2013 World of Coal Ash (WOCA) Conference - April 22-25, 2013 in Lexington, KY
http://www.flyash.info/

Dry Fly Ash Placement - Overcoming Unique Challenges and Streamlining Field Operations

Ali Ebrahimi[1], Sarah B. Fick[2], Cuneyt Gokmen[1], Mehmet Iscimen[2], Rachel B. Combs[3], Vernon J. Dotson, Jr.[3]

[1]Geosyntec Consultants, 1255 Roberts Blvd, Kennesaw, GA 30144; [2]Geosyntec Consultants, One Central Plaza, Suite 700 835 Georgia Ave., Chattanooga, TN 37402; [3]Tennessee Valley Authority, 1101 Market St., Chattanooga, TN 37402

KEYWORDS: fly ash, dry disposal, field testing, cementitious, compaction, shear strength, quality control

ABSTRACT

Fossil plant owner/operators are currently anticipating that EPA will more strictly regulate disposal of coal combustion residuals (CCRs) in the near future. Many facilities that operated wet disposal ponds are in the process of converting to dry disposal practices and facing new operational challenges. Dry fly ash has highly variable and time-dependent compaction characteristics due to pozzolanic and cementitious properties and the source of coal. Therefore establishing a compaction criterion, based on conventional soil mechanics using target relative compaction and moisture content, becomes challenging and often impractical from a construction perspective and increases the level of uncertainties in the construction quality assurance procedure. This paper presents a summary of field observations from actual dry fly ash placement operations at a fossil power plant, along with laboratory and field-scale testing of representative fly ash materials from the same fossil plant. Physical and engineering properties of dry fly ash relevant to construction quality control during disposal operations are discussed. The result of this study provides insight into the in situ density, stiffness, and strength properties of compacted dry fly ash with the ultimate goal of developing an alternative criterion and/or a method-based specification for fly ash placement. The findings of this study can lead into streamlining field operations, including placement, testing, and quality control, which could result in significant operational cost savings over the life of a fly ash disposal facility.

INTRODUCTION

About 130 million tons of coal combustion residuals (CCRs) are produced annually by fossil power plants in the United States, and the majority of which are disposed of in landfills and pond impoundments based on the survey by American Coal Ash Association[1]. Fly ash is one of the CCRs which its quantity and physical and chemical properties are known to differ based on coal sources[2], coal blends, firing/cooling time and temperature, type of burners, scrubber systems, and fly ash moisture conditions[3]. Fly ash is a well-known pozzolan (i.e., it reacts in the presence of water over time) which their short-term strength is related to carbon, silica and alumina content and their long-term strength is related closely to the SiO_2 contents[4]. As a result of the pozzolanic and cementitious properties, compaction and strength behavior of “dry” fly ash may significantly differ from those typically observed in soil materials. For clarification, in this paper, “dry” terminology is used for fly ash that is pneumatically transported from the point of origination to a dry storage area, while “wet” terminology is used for fly ash that is hydraulically transported and/or stored at a wet storage area (e.g., a pond).

The traditional soil mechanics approach typically designates a moisture content window within a few percentage of an optimum moisture content, w, (e.g., ±2 to 4%) and a minimum relative compaction, RC, (e.g., greater than 90 to 95% of standard Proctor maximum dry density) as target compaction criteria. Achieving these targets generally results in material behavior that meets or exceeds the geotechnical design requirements for strength and permeability. Some previous studies suggest that the optimum moisture content for maximum dry density may not necessarily provide a higher shear strength for compacted fly ash stabilized soils. Optimum moisture content for maximum strength of fly ash can be one to eight percent lower than the optimum moisture content for maximum density, as observed for fly ash stabilized soils[5,6]. Therefore, specifying moisture content window for compaction solely based on the compaction properties of fly ash can reduce the strength properties more than 50%, as reported for fly ash stabilized soils[5,6].

Figure 1 illustrates variation of fly ash produced in a fossil power plant and also changes of fly ash compaction properties at this plant. The 93% relative compaction lines (target RC criteria for this facility) for each fly ash compaction curve are plotted for comparison. This plot implies that construction quality assurance (CQA) procedures for fly ash placement only based on compaction properties can be very difficult, particularly while there are significant uncertainties to match the material being tested during field CQA with the materials used for developing compaction curves. One-point standard Proctor test are typically used to identify which compaction curve corresponds to a given material. The results of one-point standard Proctor field tests for one type of fly ash with 1-day and 3-day compaction delay after moisture conditioning are shown in Figure 1. The results of the one-point standard Proctor field tests did not show a good correlation with the compaction curves developed through a conventional testing procedure where bulk samples were shipped to an off-site laboratory after “dry” fly ash was moisture adjusted in the field. One-point field tests also indicated that, the dry density of fly ash reduces about 10 to 12 pcf (10 to 13% decrease in RC), if compaction is conducted three days after moisture adjustment for the same source material. This behavior is unusual for soil materials, however is similar to observations in fly ash stabilized soil [5,3]. Additionally, the recently developed ASTM D7762 standard for soil stabilization[6] reports that self-cementing fly ash can hydrate at a higher rate than Portland cement, and a delay of two hours in compaction may decrease the maximum dry unit weight. ASTM D7762 recommends a 1 or 2 hour conditioning period after adding moisture and prior to compaction, to standardize the compaction testing procedure. The level of variability observed in compaction properties of fly ash adds significant complications to CQA procedures and increases reliance on personal judgment in selection of the most applicable criteria to represent field conditions. For example operational variability associated with field activities (e.g., lapsed time between the initial moisture conditioning of “dry” fly ash and the completion of compaction) can lead to a high level of uncertainty with evaluation of field compaction results as some the of the field variables in compaction properties are not likely be captured through conventional laboratory testing. As a result of highly variable and time-dependent compaction characteristics of “dry” fly ash, establishing target compaction criteria for “dry” fly ash becomes very challenging and quite often impractical from a construction perspective.

To minimize the complication during CQA induced by change in fly ash properties and to become less reliant on personal judgment during CQA effort, alternative placement criteria including method based placement techniques and performance-based quality control methods are evaluated. This paper presents a summary of laboratory and field-scale testing of two blends of fly ash (at three conditions) and summarizes the in situ density, stiffness, and strength of compacted dry fly ash under varying compaction effort and construction delays. The testing program is intended to provide data to ultimately develop a strength-based criteria and/or a method-based specification for dry fly ash disposal.

MATERIALS

The fly ash tested in this study is from a fossil power plant located east of the Mississippi River. The Plant removed the wet fly ash handling system (i.e., water-driven hydroevacuators) and the dry collection system was commissioned in December 2011. This change required construction of dry ash silos and supporting infrastructure. The new system pneumatically conveys dry ash from the precipitators, selective catalytic reduction systems, and economizers to one of two dry ash storage silos using a negative pressure air system. Dry fly ash collected in the storage silos is loaded into trucks for transportation to the on-site disposal facility. Immediately prior to loading for transport and disposal, water is introduced as a dust control measure and to improve workability for final placement, generally increasing the moisture content from less than 0.5% to approximately 11% to 15% (measured in accordance with ASTM D 2216–110^{o}C procedure). For the specific fossil power plant referenced in this study, coal is sourced from the Powder River Basin (PRB) and Illinois Basin (ILB). It should be noted that the cementitious nature of fly ash increases with the PRB content of the coal mix[2]. During the period of this study, the coal blends burned typically varied between the two extremes of 75%(PRB)/25%(ILB) and 50%(PRB)/50%(ILB), referred herein to 75/25 and 50/50 blends.

The study presented here consists of three test pads in which three conditions of fly ash (for two types of fly ash) are studied. Each test pad is briefly described below:

Test Pad 1: “Fresh” fly ash (Ash-03) represents an operational condition with a 75/25 blend where fly ash received initial moisture conditioning at the silos, then hauled, placed, and compacted within a few hours.

Test Pad 2: “Aged” fly ash (Ash-04) represents an operational condition with a 75/25 blend, where fly ash (i.e., “Fresh” Ash-03) received initial moisture conditioning at the silos, then hauled to the field and staged under tarps for approximately seven days prior to placement and compaction.

Test Pad 3: “Fresh” fly ash (Ash-05) represents an operational condition with a 50/50 blend where fly ash received initial moisture conditioning at the silos, then hauled, placed, and compacted within a few hours.

