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An Experimental Study and Modelling of Water Retention Characteristic Curve of Pond Ash

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Abstract: Thermal power plants produce a large quantity of coal ash as a by-product from the combustion of pulverized coal. A small quantity of total coal ash produced is currently being utilized whereas unutilized coal ash is deposited in vicinity of thermal power plant as waste material which covers several hectares of useful land. The utility of coal ash with or without addition in various applications related to geotechnical and geoenvironmental field have been increased manifold like construction of ash dyke, road and railway embankment, landfill liners etc. In all the applications, water content of pond ash changes from saturation to dry condition during lifetime of structure. Therefore behavior of pond ash under unsaturated condition is also required to be investigated. To encourage the civil engineers to apply unsaturated soil mechanics theories in engineering practices, various numerical methods based on water retention characteristic curve have been developed. However, it is necessary to have laboratory measured data of Water retention characteristic curve. Hence, Fredlund SWCC device is used to study the water retention characteristic curve of pond ash. Drying and wetting curve were obtained for pond ash sample. The test data were best fitted using Fredlund and Xing equation, Van Ganuchten equation and estimation method. Further, the results presented in this paper signify the importance of considering WRCC hysteresis for a pond ash sample.

Keywords: Pond Ash, Water Retention characteristic curve, Hysteresis

1. Introduction

Coal Ash is obtained as a residue from combustion of a pulverised coal in Thermal power Plants. In India, the total production of coal ash was about 200 million tons in year 2016-17[1]. Despite best efforts being made since the last few decades, utilization of coal ash is only 50-60% of total production and the remaining unutilized ash is required to be disposed off. Conventionally the unitized ash is mixed with water in approx 1:10 ratio and the slurry formed is disposed off in a specially designed ash ponds. When ash slurry is deposited in an ash pond, the grain size sorting and layering occurs in the lateral and vertical directions respectively during the depositional process. Coarser particles are settled down around the inflow points whereas ash particles of smaller size are carried away with water and settled down near the outflow points. Coal ash has found wide applications in geotechnical and geoenvironmental engineering. Use of Coal ash conserves the scarce natural resources on one hand and saves the precious land which is otherwise occupied by ash pond and many environmental issues related to the deposited ash. Different properties of coal ash are required for different applications. The properties of ash are a function of several variables such as source of coal, design of boiler unit, handling and method of disposal. Thus, properties of coal ash are highly affected with the change in above mentioned factors. If Coal ash is used to be in place of natural soil material, the variation in the engineering and hydraulic properties of coal ash are required to be ascertained on account of its spatial variation within an ash pond. Coal ash has been successfully used in road and rail embankments, in dams, in low lying lands and dumping yard and in most of these applications coal ash remains in unsaturated state.

Rapid advancement and growth in field of unsaturated soil over the last few decades has led today's civil engineer to focus in understanding the behavior and to solve problems relating to unsaturated soil. Geotechnical engineering practices related with landfill covers, mine reclamation, contaminant flow and the natural slopes subjected to environmental changes have embraced unsaturated soil mechanics theories and practices [2, 3, 4 & 5]. However, there are various practices involving complexities in the behavior of unsaturated soil, intensive characterization subjected to cost and time which creates problem to be put into practice. [6, 7]. Hence, all these problems arises the need of extensive research in the field of unsaturated soil in order to understand and facilitate the solutions of problems. The measurement of the water retention characteristic curve (WRCC) has risen among all other constitutive relations as the necessary information required in the field of unsaturated soil mechanics. WRCC have a wide range of application like to study the natural slopes subjected to environmental changes, in process of mounding below contaminant retention ponds, in Stability of deep Vertical or Near-Vertical Excavations, Bearing strength for Shallow Foundations, Road and Railroad Structures. The study of behavior of unsaturated soil is related to the relationship between soil suction and volumetric water content (or gravimetric). This relationship is represented in the form of graph known as water retention characteristic curve (WRCC). The precise measurement of soil suction is important to determine the WRCC accurately. The interaction among the three phases of soil i.e solid, water and air phase develops a state of complex energy that results in negative pore water pressure known as soil suction. The soil suction present in the unsaturated soil is responsible for its transient behaviour as compared to the steady state behaviour of saturated soils. Thus, the parameters in saturated soil such as water potential, permeability, strength etc. becomes a function in unsaturated soil. The present paper deals with the water retention behaviour of Pond ash to assess its potential to be used in different Civil Engineering applications in place of natural soil like sand, silt etc.

1.1 Theoretical Background for WRCC

The water retention characteristic curve (WRCC) is the relationship of the pressure head of soil water and water content of the unsaturated soil. The relationship for a soil usually varies with the water flow process depending on whether the flow is into or out of the soil section. In the field, with the change in climate type or with other influencing factors, there exists cycles of drying and wetting paths in the soil. Early research [2, 8 & 9] recognized different WRCC trends depending on the cycles of path followed. The drying WRCC shows that water content decreases as soil suction increases, while in wetting WRCC, there is increase in water content with decrease in soil suction. The cycles of drying and wetting is responsible for moisture hysteresis of WRCC. Consequently, it is important to consider WRCC hysteresis for understanding the unsaturated behavior of soil in all climate type [10, 11].

