CHARACTERIZING THE UNSATURATED AND SATURATED HYDRAULIC PROPERTIES OF COAL COMBUSTION BY-PRODUCTS IN LANDFILLS OF NORTHWESTERN NEW MEXICO[1]

R.W. Webb[2], J.C. Stormont, M.C. Stone, and B.M. Thomson,

Abstract. Coal combustion byproducts (CCBs) disposed of in unlined landfills can affect the quality of adjacent water resources. In previous studies, CCBs have been found to leach toxic heavy metals such as arsenic, mercury, and lead into groundwater. CCBs include fly ash, bottom ash, and flue-gas desulfurization product (FGD gypsum). Within a landfill, CCBs may be present at different densities associated with depth, compacted primarily from the weight of above materials. This investigation focused on determination of the unsaturated and saturated hydraulic properties of fly ash and bottom ash as a function of density and thus a function of depth within a landfill. Ash samples from a power plant in northern New Mexico were collected for laboratory analysis. Compressibility curves were developed in order to determine what densities may be experienced at a range of pressures. Saturated hydraulic conductivity was determined using falling head tests for multiple densities of each material. Moisture characteristic curves were developed from hanging column tests, pressure plate tests, dew point potentiometer measurements, and relative humidity measurements. The moisture characteristic curves were also measured at a range of densities for each material. Results indicated that the fly ash saturated hydraulic conductivity varied as a function of density for the materials tested and the density could be reasonably predicted using an equation presented. Fly ash unsaturated properties also show trends with variations in density with the variability decreasing as density increases. Fly ash in a landfill can have estimated density, unsaturated and saturated hydraulic properties as a function of depth using the methods in this paper. Bottom ash showed similar trends in compressibility with less variability with respect to the fly ash. The unsaturated and saturated hydraulic properties show some trends, though with high amounts of variability. The density of bottom ash materials in a landfill may be reasonably estimated using methods proposed in this study while unsaturated and saturated hydraulic properties have greater uncertainty.

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[2] R.W. Webb, J.C. Stormont, M.C. Stone, and B.M. Thomson, Department of Civil Engineering, University of New Mexico; 210 University Blvd NE, Albuquerque, NM 87106, Present address of senior 518 Fox Glove Ct, Fort Collins, CO 80524.

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Introduction

Millions of tons of coal combustion bi-products (CCBs) are produced every year by coal burning power plants. The American Coal Ash Association (ACAA) reported over 118 million metric tons were produced in the year 2010, making CCBs one of the most predominant forms of waste related to energy production (Yeboah and Burns, 2011). Three major types of CCBs are fly ash, bottom ash, and flue-gas desulfurization gypsum (FGD gypsum). In 2010 fly ash made up 63% of these major CCBs by weight, bottom ash 17%, and FGD gypsum 20% (ACAA, 2010).

Fly ash is the CCB made up of finer particles which rise with the flue gas stream and is collected by air quality control devices prior to entering the atmosphere. Fly ash generally ranges in particle size from 0.01 to 100 µm (Adriano et al., 1980). Bottom ash is the material that remains in the furnace after the coal combustion process is complete. Bottom ash generally consists of angular, porous particles that range in particle size from 0.1 to 10 mm (Seals et al., 1972). FGD gypsum is produced from the removal of sulfur oxide from the flue gas and is often extracted by scrubbers (Adriano et al., 1980; Kumar and Stewart, 2003).

One of the most common methods for CCB disposal in the western United States (U.S.) is landfilling. The other common disposal methods include stockpiling and settling ponds. During the landfill process, materials are generally placed back into the pits and ramps used to mine the parent coal. Depending on the source of the parent coal, ash materials can contain every naturally existing chemical element. Trace elements have been shown to increase in concentration with decreasing particle sizes of ash materials creating the tendency for fly ash to have more trace elements than bottom ash (Adriano et al., 1980; El-Mogazi et al., 1988).

The major concern of landfills containing CCBs is the potential leaching of trace elements to adjacent water resources. Leachability of potentially toxic elements from CCB deposits depends on a number of different factors such as solubility of the element, interstitial flow rate, and the pH of water (Adriano et al., 1980; El-Mogazi et al., 1988; Joshi et al., 1994; Palmer et al., 2000; Mudd and Kodikara, 2000). Each of these factors can be associated specifically to source coal, CCB collection methods, and setting of disposal site. The unsaturated and saturated hydraulic properties of the CCBs will control the rate at which water moves through or remains within the buried material and potentially leaches elements from the pit.

Because of potential environmental impacts from trace elements, federal and state regulations are in place for the disposal of CCBs. Most landfill pits are lined with engineered material considered to be impermeable by standard practices (Huang et al., 1998; Ferraiolo et al., 1990). There are, however, some landfill sites that remain unlined in regions such as northern New Mexico.

Hjelmar et al. (2008) proposed an equation to calculate leaching behavior in terms of time. This does, however, consider only situations such as the site of the study in which the primary method for contaminant transport is from precipitation infiltration through the landfill pit in the vertical direction only. In regions such as the southwestern U.S., unlined landfills may lie within regions with lateral hydraulic gradients (Kernodle, 1996). These unlined landfills could potentially pose more of a threat from lateral transport of contaminants in the future rather than solely from vertical leaching should the water table rise. In semi-arid regions, such as the semiarid southwest, precipitation is unlikely to infiltrate beyond the root zone of the vegetation types in the region (Steinwand et al., 2001) making flow in the saturated zone of higher concern. However, often times a landfill rests in the unsaturated zone, water tables could rise after mining and de-watering operations cease in the area causing the landfill to be subjected to lateral hydraulic gradients. This would mean that the hydraulic properties of the entire vertical profile of a landfill pit could be crucial in determining the potential impact of contamination to adjacent water resources.

As CCBs are disposed of in a landfill, stresses can increase considerably as the depth of a pit increases. As stress increases, particles will rearrange themselves into a higher density configuration with a corresponding decrease in porosity and void ratio. The manner in which a material's density changes in response to changes in stress is known as the material's compressibility. Changes in porosity and within pore structure can have a significant impact on both unsaturated and saturated hydraulic properties of a material (Lu and Likos, 2004) as flow though a porous material depends largely upon the size and distribution of pores within the material at any given time. Studies have found that for clay soils and silty soils, both saturated hydraulic conductivity and unsaturated hydraulic properties such as conductivity and moisture retention are impacted by compaction and variations in void ratio (Zeng et al., 2011; Richard et al., 2001). Seals et al. (1972) found bottom ash to have compressibility characteristics similar to that of sand. Due to the fact that CCBs are subjected to a range of stresses corresponding to their depth of burial, it is important to determine the compressibility of the CCBs within a landfill in order to estimate how densities and porosity may change with depth. For many materials, such as clay, sand, and likely CCBs, saturated hydraulic conductivity steadily decreases as void ratio decreases (e.g., Zeng et al., 2011). Because CCBs in landfill sites are subjected to various overburden conditions creating a range of bulk densities, it is important to determine variations in the hydraulic properties associated with changes in bulk density.

Although there is no direct data regarding the change in unsaturated properties of CCBs due to compaction, testing on soils reveal that changes in porosity due to compaction have an impact on their unsaturated hydraulic properties (Richard et al., 2001; Assouline et al., 1997; Hill and Sumner, 1967). Fly ash tends to have a texture similar to a clay whereas bottom ash has a texture similar to a sandy soil. Therefore, it is expected that as bulk density of CCBs increase, the unsaturated properties have the potential to vary in a similar fashion as soils. These variations may assist in understanding the possible behavior of water in landfill sites.

