Effect of Freezing-Thawing Cycles on Suction Measurement of Unsaturated Soil

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Abstract. The basic relationship between the volumetric water content of soil and suction value is defined as soil water characteristic curve or soil retention curve that plays an important role for determining properties of unsaturated soil and estimating its mechanical behavior. The present study is an attempt to evaluate the effect of freezing-thawing cycles on suction parameter of unsaturated soil. Suction is measured by filter paper method. Experiments have been conducted on 5 Cycles of freezing-thawing of samples and their soil water characteristic curves have been developed with the change in its air entry value and residual water content of soil for each cycle are presented in this paper.

Keywords: Unsaturated soil, Soil Water Characteristic Curve, Suction Measurement.

1 Introduction

1.1 Freezing-Thawing of soil

Jammu and Kashmir is the coldest region in India. Indian meteorological department reports the temperature ranges from -20℃ in winter to 35℃ in summer. Freeze-thaw cycle causes frost action which leads to frost heave and thaw weakening. The former is due to formation of ice crystal, ice lenses and later is due to melting of ice.

Silt is the most frost susceptible soil. Silt pores are large enough to transport an enough supply of moisture to the freezing front and small enough to promote suction and capillarity. Casagrande (1931) observed that ice segregation did not appear in soils containing less than 1% of grains smaller than 0.02 mm. Efforts done to investigate the influence of freeze–thaw cycles on soil properties were reviewed and summarized its influence in two parts: physical properties such as density and hydraulic permeability and mechanical properties such as ultimate strength, strain–stress behavior and resilient modulus. Loose soils tend to be densified and dense soils become loose after freeze–thaw cycles and both loose and dense soils may attain the same void ratio after a number of cycles. Having increased the large pores that are left after the thaw of ice crystals, permeability will increase.

Freezing can be of two type open and closed system. De Groot (1951) defined an open system as exchange of matter, heat, work and energy with its surroundings. Jones (1987) defined open-system freezing for soil as the condition where pore water in excess of that available in the voids of the soil is available to be moved to the surface of freezing to form segregated ice in frost susceptible soil. De Groot defined as closed system as exchange of heat, work and energy but no matter. Jones defined closed system of soil as no source of water available during the freezing process beyond the originally available in the voids of the soil or near the zone of freezing and the ice lenses may or may not form. In an open system water is drawn up from a free surface through the soil as the freezing front moves downward. This movement of water due to freezing level creates ice lenses in the soil. Closed System there is a redistribution of moisture to the freezing front occurs and this movement causes an increase in water content and decrease in dry density near the freezing front.

1.2 Unsaturated Soil

According to Fredlund and Raharjdo, the unsaturated is generally neither in totally dry condition nor in saturated condition, but has degree of ranging from 0 to 100 percent. Theories developed for saturated and dry condition cannot be developed directly for unsaturated condition.

Terzaghi came up with a concept contractile skin which is nothing but a thin layer of air-water interface and suggested that the contractile skin might be in the order of 10^{-6} mm in thickness. Lyklema (2000) showed that the distribution of water molecules across the contractile skin takes the form of a hyperbolic tangent function. Properties of the contractile skin are different from that of ordinary water and have a water molecular structure similar to that of ice (Derjaguin and Churaev 1981; Matsumoto and Kataoka 1988).

1.3 Soil Water Characteristic Curve

Soil water characteristic curve (SWCC) or soil water retention curve is a graphical presentation of Suction pressure in soil with its varying Volumetric water Content as shown in fig 1(Fredlund 1995, 2000). However the term “characteristic” shows that a distinctive relationship can characterised many of hydraulic and mechanical behaviour of the unsaturated soil, despite of the high dependency of this relationship on the initial state such as sample’s degree of saturation and void ratio, fabric, state of stress, hydraulic path, temperature, etc. Air entry value is defined as the matric suction value that must be exceeded before air recedes into soil pores. The definitions of residual water content are based on developed statistically by various researchers and each of them has different approach. It has no significant physical meaning and is only used for fitting parameters.

