Shear Strength of Coal Combustion Product by Vane Shear

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A B S T R A C T

The objective of this study was to evaluate the shear strength of a coal combustion product (CCP) by using the vane shear test. A series of small-scale vane shear (SS-VS; diameter = 12.7 mm and height = 25.4 mm) and large-scale vane shear (LS-VS; diameter = 25 mm and height = 50 mm) laboratory tests were conducted. Undrained and drained strength envelopes were determined using consolidated undrained triaxial compression tests, and drained strength was checked via consolidated drained direct shear. In addition, effects of (1) rate of vane rotation, (2) time delay between vane insertion and beginning rotation, and (3) elapsed time under the final vertical effective stress before shear were evaluated via SS-VS. Vane shear strength results were represented in terms of peak shear strength and the initial horizontal effective stress acting on the vertical-oriented failure surface during rotational shear. Both SS-VS and LS-VS yielded shear strengths that plotted between the drained and undrained triaxial strength envelopes. Shear strength of CCP increased with increasing time under load, which was potentially attributed to diagenesis. Peak shear strength in SS-VS was reached after approximately 72 hours of elapsed time under constant vertical effective stress. Peak shear strength in SS-VS and LS-VS compared favorably to the drained strength measured via direct shear testing.

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A R T I C L E I N F O

Article history: Received 10 January 2019; Received in revised form 9 June 2019; Accepted 8 July 2019

Keywords: coal ash; coal combustion product; direct shear; shear strength; triaxial; vane shear

1. Introduction

Coal combustion product (CCP) includes the by-products from generating electricity by burning coal (U.S. Environmental Protection Agency [US EPA], 2018). In 2017, production of CCP in the United States was 100 million Mg and has generally decreased in the last decade due to the growing transition to more renewable energy sources (American Coal Ash Association [ACAA], 2018). In 2017, approximately 64% of CCP was beneficially reused in the United States, with predominant end-use as a cementing agent or aggregate in construction applications (ACAA, 2018). The remaining CCP was generally disposed of in either surface impoundments or compacted in landfills (dry stack), both of which present varying costs and liability to utility companies (US EPA, 2018). For example, in

2008 at the Tennessee Valley Authority's (TVA's) Kingston Power Plant, failure of a CCP impoundment released 4.2 million m³ of CCP that inundated surrounding land and waterways, covering an area of 1.2 km² (US EPA, 2016). The cost of the spill to the TVA exceeded USD 1 billion (Gang, 2014).

Disposing of CCP in surface impoundments includes numerous geotechnical challenges, and as was observed in the TVA incident, failure can be catastrophic. The flowing nature of CCP in the TVA failure was, in part, attributed to large volumes of water that are added to CCP to produce a high water-content slurry that facilitates pumped transport for disposal into surface impoundments (Bachus and Santamarina, 2012; Evans et al., 2017). Deposition of CCP at high water contents can result in limited consolidation, resulting in a deposit with high moisture content and low shear strength. These conditions present challenges during closure when equipment needs to be safely mobilized onto the impoundment surface for capping and construction activities. Mobilizing equipment onto CCP

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surfaces without sufficient shear strength can lead to bearing capacity failure that may cause construction delays, economic losses, injuries, or loss of life.

The vane shear test is used to assess in situ shear strength of CCP before mobilizing construction equipment on the impoundment surface (Evans et al., 2017). The vane shear test is inexpensive and fast and can be performed with a commercially available, hand-held device by field personnel. Vane shear has been shown to yield reasonable measures of undrained shear strength for clayey materials, as the low permeability of clay does not allow drainage during shear (Cadling and Odenstad, 1948; Carlson, 1948; Skempton, 1948; Blight, 1968). However, CCP generally consists of non-plastic, silt-sized particles, making CCP more permeable than clay. Because of the higher permeability, partially drained or fully drained conditions can develop during vane shear on CCP, whereby some or all of the excess pore pressure is able to dissipate (Reid, 2016). Dissipation of excess pore pressure during shear increases effective stress for contractive soils and results in an overestimation of undrained shear strength. In general, limited studies have been completed that compare shear strength measured with vane shear to standard laboratory experiments, and most available studies have focused on shear strength of clayey materials (e.g., Lefebvre et al., 1988; Quiros and Young, 1988). Continued use of vane shear to assess in situ shear strength of CCP requires that vane shear results be compared with standard shear strength experiments to determine whether the measured shear strength via vane shear is drained, undrained, or partially drained.

The objectives of this study were to (1) evaluate the shear strength of CCP via common laboratory experiments and (2) compare shear strength measured via vane shear to determine an appropriate laboratory vane shear methodology that yields an understandable shear strength. Common laboratory strength tests included direct shear and consolidated undrained triaxial compression. A small-scale vane and large-scale (i.e., field-scale) vane were used in the laboratory to measure shear strength via vane shear. Seepage-induced consolidation testing was used to measure the compressibility and hydraulic properties of CCP.