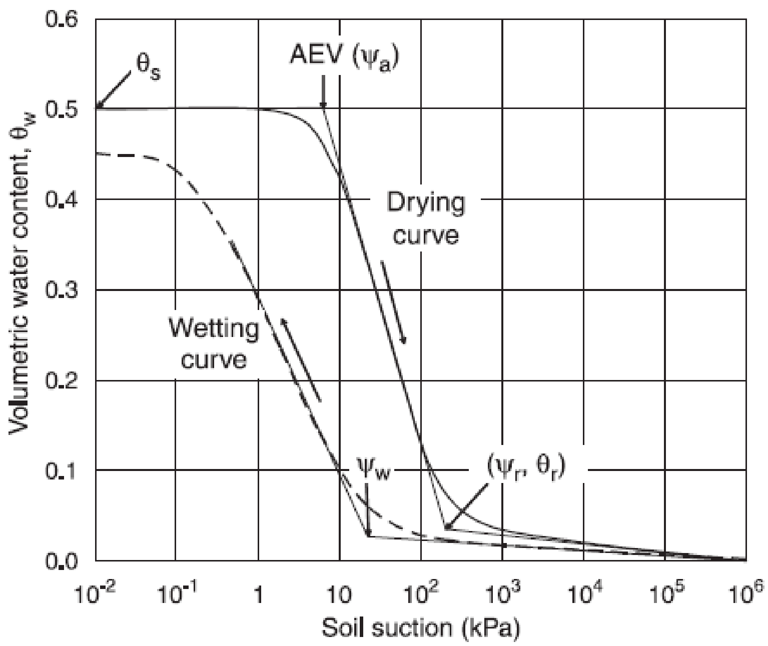


Figure1. Idealized Water Retention Characteristic Curve

Idealized water retention characteristic curve is shown in Fig.1.The WRCC depends upon the type of soil. WRCC relates the volumetric water content, $\boldsymbol{\theta}_w$ (it is defined as volume of water in soil to the total volume of the soil), to the soil suction. The air entry value (AEV) or Ψ_a is the suction during a drying process at which air first starts entering the largest pores of the soil [12]. The Air entry value corresponds to the height of the passive capillary rise. It indicates the soil suction at which air permeates into the soil and drying occurs. In drying curve as soil suction is increased up to the AEV of the soil, the water content of the soil, θ_w, does not changes significantly. As the matric suction increased after AEV the water content steadily decreases and reached up to residual water content, θr. The water-entry value, Ψ_w, on the wetting WRCC is the soil suction at which the water content of the soil starts to increase significantly during the wetting process. There are various different methods available for obtaining WRCC in the laboratory [2, 3, 4, 5 &13]. Agus and Schanz [14] have compared the various methods for determining the WRCC like noncontact filter paper method, psychrometer technique, relative humidity sensor, and chilled mirror hygrometer technique and all these instruments is based on the methodology of relative humidity. Sreedeep and Singh [15] have investigated the effect of different measurement methodologies on the WRCC's of two fine-grained soils. It was found that the chilled-mirror hygrometer technique was most accurate and it produced accurate results. However, when the samples of same age were tested, the results of filter paper method were equivalent to the chilled-mirror hygrometer. The psychrometer method showed slow response and the value of total suction is lower than chilled-mirror hygrometer method. In the present study, Fredlund SWC-150 device is used which is a pressure plate device with interchangeable ceramic disks. The experimental results obtained from this device is upto matric suction value of 1500 kPa. The advantage of this device is that the drying and wetting of the sample can be done continuously without disturbing the sample.

2. Materials

The material used in the present study was pond ash which is a by-product obtained from the combustion of pulverized coal.

2.1 Pond Ash

The Pond ash used for determining WRCC was collected from an ash pond of Ropar thermal power plant (India). The coal ash slurry pipe runs over partition dyke and there are different inlet points along the partition dyke. Representative ash pond sample was collected from outflow point approx. at a distance of 450 m from partition dyke. The collection point is marked in Fig.2.

Figure2. Satellite image of Ropar ash pond

2.1.1 Geotechnical Characterization

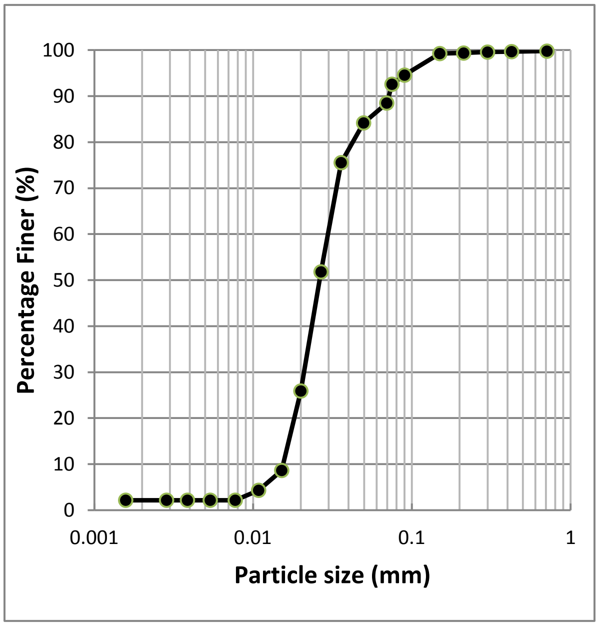
The specific gravity of sample (pond ash) was determined following the procedures outlined in IS 2720-Part 3 [16]. The specific gravity of ash sample for outflow point is 2.13. The grain size distribution of ash samples is determined following the method prescribed in IS: 2720- Part 4 [17]. Particle size distribution of the portion of the ash coarser than 0.075 mm sieve was measured by sieve analysis and the portion finer than 0.075 mm was measured by hydrometer test. The gradation curve of the pond ash is shown in Fig.3. The particle size distribution of ash provides considerable details about its properties and behavior. It is observed from the grain size distribution that the ash sample is in the range of silt size. Pond ash sample used in the study is non plastic and is classified as ML as per IS 1498:1970.

Compaction characteristic of pond ash sample is determined using Standard Proctor test as described in IS: 2720- Part-7 [18]. The maximum dry unit weight (MDD) and optimum moisture content (OMC) of pond ash sample is 10.67 kN/m^3 and 35.5% respectively. The coefficient of permeability of saturated pond ash sample has been determined using falling head method. The procedure for the measurement of coefficient of permeability was carried out as per IS: 2720- Part 17 [19]. Pond ash sample was prepared at 95% MDD and 70% MDD to determine the permeability at dense and loose state respectively [20, 21]. The values of coefficient of permeability are shown in Table 4. Values of coefficient of permeability are in the range of permeability of sand and silt; therefore, pond ash could be used as embankment/outer shell of earthen dam. The pond ash could not be used as barrier material on account of its permeability greater than 10^{-9} m/s which is statutory requirement. However, the permeability of coal ash can be decreased with addition of bentonite in order to be used as barrier material [22, 23].