CCBs can vary significantly depending upon the source coal and collection method. Disposal methods in landfill sites create a profile of varying overburden pressures and a potential range of unsaturated and saturated hydraulic properties. Proper knowledge of the manner in which these properties vary with depth within a CCB landfill pit are essential in analyzing the potential future impact on local water resources. The objectives of this study are to determine, through laboratory testing, the unsaturated and saturated hydraulic properties of fly ash and bottom ash as a function of bulk density in order to be related to a change in properties as depth increases within a landfill. These laboratory tests were developed to specifically determine CCB compressibility in order to measure the saturated hydraulic conductivity and develop a moisture characteristic curve (MCC) for multiple densities and observe the trends associated with density.

Methods

Source of Samples

Fly and bottom ash samples for this study were received from the San Juan Mine and Power Generating Station (SJM) in northwestern New Mexico. These samples were taken directly from the collection units prior to transport to the landfill site, and are subsequently referred to as fresh samples. The samples were received by mail in June of 2011 and were contained in plastic bags specific to a single burning unit. Approximately 10 kg were received. All samples used for this study were taken from this bag after proper mixing.

The SJM is the location from which the coal is mined and CCBs are placed back into the mined pits. Coal in the basin is of the late-Cretaceous age and characterized as ranging from sub-bituminous A to high volatile bituminous C. The formation mined is primarily sub-bituminous coal consisting of <1% sulfur. Silica, alumina, oxides of Ca, Mg, and Fe are the principle components of the CCBs disposed of at the site with secondary elements consisting of carbon and other trace elements (Luther et al., 2009). The chemical composition of the fly ash can be considered as Class F fly ash based on chemical analysis (Parker, 2011).

Testing Methods for Physical Properties

Grain size distributions were determined for a sample mass of approximately 100 g of oven-dry fly ash and approximately a 230 g sample of oven-dry bottom ash following the methods of ASTM D422-07: Standard Test Method for Particle-Size Analysis of Soils (2007). The sample materials were washed through a #200 sieve, and a hydrometer test was conducted for the material passing through and a sieve analysis conducted for the retained material.

Specific gravity testing was conducted following the methods described by ASTM D854-09: Standard Test Methods for Specific Gravity of Soil Solids by Water Pycnometer (2009). Three tests were conducted on fly ash and three tests on bottom ash.

Relative density tests, as described by the Department of the Army Office of the Chief of Engineers (1970), were also conducted on one oven-dry sample of fly ash and one oven-dry sample of bottom ash using a 15 cm diameter proctor mold.

In situ samples were collected by means of a geo-probe to determine field conditions present at the site in a separate study (Chan, 2010) and used to determine possible conditions present during CCB compaction at the landfill site. Moisture contents were determined by methods described in ASTM D-2216-10: Standard Test Methods for Laboratory Determination of Water (Moisture) Content of Soil and Rock by Mass (2010) and densities by ASTM D-7263-09: Standard Test Methods for Laboratory Determination of Density (Unit Weight) of Soil Specimens (2009), method B. The known volume from the density tests and mass of water from moisture content were then used to produce volumetric water contents.

In situ samples of 100% ash were not found during the study by Chan (2010). However, a second investigation was conducted in 2011 in which drilling was able to produce two "clods" large enough for density tests. Clod density tests were performed with methods similar to ASTM

D-7263-09 (2009) method B. The clods were too small for the standard sample size. Copper rings measuring 16 mm in inner diameter and 29 mm in length were sharpened on one end and inserted into the clods. Excess material was removed with a razorblade from either end of the rings to ensure the soil was level with the edges. Two samples were collected from one clod and one sample from the second clod.

Testing Methods for Compressibility

Compressibility curves were developed for four samples of fly ash and four samples of bottom ash. Test methods similar to ASTM D-2435-09: Standard Test Method for One-Dimensional Consolidation Properties of Soils (1996) was performed. Rather than saturated consolidation, tests provided one-dimensional pressure loading on samples at gravimetric moisture contents of 20% in order to be consistent with field conditions observed by Chan (2010). Samples are not dry when placed in landfills meaning an antecedent moisture condition should be used for compressibility testing with the observed gravimetric water content of the soils being chosen as this condition. The initial density of all samples for the compressibility set were packed to a bulk density equal to the loose bulk densities measured from the relative density testing. It was observed that, for these particular materials, most of the volume change occurred in the first 15-30 minutes; there were no measurable sample height changes that occurred following 1 hour of each load being applied.

Testing Methods for Saturated Hydraulic Conductivity

Fly and bottom ash samples were tested for the coefficient of saturated hydraulic conductivity (K_{sat}) in accordance to ASTM D5856-07: Standard Test Method for Measurement of Hydraulic Conductivity of Porous Material Using a Rigid-Wall, Compaction-Mold Permeameter (2007), method B (constant tail water). Porous stones were used on the bottom and top of each sample within a rigid-walled permeameter. Each compacted sample measured 76 mm in diameter and 25 mm in height, compacted by hand in four lifts. University of New Mexico tap water was used as the permeant liquid. Saturation of samples was done by allowing constant flow of water through the sample for at least 16 hours. Hydraulic gradients, defined as the difference in head between the headwater and tail water per unit length of sample, ranged from 4 to 25 in order to calculate a K_{sat} value under different hydraulic forcing conditions.

Fly ash and bottom ash samples were both tested at three different bulk densities (Table 1), with two samples at each bulk density experiencing three repetitions of the testing method. These densities were determined from the results of the compressibility tests, chosen to represent a lower, middle, and higher density of each material.

Table 1. Densities chosen to be tested for unsaturated and saturated hydraulic properties of both fly ash and bottom ash. These densities were chosen from the results of the compressibility tests.

	Density 1 (kg/m^3)	**Density 2 (kg/m^3)**	**Density 3 (kg/m^3)**
Fly Ash	1028.4	1113.3	1169.3
Bottom Ash	727.2	800.9	913.1

Testing Methods for Moisture Characteristic Curve Measurements

The MCC provides the matric potential head of a material at a given moisture content. MCCs during desorption were developed for the three bulk densities for fly ash and bottom ash shown in Table 1. Testing methods used to collect data for the MCCs follow those described in the following: ASTM D6836-08: Standard test Methods for Determination of the Soil Water Characteristic Curve for Desorption Using a Hanging Column, Pressure Extractor, Chilled Mirror Hygrometer, and/or Centrifuge (2008) for hanging column and pressure plate tests. Klute (1986) for relative humidity box measurements; and Decagon Devices (2010) for chilled mirror hygrometer readings using a WP4 dew point potentiometer. Hanging column tests were used in order to obtain points for negative pressure heads from 5 to 160 cm. Pressure plate tests were used for negative pressure heads of 510 and 1,275 cm, and WP4 readings measured negative pressure heads from 7,600 to 15,000 cm, and relative humidity measurements of negative pressure heads of approximately 4×10^5 and 3×10^6 cm. The ranges of the suction heads utilized for each method are those described as within the range of highest accuracy for each respective method (Decagon Devices, 2010; Klute, 1986). Six points were taken using the hanging column, two points using the pressure plate, four points using the WP4 dew point potentiometer, and two points using the relative humidity box.

For the hanging column and pressure plate tests, three samples at each of three specified bulk densities were prepared and tested for both fly and bottom ash, producing a total of 18 samples tested (9 fly ash and 9 bottom ash). Each sample was compacted in four lifts using a hand tamper to the specified bulk density so as to completely fill a brass ring of 60 mm diameter and 25 mm height. Synthetic nylon screening with openings measuring 25 microns were attached to the top and bottom of each sample ring by a hose clamp to contain the sample while allowing free movement of water.

