soil was homogenized and quartered to obtain a representative sample in sufficient quantity to carry out the characterization tests.

### 3.1. Physical characterization of the soil

Figure 6 shows the particle size distribution curve of the studied soil. The analyzed soil is classified as a silty sand (SM), according to the D2487 (ASTM, 2011), which governs the classification of the Unified Soil Classification System (USCS), and has a particle size distribution of 1.0% gravel, 7.0% coarse sand, 27.0% medium sand; 48.0% fine sand, 7.0% silt and 10.0% clay. It has a coefficient of non-uniformity (CNU) in the order of 37 and curvature coefficient (CC) in the order of 3, being characterized as a non-uniform and well graded soil. The grain size curve showed predominance of the sand fraction, 82%, to the detriment of fine fractions, silt 7.25% and clay 9.75%.

**Figure 6 - Granulometric soil curve**



The Table 3 presents the soil physical indexes. It behaves as a non-liquid (NL) and non-plastic (NP) material, corroborated by the low hygroscopic moisture content of 0.80%, typical of sand predominant soils with low water retention. According to Sá and Silva (2010), in the semi-arid environment, where the municipality of Campina Grande-PB and its district of Catolô de

Boa Vista are located, climate and geology play a major role in the formation of soils. In this region, the geology is quite variable with predominance of crystalline rocks, followed by sedimentary areas, covered by sandy or clayey materials and of small thickness.

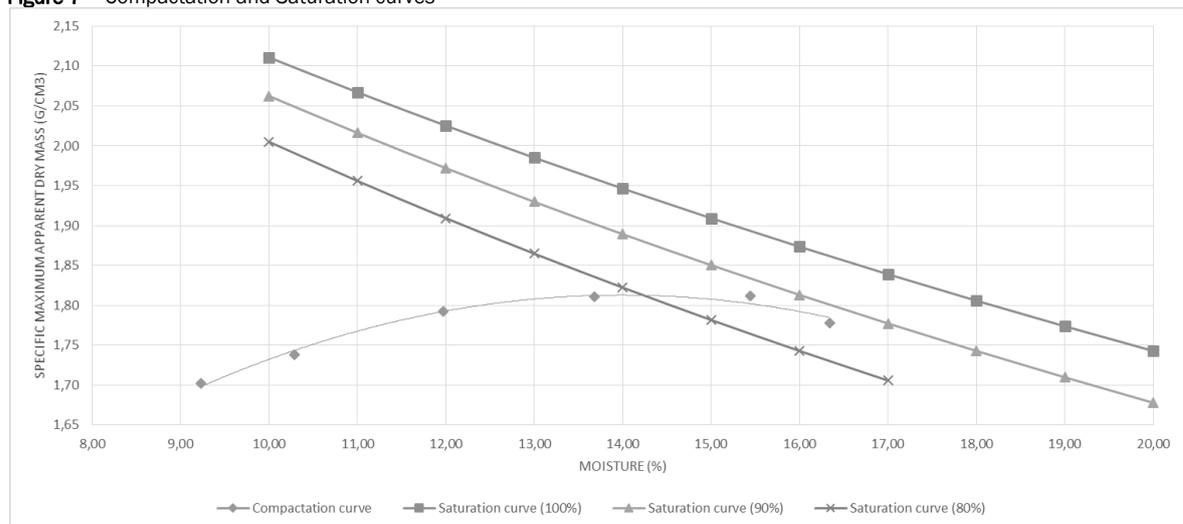
**Table 3 - Atterberg Limits and Specific Gravity of Soil**

Specific Gravity of Soil (g/cm <sup>3</sup> )	Liquid Limit (%)	Plasticity Limit (%)	Plasticity Index (%)
2.68	NL	NP	< 4

Figure 7 shows the soil saturation curves for the Proctor compaction test. From the compaction test, an optimum moisture content of 12.0% was obtained, lying between 80% and 90% of soil saturation, as observed by Pinto (2006). It has a maxi-

imum specific apparent dry weight of 18.20 kN/m<sup>3</sup>, which according to Dantas Neto *et al.* (2013), soils with predominance of sand in their composition, when compared with clayey soils, present higher values of specific maximum dry weight.