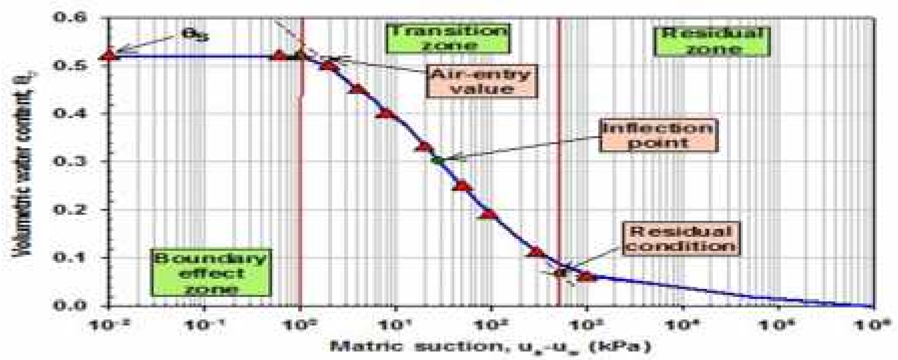

Fig.1. Soil Water Characteristic Curve

Brooks and Corey (1964) defined residual water content as water content at which suction reaches infinity. This is the disadvantage of this method as it is not possible to extend SWCC to infinity. The soil suction up to 1000000 Kpa is acceptable (Mitchell 1976). There is experiment evidence supporting this value provided by many researchers (Croney and Coleman 1961; Russam 1958; vanapalli 1994 and Fredlund 1964). Thermodynamics principles also support zero water content at 1,000,000 Kpa suction (Richards 1965; Wilson et al 1994). Van Genuchten in 1980 defined residual water content as the water content as soil suction of 1500 Kpa. This is the limit of most soil suction testing device as models are used from agricultural and generally does not require to model beyond the wilting point. But in 1991 residual water content is defined as water content at which slope of SWCC and a coefficient of permeability goes zero when soil suction becomes very large. But coefficient of permeability is a non zero, finite number (Nitao and Bear, 1996) so definition is an irony to the interpretation.

1.4 Empirical Models For SWCC

There are several empirical equations that have been proposed to describe SWCC such as Gardner(1959),Brooks and Corey (1964), Campbell (1974), Van Genuchten (1980), Fredlund and Xing (1994), Gitirana and Fredlund (2004), Fredlund and pham (2006). Many SWCC equations take the form of a continuous function that that is asymptotic at the extremities. It is a zone between air entry value and residual suction where the curve has sufficient slope for calculation soil suction. Van Genuchten(1980) and Fredlund Xing (1994) empirical model is widely used.

1.4.1 Van Genuchten fitting method (VG model)

The van Genuchten equation is the most common equation used SWCC equation. This equation has 3 parameters as follow:

$$w(\psi) = \frac{w_s}{[1 + (\alpha\psi)^{n}]^{m}} \quad (1)$$

Where 'a' is air entry fitting parameter, m and n are the parameters of fittings for inflection of curve and w_s is saturated water content. The above equation can be rearranged to solve suction in terms of water content.

$$\psi = \frac{1}{a}\left[\left(\frac{w_s}{w}\right)^{\frac{1}{m}} - 1\right]^{\frac{1}{n}} \qquad (2)$$

The usage of this equation is limited to air entry value and the residual suction of a soil because of the asymptotic nature of equation.

1.4.2 Fredlund and Xing fitting method (FX model)

They proposed the equation that has range beyond residual suction to completely dry conditions:

$$w(\psi) = C(\psi)\frac{w_s}{\left\{\ln\left[e + \left(\frac{\psi}{a}\right)^{n}\right]\right\}^{m}} \qquad (3)$$

Where w (ψ) is water content at any soil suction; w_s is the saturated water content; a, n and m are the fitting soil parameters associated with the SWCC. The e is the base of natural logarithm. The correction factor, C (ψ) is written as follow:

$$C(\psi) = 1 - \frac{\ln\left(1 + \frac{\psi}{\psi_r}\right)}{\ln\left(1 + \frac{10^6}{\psi_r}\right)} \qquad (4)$$