The loss on ignition (LOI) test was performed as per IS: 1917- Part 1[24]. In this study, the sample was first oven dried. The muffle furnace temperature was increased incrementally till the temperature reaches 1000^{o}C. It is observed from the value given in Table1 that LOI value of the ash samples is than 6.25%. Loss on ignition indicates the presence of unburnt carbon in coal ash. Due to this low presence of unburned carbon, there is no risk of self heating or spontaneous heating. Therefore, the ash sample could be used in bulk quantity in embankment construction or filling of area without any danger of overheating.

Table1. Basic properties of soil

Test	Value
Specific Gravity, G_s	2.13
Sand (%)	7.40
Silt (%)	90.40
Clay (%)	2.20
D_{10} (mm)	0.016
D_{60} (mm)	0.030
Coefficient of uniformity (C_u)	1.87
Coefficient of curvature (C_c)	0.92
Maximum dry unit weight (MDD) (kN/m^3)	10.67
Optimum moisture content (OMC) (%)	35.50
Coefficient of Permeability (m/s)	Dense - 9.1 E-07
	Loose- 2.5 E-06
LOI value (%)	6.25



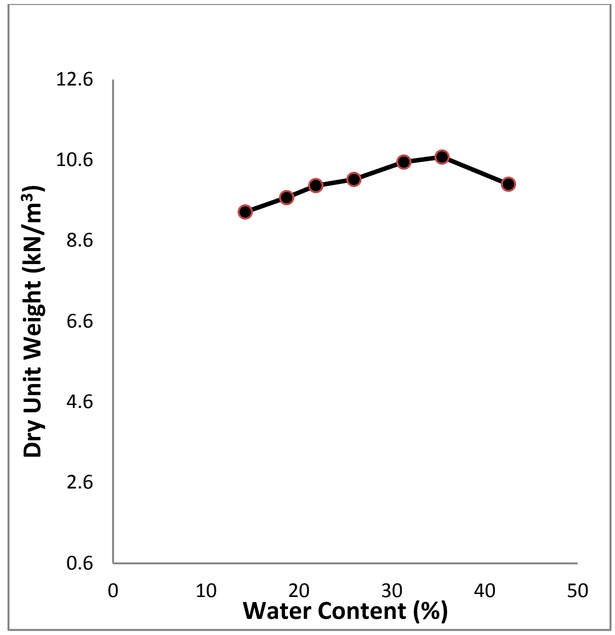


Figure 3. Grain size distribution curves of representative pond ash sample

Figure 4. Compaction curve of Ropar Pond ash

2.1.2 Morphological and Mineralogy Characteristics

The nature of particles (Morphological Characteristics) of the pond ash sample was carried out using Scanning electron microscope (SEM) technique. The results of SEM of pond ash for magnification (x100) and (x500) are shown in Fig. 5a-b. It is observed from Fig. 5 that pond ash particles are having spherical and irregular shaped particles with complex pore structure. Ash sample is spherical in shape of different sizes whereas some larger pond ash particles are combination of smaller ash particles and it contains intraparticle voids. It is observed that the surface of ash particle has highly porous structure with irregular shapes.

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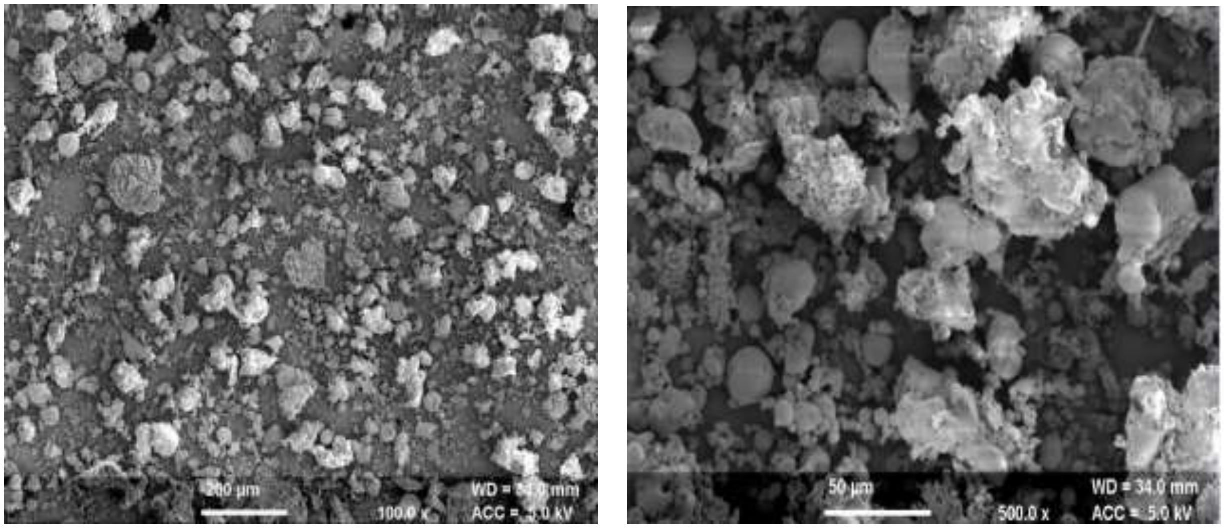

(a) x100 Magnification (b) x500 Magnification

Figure. 5 (a-b) SEM micrographs of pond ash at x100 and x500 magnification.

The Mineralogical analysis of the pond ash sample was carried out using XRD technique. Prepared sample was run on Cu-Kα (λ = 1.5406 Å) source, Diffractometer (45 kV potential difference and 40 mA current) at scan speed 1°/min, step size of 0.017° and 2θ in the range of 10°–90°. The XRD raw data, after removal of unwanted noise and spikes was studied. The presence of inert minerals for finer pond ash is shown in Fig.5-c. From the XRD results it is found that this material predominantly consists of quartz and mullite.