Saturated samples were placed directly into saturated Buchner funnels connected to reservoirs/burettes by flexible tubing. The samples and Buchner funnels were saturated according to ASTM D6836-08 (2008) with a thin layer of a diatomaceous earth spread on each porous plate to improve the hydraulic contact with the sample. In order to eliminate evaporation losses, rubber stoppers were placed on top of the Buchner funnels with rubber tubing running to another stopper plugging the opening of the reservoir/burette to ensure appropriate atmospheric pressures remained the same between the samples and reservoir/burettes. Samples were allowed to equilibrate at 6 different negative pressure heads ranging from 5 cm to 160 cm of water, taking 6 to 7 days for most samples.

After the final measurement in the hanging column, the samples were moved to the pressure plate apparatus. The porous plate was saturated according to ASTM D6836-08 (2008) with a thin layer of a diatomaceous earth spread on the plate to improve the hydraulic contact with the sample. The pressure plate test was used to produce negative pressure heads of 510 and 1275 cm of water. Readings were taken from the pressure plate test by allowing the samples to equilibrate for 14 days.

A chilled mirror hygrometer was used to collect data for the MCC at negative pressure heads ranging from 7,600 cm to 15,000 cm of water. A WP4 dew point potentiometer from Decagon Devices, Inc. was used as the testing apparatus. It was determined that, for values of negative pressure head less than 7,600 cm of water for bottom ash and 9,900 cm of water for fly ash, the WP4 readings were outside the range of accuracy (Decagon Devices, Inc., 2010). This was determined based on the readings being erroneously high at negative pressure heads below these values, it is unclear as to the cause of this. Five readings were produced for fly ash and three for bottom ash with the difference in the number of measurements being due to bottom ash samples producing more results outside the range of accuracy for the WP4 instrument. The sampling and measurement methods follow those described in the procedures written specifically for this instrument (Decagon Devices, Inc., 2010). Gravimetric water contents and water potentials were converted to volumetric water contents and negative pressure heads, respectively, for each bulk density.

A relative humidity box was used to measure two final readings for the MCC. Saturated solutions of NaCl and LiCl were used to achieve negative pressure head equivalents of over 4 x 10^5 cm and 3 x 10^6 cm of water respectively (Lu and Likos, 2004). The saturated solutions were placed in the bottom of a desiccator. Fly and bottom ash samples (~10 g) were then placed directly above the salt solution atop a plastic grate and allowed seven days for equilibration, after which masses were measured and converted to volumetric water contents.

MCC development

Measured data points were fit to the van Genuchten model for the MCC in order to allow for a continuous curve from a degree of saturation from 0 to 1. The van Genuchten model is given as (van Genuchten et al., 1991):

$$\theta = \theta_r + (\theta_s - \theta_r) \times (1 + (\alpha h)^n)^{-m} \quad \textbf{(1)}$$

Where:

θ = volumetric moisture content (dimensionless [L^3/L^3]); θ_r = residual volumetric moisture content (dimensionless [L^3/L^3]); θ_s = saturated volumetric moisture content (dimensionless [L^3/L^3]); α = curve fitting parameter representing the inverse of air-entry suction (1/L); h = negative pressure head (L); n = curve fitting parameter (dimensionless); m = 1 – 1/n (dimensionless)

The Retention Curve (RETC) Program for Unsaturated Soils (van Genuchten et al., 1991) was used to fit the data to the van Genuchten model for MCCs. RETC allows the user to assign a weight to each data point. The weight of a data point is defined as a ratio of the impact each particular data point will have on the final curve. Weighted values for this study were chosen in a manner such that all weighted values for a particular testing method were the same, with strong consideration being given to the estimated accuracy of testing method prior to acceptance of final weighted values. Weighted values were altered within the RETC limits of one and three in increments of 0.5 until an acceptable curve was observed through the data points.

Once MCCs had been produced for each individual sample of CCBs, MCCs were created using RETC to be representative of each bulk density of material. This was done by including all of the data from the three samples at each respective bulk density to create a single MCC for that density.

The input data for RETC used the same calibrated weights for each data point as determined by MCC curve creation for individual samples.

MCCs were then plotted as degree of saturation instead of volumetric water content for comparison purposes. Degree of saturation (S) was calculated as follows:

$$S = \theta / \theta_s \tag{2}$$

Results

Physical Properties of Samples

Grain size distributions tests determined fly ash to be 85.4% finer than a #200 sieve (0.075 mm diameter) and bottom ash was 22.3% finer (Table 2). The fly ash had a D_{50}, coefficient of uniformity (C_u), and coefficient of curvature (C_c) of 0.026 mm, 7.5, and 1.8, respectively. Bottom ash has a D_{50}, C_u, and C_c of 0.52 mm, 45.6, and 1.6, respectively. Grain-size distribution curves are shown in Fig. 1. Results for the average specific gravity are shown in Table 2, fly ash was found to have an average specific gravity of 2.00 with a standard deviation of < 0.01 and bottom ash had an average specific gravity of 2.06 with a standard deviation of 0.02. Relative density testing showed oven-dry fly ash to have a loose density of 1007.4 kg/m^3 and a maximum relative density of 1184.4 kg/m^3. Oven-dry bottom ash had a loose density of 692.2 kg/m^3 and a maximum relative density of 813.8 kg/m^3. Results of the relative density test are also summarized in Table 2.

Table 2. Fly ash and bottom ash physical properties including percent fines, minimum and maximum relative densities, and average specific gravity.

Property	Fly Ash	Bottom Ash
% finer #200 sieve (0.075 mm)	85.4	22.3
% larger #200 sieve (0.075 mm)	14.6	77.7
Minimum Relative Density (kg/m^3)	1007.4	692.2
Maximum Relative Density (kg/m^3)	1184.4	813.8
Average Specific Gravity	2.00	2.06

Results of a geo-probe investigation by Chan (2010) included samples from three different locations, showing the average gravimetric moisture content of the soil at depths ranging from two to ten meters. The average gravimetric water content was calculated to be 19% with a standard deviation of 4%.

Clod density tests performed on clods collected at 38 m below the ground surface show an average bulk density at this depth and location to be 1028.8 kg/m^3 (Table 3) with a standard deviation of 32.5 kg/m^3. This material was determined to be bottom ash through a separate study (Parker, 2011).

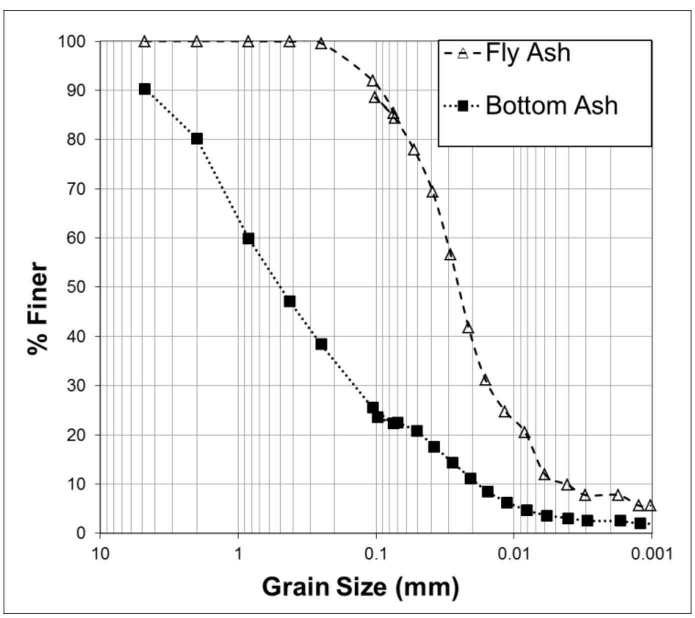

Figure 1. Grain size distribution of fresh fly ash and bottom ash samples received in June 2011.

