The Mechanical Experiments on Coal Combustion Residuals in Coal-Fired Power Plants

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***Abstract*—Coal ashes are the inevitable production in the process of coal-fired power plants. Their storage expands greatly and have potential risks all over the world. To have more knowledge about the project characters and mechanical characters of coal ashes also referred to as coal combustion residuals or CCRs, this paper researched the particle distribution, dried bulk density and its moisture content, compaction abilities and penetration characteristics based on the particle analysis test, density test, compaction test and penetration test. The results show that the particles of this sample from power plant are coarse granularity and distributed unevenly. The smaller the dry density is, the higher the penetration coefficient is. The compaction density is not sensitive to sample moisture. The high compaction makes the coal ash particles and soil particles denser and the pore ratio smaller which results the penetration coefficient tend to decrease.**

***Index Terms*—coal combustion residuals (CCR), particle distribution, density experiment, permeability experiment, mechanical characteristic**

I. Introduction

Coal-fired power plants is the world's largest coal consumer industry. Coal consumption accounts for almost 70% of China's primary energy consumption. The proportion of coal-fired power plants is more than 50% of national coal consumption [1]. The amount of coal ash emissions from coal-fired power plants have increased 2.5 times in the past eight years. The production of coal ash has reached 375 million tons, which can reach 424 million cubic meters. It has become the largest single source of industrial solid waste emissions in China [2]. Coal ash is inevitable product of coal-fired power plants and its amount produced by power plants increases along with the expansion of installed capacity of power generators [3]. Coal ash is the toxic waste formed from burning coal in power plants to make electricity. The second largest industrial waste stream in the U.S. According to the American Coal Ash Association's Coal Combustion Product Production & Use Survey Report, nearly 110 million tons of coal ash was generated in 2012. A total of 1.25 billion tons of coal ash is stored in China with an annual emission of 1.5 million tons [4].

Hundreds of contaminated sites and spills have been documented among the 1,400+ coal ash waste dumps across the U.S. [5]. Many coal ash dumps lack basic safety features and regular inspections, leaving communities at risk of large scale disasters like those in Kingston, Tennessee and North Carolina.

To ensure the stability and safety of the coal ash dam, the mechanical properties and engineering properties must be studied thoughtfully. Its mechanical characters are similar with the tailings dam. At present, there are quite a few researches about the safety of tailings dam [6]-[8]. There are relatively few studies on the basic mechanical properties of the coal ash although ash storage has similar structural characteristics with tailings dam. The purpose of this paper is to study the physical and mechanical properties of coal ash from a coal-fired power plant of Virginia, USA by using particle test, density test, compression test, penetration test. The deposition distribution regular, compression characteristics and permeability characteristics are concluded from the experiments, which are key factors for study of the coal ash storage dam stability.

II. Coal Ash Dam Fialures and Its Effects

The storage of coal ash is accumulated as dam for it is used as foundation material of dam. The coal ash storage dam with heavy metals and hazardous substances is a major hazard. Once the dam fails, spills or breaks, it leads to catastrophic damages and impacts on the surrounding environment [9].

Coal ash dam failures cause hundreds of people dies in history. In 1966, the dam of a coal refuse dump in Aberfan, Wales, UK, collapsed early on a weekday morning. Tragically, the dump was situated uphill from a school which had just started its school day. 144 people died that day, including 116 children [10]. In 1972, one of

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the worst mining disasters in the US coal waste from mining operations (similar to the coal combustion waste in ponds) was placed into the river, and then dammed in Buffalo Creek, West Virginia. People lived in the narrow valley below the two dams where buffalo creek flowed. The dam burst after days of heavy rain killing 118 people, injuring 1,100 and leaving over 4,000 homeless [11]. In 2000, a spill of coal ash in Martin County, Kentucky released 306 million gallons of coal ash, which the EPA at the time called "one of the worst environmental disasters in the Southeastern United States". In 2008 Kingston, Tennessee coal ash failure, which was unlike the disasters in 1966 and 1972, the dam failure at Kingston did not result in a loss of life [12]. Even so, three houses were destroyed, 28 damaged, and to this day the creek remains flooded with waste.

The coal ash failure results the surface release of coal ash with high levels of toxic elements and radioactivity to the environment has the potential to generate re-suspended ambient fine particles (<10μm) containing these toxics into the atmosphere that may pose a health risk to local communities. The leaching of contaminants from the coal ash caused contamination of surface waters in areas of restricted water exchange, but only trace levels were found in the downstream Emory and Clinch Rivers due to river dilution. The accumulation of Hg- and As-rich coal ash in river sediments has the potential to have an impact on the ecological system in the downstream rivers by fish poisoning and methylmercury formation in anaerobic river sediments [12].