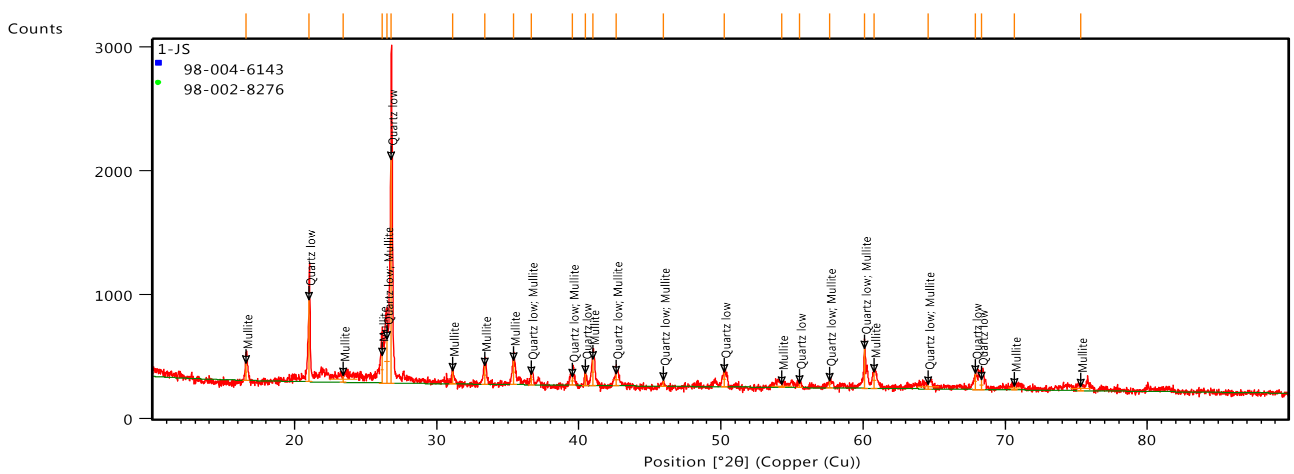

Figure 5(c). X-ray diffraction (XRD) of finer ash material (RP-O)

3. Experimental Methods

Pond ash could be used as a filling material in construction of dam, embankments. Pond ash is compacted to OMC in all these applications where negative pore pressure plays an important role in determining the behaviour of material. Since the drying and wetting cycle of ash pond/ ash dyke/embankment constructed with pond ash as fill material persists during its operation, it is necessary to understand the water characteristic behaviour of an ash pond to maintain its stability. The behavior of pond ash in unsaturated phase may not be consistent with the principles and concepts of classical, saturated soil mechanics. Therefore, behavior of pond ash in unsaturated condition with alternate wetting and drying cycle has been studied. In order to understand unsaturated behaviour of pond ash water retention characteristic curves for both drying and wetting cycles was determined.

3.1 Water Retention Characteristic Curve

The water retention characteristic curve was experimentally determined by Fredlund SWCC device. It is a pressure plate device with interchangeable ceramic disks. It consists of a assembly of pressure cell with a panel. The water released from representative specimen is measured using volume tubes attached on panel as shown in Fig.6. Pond ash sample was compacted at 95% MDD i.e. 10.13kN/m^3 into the rings and then samples were saturated prior to each test by partially submerging the specimens in a bath of water to attain the maximum possible saturation as shown in Fig 7. The saturated ash samples were placed on a ceramic disk. Ceramic disk was held in place through four screws which are fixed to the plate. The ceramic disk acts like a semi-permeable medium as it allows water but restrict the air to pass up to air entry value of the ceramic disk. It is required to maintain the atmospheric pressure at the bottom of ceramic disk. After placing of sample, the required soil suction was applied to the ash sample. Water oozed out from sample and the volume of water moved out was noted down on the volume indicator tubes till the equilibrium is reached.

Figure.6 Fredlund SWC- 150 device

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After noted down the reading in volume tubes, the pressure to desired soil suction was increased and again noted down the reading in volume tube after attaining equilibrium. The pressure in the soil was increased in order of 0, 5, 10, 20, 50, 100, 200 & 400 kPa. When the pressure reaches 400 kPa the soil gets nearly desaturated. Before increment of the next soil suction, there may be chances of air diffusion in the volume tubes so it is required to regularly flush out the air by flushing device. This eliminated the chances of error of accurate reading of water level. After reading the water level, the water content at particular matric suction was calculated. This procedure was repeated and matric suction was increased till the water movement form the sample ceased out and sample became dry. This process is known as drying water retention curve. When the sample became fully dry, matric suction decreased in the reverse order. This decrease in pressure forced water to enter the sample through ceramic disk. The reading of water content for matric suction for wetting cycles was noted down. The sample was removed from the device and water present at full saturation was determined by oven dry method.

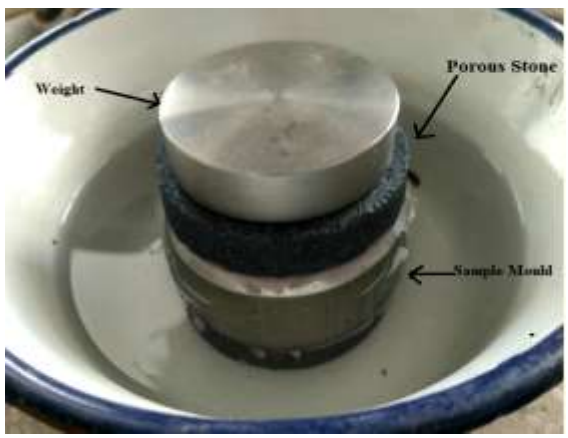

Figure.7 Saturation of sample

4. Results and Discussions

4.1 Drying Water Retention Characteristic Curve

Drying water retention characteristic curve for pond ash sample was determined using a Fredlund SWCC device. The experimental data of matric suction (Ψ) and volumetric water content (**θ_w**) for ash sample for drying is shown in Fig 8. The volumetric water content at low suction pressure *i.e.*0.1 kPa is the nearly saturated water content. It has been observed form the test data that the sample gets nearly desaturated at application of pressure of 400 kPa. The air entry value(AEV) and residual suction(Ψ_r) were determined by conventional graphical method. First, the inflection point (Ψi, θi) was located visually on the water retention characteristic curve and tangent line was drawn through this point as shown in Fig 8. Another tangent was drawn through saturated volumetric water content which intersects the tangent line passing through inflection point . The air entry value (AEV) corresponds to the intersection point between the horizontal line through the saturated volumetric water content and the line of tangency through the inflection point. The value of AEV as determined from the Fig.8 was 30 kPa. The graphical method relies on subjectively identifying the inflection point. After matric suction reaches air entry value, air starts entering the fine ash samples progressively which is indicated by the steep increase in matric suction (Ψ) and corresponding decrease in water content (θ). The residual soil suction (Ψ_r) corresponds to water content at which water phase is discontinuous at the residual state. The value of Ψ_r from the experimental drying graph comes out to be 120 kPa.