Table 3. Clod Density Results of *in situ* ash samples obtained from the field at 42 m depth.

	Volume (cm^3)	Dry Sample Mass (g)	Bulk Density (kg/m^3)
Sample 1	561.9	5.69	1012.66
Sample 2	564.1	6.06	1074.21
Sample 3	566.3	5.66	999.43
		Average:	**1028.76**

Compressibility

Results of the compressibility tests are summarized in Table 4 and presented graphically in Fig. 2, it is important to note the differences in the vertical axis values between graphs. Fly ash and bottom ash samples experienced maximum changes in height ranging from 2.2 to 3.4 mm and 5.1 to 6.1 mm, respectively. These values represent a 10.0 to 15.3% and 23.0 to 27.5% change in sample height for fly ash and bottom ash, respectively. All samples experienced the maximum change in height while experiencing the maximum applied pressure of 984.2 kPa. The maximum bulk densities occurring under this pressure ranged from 1119.5 to 1189.0 kg/m^3 for fly ash with an average of 1153 kg/m^3 and 898.2 to 954.8 kg/m^3 for bottom ash with an average of 930 kg/m^3. Measured values showed a maximum percent difference from the average of 3% and 2% for fly ash and bottom ash, respectively.

The data from this study was used to develop an empirical equation. The parameter values are summarized in Table 4 and the equation defined as:

$$\rho(\sigma) = r\cdot(1 - n^{-s\sigma}) + \rho_I \qquad \textbf{(3)}$$

Where: ρ = bulk density (kg/m^3); σ = overburden pressure (kPa); r = total range of densities for curve (kg/m^3); n = steepness of the curve (dimensionless); s = sharpness of curvature (kPa^{-1}); ρ_I = Initial bulk density of the material (kg/m^3)

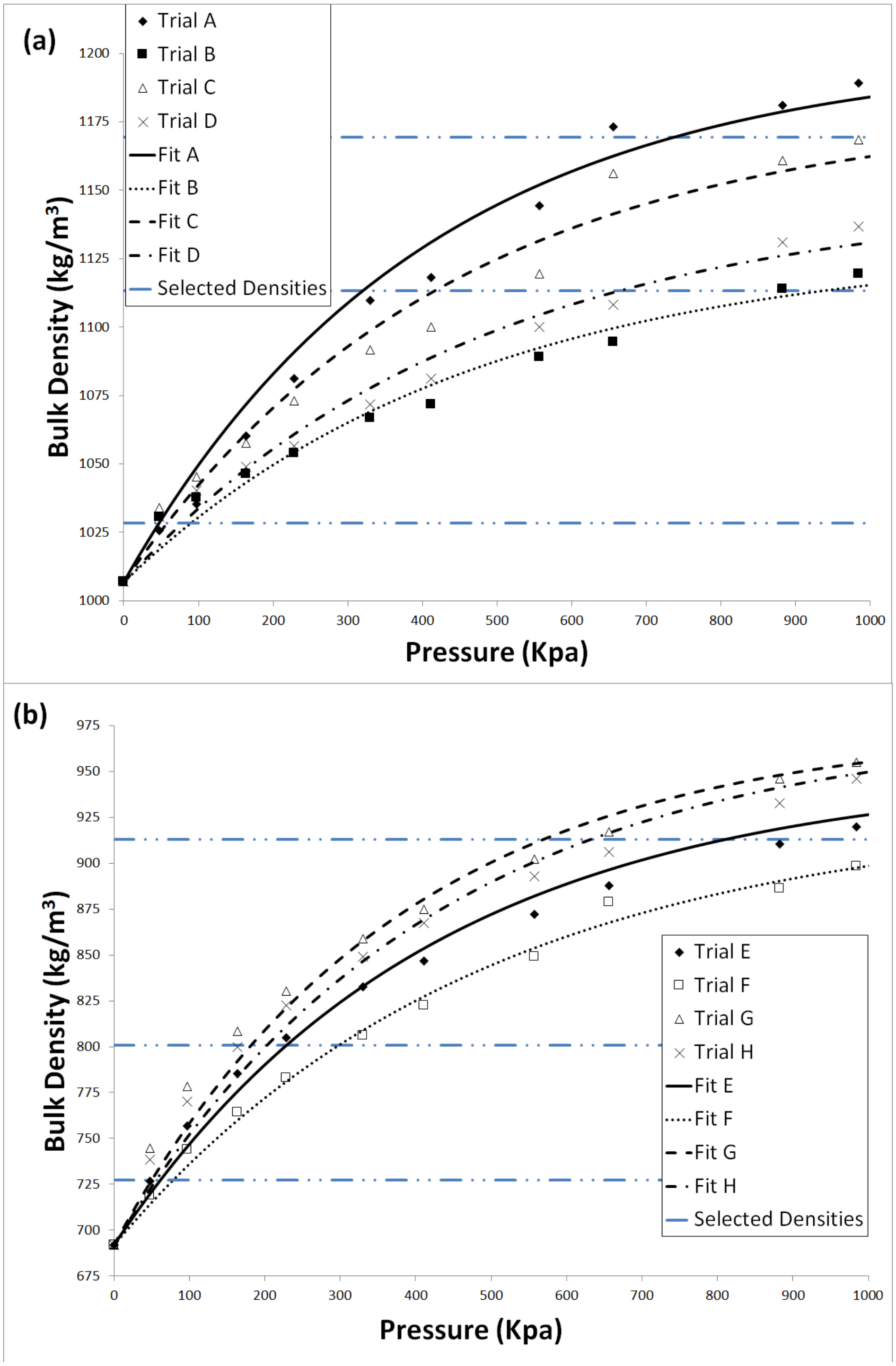

Figure 2. Compressibility data results with curves fit using equation (3) for (a) fly ash and (b) bottom ash. Each graph shows all 11 data points for each trial used for each fitted curve. Blue dashed lines represent the selected densities of each material for further testing.

Table 4. Summary of compressibility results and fitted parameters for equation (1) including R^2 values of the fit curves for each curve.

Sample	Initial Density ρ_d (kg/m^3)	Total ΔH (mm)	Final Density ρ (kg/m^3)	Range of Density r (kg/m^3)	Steepness of Curve n	Sharpness of Curvature s (kPa^{-1}x10^{-4})	R^2
Fly Ash A	1006.9	3.4	1189.0	193	3200	3.1	0.980
Fly Ash B	1006.9	2.2	1119.5	123	1580	2.9	0.974
Fly Ash C	1006.9	3.1	1168.5	173	700	3.5	0.974
Fly Ash D	1006.9	2.5	1136.9	141	500	3.4.	0.979
Bottom Ash E	691.8	5.5	920.0	258	400	4.0	0.989
Bottom Ash F	691.8	5.1	898.2	236	1000	3.0	0.993
Bottom Ash G	691.8	6.1	954.8	283	800	4.0	0.981
Bottom Ash H	691.8	6.0	945.9	284	5000	2.8	0.981

Selection of the equation was based upon the asymptotic approach towards a theoretical maximum bulk density (r-ρ_I) and a predetermined vertical axis intercept for the loose density (ρ_I). Variations in the n and s parameters fit the curve to the data.

The three selected bulk densities to further test, as described in Table 1 are represented by the blue dashed lines in Fig. 2. The lowest density was chosen specifically to be near the initial un-compacted density but slightly greater than since, it is unexpected for any material to be found without experiencing some compaction. Thus, the lowest density chosen for testing may represent a material near the top of a landfill with some cover material. The highest density was selected to be near the higher end of the density curves in order to represent a material buried further down within a landfill. This highest density of material tested is not expected to represent the maximum possible density of the material but rather a material buried deeper within the landfill and possible to be represented within the limitations of laboratory re-packing of samples. The third density to be tested was arbitrarily chosen in between the selected maximum and minimum bulk densities to be tested in order to capture properties of an intermittent bulk density.