2. Materials and Methods

2.1. Coal combustion product

The CCP samples classified as off-spec ash and were collected from an unnamed impoundment in the eastern United States. The CCP samples were received in a saturated condition and were subsequently air dried. Particle-size distribution (PSD) curves for five CCP samples ranging in depth to 2.1 m within a CCP impoundment are shown in Figure 1. Samples were evaluated via mechanical sieve (American Society for Testing and Materials [ASTM] International, 2017a) and hydrometer (ASTM International, 2017b) and indicated that the CCP was predominantly silt, with 8–47% sand-sized material (>0.075 mm) and less than 2% clay-sized particles (<0.002 mm). In general, PSDs were similar and a single composite material was created for laboratory testing (Figure 1), whereby all samples were air dried and homogenized.

The composite CCP had a maximum particle size of 2.0 mm, 15% sand, 83% silt, and 2% clay-sized particles. Atterberg limits were determined using the fall cone test for liquid limit (LL) following BS

Fig. 1. Particle-size distributions of coal combustion product (CCP) samples from various depths below ground surface and the composite CCP that represented the homogenized mixture of all samples.

EN ISO 17892-12:2018 (International Organization for Standardization, 2018), and plastic limit (PL) was determined following ASTM International (2017c). The LL was 41 and no PL was measured, such that the material classified as non-plastic. The CCP classified as low plasticity silt (ML) according to the Unified Soil Classification System. Specific gravity (G_s) was determined via ASTM International (2014) and the G_s was 2.35. Geotechnical characteristics of the CCP used in this study were comparable to typical characteristics reported by Bachus and Santamarina (2012).

2.2. Slurry preparation and void ratio calculation

Specimens for all experiments conducted on CCP in this study were prepared via slurry deposition, that is, seepage-induced consolidation, triaxial compression, direct shear, and vane shear. The CCP slurries were prepared via mixing tap water and air-dried CCP manually with a stirring rod. Slurries for triaxial testing were prepared using de-aired water instead of standard tap water to accelerate specimen saturation. The CCP slurry was prepared at a solids content of 57%, equating to a gravimetric water content (w) of 75%. The consistency of the CCP slurry was such that the material could easily be poured to create test specimens.

The w values of prepared slurries were measured to confirm consistency. Using the initial w and assuming the specimen was saturated, an initial void ratio (e_i) was calculated as the product of w and G_s . Similarly, void ratio (e) values were determined for all test specimens after consolidation and shearing via measuring final water contents and assuming specimens were saturated.

2.3. Seepage-induced consolidation testing

Seepage-induced consolidation tests (SICTs) were conducted to determine compressibility and hydraulic conductivity behavior. In

a SICT, downward seepage was used to create low vertical effective stresses ($\sigma'_v \approx 0.05\text{--}5$ kPa) to measure the behavior of a soft material directly after transition from slurry to soil. Subsequently, vertical loading was used to generate higher effective stress (≥ 10 kPa). The SICTs conducted for this study incorporated the equipment and followed the methodology described in Tian et al. (in press) and Herweynen et al. (2017).

The SICT procedure consisted of three steps. First, the e at zero effective stress (e_0) was determined, which corresponded to the e at the transition from slurry to soil. The e_0 was determined via depositing a known mass of slurry into the specimen cell, allowing sedimentation and self-weight consolidation, and subsequently removing supernatant water. The final specimen thickness was measured via a measuring tape affixed to the outside of the specimen cell, and the average w and e_0 were computed assuming saturation.

After self-weight consolidation, filter paper and a porous plastic disk were placed atop the specimen along with two linear potentiometers in contact with the plastic disk, which induced $\sigma'_v = 0.28$ kPa on the specimen. A flow pump was then used to create downward seepage within the slurry and induce consolidation. Saturation of the specimen was maintained during seepage via a Mariotte bottle that added water to maintain a constant water depth atop the specimen. A constant flow rate was imposed on the specimen until steady state was achieved, which was identified as a constant pressure difference across the specimen (± 0.1 kPa). The pressure difference was computed via pressure transducers at the top and bottom of the specimen. A steady-state e and hydraulic conductivity (k) were calculated for each imposed flow rate. The k was computed by Darcy's law using the pressure difference and specimen height at steady state. This seepage step was repeated for at least three unique flow rates to obtain e and k that corresponded to three different σ'_v .