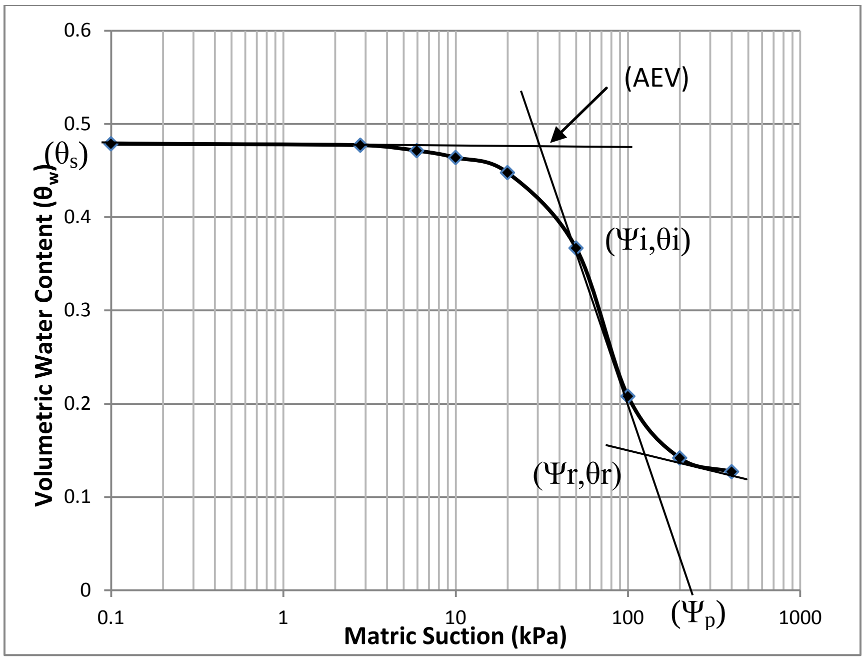

Figure.8 Drying water retention characteristic curve

4.2 Modelling of Experimental Data

The experimental data obtained were best fit using the equation proposed by Fredlund and Xing (FX) [25], Van Ganuchten (VG) [26] and estimation method.

4.2.1 Fredlund and Xing Method

The Fredlund and Xing method (FX) is a closed-form type solution which can be used in developing the volumetric water content function for all range of negative pressures between zero and minus one million kPa based on the soil fit parameters(a, n, m).

The governing equation of the FX is as follows:

$$\boldsymbol{\theta} = \boldsymbol{\theta}_s \left[\frac{1}{ln\left[e + \left(\frac{\Psi}{a}\right)^n\right]} \right]^m \quad [1]$$

where,

$\boldsymbol{\theta}$ = the volumetric water content

$\boldsymbol{\theta}_s$= the saturated volumetric water content

a,n,m= soil fit parameters

Ψ= soil suction

Parameter a (with the unit of kPa) is closely related to the air entry value. Parameter n controls the slope of water retention characteristic curve. These three parameters a,n,m and slope (s) were determined as follows:

$$a = \Psi_i \quad [2]$$

$$m = 3.67 \ln\left(\frac{\theta s}{\theta i}\right) \quad [3]$$

$$n = \frac{1.31^{m+1}}{m\ \theta s} 3.72\ s\ \Psi_i \quad [4]$$

The slope of the tangent line was calculated as

$$s = \frac{\theta i}{\Psi p - \Psi i} \quad [5]$$

where,

Ψ_p is the intercept of the tangent line and the matric suction axis;

Ψ_i is the matric suction corresponds to inflection point;

θ_i is the volumetric water content at the inflection point.

The fitting parameters a, n, m were used to predict the water retention behavior of sample using Geostudio software SEEP/W version 2012. Table 2 shows the value of fitting parameters. The results obtained experimentally from Fredlund SWC-150 device are upto certain limit. As the matric suction reaches beyond that limit, the values of volumetric water content can be numerically predicted through different models using SEEP/W. It is observed from Fig 9 that the FX equation fitted well with the measured data for pond ash sample. As the matric suction increases beyond 400 kPa, the values of volumetric water content is predicted upto matric suction of 10^6 kPa till the sample gets dry.

Table2. Parameters for drying WRCC

WRCC Model	Description	Pond Ash
Fredlund and Xing	Saturated Volumetric Water content (θ_s)	0.478
	Residual Volumetric Water content (θ_r)	0.136
	Residual matric suction Ψ_r	120
	Air Entry Value (kPa)	30
	Volumetric Water content at inflection point (θ_i)	0.368
	a (kPa)	50
	n	1.632
	m	0.9616
	s	2.374×10^{-3}