TEST PAD CONSTRUCTION

Each test pad consisted of two to three lanes. The lanes for each test pad were designed to study the impact of moisture on density and strength. Test Pads 1 and 2 were built approximately 50-foot long with lane widths of 20 feet. Due to the consistency of the measurements obtained in Test Pads 1 and 2, the length of Test Pad 3 was shortened to 25 feet.

Prior to placing the material in each lane, the subbase (i.e., previously placed fly ash surface) was prepared by a minimum of 10 passes using a Caterpillar smooth drum vibrating roller (CAT CS-563C). After preparing the subbase, fly ash was hauled to the location of the test pad. The test pad was graded in an approximate 14-inch thick loose layer of fly ash using a bulldozer (CAT D6N). Moisture was added, if necessary, using a water truck, and a dozer was used to mix until relatively homogeneous and uniform color material was observed. Figure 2 shows the test pad general construction process. Moisture condition of each test pad is summarized below:

Test Pad 1 (Ash-03): (i) Lane 1 moisture content was as-received after initial moisture conditioning at the silos and had an average moisture content of 11%. Moisture contents of Lanes 2 and 3 were adjusted; (ii) average moisture content of Lane 2 was 18.5%; and (iii) average moisture content of Lane 3 was 22.7%.

Test Pad 2 (Ash-04): (i) Lane 1 moisture content was as-received from the stockpiled “aged” ash, and average moisture content of Lane 1 was 13.2%; (ii) Moisture content of Lane 2 was adjusted to 24.6%.

Test Pad 3 (Ash-05): (i) Lane 1 moisture content was as-received after initial moisture conditioning at the silos and had average moisture content of 14.5%; (ii) Moisture content of Lane 2 was adjusted to 21.7%.

After the moisture adjustment, each test pad was compacted using CAT CS-563C. Four or five levels of compaction effort (i.e., 0, 2, 5, and 8 passes or 0, 2, 4, 6 and 8 passes) were applied. The test pads were generally constructed as single lifts, if there was no interruption due to weather condition. Once construction of a test pad was completed, half of the pad was covered with a tarp to evaluate the impact of time and environmental factors (i.e., precipitation, wet and dry cycles, etc.) on strength properties of the compacted fly ash.

PILOT STUDY TESTING PROGRAM

The testing program included both field and laboratory testing. Routine field CQA testing [i.e., in situ density and moisture measurements using the Drive Cylinder (DC) method in accordance with ASTM D2937] was conducted in conjunction with Dynamic Cone Penetrometer (DCP) and Light Falling Weight Deflectometer (LWD).

DCP and LWD were used as an alternative CQA method for estimating the strength/stiffness properties of in situ compacted fly ash. The collected LWD data appeared to be inconsistent and not very sensitive to the changing conditions, and are not presented in this paper. It is observed that as fly ash cures and gains stiffness and strength, the compacted smooth surface becomes irregular and establishing full contact between the irregular fly ash surface and the LWD plate becomes more difficult, possibly contributing to data inconsistencies.

The DCP testing was conducted in accordance with ASTM D695 during and after test pad construction. Number of blows to achieve total penetration [recorded as DCP Penetration Index (DPI) in blows per inch (bpi)] provides an indication of the in situ material strength. Increased resistance to cone penetration results in higher DPI, which is indicative of higher strength/stiffness. DCP testing began by seating the cone tip approximately one (1) inch into the surface. The number of blows required for two (2) inches of penetration was recorded at five (5) intervals totaling 11 inches of lift thickness. Testing was terminated if a DPI greater than 15 bpi was required. The DCP and DC tests were conducted for selected levels of compactions on each lane.

Bulk samples and Shelby tubes (ST) of fly ash were also collected to conduct the laboratory index, physical, and strength property tests. Bulk samples for Ash-03 and Ash-05 were collected directly from silo dry spout prior to any moisture adjustment (i.e., “virgin” fly ash). The bulk sample for Ash-04 was taken from the stockpiled Ash-03 aged in the field for approximately seven days after initial moisture adjustment at the silos during load out. The following laboratory tests were conducted on bulk and ST samples: (i) index tests including moisture content (ASTM D2216 with 110^oC procedure), particle size analysis (ASTM D422), and loss on ignition (ASTM D2974-Method D using 750^oC oven); (ii) standard Proctor test (ASTM D698); (iii) volumetric expansion/swelling (laboratory procedure); (iv) consolidated-undrained (CU) triaxial test (ASTM D4767); (v) scanning electron microscope (SEM); (vi) one-dimensional consolidation test (ASTM D2435); and (vii) x-ray diffraction (XRD). The results of consolidation tests and XRD are not included in this paper.

It is noted that the standard Proctor tests, as well as, remolded triaxial, consolidation, and swell tests on Ash-03 and Ash-05 were conducted on specimens prepared from "virgin" fly ash bulk samples. Aging and hydration of specimens prior to testing varied as discussed in the results section.

PILOT STUDY TEST RESULTS

Laboratory Index Test Results

Basic Index Properties

Particle size distribution and loss on ignition (LOI) test results are summarized in Table 1. All fly ash samples consisted of mostly fine particles [93% or higher fines content with predominately silt-size particles (67 to 77%)], and they were all non-plastic based on visual observations. Loss on Ignition (LOI) test results indicated that approximately 3 to 4% of unburned coal may be remaining in the fly ash.

Compaction Properties

To capture the time effect on compaction properties fly ash, specimens of ash were prepared in advance to a target moisture content and allowed to "age or cure" over different time intervals prior to compaction under standard Proctor energy. A minimum of three time intervals were tested between 30 minutes and 10 days with some testing up to 35 days and the compaction curves are presented in Figure 3 and summarized in Table 1. The time intervals were selected to understand the effects of compaction delays that are likely to occur during routine operations. The compaction test on Ash-03 and Ash-05, both fresh fly ash, shows that the maximum dry unit weight (γ_{dmax}) drops whereas the optimum moisture content (w_{opt}) increases with the delay time between initial moisture conditioning and completion of compaction. The compaction properties of Ash-04 (aged ash) appear to be relatively independent of time. The compaction properties of fly ash are summarized below.

- The γ_{dmax} and w_{opt} of Ash-03 (fresh 75/25 ash) were 94.1 pcf and 22.4%, respectively, after 1-hour curing period. The γ_{dmax} and w_{opt} of Ash-03 changed to 84.4 pcf (10% decrease) and 29.3% (30% increase), respectively, after a 21-day curing period, and remained relatively unchanged after 35 days.
- The γ_{dmax} and w_{opt} of Ash-04 (aged 75/25 ash) were generally stable and remained in the range of 87 to 89 pcf and 25 to 27%, respectively over a 3-day curing period. It should be noted that curing time for Ash-04 is the time after laboratory moisture conditioning of the already-field-aged ash sample.
- The γ_{dmax} and w_{opt} of Ash-05 (fresh 50/50 ash) were 98.0 pcf and 20.6%, respectively, after 1 hour of curing time. The γ_{dmax} and w_{opt} of Ash-03 changed to

90.3 pcf (8% decrease) and 24.8% (20% increase), respectively, after a 10-day curing period.

Figure 4 shows the change in γ_{dmax} with curing time. The γ_{dmax} of fresh fly ash (i.e., Ash-03 and Ash-05) decreases relatively rapidly in first three days after initial moisture conditioning and reaching steady-state conditions in approximately three weeks. Whereas, aged fly ash (i.e., Ash-04) did not exhibit any significant changes in γ_{dmax} with curing time, suggesting that secondary moisture adjustment did not result in any significant additional reactions. It is surmised that most of the hydration/cementation reaction occurred during the 7-day curing period in the field.

Swelling Properties

During the test pad construction, indications of potential swelling were observed at the surface of compacted fresh fly ash. Volume change of fly ash in presence of water is expected due to hydration of sulfur trioxide during the pozzolanic reactions of fly ash. Ferguson and Levenson[7] stated that dry scrubber ash might have more than 10% sulfur trioxide content and expansion in fly ash results from the formation and subsequent hydration of the ettringite crystals. A laboratory procedure was developed to study the swelling properties of fly ash. Test specimens were prepared using the “virgin” fly ash bulk samples by adjusting the moisture content to approximately 20% and compacting the fly ash within 1 hour of moisture adjustment to achieve a dry density that is consistent with the compaction curve established based on the standard Proctor tests. Volumetric changes over time were recorded and presented in Table 1. Volumetric expansions for Ash-03 and Ash-05 (both fresh ash) were reported as 5.7% and 3.4%, respectively, 24 hours after initial moisture adjustment. The data also suggest that the most of the volumetric expansion occurs within the first 12 hours and after 24 hours changes become insignificant, indicating the majority of expansive reactions occurred rapidly. Ash-04 (aged ash) experienced less than 0.5% volumetric expansion, indicating that most of the expansive reactions had already occurred during the 7-day field stockpiling (aging) period.