Where ψ is any soil suction value and ψ_r is soil suction at residual conditions. Usually correction factor is taken as 1. To calculate soil suction in terms of water content the equation can e written as

$$\psi = a\left[e^{\left(\frac{w_s}{w}\right)^{\frac{1}{m}}} - e\right]^{1/n} \qquad (5)$$

1.5 Filter paper method for Suction measurement

Filter paper technique is the only method from which both total and matric suction can be deduce. Using the filter paper method, the soil specimen and filter paper are brought to moisture equilibrium either in contact (matric suction) or not in direct contact (total suction) in a constant temperature environment (Fig.2). Direct contact between the filter paper and the soil allows water in the liquid phase and solutes to exchange freely. The water content of filter is measured after equilibrium is established. Then, by using the suitable filter paper calibration curve, the suction of the soil is estimated.

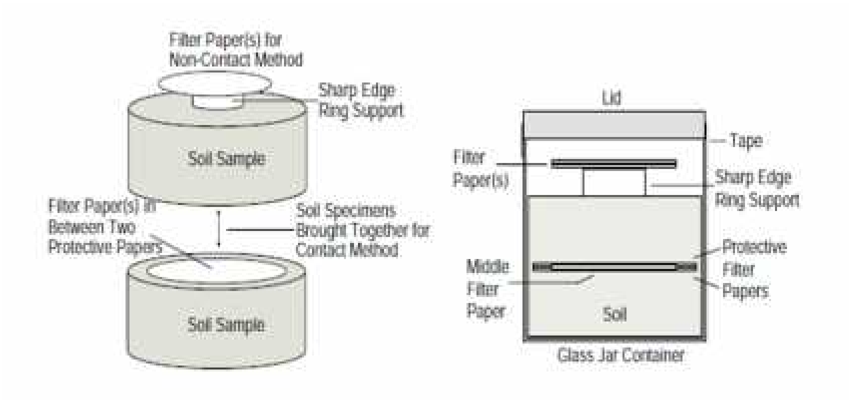

Fig.2. Filter paper Method to measure suction

Different filter paper method calibrations are attributed by the different researchers. Whatman No.42 Filter paper was used to measure suction and its calibration curve is given in fig.3.

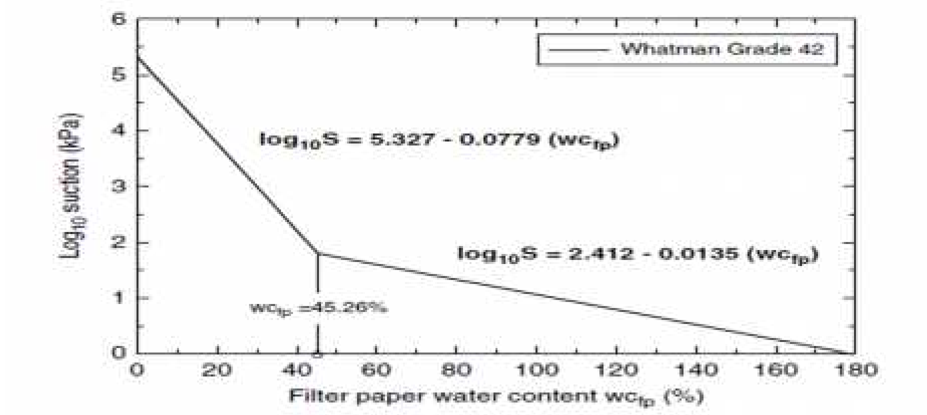

Fig.3. Calibration curve for Whatman Grade 42(ASTM D5298-10)

2 Material and its properties

In this study laboratory test was carried out on Silty clayey sand as per IS code Classification and Unified soil classification system. The properties of soil are depicted in table 1. Whatman Grade 42 filter paper was used having thickness of 200 µm and pore size of 2.5 µm.

Table.1. Properties of soil.