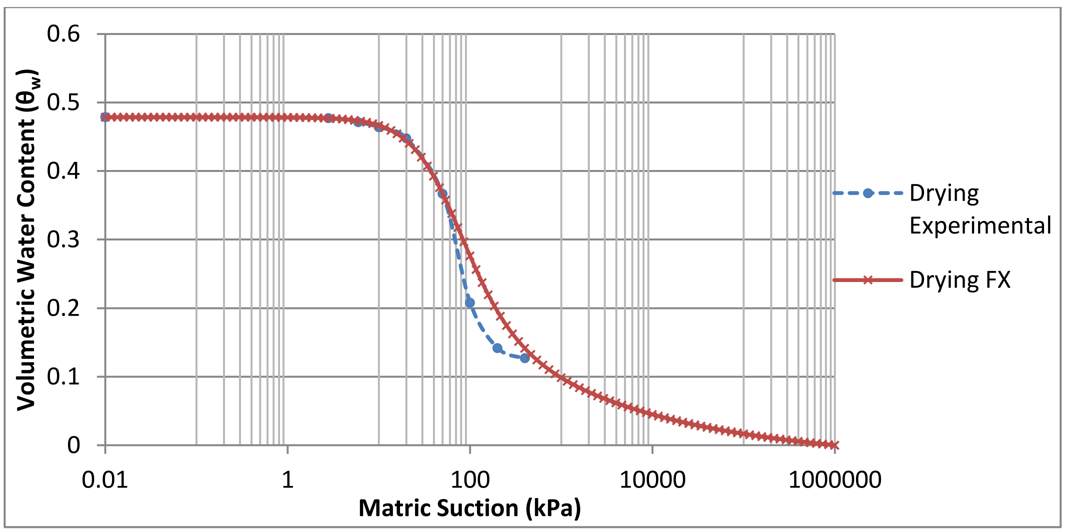

Figure.9 Measured and Predicted Drying WRCC using FX Model

4.2.2 Van Genuchten Method

Van Genuchten (VG) proposed a four-parameter equation which is a closed form type solution that can be used for predicting the volumetric water content function. The governing equation is as follows:

$$\theta = \theta_r + \frac{\theta s - \theta r}{\left[1+\left(\frac{\Psi}{a}\right)^n\right]^m} \qquad [6]$$

where:

θ = the volumetric water content,

θ_s= the saturated volumetric water content,

Ψ= soil suction

a, n, m = curve fitting parameters

The terminology of the a, n and m parameters used in Van Genuchten (VG) equation is similar to those of Fredlund and Xing. The soil fit parameters a and n are used to best fit the Van Genuchten (VG) equation. It is observed from Fig.10 that the VG equation fitted well with the measured data for soil suction upto 100 kPa. After 100 kPa the WRCC Curve derived from VG function shift upward as compared to measured WRCC.

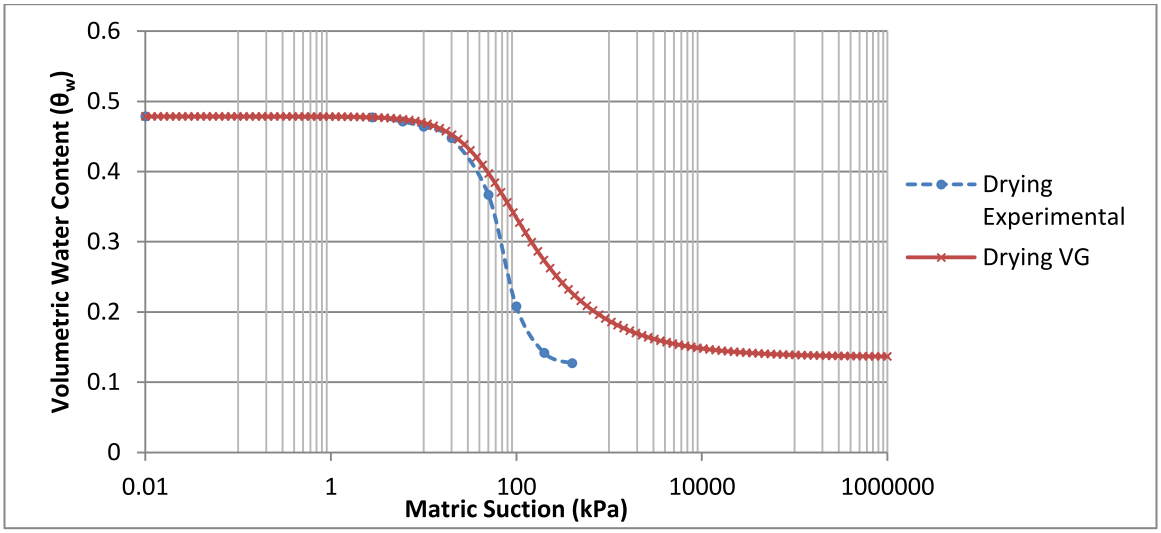

Figure.10 Measured and Predicted Drying WRCC using VG Model

4.2.3 Estimation Method

Aubertin et al [27] presented a method that can be used to predict the volumetric water content function. The Aubertin et al. method predicts the volumetric water content function using basic material properties which can be useful, particularly for preliminary analysis. In the present study a comparative study between measured WRCC and estimation method was done to understand the amount of deviation. In estimation method the WRCC of pond ash sample was predicted using grain size parameters (D_{10}, D_{60}), consistency limits and saturated water content in SEEP/W.

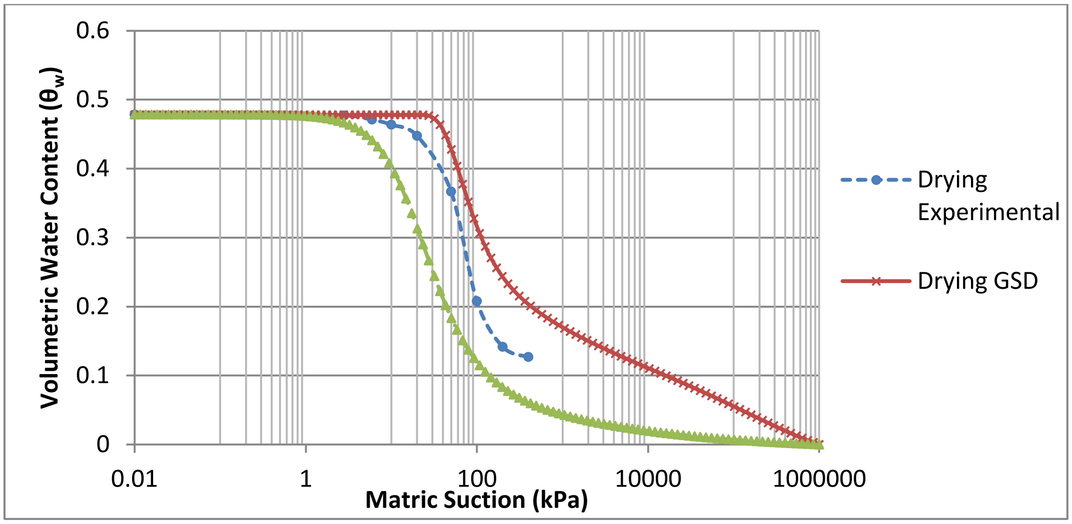

Figure.11 Measured and Predicted Drying WRCC using Estimation Method

The water retention characteristic curve can also be estimated using SEEP/W which also provides several typical water content functions for different types of soils. From the geotechnical characterization of sample it is observed that pond ash sample lies in the range of Silt. Therefore, Silt sample function was selected to predict the WRCC. These functions are provided as a means to set up some test models quickly, change functions easily, decide how sensitive the results are to function shape. The measured and estimated WRCC are shown in Fig.11. It is observed from the Fig.11. that the WRCC obtained using estimation procedure closely relates with measured WRCC upto 10 kPa. As the matric suction increases there is upward shift of curve in case of grain size method and downward shift in case of sample function as compared to measured WRCC.