Saturated Hydraulic Conductivity

Results from the falling head permeability tests, constant tail water method, are presented in Table 5. Fly ash samples yielded K_{sat} values ranging on the order of 10^{-4} to 10^{-5} cm/s while bottom ash samples yielded values on the order of 10^{-3} cm/s. Two measurements at each bulk density were taken with the highest K_{sat} values measured being 1.3 x 10^{-4} cm/s and 6.5 x 10^{-3} cm/s for fly ash and bottom ash, respectively. These values were achieved at bulk density values of 1024.0 kg/m^3 for fly ash and 724.4 kg/m^3 for bottom ash, which represent the lowest bulk density values that were tested for each material. The lowest K_{sat} values were 5.5 x 10^{-5} cm/s for fly ash and 1.5 x 10^{-3} cm/s for bottom ash. These values were measured at the highest densities tested for both fly ash (1163.0 kg/m^3) and bottom ash (910.4 kg/m^3). Graphical representation of K_{sat} vs. bulk density is shown in Fig. 3. Trend lines were fit to the data displaying an R^2 value of 0.61 for fly ash and 0.27 for bottom ash.

Table 5. K_{sat} test results summarized by bulk density of each material.

Material	Bulk Density (kg/m^3)	Sample 1 K_{SAT} (cm/s)	Sample 2 K_{SAT} (cm/s)
Fly Ash	1024.0	7.81E-05	1.30E-04
Fly Ash	1108.2	6.62E-05	8.10E-05
Fly Ash	1163.0	5.45E-05	5.96E-05
Bottom Ash	724.4	3.53E-03	6.45E-03
Bottom Ash	796.9	2.27E-03	6.26E-03
Bottom Ash	910.4	1.48E-03	3.90E-03

Moisture Characteristic Curves

Van Genuchten model parameters obtained using RETC are presented in Table 6. Table 6 identifies each individual sample with a letter: fly ash is presented as “FA” and bottom ash as “BA” and the following letters were chosen arbitrarily and meant only to identify samples individually. Graphical representation is shown in Fig. 4 for the three MCCs for the fly ash material at 1169.3 kg/m^3. Best-fit MCCs for each target bulk density are displayed graphically in Fig. 5 with fitted parameters summarized in Table 7. The three fly ash best-fit curves are displayed on the same graph to compare differences between bulk densities, and the same is done for bottom ash. All but one curve was fit with a residual water content of 0.00 (Table 6). This is similar to data collected from the relative humidity box tests. The average measured residual water content for fly ash was 4.8 x 10^{-3} cm^3/cm^3 volumetric water content with a standard deviation of 2.5 x 10^{-4} cm^3/cm^3 and the average measured residual water content for bottom ash was 1.1 x 10^{-3} cm^3/cm^3 with a standard deviation of 9.0 x 10^{-5} cm^3/cm^3.

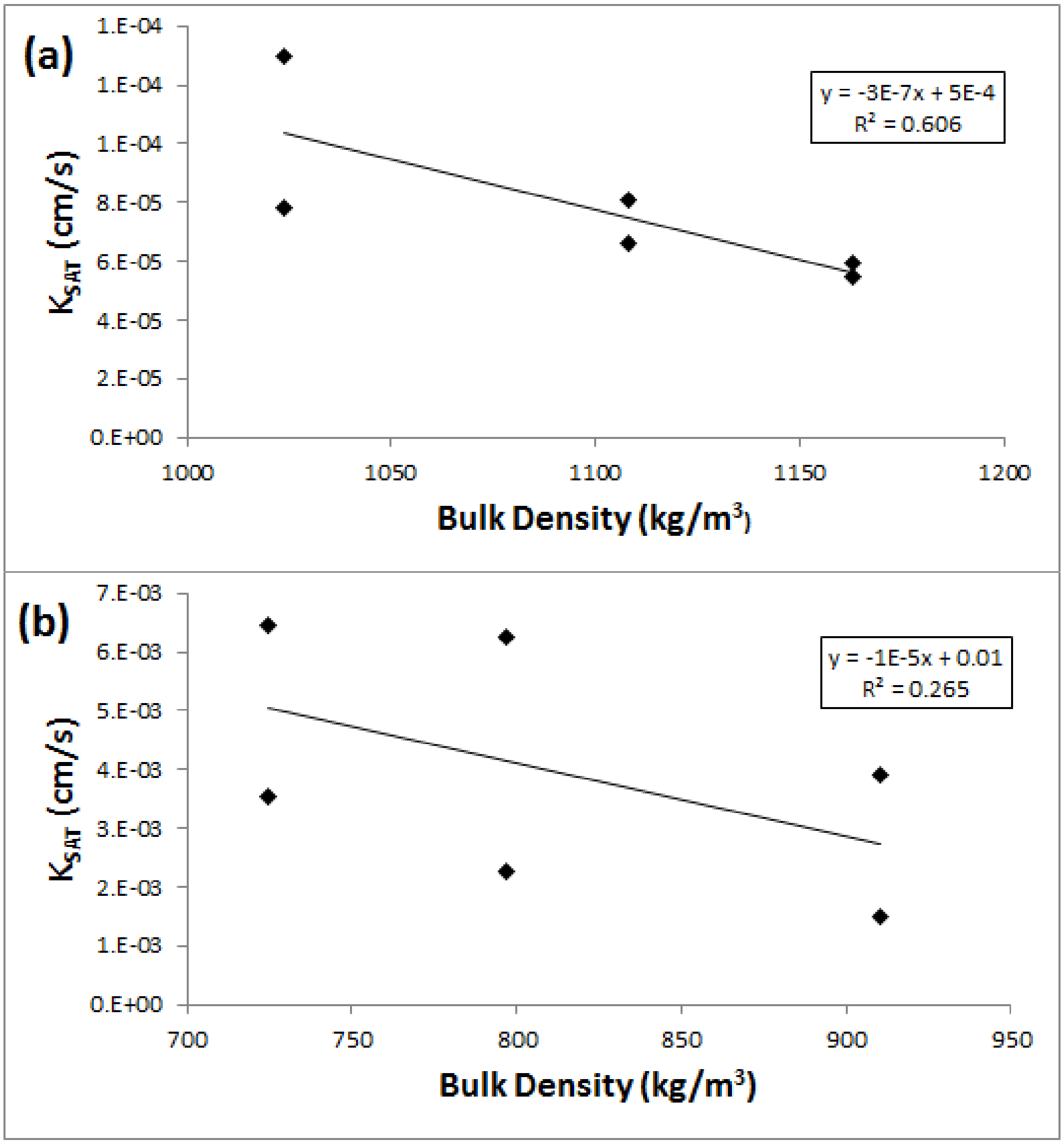

Figure 3. K_{sat} vs bulk density for (a) fly ash and (b) bottom ash with trend lines fit to data with equations and R^2 values shown on each respective graph.

Table 6. Fitted van Genuchten model parameters for all fly ash (FA) and bottom ash (BA) samples tested and the actual bulk density of each individual sample.