Scanning Electron Microscope (SEM)

During the field study, aged fly ash (Ash-04) compared to the fresh fly ash (Ash-03) appeared to be more granular at the time of compaction and exhibited significantly less post-compaction strength gain over time. Additionally, in situ dry densities recorded at Ash-03 and Ash-04 test pads were significantly different (Ash-04 test pad exhibited significantly lower dry densities than Ash-03 test pad) although they were constructed under similar compaction energy and at similar moisture contents. SEM analyses were performed to better understand the changes that occur in fly ash microfabric after the moisture is introduced to “virgin” fly ash, and how these changes may be influencing the physical characteristics of the compacted fly ash. In the first set, the SEM analyses were performed on Ash-04 (field aged ash) and virgin samples of Ash-03 and Ash-05 (fresh dry ash). In the second set, Ash-03 and Ash-05 were hydrated with 25% moisture and cured for three days prior to SEM analyzes. SEM images are presented in Figure 5. Fresh fly ash comprises smooth spherical particles; however, the hydrated/cured fly ash and Ash-04 (field aged ash) show cementing agglomerates with irregular shapes and secondary minerals due to pozzolanic reactions. Similar observations were also noted by Yehleyis et al.[8]. These observations are consistent with the results of particle size distribution and compaction tests on fly ash. As presented in Table 1, Ash-04 is coarser than Ash-03, most likely due to the formation of cementing agglomerates. The change in fly ash agglomerates and their shapes during curing period can change the compaction properties of fly ash with time. Fly ash agglomerates with irregular shapes and internal voids would be contributing factors to the observed decrease in the maximum achieved dry density as discussed in compaction properties.

Field Test Results

In-Situ Compaction Data

The average measured field dry density (γ_d) and moisture content (w) from drive cylinder tests for different fly ashes and compaction efforts are shown in Figure 3 and Figure 6. Figure 3 also includes the laboratory standard Proctor compaction curves and the line of RC of 93% based on 1-hour laboratory compaction data for the comparison purposes. The summary of field observation for the achieved dry density and moisture contents is discussed below.

Ash-03: The γ_d of fly ash at as-received moisture (11% avg., Lane 1) increased from 84.1 pcf when placed (i.e. zero pass) to 92.9 pcf after four passes; but then decreased to 85.1 pcf as additional compaction effort is applied (up to eight passes). It is noted that this lane was constructed in two lifts due to a weather delay. The first one-foot lift was used for zero and two-pass measurements. The second one-foot lift was constructed after a day of weather delay and used for four to eight-pass measurements. The significant decrease observed in γ_d with increased compaction effort (approximately 8% decrease from four passes to eight passes) could not be fully explained with the available data, and therefore, was considered a potential anomaly.

The two moisture conditioned lanes (w_{ave} of 18.5% and 22.7%) generally showed negligible changes in density with increasing compaction effort ($\gamma_{d\text{-}ave}$ values were generally in the range of 93 to 96 pcf). Increasing moisture content of Ash-03 from 11% to 18.5% and 22.7% resulted in higher dry unit weights closer to a relative compaction of 100% based on the 1-hour compaction curve.

Ash-04: The γ_d of fly ash at 13.2% moisture content (Lane 1) at all levels of compaction effort was less than RC of 93% established based on the 1-hour laboratory compaction curve. Increasing moisture content at the time of placement from 13.2% to 24.6% (Lane 2) increases the RC to above 93% RC line. Generally negligible to slight increase (i.e., less than 5%) in γ_d values were observed with increasing compaction effort (i.e., $\gamma_{d\text{-ave}}$ of 75 to78 pcf for Lane 1 and $\gamma_{d\text{-ave}}$ of 84 to 88 pcf for Lane 2, with inconsistent trends).

Ash-05: Generally negligible to slight increase (i.e., less than 5%) in γ_d values were observed with increasing compaction effort and there were no consistent trends (i.e., $\gamma_{d\text{-ave}}$ of 87 to 90 pcf for Lane 1 with w_{ave} of 14.5% and $\gamma_{d\text{-ave}}$ of 86 to 90 pcf for Lane 2 with w_{ave} of 21.7%). Increasing the moisture content from 14.5% to 21.7% had negligible effect on dry unit weights. The field-achieved densities were all less than 93% RC established based on the laboratory 1-hour compaction curve. However, an increase in time of only a few hours prior to compaction may have a significant reduction in maximum dry unit weight. As shown on Figure 4, $\gamma_{d\text{-max}}$ corresponding to 4-hour compaction curve is significantly lower compared to the 1-hour compaction curve.

The time dependency and changes in compaction properties observed in dry fly ash makes the relative compaction approach highly subjective. It is likely that the time variability in the field with respect to initial moisture conditioning and completion of compaction has significant influence on the material compaction behavior and the selection of the “right” standard Proctor curve at any given time.

Dynamic Cone Penetrometer Data

The results of DCP testing are presented in Figure 3 and Figure 6 in terms of DPI (bpi) for average dry unit weight and moisture contents at each lane and with applied compaction efforts. Figure 6 also includes the line of RC of 93% and 100% based on 1-hour laboratory compaction curves for comparison purposes. Variations of DPI with curing time for each test plot (Ash-03, Ash-04, and Ash-05 with multiple test lanes representative of different moisture conditions) are presented in Figure 7. The DCP test results are summarized below.

Ash-03: DPI generally ranged from approximately 1 bpi to nearly 6 bpi. DPI appeared to increase with compaction efforts and moisture content. Increasing average moisture content from 18.5% to 22.7% resulted in higher DPIs after two (2) passes and lower DPIs after five (5) and eight (8) passes. This anomaly is likely because this lane was compacted in two lifts and the 5-pass and 8-pass data are from the second lift compacted in the following day due to weather delay. The 2-pass data collected from the first lift in day one versus 8-pass data collected from the second lift in day two corresponds to two different time durations (from initial moisture conditioning to data collection). As shown on Figure 7, DPI readings are strongly influenced by strength gain over time associated with pozzolanic and cementitious properties of fly ash. It should be noted that the increase in DPI with number of passes shown on Figures 3 and 6 are more likely due to ash cementation over the course of several hours as opposed to compaction energy (e.g., the data obtained from higher number of passes corresponds to longer durations between the initial moisture adjustment to data collection and longer curing time). No direct correlation is found between γ_d and DPI. While γ_d remained almost constant, higher DPI was measured with increasing the number of passes and more likely with time due to the strength gain of fly ash.

Ash-04: DPI remained relatively constant between 1 to 3 bpi with compaction efforts; coupled with density observations discussed earlier. It appeared that adequate compaction was achieved even at lower compaction energy (e.g., two passes). Increasing average moisture content from 13.2% to 24.6% resulted in DPI increases from 1.4 to 2.8 after eight passes. An apparent trend was observed between DPI and dry unit weight (i.e., higher dry unit weight corresponded to higher DPI values). The reason for the observed correlation between dry unit weight and DPI in Ash-04 is attributed to less cementitious properties and less time dependency of Ash-04 strength. As shown in Figure 7, DPI increased during the first seven (7) days and remained relatively constant afterwards. Increasing average moisture content from 13.2% to 24.6% increased DPI; however, the strength gain of Ash-04 by time was significantly smaller than Ash-03. Especially, the Ash-04 with 13.2% moisture content showed almost no strength gain in time, suggesting that most of the cementation reactions occurred while Ash-04 was aged in the stockpile. Ash-04 with 24.6% showed signs of some residual cementation with the addition of more moisture prior to compaction. Ash-04 appears to behave similar to silty soil with only slight cementing properties. Therefore, during compaction efforts, increasing density would be captured by the cone resistance or DPI values.

Ash-05: DPI appeared to slightly increase with compaction efforts but remained relatively constant in the range of 2 to 3 bpi for five and eight passes. Increasing moisture content from 14.5% to 21.7% resulted in a slight increase in DPI as observed in five and eight-pass results. No apparent trend was observed between the density and DPI values. As shown in Figure 7, generally increasing DPI values with time suggest that Ash-05 also exhibits cementitious behavior; however, the strength gain (as indicated by DPI values) was observed to be less than Ash-03. This observation is consistent with the other conducted tests indicating that 50/50 fly ash is less cementitious than the 75/25 fly ash.