The coal ash dam foundation, slope instability, overtopping, unusual rain, snow melt, seismic liquefaction, structural stability, and other unknown reasons will cause the coal ash dam failure. It is important to analyze the mechanical characters of coal ash to make sure the coal ash dam safety. Especially, the particles distributions regulation and the permeability coefficient under different compaction conditions are helpful to evaluate the coal ash dam stabilities. In the following section, the mechanical parameters of coal ash are tested in the rock mechanical lab.

III. Experimental Principles and Methods

Particle analysis test is to determine the percentage of coal ash in various grain group quality, which is to define the distribution of particle sizes. The sieving and hydrometer method are commonly used according to the particle sizes and gradation. Sample hydrometer method is suitable for a particle size less than 0.074 mm. The sieving method is suitable for the analysis of the sample is greater than the diameter of 0.074 mm. When the particles in both of these two grain groups, the conjunction sieve analysis and hydrometer method should be used at the same time [13].

The test equipment includes type A densitometer and type B species density meter. Type A species density readings indicate that a certain amount of suspension of dry coal ash quality, type B densities readings indicate that the suspension ratio, the 1000 mL graduated cylinder volume, volume of 500 ml conical flask, boiling apparatus, comprising an electric heater, an Erlenmeyer flask, dispersant: 4% or 25% sodium hexametaphosphate aqueous ammonia, a stirring rod, a thermometer, a mortar, a stopwatch, beakers, porcelain dish etc.

Taken a representative coal ash sample of 200 -300 g, air-dried and air-dried moisture content of the sample was measured, and the sample was placed in a mortar grinded by a pestle with a rubber head. A weighted 30 g coal ash sample was poured into 500 mL flasks, soaked with 200 mL water and stayed overnight. After shaking the flask contained the mixture, it was placed on fire to boil. The suspension was cooled and was poured into the breaker. The suspension was grinded by a pestle with a rubber head. The mixture was place steadily for about one minute. The upper suspension was poured on a 0.075 mm sieve hopper and injected in to 1000 mL cylinder. The precipitate left on the bottom of the cup was grinded by a pestle with a rubber head. A certain amount of purified water was added and stirred. The mixture of the upper portion was sieved and poured into the cylinder once again. This process was repeated until the suspension was clarified after all samples were sieved. All the coal ash particles on the screen were moved into the evaporating dish. The percentage of each sized particles was calculated after oven dried. Adding 4% hexametaphosphate 10 mL into the cylinder and mixed with 1000 mL water. The stirrer was placed into a graduated cylinder and stirred the suspension for one minute vertically until the coal ash particles were distributed in the suspension uniformly. The stirrer was then removed from the cylinder and immediately started the stopwatch as a hydrometer was put into the suspension. The results were recorded at 0.5, 1, 2, 5, 15, 30, 60, 120 and 1440 min sharp. According to (1), the diameter of coal ash can be calculated as:

$$\mathrm{d}=\sqrt{\frac{1800\times10^{4}\eta}{(\mathrm{G}_{S}-\mathrm{G}_{\omega t})\ \rho_{\omega 0}\mathrm{g}}\times\frac{L}{\mathrm{t}}}=K\sqrt{\frac{L}{\mathrm{t}}} \tag{1}$$

where, d is particle size in mm; η is viscosity of water ($kPa\cdot s\times10^{-6}$); G_s is the specific gravity; $\mathrm{G}_{\omega t}$ is the specific gravity at t ^{o}C; $\rho_{\omega 0}$ is the density of pure water at 4 ^{o}C, g/cm^3; L is the particle sinking distance at a certain time of t , cm; t is particles sinking time, s; g is the gravity acceleration (cm/s^2); K is Diameter calculation coefficient, which is related to the temperature of suspension and specific gravity.

For the particles, that were less than 0.1 mm in size, were turned into suspension after chemical and physical processing. According to Stokes Law and the average effective depth of hydrometer float bubble in the suspensions, the mass per liter of suspension particles contained levels can be recorded directly based on the hydromenter after placed at different period. According to (2) and (3), the percentage of particles can be calculated as: [14]

$$X=\frac{100}{m_d}C_s(\mathrm{R}+m_t+\mathrm{n}-\mathrm{C}_D) \tag{2}$$

$$C_s = \frac{\rho_S}{\rho_S - \rho_{\omega_{20}}} \times \frac{2.65 - \rho_{\omega_{20}}}{2.65} \tag{3}$$

where, X is the percentage of the sample particle size less than a certain size (%); m_d is the dry mass of the sample (g); C_s is the correction of specific gravity; R is hydrometer readings; m_t is the correction of suspension temperature; n is the meniscus correction; ρ_S is the particle density (g/cm^3); C_D is the value of the dispersing correction.