Specific Gravity	2.63
Liquid Limit (%)	24.33
Plastic limit (%)	18.75
Plasticity index (%)	5.58
Maximum dry density(gm/cc)	1.86
Optimum Moisture Content	14

3 Testing procedure

3.1 Specimen Preparation

To estimate suction soil sample was prepared in consolidation ring and was removed and put in air tight container. Two cakes of soil sample were prepared at same degree of saturation as shown in fig.4. Water content at degree of saturation of 90%, 80%, 70%, 60%, 50%, 40%, and 30% was taken to prepare the sample by simple relation between water content, degree of saturation, mass of dry soil, void ratio and specific gravity. As shown in Fig.2 Three layers of filter paper were kept between the two cakes of the sample (Fig.4). Two layers of filter paper one above and one below the main filter paper was kept as a protecting layer.

Fig.4. Sample to measure suction

3.2 Freeze-thaw Cycle

Samples were subjected to five cycles of freeze-thaw in closed system. Freezing was done below -23℃ for 24 hours and thawing was done for 23 hours at normal temperature varying between 25℃ to 30℃ according to IS code 4332.4.1968. To obtain closed system for the sample it was doubled wrapped with black polythene bag and kept in air tight container so that no moisture can come in or go out to or from the system. The samples were weighted before and after freeze-thaw cycles to see the difference in moisture before and after placing and the change in weight for first two cycles were zero and for rest cycles it was ± 1 gram for many samples. For few samples that have low moisture content (at S_r = 60%, 40%, 30%) have no change in its weight which shows that there is no loss or gain of moisture.

3.3 Estimation of Soil Water Characteristic Curve

ASTM D5298-10 code was used to follow guidelines for Filter paper method of Whatman Grade 42 and its calibration Curve (Fig.5) to estimate suction and empirical models of Van Genuchten (1980) and Fredlund and Xing (1994) to estimate SWCC with the help of SOIL VISION software.

4 Results

The results by both empirical models are given in Table 2. The samples were subjected to 5 cycles of Freeze-thaw because there was no much change in the parameters after 3rd, 4th cycle. The fig 5.1 to fig 5.6 shows the SWCC found by VG model and fig 6.1 to fig 6.6 shows SWCC found by FX model for 0th to 5th cycle. Air entry value for 0 to 2 Cycles for both model shows decrease in value and then from cycle 3 it was random but when compared between two fitting models it was not much of difference except 4th cycle while air entry parameter for VG model (α) was random and that for FX model (A_f) was decreasing up to cycle 2 and then remained same (2500 kpa). For all cycles for both models saturated water content was same. For VG model inflection parameter n and m have no significant change after 2nd cycles of freeze-thaw and that for FX model there was sudden change between cycle 2 and 3. R^2 Value close to 1 is most accurate fitted Curve.

Table. 2. Fitting Parameters with air entry value and residual water content for both models.

			VG MODEL DATA			
CYCLES	0	1	2	3	4	5
α	0.006	0.001	0.001	0.0002	0.0003	0.0003
R^2	0.917	0.934	0.91	0.980	0.956	0.9688
Air entry (kpa)	48.02	7.68	5.45	226.83	41.4	60.63
Saturated W.C (%)	28.66	28.42	28.42	28.77	29.05	29.20
Residual W.C (%)	13	14	12	20	19	17.5
Residual Pressure (Kpa)	1500	1500	1500	1500	1500	1500
n	3	0.38	0.517	0.612	0.418	0.489
m	6.84	0.902	0.562	0.957	0.754	0.9271
			FX MODEL DATA			
A_f (kpa)	47.70	28.16	23.60	2500	2500	2500
R^2	0.915	0.965	0.982	0.9819	0.968	0.9705
Air entry (kpa)	40.08	21.79	20.67	217	223.24	67.48
Saturated W.C (%)	29.22	29.22	29.22	29.15	28.92	29.15
n	20	20	14.64	0.62	0.336	0.4622
m	0.111	0.084	0.126	1.62	1.59	2.12
Residual W.C (%)	18.33	19.75	17.21	5.35	11.66	3.83
Residual pressure (Kpa)	74.21	75.53	75.45	62129	340689	77219