In general, higher moisture contents at the time of placement resulted in higher DPIs over time. The increase in cone resistance (or DPI) with moisture over time appears to be related to availability of moisture for cementing reactions. DPI readings were significantly influenced by pozzolanic and cementitious properties of ash (i.e., strength gain) and less influenced by the compaction efforts. EPRI[2] reports that the pozzolanic reactions in fly ash continue as long as free lime and sources of silica and alumina remain.

Observed increase in DPI with number of passes for Ash-03 and Ash-05 was likely due to fly ash cementation over the course of several hours as opposed to compaction energy (higher number of passes corresponded to longer durations between the initial moisture adjustment and DCP testing, while no significant changes in density values were observed).

Laboratory Strength Test Results

To evaluate the strength properties of fly ash under conditions similar to those obtained during the field study, series of consolidated undrained (CU) triaxial tests were performed under effective consolidation pressures of 5 psi (720 psf) and 30 psi (4,320 psf). Remolded samples of Ash-03, Ash-04, and Ash-05 were prepared in the laboratory and used for triaxial testing. A limited number of undisturbed Shelby tube (ST) samples collected during the pilot study were also used for triaxial testing. Undisturbed ST samples of Ash-03 and Ash-05 could not be extruded in the laboratory. These samples were fully hardened, and volumetric expansion was noted. Two undisturbed ST samples of Ash-04 were successfully extruded in the laboratory for triaxial testing. Remolded samples were prepared at the lowest average γ_d and moisture content observed during the field study. This conservative approach represents those conditions where compaction efforts were minimal (e.g., only two passes of compaction) and the moisture conditions were at as-received conditions. It should be noted that as-received moisture conditions are based on initial moisture conditioning at the silos immediately prior to loading for transport and disposal as a dust control and workability measure. For optimum operational effectiveness at the subject facility, this initial moisture conditioning of dry fly ash is conducted in a controlled manner with resulting moisture content typically being in the range of 11% to 15%. As noted earlier, DCP field measurements indicated that additional moisture adjustments (e.g., up to 25%) generally improve strength properties of the compacted fly ash by optimizing hydration/cementation process. Therefore, conservatively as-received moisture contents were simulated in remolded samples. To minimize the impact of strength gain and time-dependent variables associated with cementitious properties of ash, a lab protocol was developed and followed for triaxial testing of all remolded samples. In summary, this protocol consisted of: (i) remolded fly ash samples were prepared from the virgin ash at target moisture and density conditions; (ii) samples were cured only for 1 day; and (iii) samples were saturated and consolidated for 2 days prior to shearing (total curing time of 3 days).

The CU triaxial test results are presented in Figure 8 and Table 2. The triaxial tests performed on remolded ash samples were analyzed and interpreted based on the dimensions of samples after one day of curing to consider the impact of volumetric changes on the calculated stress on the specimen. Using the stresses at 15 percent axial strain, Mohr-Coulomb failure envelopes are plotted, and drained and undrained shear strength parameters are calculated, as presented in Table 2. The undrained shear strength is presented in undrained shear strength ratio (S_u/σ'_v), which were generally in the range of 0.35 to 0.64. Minimum undrained shear strength values ($S_{u,min}$) ranged from 300 psf to 1,950 psf. The calculated effective friction angles (ϕ') for fly ash samples tested were in the range of 36 to 38 degrees. Fly ash specimens show mainly a contractive behavior (Table 1 and Figure 8). Only Ash-04-ST and Ash-05 at lower confining pressure (5-psi) show a dilative behavior. The stress-strain curves for Ash-03, Ash-04 and Ash-05 specimens shown in Figure 8 indicate that the fly ash tested in this study did not exhibit significant strain softening (or 'brittle' behavior) during triaxial testing.

The remolded specimens used in this CU triaxial testing program were prepared at relatively low densities representative of those conditions observed in the field with minimum compaction effort (e.g., only two passes of compaction). These densities corresponded to relative compaction values of 82 to 87% (based on the standard Proctor compaction curves developed for a 1-hour curing period). The result of CU testing indicated that the relative compaction of fly ash is not necessarily a controlling factor in shear strength of a compacted dry fly ash because of its pozzolanic and cementitious properties. The calculated effective friction angle (ϕ') of fly ash between 36 and 38 degrees appears to be independent of type of dry fly ash samples tested in this study and not directly correlated with the relative compaction.

SUMMARY AND CONCLUSIONS

The site-specific study, including laboratory and field testing, was conducted to primarily evaluate the commercially available practical methodologies, such as dynamic cone penetrometer (DCP), and assess the placement criteria for dry fly ash. A summary of findings from this study are listed below.

Compaction characteristics of fly ash are highly variable and influenced by moisture conditions and curing time (i.e., aging). The compaction properties of fly ash vary significantly due to pozzolanic and cementitious properties. The volumetric expansion potential associated with early age reactivity of fly ash may have some influence in density measurements.

Establishing a compaction criterion, based on conventional soil mechanics using target relative compaction and moisture content, becomes challenging and often impractical from a construction perspective and increases the level of uncertainties in the construction quality assurance procedure. The basis for relative compaction varies significantly depending on which time-dependent Proctor curve is used. The actual delay time between the time of initial moisture adjustment, the time of compaction, and the time of CQA testing needs to be considered in developing time-dependent Proctor compaction curves.

Strength properties of fly ash appear to be independent of type of dry fly ash used in this study and not directly correlated with the relative compaction and moisture content. It can be suggested that, during the compaction operations, moisture content of ash being placed can generally be in the range of 10 to 30 percent, with lower bound defined by dust control measures and upper bound defined by material workability (e.g., no water bleeding during compaction).

A significant scatter in DCP data with density is observed, introducing difficulties to correlate DCP with density. This scatter is mainly related to the strength gain of fly ash with time due to pozzolanic and cementitious properties, which increased the strength and stiffness measured by DCP while density stays constant.

Use of DCP as part of CQA efforts can be considered to confirm that compaction efforts are in compliance with a method-specific procedure (e.g., minimum 2 passes for compaction to achieve firm ground). The DCP can be used to document achievement of proper compaction as defined by stiffness/strength of the compacted ash.

Periodic standard Proctor compaction tests should be conducted to evaluate any potential significant changes in fly ash compaction characteristics during fossil plant operation. It is recommended that standard Proctor compaction tests be performed on “virgin” fly ash samples collected directly from silo pneumatic spout prior to any moisture adjustment. To capture the time dependent nature of ash, laboratory test specimens should be prepared using the “virgin” fly ash samples adjusted to a target moisture content and allowed to ‘cure’ prior to compaction tests. At a minimum, two time intervals (representative field conditions that would likely occur) should be tested (e.g., within an hour of moisture conditioning and approximately three days following the moisture conditioning).

ACKNOWLEDGEMENT

The authors would like to express their appreciation to the Tennessee Valley Authority for sponsoring the testing program presented in this paper. Appreciation is also extended to Trans-Ash for their input and support during test pad construction efforts and Dr. Nader Rad in Excel Geotechnical Testing during the laboratory testing.

REFERENCES

[1] American Coal Ash Association (2010), Production and Use Survey, www.acaa-usa.org/.

[2] EPRI, Soil Stabilization with Fly Ash, Electrical Power Research Institute, Technical Report 1010386, March 2006b.

[3] Mackiewicz, S. and Ferguson, G., Stabilization of Soil with Self-cementing Coal Ashes, 2005, World of Coal Ash, Lexington, Kentucky, USA.

[4] Thorne, D. J. and Watt, J. D. Composition and Pozzolanic Properties of Pulverized Fuel Ashes. II. Pozzolanic Properties of Fly Ashes, as Determined by Crushing Strength Tests on Lime Mortars, 1965, Journal of Applied Chemistry, Vol. 15, pp. 595-604.

[5] Senol, A., Edil, T. B., and Bin-Shafique, M. S. Laboratory Evaluation of Stabilization of Soft Subgrades by Class C Fly Ash, Proceedings of the 15th Southeastern Asian Geotecnical Engineering Conference, Bangkok, Thailand, S. Sambhandharaksa, D. T., Bergado, T. Boonyatee, 2004, Vol 1, pp. 593,596.