Sample ID	Bulk Density (kg/m^3)	Residual Water Content Θ_r (cm^3/cm^3)	Saturated Water Content Θ_s (cm^3/cm^3)	Inverse of Air Entry α (cm^{-1})	Curve Fitting Parameter n
FA A	1030.83	0.00	0.52	4.0E-03	1.59
FA B	1033.12	0.00	0.57	3.9E-03	1.64
FA C	1034.74	0.02	0.56	3.7E-03	1.97
FA D	1113.3	0.00	0.51	2.4E-03	1.66
FA E	1113.3	0.00	0.49	2.4E-03	1.67
FA F	1118.8	0.00	0.57	2.8E-03	1.60
FA G	1172.19	0.00	0.47	1.3E-03	1.80
FA H	1173.41	0.00	0.46	7.3E-04	1.99
FA I	1175.2	0.00	0.49	1.4E-03	1.77
BA A	729.21	0.00	0.51	2.6E-02	1.51
BA B	726.52	0.00	0.58	4.6E-02	1.45
BA C	724.22	0.00	0.60	5.6E-02	1.44
BA D	795.18	0.00	0.66	5.4E-02	1.47
BA E	797.06	0.00	0.68	3.4E-02	1.61
BA F	798.68	0.00	0.64	4.6E-02	1.50
BA G	912.26	0.00	0.69	3.4E-02	1.51
BA H	913.47	0.00	0.60	2.4E-02	1.54
BA I	916.85	0.00	0.60	1.8E-02	1.57

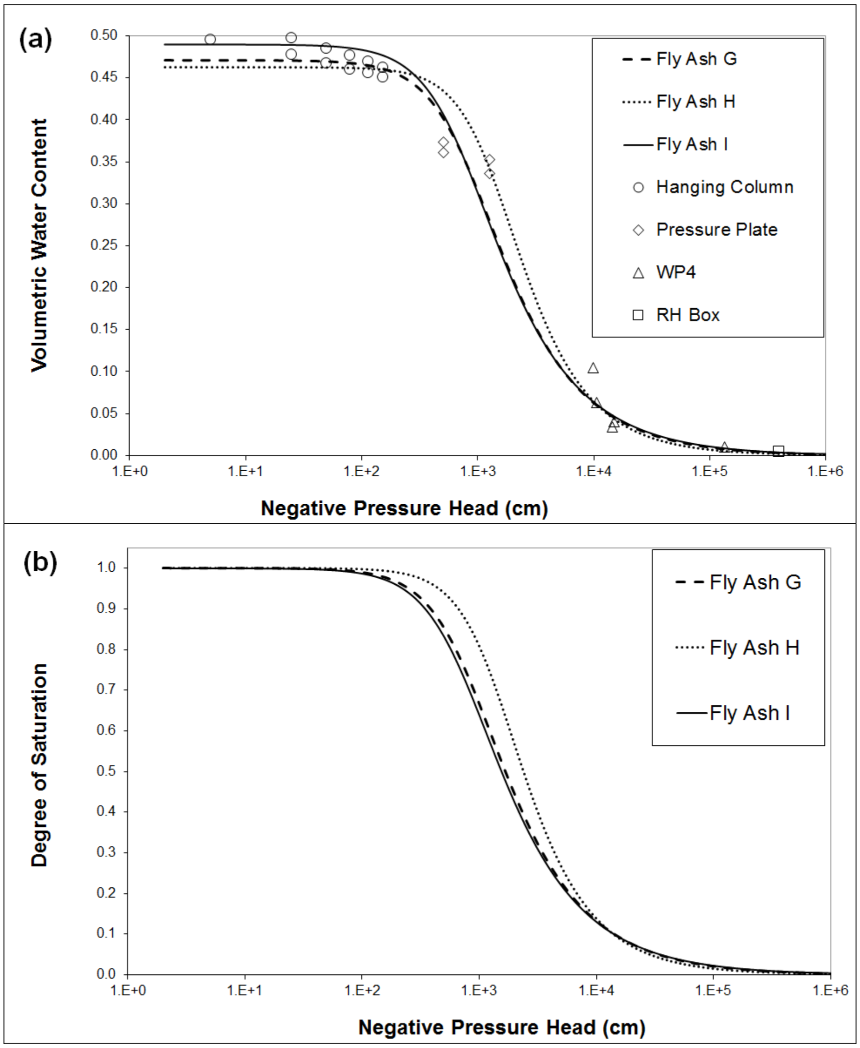

Figure 4. (a) Data and fitted MCCs for the three fly ash samples as tested and measured at ~1169.3 kg/m^3 as well as (b) The same MCCs for fly ash at ~1169.3 kg/m^3 plotted as degree of saturation.

Table 7. Van Genuchten model parameters for best fit curves at each bulk density created by fitting a curve to data from all 3 samples for each target bulk density.

Material	Target Bulk Density (kg/m^3)	Residual Water Content Θ_r (cm^3/cm^3)	Saturated Water Content Θ_s (cm^3/cm^3)	Inverse of Air Entry α (cm^{-1})	Curve Fitting Parameter n
Fly Ash	1028.4	0.003	0.55	3.9E-03	1.68
Fly Ash	1113.3	0.00	0.52	2.4E-03	1.66
Fly Ash	1169.3	0.00	0.47	1.1E-03	1.85
Bottom Ash	727.2	0.00	0.56	4.1E-02	1.46
Bottom Ash	800.9	0.00	0.66	4.3E-02	1.52
Bottom Ash	913.1	0.00	0.63	2.5E-02	1.54

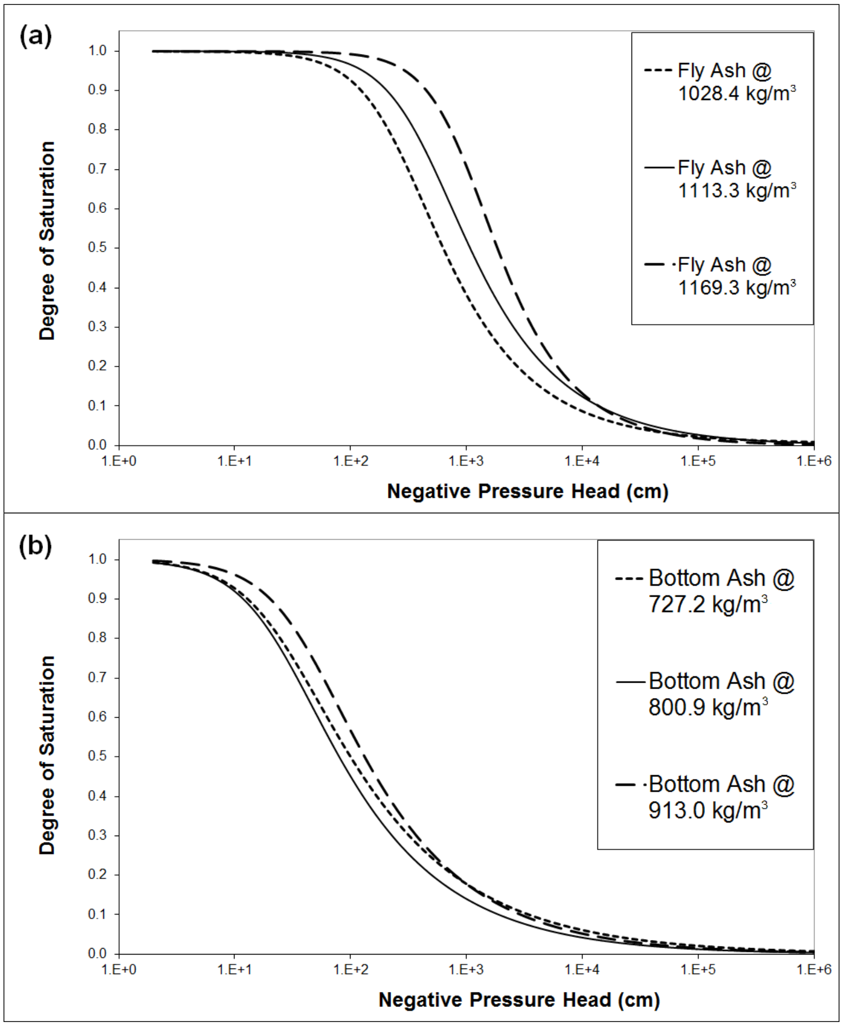

Figure 5. Best fit MCCs showing degree of saturation vs. pressure head for comparison between the three tested bulk densities of (a) fly ash and (b) bottom ash.