4.2 Wetting Water Retention Characteristic Curve

Wetting water retention characteristic curve for pond ash sample was also determined using a Fredlund SWCC device. As sample gets nearly desaturated, the wetting process of sample initiated by decreasing the matric suction and finally reached zero pressure. The experimental data of matric suction (Ψ) and volumetric water content (**θ_w**) for ash sample for wetting is shown in Fig.12. The water entry value (WEV) corresponds to the matric suction at which the water content of the soil starts to increase significantly during the wetting process. It has been observed from the Fig.12 that water entry value of sample is 90 kPa.

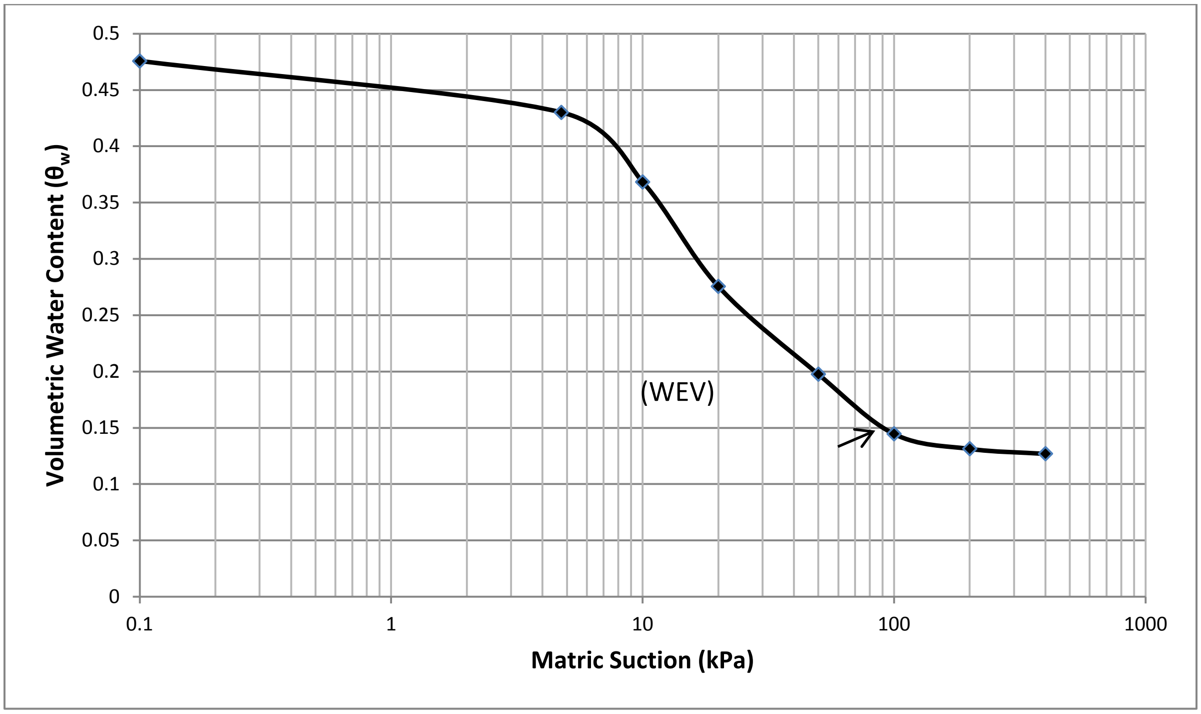

Figure.12 Wetting water retention characteristic curve

The Drying water retention characteristic curve was best fit using FX, VG and estimation method. It is found from the comparison that the FX method closely relates with the experimental result. The WRCC curve predicted from VG method closely fit upto 100kPa after that there is variation in VG result as compared to experimental results. The estimation methods using grain size and sample function shows wide variation in WRCC as compared to the experimental curve. It is significant to understand the variation between experimental and analytical models. There are certain limits of experimental equipments upto which the soil suction can be induced in the sample. The soil of low permeabilty requires high matric suction to reach upto residual water content. Hence, it is required to understand the relation of experimental and analytical models. Therefore, the calculated a, n and m parameters can be used to produce the WRCC curve by fitting these parameters in FX, VG and estimation method. In the present study it is observed from Fig.13 that FX method closely fits well with the experimental results, therefore this method is best fit to predict the WRCC of pond ash material.