**Figure 7 - Compaction and Saturation curves**



Its saturated permeability to water is of the order of  $1.0 \times 10^{-6}$  m.s<sup>-1</sup>. According to Pinto (2006), soils with this permeability are characterized as silty soils; as for Knappett and Craig

(2016), such permeability is typical of very fine sands. From the value of soil water permeability, one can accept the statement by Ramos *et al.* (2016), that soils with coarse texture

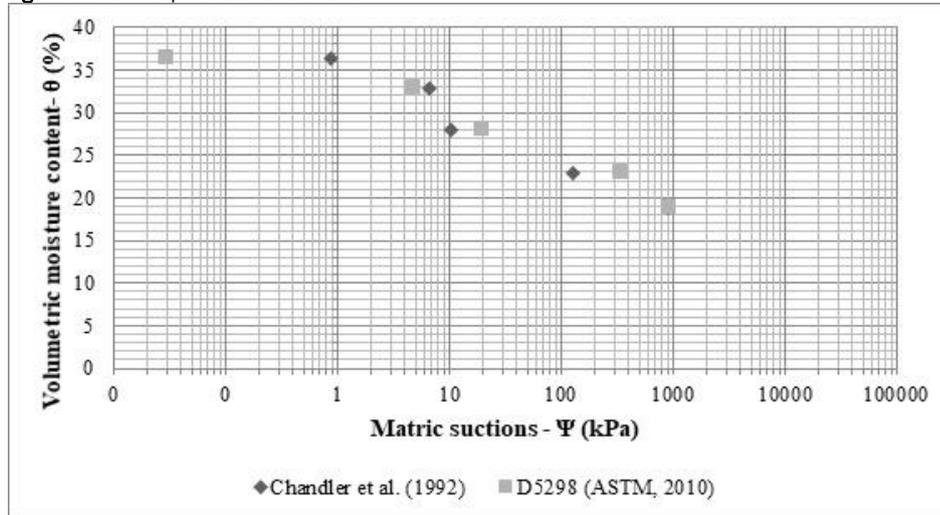
have a lower water retention capacity due to the small percentage of fine materials (silt and clay) in their composition. The analyzed soil presents 82% of sand in its composition.

### 3.2. Water retention curve in soil

With the calibration of the parameters contained in the adjust-

ment equations of Chandler *et al.* (1992) and ASTM (2010), the experimental data obtained in the suction test by the filter paper method was adjusted, finding a semi-logarithmic graphical relation between the soils matric suctions ( $\Psi$ ) by their respective volumetric moisture content ( $\theta$ ), (Figure 8).

Figure 8 - Filter Paper Calibration Curve



It is observed in Figure 13, values close to matric suction between the two forms of calibration of the filter paper, ranging from about 1.0 kPa to 1000.0 kPa. As expected, there is an increase in soil suction as the volumetric moisture of the material tends to decrease.

### 3.3. Curve Adjustment and Statistical Analysis

After the treatment of the experimental data in the Statistica 12.0 software, the following statistical parameters can be obtained for the analysis of the curve adjustment, Table 4. It is worth noting that the order of analysis initially follows the determination coefficient ( $R^2$ ), the Mean Square Error (MSE), the standard error and finally the Akaike information criterion (AIC).