Van Genuchten model parameters are plotted vs. bulk densities in Fig. 6. Linear trend lines have been fit to the data for θ_s and α values. Fly ash shows a linear trend, with R^2 values of .59 and .94 for θ_s and α, respectively, where bottom ash shows little trend, with R^2 values of .17 and .38 for θ_s and α, respectively.

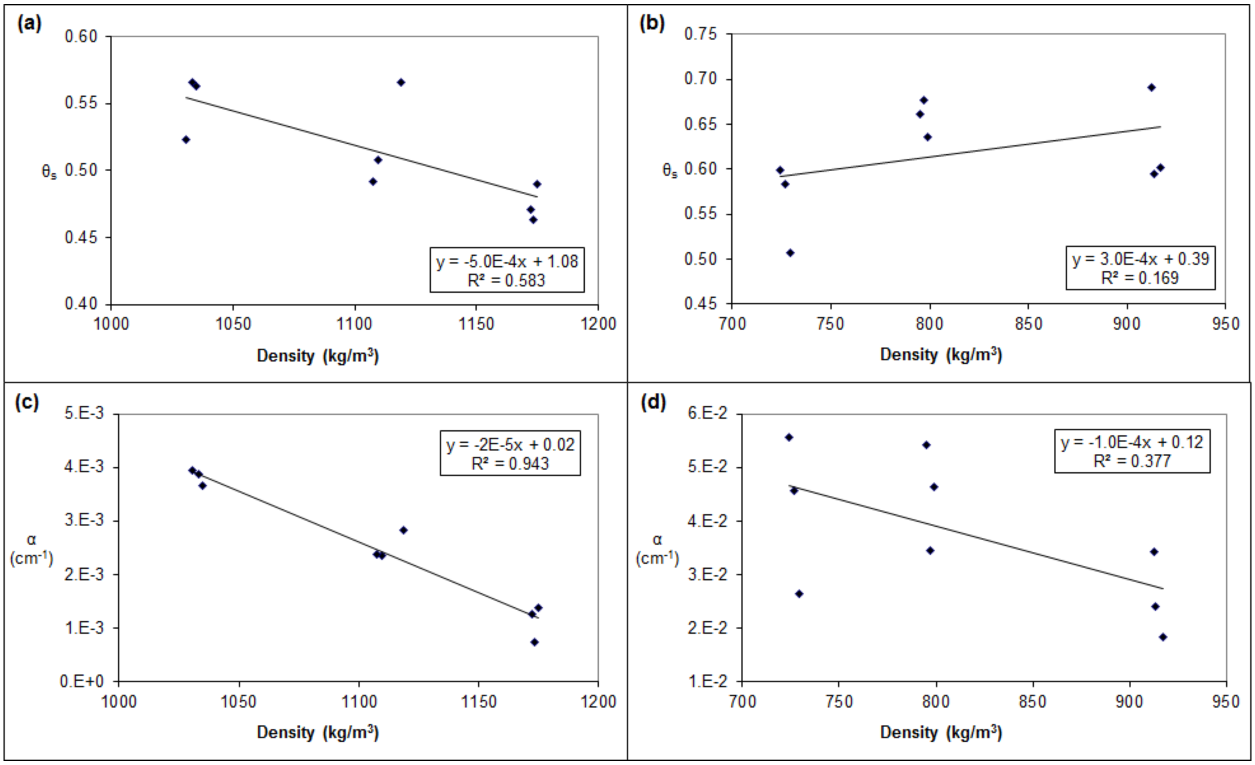

Figure 6. θ_s and α van Genuchten model parameters plotted with respect to sample bulk densities and trend lines fit and shown on each graph along with the associated R^2 value for: (a) fly ash θs vs. density, (b) bottom ash θs vs. density, (c) fly ash α vs. density, and (d) bottom ash α vs. density.

Discussion

Specific Gravity and Calculated Porosity of Fly Ash and Bottom Ash

Specific gravity tests resulted in an average specific gravity of 2.00 for fly ash and 2.06 for bottom ash with relatively low standard deviations giving confidence in these values. These results are also within the range of results from other studies (El-Mogazi et al., 1988; Palmer et al., 2000; Prashanth et al., 1998; Seals et al., 1972). Total porosity was calculated using the following equation:

$$\text{Total Porosity} = 1-\rho/G_s \qquad \textbf{(4)}$$

Where: ρ = sample density in g/cm^3 ;G_s = material specific gravity

When porosities are compared to fitted θ_s values for each of the tested densities, most samples have calculated porosities less than θ_s (Table 8). This result is consistent throughout all samples except for bottom ash samples with a target bulk density of 727.0 kg/m^3. It can be seen in the MCCs fitted with data (Fig. 4a) that the fitted θ_s values are often less than the volumetric water content measured at low negative pressure heads measured with the hanging column. It is highly unlikely that the samples were over saturated at the fitted θ_s values, as this may suggest, because no ponding water was observed on the samples while taking measurements.

Table 8. Calculated porosity and van Genuchten model parameter saturated water content for comparison purposes.

Sample	Bulk Density (kg/m^3)	G_s	Calculated Porosity (%)	Θ_s (cm^3/cm^3)	Apparent % Saturated
FA A	1030.8	2.00	48.5	0.52	108.0
FA B	1033.1	2.00	48.3	0.57	117.1
FA C	1034.7	2.00	48.3	0.56	116.6
FA D	1,113.3	2.00	44.5	0.51	114.1
FA E	1,113.3	2.00	44.6	0.49	110.2
FA F	1,118.8	2.00	44.1	0.57	128.5
FA G	1172.1	2.00	41.4	0.47	113.8
FA H	1173.4	2.00	41.3	0.46	112.0
FA I	1,175.2	2.00	41.2	0.49	118.8
BA A	729.2	2.06	64.6	0.51	78.5
BA B	726.5	2.06	64.7	0.58	90.1
BA C	724.2	2.06	64.8	0.60	92.5
BA D	795.2	2.06	61.4	0.66	107.8
BA E	797.1	2.06	61.3	0.68	110.5
BA F	798.7	2.06	61.2	0.64	103.9
BA G	912.3	2.06	55.7	0.69	124.1
BA H	913.5	2.06	55.7	0.60	106.9
BA I	916.9	2.06	55.5	0.60	108.6

A possible reason that some of the bottom ash samples appear under saturated may be that some of the bottom ash particles were observed to have large hollow cores that are inaccessible to water. Attention was given during saturation to ensure fully saturated samples. There were no observations during testing to support that any of the samples were under or oversaturated. Therefore, calculated porosities using specific gravity are not used for comparison purposes or further calculations such as void ratios.

However, the saturated water contents still show inconsistency in that the bottom ash samples with the lowest density values also have the lowest saturated water content values. These were the samples that were first compacted and tested, which may have damaged the grains and caused the inconsistency seen in Table 6. The bottom ash grains tend to have hallow cores as previously mentioned that may have broken apart from the multiple re-packing of samples. Another possibility is that the samples used for these tests were too small for the grain size distribution observed in the bottom ash even though the sample sizes are of correct measurement according to standards. Too small of samples for the bottom ash may have caused a higher variability between samples. This inconsistency shown in the bottom ash sample data suggests errors within the measurements that have been unaccounted for and could explain the higher amount of variability seen in the results of the bottom ash data with respect to fly ash data.