[6] ASTM D7762, Standard Practice for Design of Stabilization of Soil and Soil-Like Materials with Self-Cementing Fly Ash, 2011, Annual Book of ASTM Standards, ASTM International, West Conshohocken, PA.

[7] Ferguson, G., and Leverson, S., Soil and Pavement Base Stabilization with Self-Cementing Coal Fly Ash, American Coal Ash Association, May 1999.

[8] Yeheyis, B. M., Shang, Q. J., and Yanful, K. E. Chemical and Mineralogical Transformations of Coal Fly Ash after Landfilling, 2009, World of Coal Ash Conference, Lexington, KY, USA.

Table 1. Summary of Laboratory Test Results on Fly Ash

Sample ID	Index Properties			Swelling Test [3]					Compaction Properties after Moisture Conditioning Duration [4]						
	Particle Size Distribution[1]		Loss on Ignition [2] (%)	Change in Volume, ΔV (%)					Maximum Dry Unit Weight, γ_{dmax} (pcf) / Optimum Moisture Content, OMC (%)						
	% Fines < 0.075 mm	% Clay-Size Fraction < 0.005 mm		0.5 Hr	4 Hr	8 Hr	24 Hr	72 Hr	30-60 min	4-5 hours	1 day	3 days	10 days	21 days	35 days
Ash-03	93.1	26.4	4.1	0.5	3.4	5.6	6.2	6.2	94.1 / 22.4	-	91.0 / 24.3	88.9 / 26.3	86.2 / 27.4	84.4 / 29.3	84.9 / 28.8
Ash-04	92.7	16.2	4.2	0.1	0.1	0.1	0.1	0.2	89.0 / 24.9	-	87.3 / 27.4	88.1 / 26.5	-	-	-
Ash-05	95.6	24.6	2.8	0	2.6	3.3	3.3	-	98.0 / 20.6	95.4 / 22.2	93.9 / 22.8	91.2 / 23.9	90.3 / 24.8	-	-

Notes:

1. Particle size distribution was determined in accordance with ASTM D422.
2. Loss on Ignition (LoI) test was conducted in acccordance with ASTM D2974..
3. For swelling tests, two replicate specimens were prepared at 20% moisture content and compacted in standard Proctor energy, and the change in dimensions of extruded specimens was measured over time.
4. Compaction tests were performed using standard Proctor energy in accordance with ASTM D698.

Table 2. Summary of Laboratory Consolidated Undrained Triaxial Testing on Fly Ash

Specimen		Compaction Condition of Specimens[10]				Triaxial Test [1, 4, 9]					
Sample ID	Test	Dry Unit Weight, γ_d (pcf)	Relative Compaction, RC (%) [7]	w (%)	w - w_{opt} (%) [7]	ΔV (%) After One Day Curing [3]	Consolidation Pressure (psi)	ΔV (%) During Consolidation [5]	Material Behavior [8]	Effective Friction Angle, ϕ' (°)[2]	Undrained Shear Strength Ratio, S_u/σ'_v [2,6]
Ash-03	1	77.4	82.3	9	-13.4	12.1	5	-0.1	Contractive	36	0.64 $S_{u\,Min}$ = 615 psf
	2	77.2	82.0	8.8	-13.6	12.4	30	-4.9	Contractive		
Ash-04	1	77.1	86.6	13.4	-11.5	-0.7	5	0.1	Contractive	36	0.35 $S_{u\,Min}$ = 300 psf
	2	76.8	86.3	13.5	-11.4	0.1	30	-2.9	Contractive		
Ash-04-ST	1	84.5	94.9	13.2	-11.7	-	5	-0.3	Dilative	38	0.55 $S_{u\,Min}$ = 1080 psf
	2	79.8	89.7	11.2	-13.7	-	30	-2.1	Contractive		
Ash-05	1	80.8	82.4	14.1	-6.5	9.3	5	0.1	Dilative	38	0.49 $S_{u\,Min}$ = 1950 psf
	2	81.1	82.8	14	-6.6	10.1	30	-1.5	Contractive		

Notes:

1. The stress condition for the triaxial tests were calculated using the dimensions of the specimens after one-day curing.
2. The shear strength properties were calculated from strength at 15% axial strain.
3. The volume change (ΔV) of each specimen was measured after one day prior to saturating the specimen. Possitive (+) sign for swelling and (-) sign for contraction.
4. Triaxial test was performed in accordance with ASTM D4764. The specimens were permeated from bottom to top and saturated and consolidated for 2 days prior to shearing.
5. Volume change was measured during consolidation. Possitive (+) sign for swelling and (-) sign for contraction.
6. For calculating undrained shear strength ratio, σ'_v was assumed to be equal to average in-situ principle stresses.
7. Optimum moisture content (OMC) and maximum dry unit weight was calculated from standard Proctor test (ASTM D 698), that is based on 1-hr standard Proctor compaction test results.
8. Material behavior was classified as dilative if excess pore water pressure is negative (-) and contractive if the excess pore water pressure is positive (+) at 15% axial strain.
9. The B-value of 0.95 was not obtained prior shearing the specimen (B-value = 0.75 to 0.93).
10. The triaxial test specimens (not marked with ST: Shelby Tube) were remolded. Shelby tube samples of Ash-03 and Ash-05 could not be extruded due to volumetric expansion and cementation in the Shelby tubes.

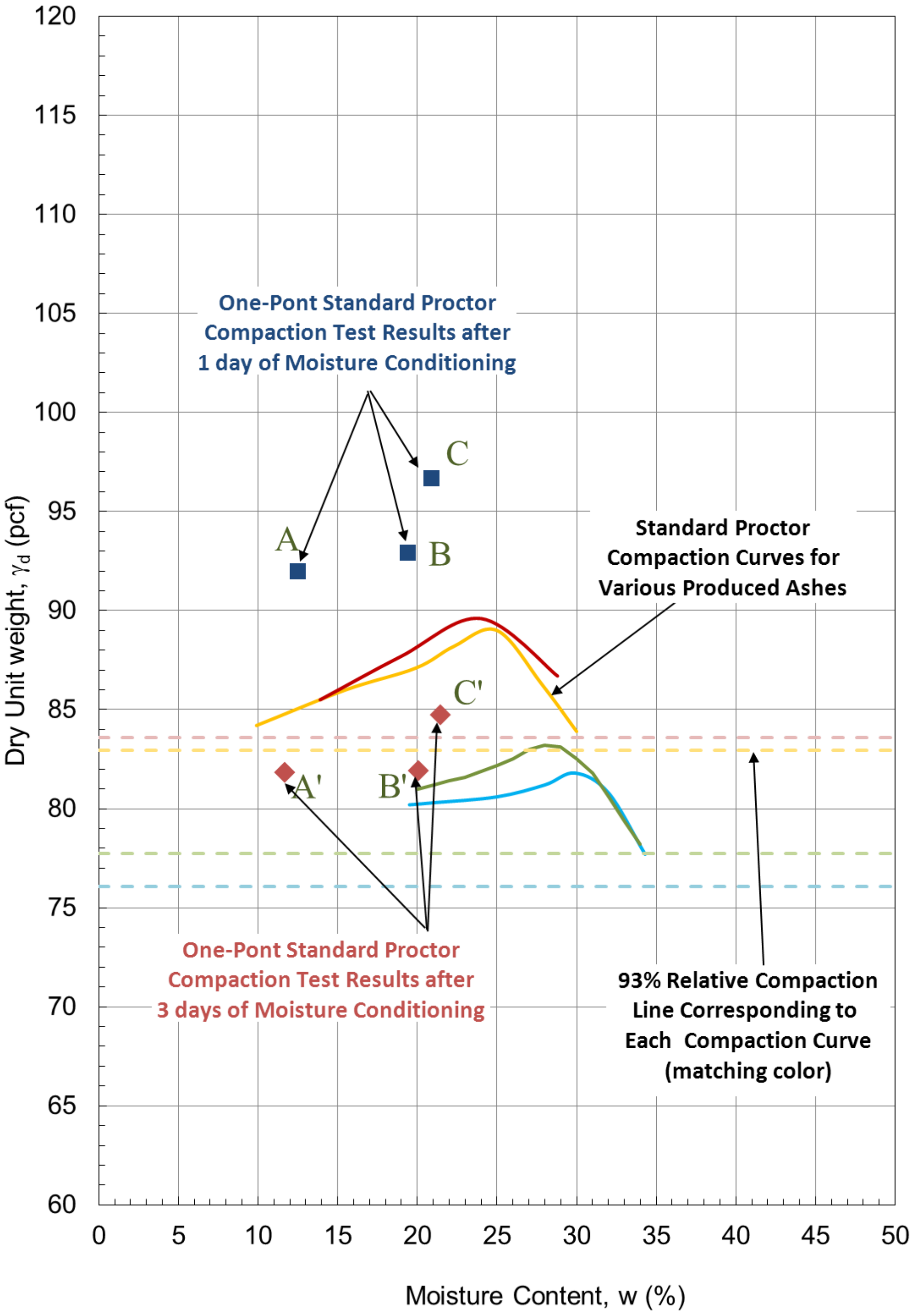

Figure 1. Variation of Fly Ash Compaction Curves and Field Measurement of Fly Ash Dry Density and Moisture Contents with Time after Moisture Adjustment