It is observed through Table 4 that for the Chandler *et al.* (1992) method, the adjustments of the experimental data to the soil characteristic curve proposed by Gardner (1956) and

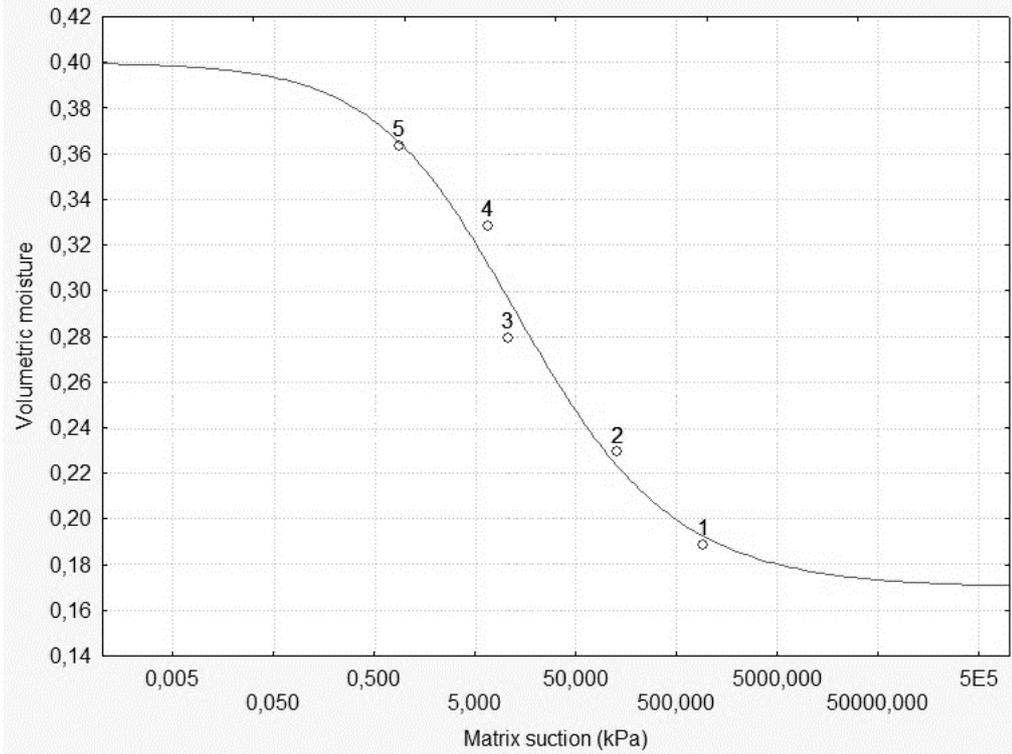
Van Genuchten (1980) present determination coefficients ( $R^2$ ) closer to the unit, the latter presents the lowest values of MSE and Standard Error. For the adjustment proposed by Gardner (1956), the calculated AIC was the largest negative value, -40.86, among those analyzed.

Figure 9 shows the Van Genuchten (1980) curve adjustment obtained from the analysis of the experimental data determined by the Chandler *et al.* (1992) method. From the curve, it is observed a maximum value of 40% volumetric moisture, a residual matric suction ( $\Psi_{Res}$ ) of 50 MPa, residual volumetric moisture ( $\theta_{Res}$ ) of 15%, and the formation of frontier zones (beginning of the curve), transition (sloping part of the curve) and residual (after point 1), as specified by Fredlund *et al.* (1996). According to Fredlund and Xing (1994), the behavior of the curve corroborates that of granular soils, because they have macropores that prevent the retention of water and the easy loss of moisture.

Table 4 - Statistical analyzes

Methods	Curve Adjustments	$R^2$	MSE ( $\times 10^{-4}$ )	Standard error ( $\times 10^{-3}$ )	AIC
Chandler <i>et al.</i> (1992)	Gardner (1956)	0.97	112.62	3.29	-40.86
	Van Genuchten (1980)	0.97	111.80	2.90	-38.94
	Fredlund and Xing (1994)	0.96	124.28	3.29	-37.88
D5298 (ASTM, 2010)	Gardner (1956)	0.95	143.27	3.02	-38.46
	Van Genuchten (1980)	0.97	110.70	1.09	-39.04
	Fredlund and Xing (1994)	0.90	196.68	5.05	-33.29