Some of the errors observed are also due to the fact that many of these parameters are fit to the data, much like an average of all the observed data. The fitted parameters allow comparison between parameters such as saturated water content through these "representative" values that have been fit to the data with the apparent error being inherent through this method.

Compressibility and Void Ratios

Equation (3) is shown to reasonably describe the load-bulk density relationship of both fly ash and bottom ash within the range of applied loads used in this study. A minimum R^2 value of 0.974 shows a well fit curve, especially since most values are above 0.98. The four trials for each material all showed similar results with a maximum percent difference of 3% from the average seen in the bottom ash material.

An important aspect of compressibility is the void ratio with respect to pressure. However, due to the relationship between void ratio and porosity no calculations were conducted for void ratios since calculated porosity was determined to be invalid, as previously discussed. A void ratio and pressure relationship is important and further investigation is necessary to form this relationship with confidence from compressibility data.

Unsaturated Hydraulic Conductivity

Unsaturated hydraulic conductivity was also taken into consideration to be calculated. Due to the fact that this study collected no data for unsaturated hydraulic conductivity, any calculated values for unsaturated hydraulic conductivity would be impossible to confirm or deny. Therefore, an appropriate method for such calculations could not be chosen and these calculations were not carried out. However, it is important to note that any analysis or application to a particular site or case study should take into consideration the change in hydraulic conductivity under unsaturated conditions

Fly Ash

The results of the saturated hydraulic conductivity for fly ash show greater variability in the samples with lower bulk densities. It can be speculated that this is caused by less uniform pore size distribution at lower densities which becomes more uniform with increasing density. Saturated hydraulic conductivity results between fly ash samples of the same bulk densities are, however, comparable with one another. These results provide a trend of K_{sat} decreasing as bulk density increases, consistent with previous studies on fly ash. The values found in this study are within the limited range of densities previously tested and are comparable to what other studies have found. (Campbell et al., 1983; Joshi et al., 1994; Prashanth et al., 2001)

The van Genuchten model parameters of fly ash also display a trend in variation with bulk density. Values of θ_s, which is related to the amount of pore space within the sample, are shown to decrease with increased density as expected. Values of α, commonly interpreted as the inverse of air entry pressure head (Mudd et al., 2007), also decrease with increases in density; this can be attributed to smaller radius in the pores within the higher density materials. Values of air entry for fly ash, calculated from α (Table 9), are similar to what was found in previous studies (Mudd et al., 2007; Chakrabarti et al., 2005). All three samples at each bulk density of fly ash provided similar results, indicating that the methods used to estimate unsaturated properties are appropriate for fly ash materials.

Table 9. Air entry values and fit the van Genuchten model parameter α for each material and target bulk density.

Material	Target Bulk Density (kg/m^3)	α (1/cm)	Air Entry Value (cm)
Fly Ash	1028.4	3.9E-03	256
Fly Ash	1113.3	2.4E-03	417
Fly Ash	1169.3	1.1E-03	909
Bottom Ash	727.2	4.1E-02	24
Bottom Ash	800.9	4.3E-02	23
Bottom Ash	913.1	2.5E-02	40

Bottom Ash

Bottom ash compressibility results showed densities less than 1000 kg/m^3, which is approximately the density resulting from the clod density test of the *in situ* sample at 38 m depth (1028 kg/m^3). Though the clod density tests used small sampling methods and thus introducing a higher potential for error, the standard deviation was approximately 3% of the average density giving confidence in the results. The *in situ* density at depth supports the compressibility results of ash materials in northwestern New Mexico and support the claim of CCBs being compacted solely as a result of overburden pressure of materials. Implications of the clod density tests are that the results of the tests in this study are applicable at depths less than 38 m.

Bottom ash compressibility results showed less variation between samples than fly ash. Bottom ash has a much higher uniformity index than fly ash while having less variability in the compressibility curves. This may be due to the higher percentage of larger grain sizes controlling the compressibility of the material which may or may not be impacted by the relatively small sample heights. The lack of variability in the compressibility curves, however, shows that equation (3) can be used to reasonably describe the load-bulk density relationship of bottom ash for the range of applied loads used.

K_{sat} values measured for bottom ash samples show a general linear trend of decreasing as density increases but with considerable variability. This variability could once again be possibly linked to the larger grain sizes controlling the results of K_{sat} values. Larger pore diameters would form in a manner controlled by the larger grain sizes, thus controlling the K_{sat} values. The larger grains would create pore size variability between samples at all the tested densities, causing the higher amount of variability at all tested densities with respect to the fly ash tests.

Unsaturated properties of bottom ash show similar variability in the results. The θ_s values show little linear trend as density increases, with a low linear R^2 value of 0.17. The θ_s values for bottom ash tend to increase slightly as density increases, which conflicts with expectations and suggest some error, possibly due to damaged bottom ash grains occurring because of the re-packing of the samples. This could also possibly be attributed to larger grain sizes. With the size of the samples, the relatively large grain sizes could control the MCC depending on the orientation of the larger grains. Values of α for bottom ash are similar to those found in other studies (Mudd et al., 2007; Chakrabarti et al., 2005). Larger samples may be able to reduce some of the variability in unsaturated properties for bottom ash in future investigations.

The variability in bottom ash properties compared to fly ash may be due to the small samples used for bottom ash. Though the same volume of samples were used for fly ash, the bottom ash samples were of less mass due to the grains having hollow cores. Larger sample volumes could possibly dampen the impact from larger grain sizes on K_{sat} and MCC measurements. The high variability seen in the bottom ash measurements of unsaturated and saturated hydraulic properties suggest that some error is encountered due to either the small sample size or re-packing methods applied in this study.

Conclusions

Fly ash K_{sat} values, for samples used in this study, are shown to decrease in a predictable manner as bulk density increases. Unsaturated properties, such as θ_s and α, for the fly ash tested show a decreasing trend with increases in bulk density. Bottom ash compressibility, for samples used in this study, shows less variability whereas hydraulic properties have more variability with respect to results from fly ash samples. K_{sat} values of bottom ash samples tend to decrease as bulk density increases. Unsaturated properties of the studied bottom ash show little trend in variations with changes in bulk density. Test results may reflect error introduced due to the small sample sizes used.

The compressibility results of CCB samples from northern New Mexico have shown that application of equation (3) may be used in order to estimate densities of fly ash materials at depth within a landfill, further investigation would need to be conducted in order to test this equation and methods above pressures tested in this study. If the profile of the landfill and cover material densities are known, a reasonable estimate of densities may be calculated. As the estimated densities increase, a higher confidence in unsaturated and saturated hydraulic properties may also be estimated within the profile of a landfill for fly ash. The deeper within a landfill a material exists, the higher amount of error can be expected in the density with a higher amount of confidence in the unsaturated and saturated hydraulic properties.

The compressibility and clod density results show confidence in equation (3) being used in order to estimate bulk density of bottom ash materials within a landfill at depths less than 38 m.

Further investigation would need to be considered in order to provide higher confidence in the unsaturated and saturated hydraulic properties of bottom ash due to the high amount of variability seen in the results of this study.

It is important to note that there is variability shown in the results of this study for the materials tested. However, the trends are shown to exist and may be useful to predict the impact of CCB landfills on local water resources in northern New Mexico. Lateral hydraulic gradient calculations may need to include these variations in material properties in order to accurately predict for scenarios when saturated flow is expected through the landfills. For those conducting research in the area of CCBs and their disposal, this study provides insight into the manner in which the materials may behave, conceptually, at various depths of a landfill site in northern New Mexico.

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