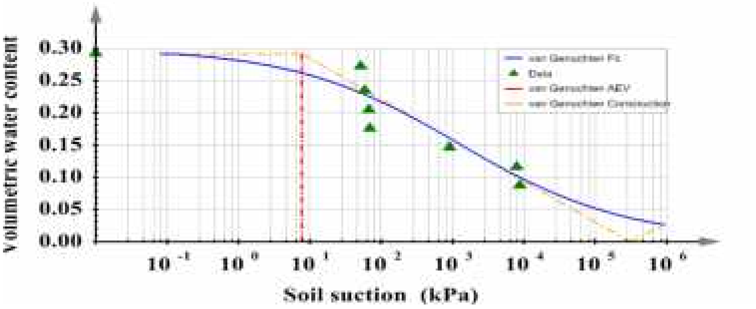

Fig.5.1. Van Genuchten fitting (0^{th} cycle)

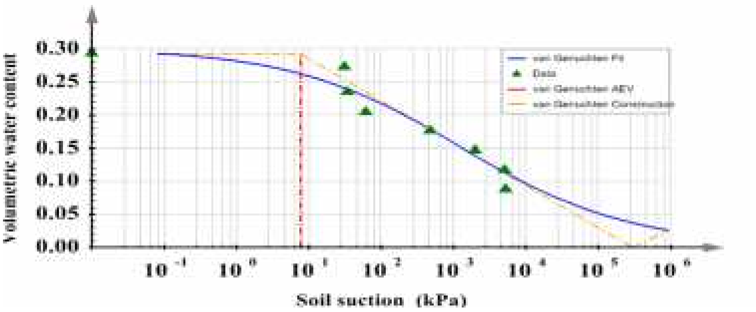

Fig.5.2. Van Genuchten fitting (1^{st} cycle)

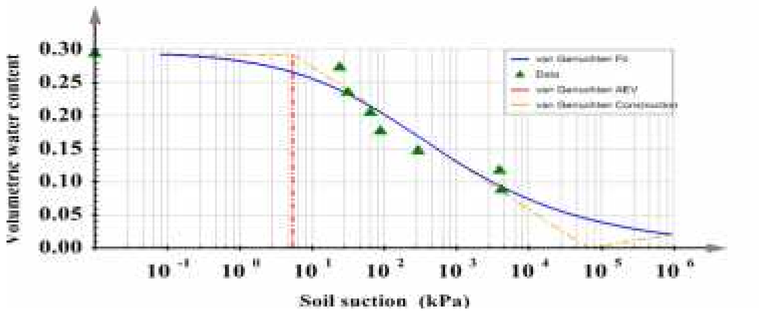

Fig.5.3. Van Genuchten fitting (2^{nd} cycle)

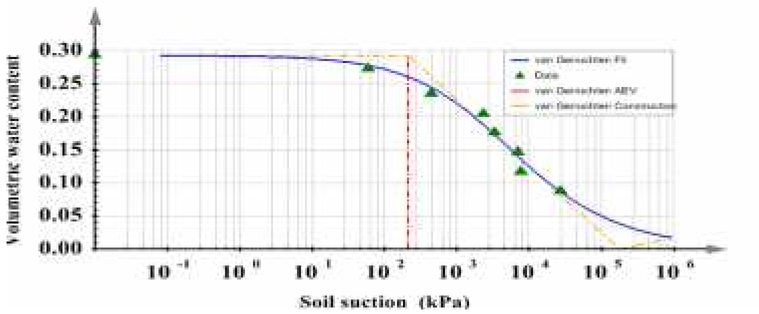

Fig.5.4. Van Genuchten fitting (3^{rd} cycle)

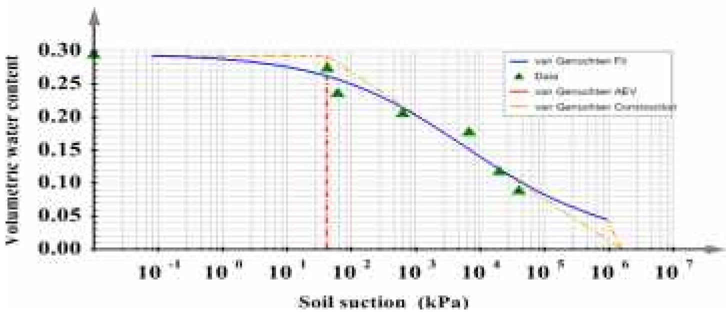

Fig.5.5. Van Genuchten fitting (4th cycle)