Figure 2. Test Pad General Construction Process (from top left: subgrade preparation, fly ash placement, moisture conditioning, and compaction)

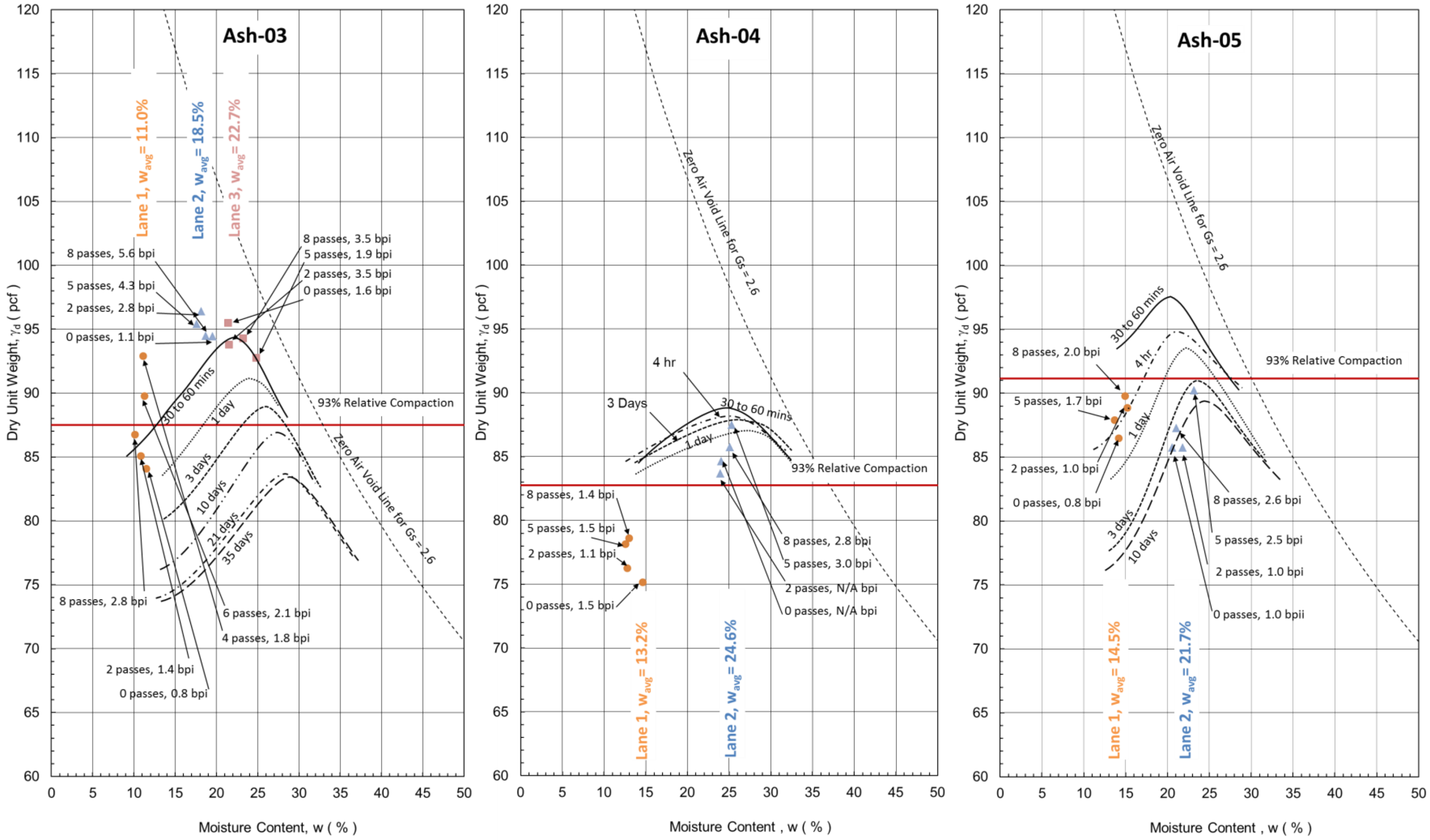

Figure 3. Laboratory Standard Proctor Compaction Curves and Average Measured Field Dry Unit Weight and Moisture Content of Fly Ash with Time

Note: Relative compaction line is based on 60-min standard Proctor compaction curves.

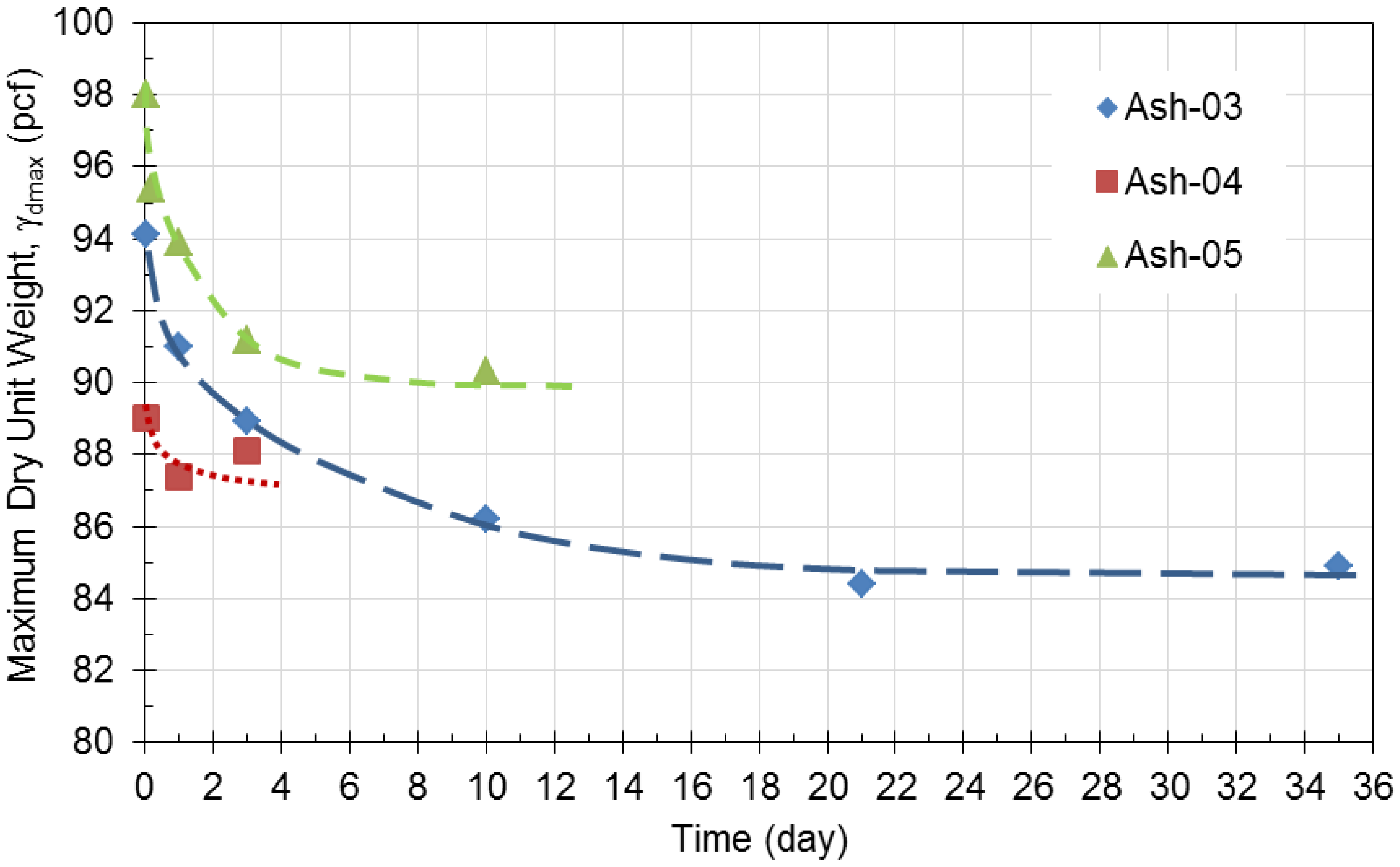

Figure 4. Reduction of Maximum Dry Unit Weight (γ_{dmax}) of Fly Ash with Delayed Time Prior to Compaction