In the coal ash density test, the minimum and maximum dry density were measured by funnel method and vibration method [15]. About 15kg baked coal ash samples were grinding and mixing evenly, and 600 g of those were distributed slowly into a graduated cylinder. The maximum void ratio was calculated after the surface was flatted by the flat whisk. The bulk density measurement apparatus as shown in Fig. 1.

Figure 1. The demonstration of dried bulk density measurement

Then another 5 kg samples were grinded and dispersed into the container uniformly. Beat both sides of the container with a fork vibration and hammer the samples on the top at the same time until the sample volume reached constant. According to (4), the minimum dried density is calculated as:

$$\rho_{\max} = \frac{m_d}{V_{\max}} \tag{4}$$

where, $\rho_{\max}$ is the minimum dried density of the samples (g/cm^3); m_d is the quality of the samples (g); $V_{\max}$ is the maximum volume (cm^3).

By using a certain function of compaction meter, the compaction of the samples were measured. The relationship between dried intensity and the moisture ratio was measured, which determined the maximum intensity and the moisture ratio at a certain compaction degree. The quality of the hammer compactor is 2.5 kg. The height of tube is 116vmm and its volume is 947.4 cm^3. The amount of 20 kg air-dried coal ash samples were placed into five plastic bags respectively after they were sieved by 5 mm sieves. A total of 600 g prepared samples were put into compaction barrel and leveled the surface. The samples were compacted 25 times. The compacted samples is about 1/3 volume of the cylinder. The compactor hammer should fall freely and evenly distributed on the top surface of the coal ash samples. The second and the third compaction layers were compacted according to the former process repeatly. The compacted samples were slightly higher that the solid cylinder (not greater than 6 mm). Solidity penetration analysis was to take compaction samples points on the compaction curves according to 98%, 93% and 85%. Each selected point made two parallels samples with a total of six compacted samples, which had three standard layers of compaction samples.

IV. Analysis of Experiments Results

A. *The Particle Size Distribution Analysis of Coal Ash*

The particle distribution of coal ash samples were analyzed depended on the combination of the hydrometer method and sieving method. Based on the results of 17 tests, sandy particles (2 mm- 0.075 mm) accounted for 64.5%, fine particles (0.075 mm -0.005 mm) accounted for 34.1% and clay particles (<0.005 mm) accounted for 1.4%. The uniformity coefficient of particles is 9.05 and the curvature coefficient is 1.18. The Particle size distribution curve is shown in Fig. 2.

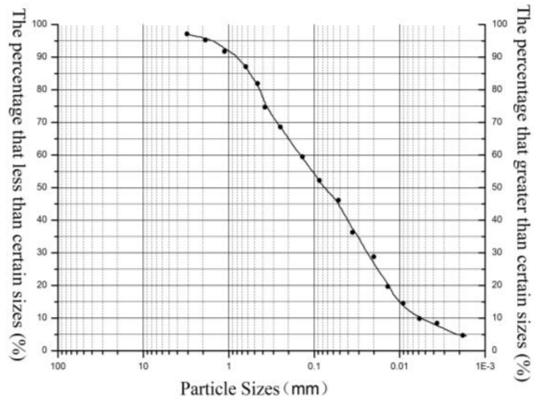

Figure 2. Particle sizes distribution curve

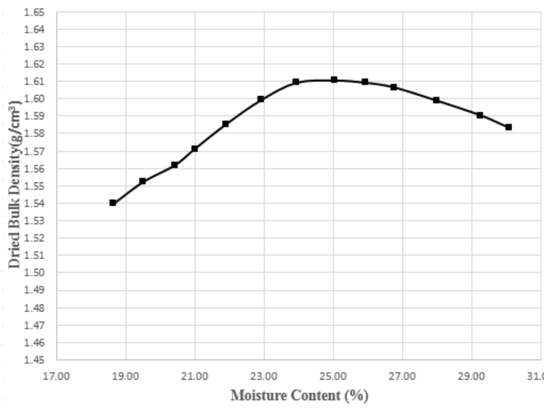

Figure 3. Dried density and moisture content distribution curve

B. *The Analysis of Dried Bulk Density*

The maximum dried bulk density of the coal ash is 1.61 g/cm^3, and the optimum moisture ratio is 24.8%. As the moisture content is low, the dried density of coal ash will increase with the increasing moisture content. After the dried density reaches the maximum, it decreased with the increasing moisture content. The dried bulk density and moisture content curve is displayed in Fig. 3.