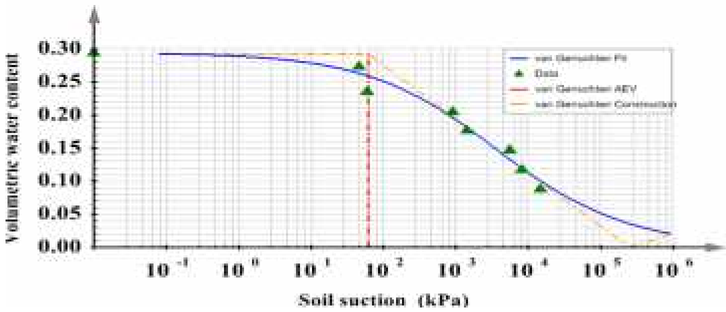

Fig.5.5. Van Genuchten fitting (5th cycle)

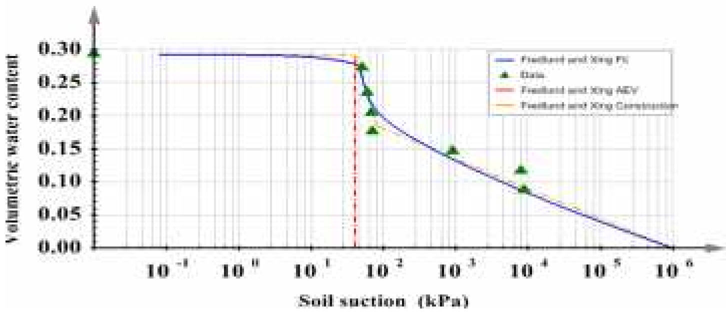

Fig.6.1. Fredlund and Xing fitting (0th cycle)

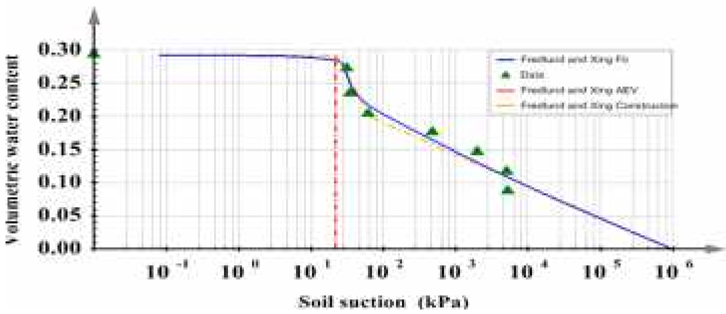

Fig.6.2. Fredlund and Xing fitting (1st cycle)

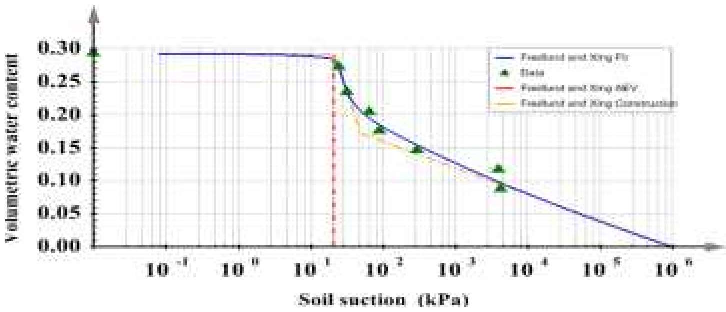

Fig.6.3. Fredlund and Xing fitting (2nd cycle)