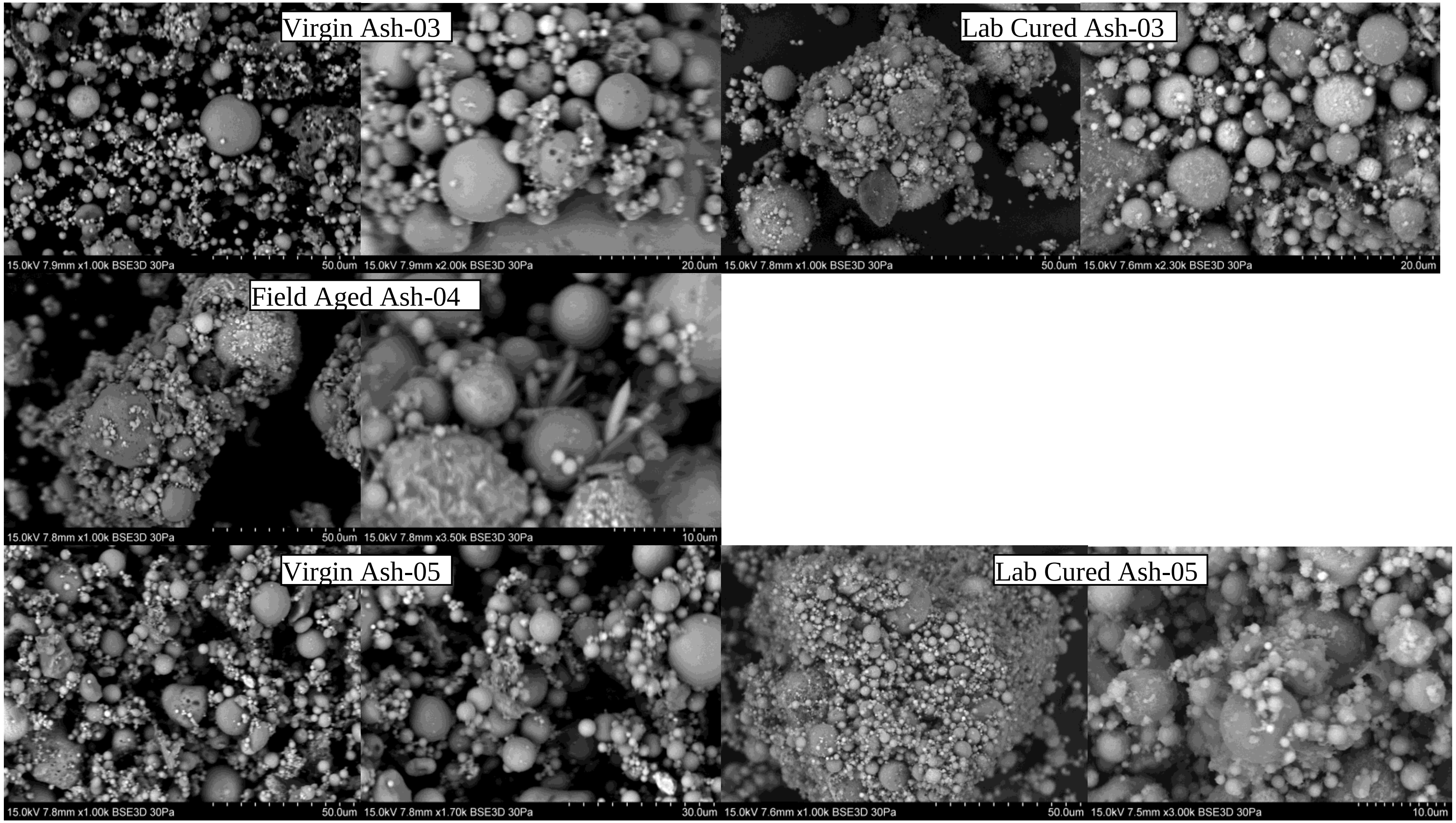

Figure 5. Results of Scanning Electron Microscopy (SEM) on Fly Ash

Notes: (1) Virgin fly ash was collected directly from silo dry spout prior to any moisture adjustment. (2) Field aged Ash-04 was taken from the stockpiled Ash-03 aged in the field for approximately seven days after initial moisture adjustment at the silos during load out. (3) Lab cured fly ash were hydrated virgin fly ash with 25% moisture and cured for three days prior to SEM analyzes.

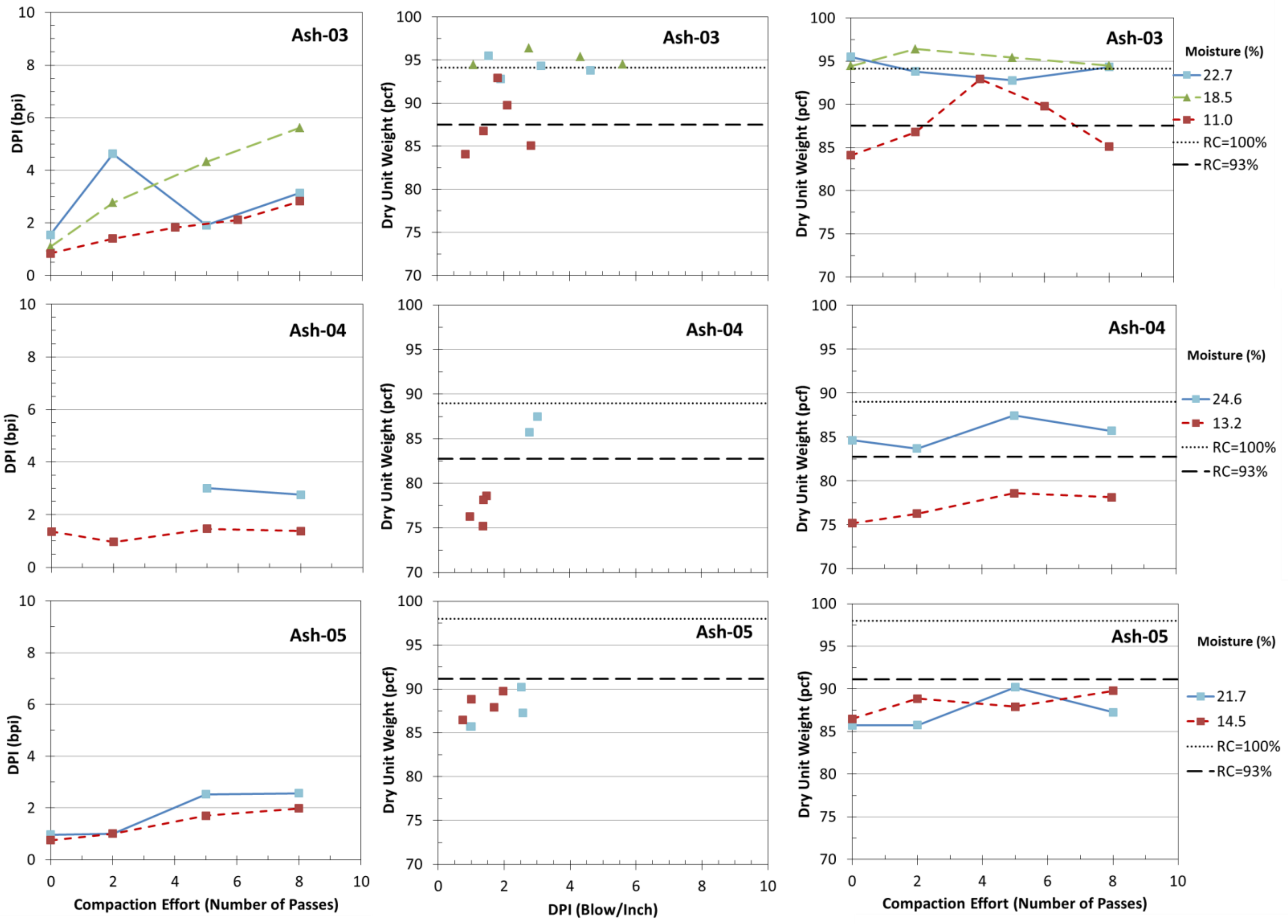

Figure 6. Comparative Evaluation of Dynamic Cone Penetrometer Index (DPI), Dry Unit Weight, and Compaction Effort