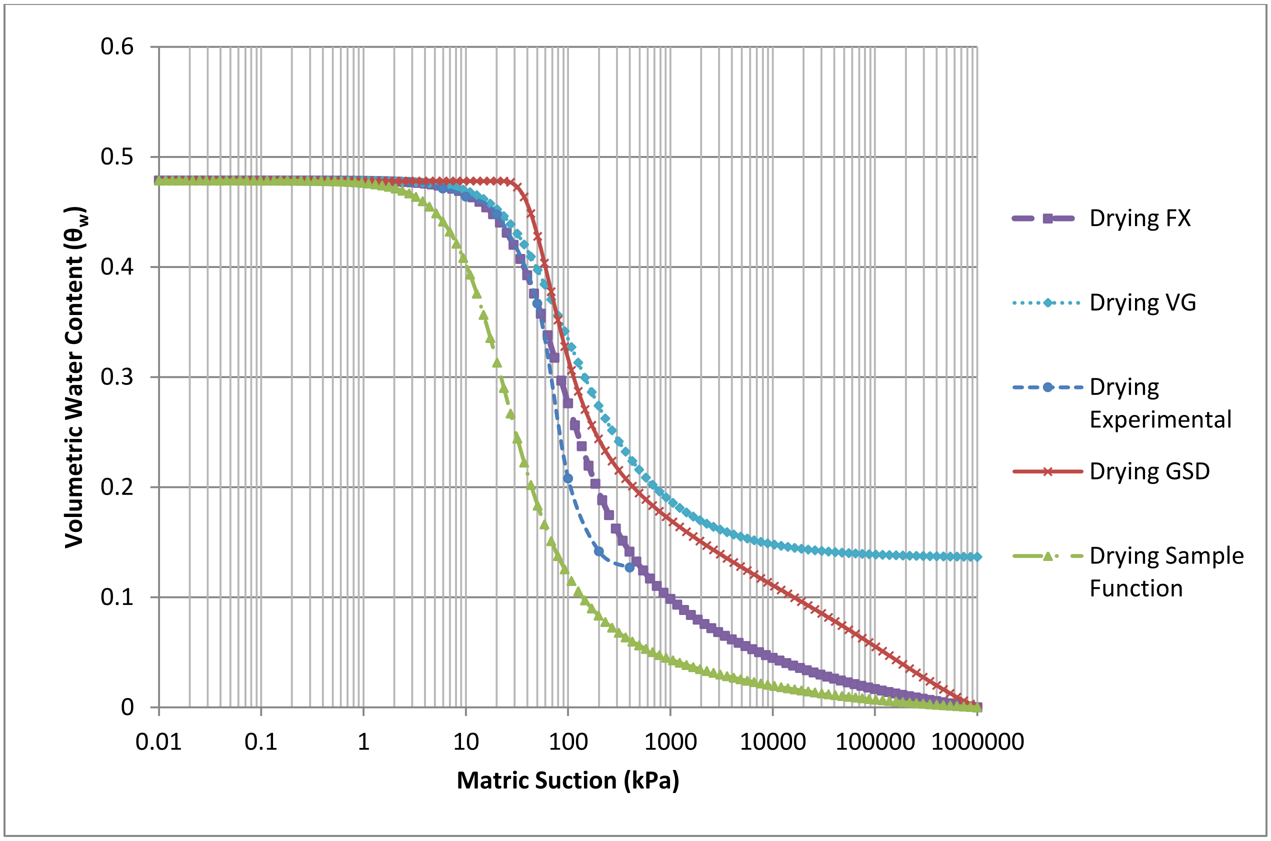

Figure.13 Measured and Predicted Drying WRCC using different methods

4.3 Hysteresis of Water retention Characteristics curve

Hysteresis in the WRCC signifies that volumetric water content in the pond ash sample is not unique for a particular suction value. It is related to the drying and wetting cycle of sample. Yang [28] proposed that hysteresis between the drying and wetting WRCC be quantified by total hysteresis, which is area between the drying and wetting WRCC. Larger the area between the drying and wetting curves indicate higher the hysteresis i.e. pronounced difference in behavior between wetting and drying phase. It is observed from Fig. 14 that there is considerable hysteresis between drying and wetting of an ash sample. This means it is important to consider WRCC of pond ash for all climate types ranging from very dry to wet. The hysteresis of water retention characteristic curve may be due to during wetting larger pores control the water movement while on draining processes the smaller pores control the flow.

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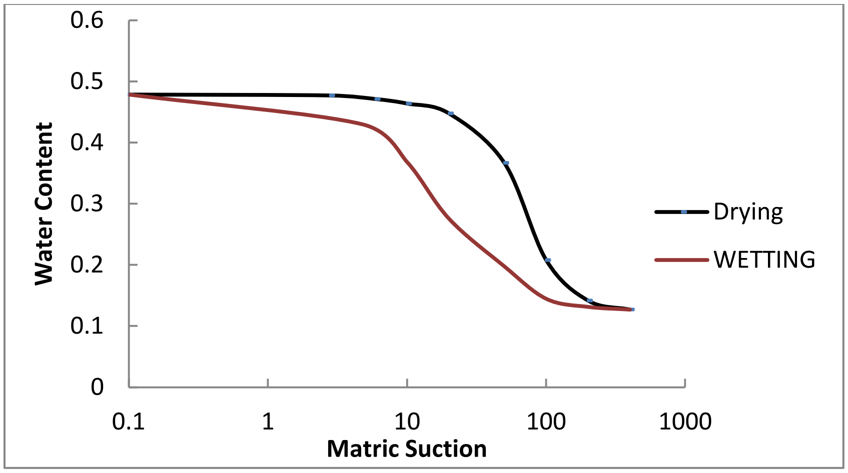

Figure.14 Hysteresis of WRCC of pond ash

5. Conclusions

The present study deals with an investigation of water retention characteristic behavior of Pond ash. The experimental data of WRCC obtained were best fitted using the Fredlund and Xing equation, Van Ganuchten equation and estimation method. Following conclusions can be drawn based on the study.

- Particles of Pond ash are predominantly in silt range.
- Loss on ignition value of the pond ash sample is low, therefore it may not be a problem of generation of heat in bulk use of pond ash as embankment/fill material.
- Particles of pond ash are of irregular shape with complex pore structure.
- The measurement of Water retention characteristic curve and its prediction has risen as the necessary information in the field of unsaturated soil mechanics to understand the behavior of soil in unsaturated phase.
- The measured WRCC match satisfactorily with predicted WRCC using Fredlund and Xing equation whereas there is upward shift in WRCC curve derived using Van Ganuchten equation as compared to experimental WRCC.
- Estimated WRCC using grain size data and sample function is an approximated method and does not best fit with measured WRCC.
- There is considerable hysteresis in drying and wetting curve of pond ash sample indicates pronounced difference in behavior between wetting and drying phase.

It can be concluded that the area under hysteresis for pond ash is large which makes it necessary to study WRCC to ensure its effective use in drying and wetting cycles. Moreover, there are many practical situations which arises the need to study the unsaturated behaviour of soil. The study also concluded that prediction of water retention characteristic curve using different models may have variation in results and require careful evaluation.

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