C. The analysis of the compaction and permeability of coal ash

The compaction requirements of coal ash dam should be not less than 96% to 99%. The compaction of other level of dams is not less than 93% to 96%. In this paper, 98% compaction is selected as the high dam standards and 93% is selected as the ordinary dam standards. The compaction of 85% is provided for determining the permeability characters in low degree of compaction. According to the different degree of compaction, coal ash is mixed with variable soil and made of conventional penetration samples. After sufficient evacuation, saturated more than 90 minutes and the samples are submerged into water for 5 hours [16]. According to the results, void ratio versus permeability coefficient curve is presented in Fig. 4.

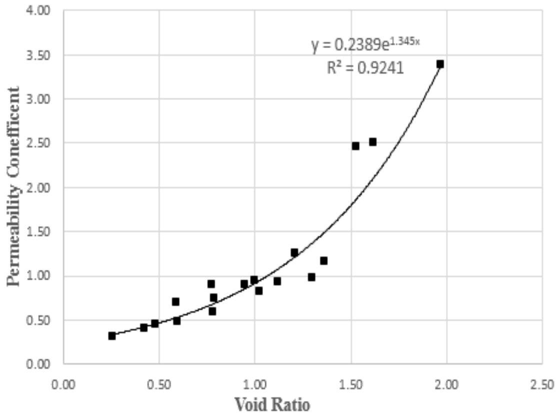

Figure 4. Void ratio versus permeability coefficient curve

The permeability coefficient does not vary a lot initially. After the void ratio is greater than 1.5, the coefficient increases fast. To understand the influence of the compaction and the amount of mixed soil on the permeability coefficient, the curve of permeability coefficient and mixed soil conditions is drawn in different degree of compaction as shown in Fig. 5.

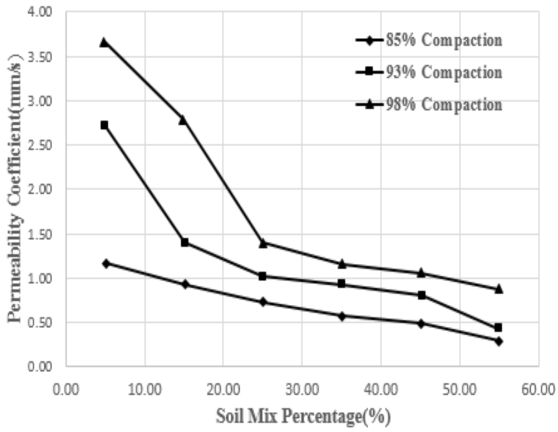

Figure 5. The curve of permeability coefficient and coal ash mixed with soil

The compaction degree effects the unsaturated permeability coefficient of coal ash. As the compaction degree and mixed soil quantity increasing, a greater degree compaction makes the particles of coal ash and soil become more dense, the pores become smaller, which resulting the permeability coefficient decreasing. When the mixed soil is about 0%- 25%, the permeability coefficient changes along with the changes of the degree of compaction greatly. It is not obviously in the other soil mixture conditions. This demonstrates that the rearrange of the loose coal ash plays dominated role in the compaction process. When the degree of compaction is 98% and 85%, 50% of the soil mixture can reduce the permeability coefficient to 20.8 originally. When the degree of compaction is 93%, 50% of the soil mixture, it can reduce to 11.5%.

The results show that the pore structure of coal ash has greater impacts on the unsaturated permeability coefficient of compacted coal ash and dried bulk density is a comprehensive reflection of the pore structure. The dried bulk density is one of the major impact factors of the unsaturated permeability coefficient. At a low degree of compaction, the lower dried density of compacted coal ash has larger pores and better connectivity, which means a larger permeability coefficient. While at a higher degree of compaction, the pore water exists in discontinuous meniscus. The transportation of pore water depends on the stream. The influence of pore structure is not obvious, which results in the difference of permeability coefficient declined.

V. Conclusions

According to the experiments, the coal ash of the coal-fired power plant is in light weight. It presents in porous particles structure and its surface area is large. These particles are mineral composition in different particle sized and shapes. The distribution of particles is uneven and the coarse particles dominate most parts of the samples. The finer the coal ash is, the greater its activity is. Its natural dried bulk density is related low. This coal ash has typical non-cohesive soil characteristics. The best ideal compaction of the coal ash can be get when the water content is in the range of 23%- 30%. The compaction density is not sensitive to moisture. It has high moisture resistance. The smaller of the dried density of coal ash, the greater of the permeability coefficient is. The higher permeability coefficient tends to make the dam leakage.

Earthquakes and heavy rainfall are the major environment factors that affect the coal ash dam safety. The further research on the mechanical properties of coal ash under the earthquake and rainfall conditions is meaningful for the analysis of distribution and deposition of coal ash dam. The proper monitoring technologies such as the saturation monitor, water fall monitor and dam displacement monitor will increase the coal ash dam safety. The coal ash dam safety monitoring and alert system will help to send out the emergency evacuation alert ahead of the dam failure.

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