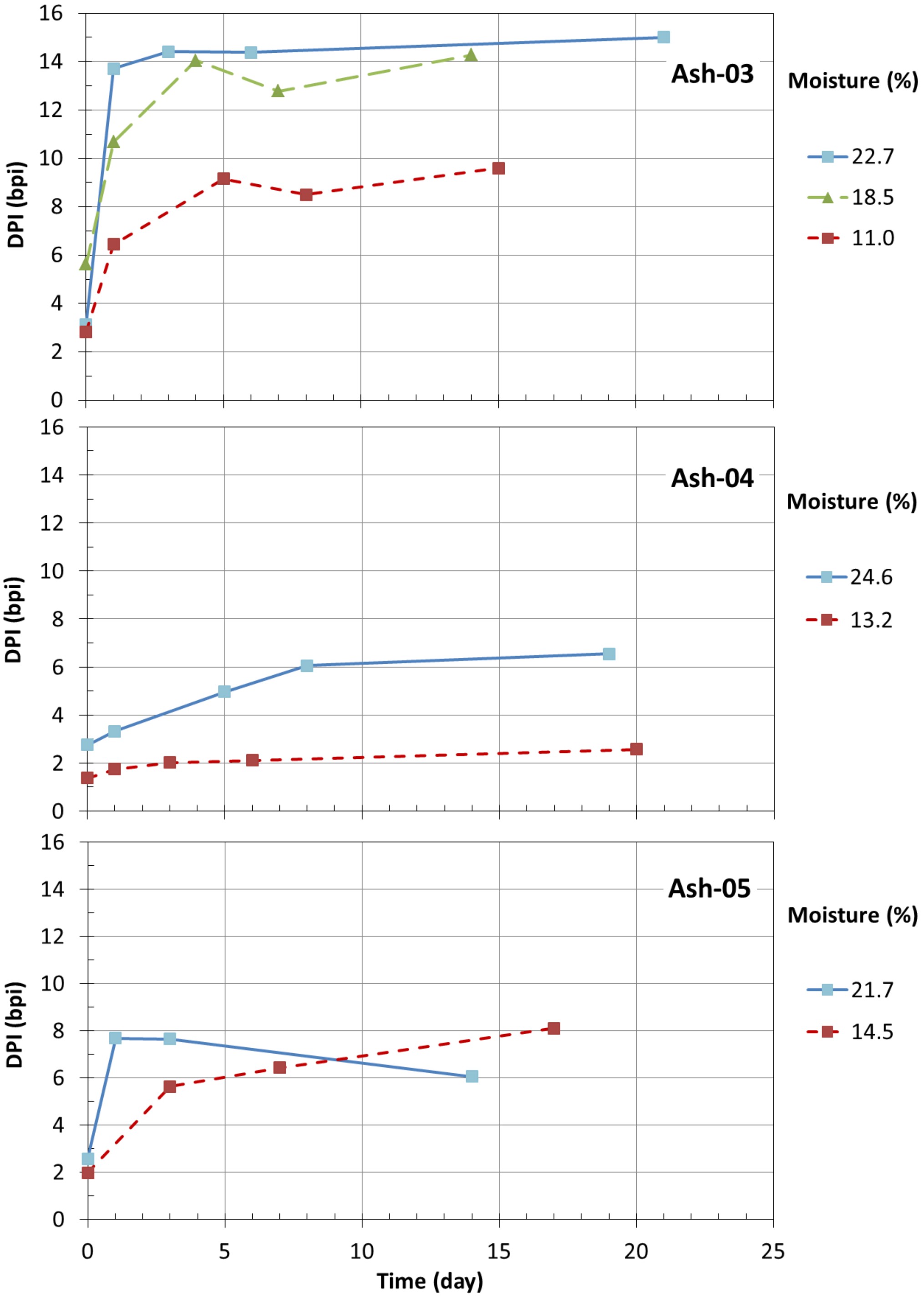

Figure 7. Change of Dynamic Cone Penetrometer Index (DPI) with Curing Time of Fly Ash after Compaction

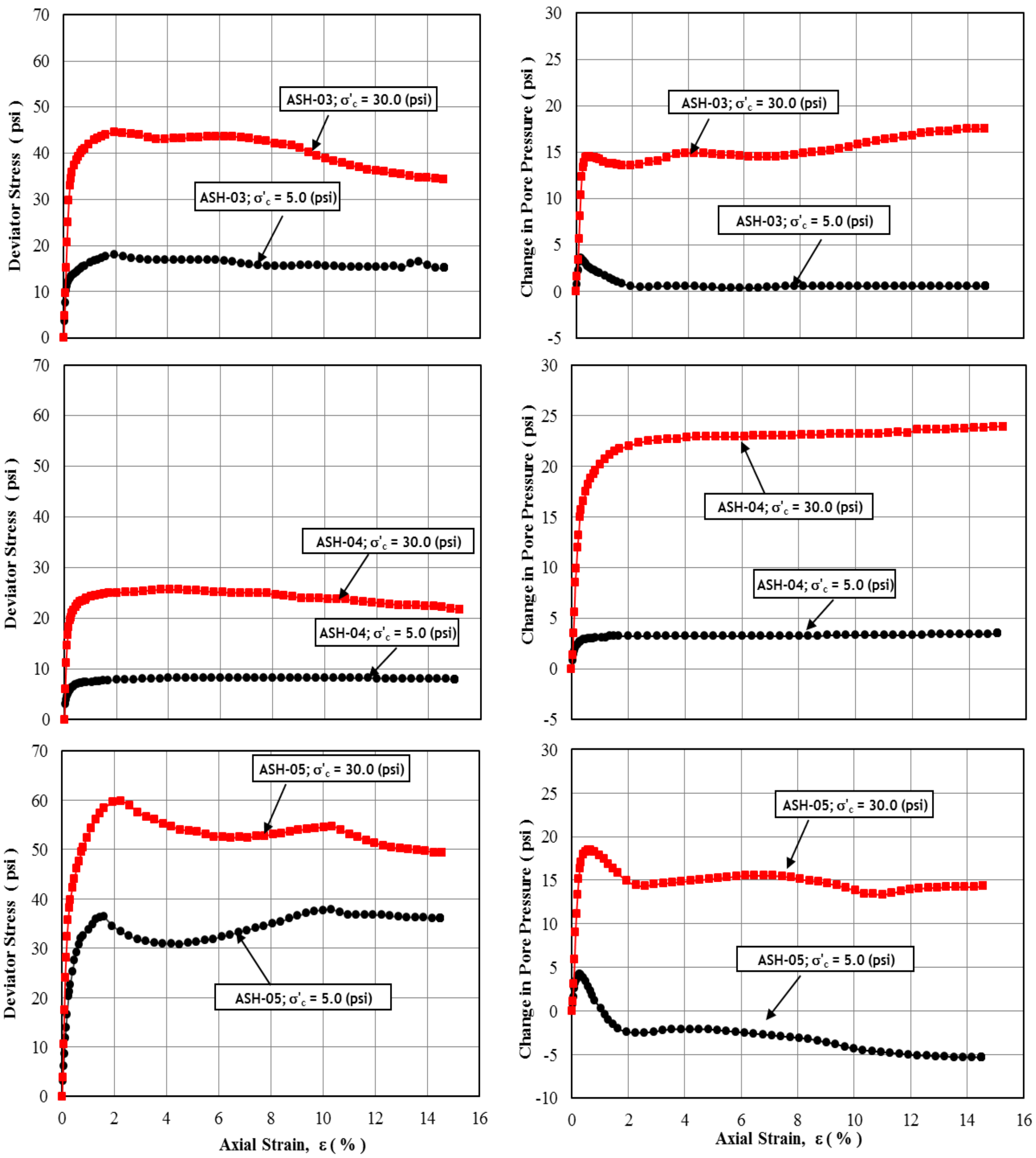

Figure 8. Stress-Strain Curve from Consolidated Undrained (CU) Triaxial Testing on Fly Ash