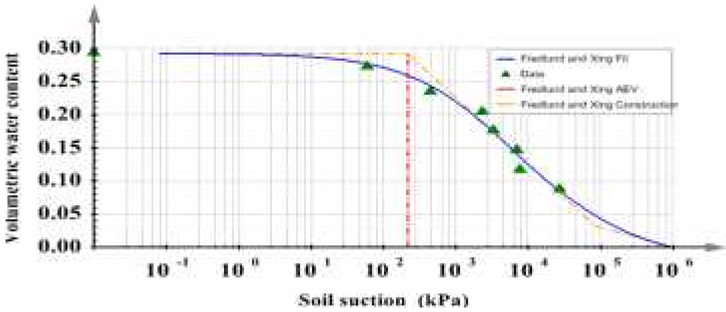

Fig.6.4. Fredlund and Xing fitting (3rd cycle)

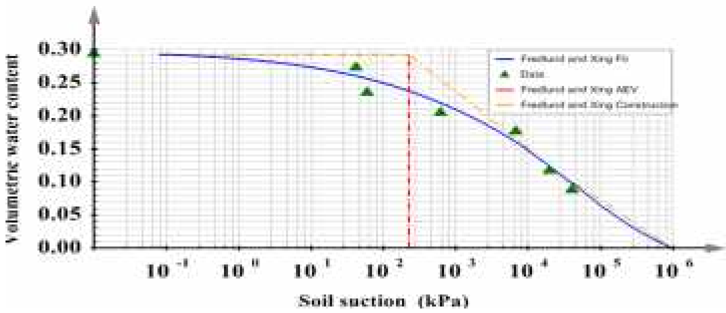

Fig.6.5. Fredlund and Xing fitting (4th cycle)

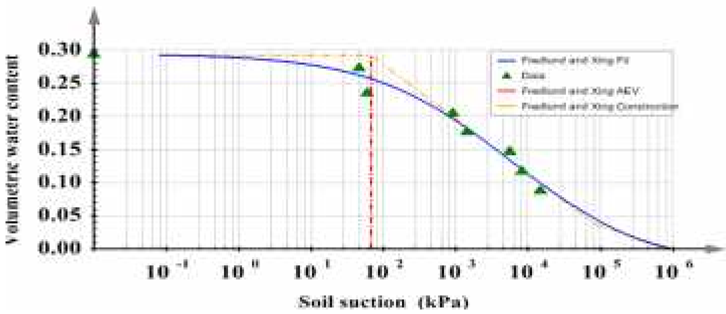

Fig.6.6. Fredlund and Xing fitting (5th cycle)

5 Conclusion

1. From Van Genuchten SWCC graph, it can be seen that the construction line (orange dotted) goes below VG fit curve (blue curve) intersecting on X axis and then joining the curve. This means that suction still exist though the soil has become dry which is practically incorrect. As per VG model, residual content is defined at 1500KPa but the results shows that there is more suction value at low water content, which shows the limitation of VG model. But there is no such problem with FX model. Furthermore, as 1500KPa is limitation for defining VG model to define residual content it is best used when the suction value for soil is low i.e. for coarse grained soil like sand having bigger pores.
2. From no freeze-thaw (0^{th} cycle) to its 2^{nd} cycle there is decrease in air entry value and suction value because there may be increase in pore size during freezing. But from 2^{nd} to 3^{rd} to 4^{th} cycle there is sudden increase in air entry value and suction value for water content (at S_r = 60% 50% 40% 30 %) except for that of VG model 4^{th} cycle. It might be because of its limitation concluded above. This sudden increase may be due to decrease in pore size from adjacent increase in pore size and equilibrium between filter paper and moisture in sample is due to suction taking place from path of decreased pore size.
3. In FX model there is no change in air entry fitting parameter (A_f) after 3^{rd} cycle of freeze-thaw. But the change in air entry value is observed. This is due to sudden decrease of fitting parameter ‘n’ (slope parameter) from 2^{nd} to 3^{rd} cycle because of decrease in suction at higher water content (at S_r = 90%, 80% and 70%) and increase in suction at lower water content (at S_r = 60%,50%,40% and 30%).
4. FX model shows very high residual suction pressure after 3^{rd} cycle which may be not possible. Therefore, other technique for measurement of suction is necessary to check the accuracy of Filter paper method.

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