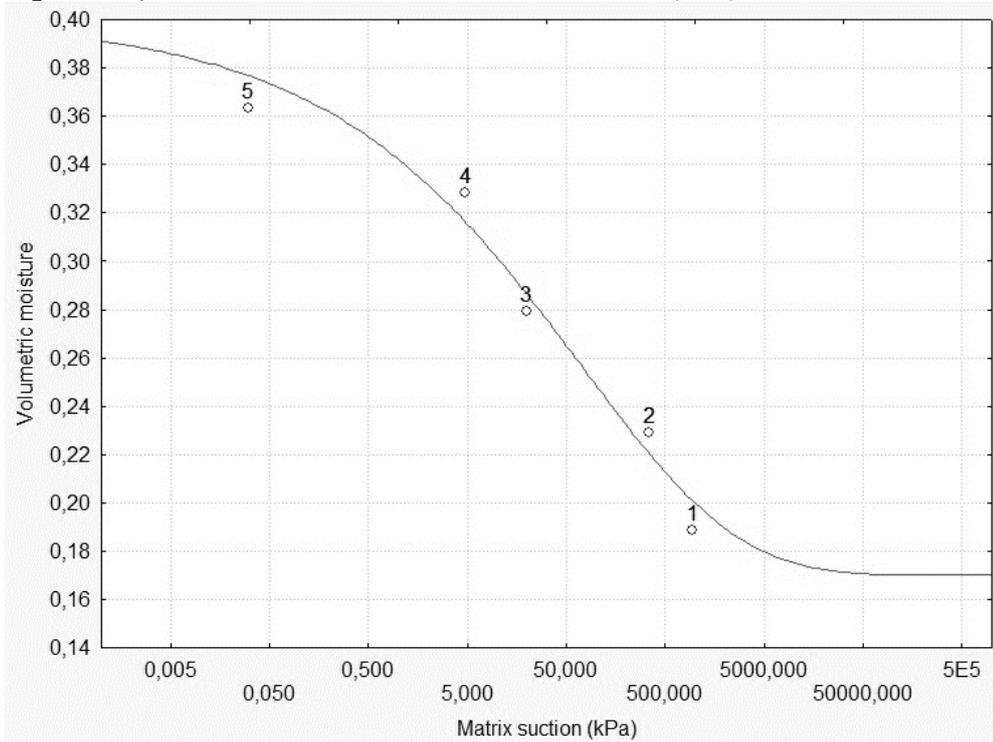
**Figure 9** - Adjustment of soil water retention curve of the Chandler *et al.* (1992) method



Still from Table 4, it can be observed that for the D5298 (ASTM, 2010) method, the Van Genuchten (1980) curve adjustment presented statistic parameters more significant than the other adjustment equations. The adjustment in question has a determination coefficient closer to the unit, lower values

of MSE and standard error, as well as the most negative value of AIC among the others. In Figure 10, the experimental data found by the D5298 (ASTM, 2010) method adjusted to the Van Genuchten (1980) equation are exposed.

**Figure 10** - Adjustment of soil water retention curve of the ASTM method (2010)



The curve of Figure 10 shows a behavior similar to that of the Chandler *et al.* (1992) method. The highest volumetric moisture ( $\theta$ ) recorded by the data was approximately 39%, with residual matric suction ( $\Psi_{Res}$ ) and residual volumetric moisture ( $\theta_{Res}$ ) equal to the previous method.

#### 4. CONCLUSIONS

It is concluded, from the study, that:

- The Van Genuchten equation is the most adequate to explain the behavior of the experimental data, with a significance level of 5.0%. This assertion could be verified by the proximity of its values to the necessary boundary conditions defined for this equation to explain the matric suction behavior of this soil as it loses moisture naturally to the environment;
- Among the calibration methods, the use of the Chandler equation is recommended. This equation presented the statistical parameters results closest to the limit values defined in this study, in addition to, being the most used equation to calibrate the filter paper and determine the soil characteristic curve;
- For the definition of the adjustment equation that best explains the behavior of experimental data, it is verified that the larger the number of statistical parameters used for analysis of the experimental data in comparison to the estimates, the more significant the results.

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