The third step involved vertical load application via a pneumatic air cylinder and piston. Steady-state consolidation during each vertical load increment was identified as excess pore pressure reducing to zero and negligible change in vertical displacement. The e at steady state was computed from mass-volume relationships assuming σ'_v transferred equally with depth in the specimen and e was constant throughout the specimen. The k at steady state was determined via applying a small flow rate that did not induce further consolidation (verified by no additional vertical displacement) but was large enough to induce a pressure difference across the specimen to compute k . This third step was repeated until a final σ'_v was reached. At the end of an experiment, the specimen was removed to measure the final w and compute a final e assuming complete specimen saturation.

2.4. Triaxial compression testing

Consolidated undrained (CU) triaxial compression tests were conducted on 38-mm-diameter CCP specimens in accordance with ASTM International (2011a). Target effective confining pressures (σ'_c) were 10, 20, 50, and 100 kPa, selected to be representative of a typical CCP impoundment. All CU specimens were back-pressure saturated to achieve b-check for saturation values (B-values) ≥ 0.95 . Shearing was conducted via loading at an axial strain (ϵ_a) rate of 1%/h to a maximum $\epsilon_a \geq 20\%$. The ϵ_a rate was determined via ASTM International (2011a) to promote pore pressure equilibri-

um throughout the specimen during shear. The specimen e after consolidation and during undrained shear was determined via weight-volume relationships using the final measured w .

The CCP specimens were prepared via slurry deposition following the method described by Jehring and Bareither (2016). The slurry was poured into a 38-mm-diameter $\times$ 100-mm-tall split mold, lined with a 0.25-mm-thick latex membrane. A 70-mm-tall extension collar was added to the top of the split mold to contain sufficient slurry such that an appropriate height-to-diameter specimen ratio was maintained after consolidation. A thin paper mold was placed around the outside of the membrane before assembling the split mold. The paper mold was held together with tape and provided stability to the test specimen upon removal of the split mold. Once water was added to the triaxial cell to apply the confining pressure, the paper lost strength and tape lost adhesion such that the paper mold fell apart before shearing.

Triaxial specimens were consolidated via vertical stress application before removing the split mold. Specimens were consolidated under σ'_v that were equivalent to σ'_c for shear testing. Consolidation under σ'_v was used to simulate anticipated stress conditions within a CCP impoundment. Slurry-deposited specimens were initially allowed to settle and consolidate under self-weight for at least 3 hours. Subsequently, dead weight was applied to reach $\sigma'_v = 10, 20, 50,$ or 100 kPa. For $\sigma'_v > 10$ kPa, the vertical load was applied incrementally and vertical deformation was monitored under each σ'_v to assess consolidation. A coefficient of consolidation (c_v) computed from settlement vs. time data via the SICT indicated that 2 hours was sufficient between each load increment for complete consolidation.

After consolidation under σ'_v , each CCP specimen was consolidated isotropically under σ'_c before shearing. During shearing, measurements of vertical load, vertical displacement, cell pressure, and pore water pressure were collected by a data acquisition system (CU Triaxial Mode, GeoTac, Houston, TX) connected to a PC. Axial load was measured using an $8900 \pm 0.4\text{-N}$ load cell (Artech Industries, Inc., Riverside, CA), and axial displacement was measured with a $50 \pm 0.003\text{-mm}$ displacement transducer (Novotechnik, Southborough, MA). Cell pressure and pore pressure were monitored with pressure transducers (GeoTac, 1378 ± 0.07 kPa; ELE International, Ltd., Loveland, CO, 700 ± 0.07 kPa).

2.5. Direct shear testing

Direct shear tests were conducted under consolidated drained conditions in accordance with ASTM International (2011b). Direct shear specimens were sheared under σ'_v between 30 and 100 kPa. Slurry was poured into a 63-mm-diameter $\times$ 33-mm-tall circular shear box with a 3-mm-thick porous plastic disc, and filter paper was placed at the bottom and on top of a test specimen. Specimens were consolidated within the shear box in the direct shear apparatus. Specimens were initially allowed to consolidate under self-weight for at least 3 hours. Sedimentation and self-weight consolidation contributed to a small decrease in specimen thickness, such that initial specimen thicknesses before vertical loading were approximately 28 mm. Subsequently, specimens were loaded incrementally every 2 hours to the target σ'_v . Vertical displacement was monitored during consolidation and shearing, and the e after shear was determined via measuring w of the specimen and assuming complete

saturation. Vertical deformation measurements collected during shear were used to back calculate ϵ before shear.

Direct shear tests were conducted in a direct shear apparatus (ELE International). Shear stress was measured using a 2220 ± 0.4 -N load cell (Interface Inc., Scottsdale, AZ), and vertical and horizontal displacement were measured with linear potentiometers (25 ± 0.003 and 50 ± 0.003 mm, respectively; Novotechnik). Data were collected using LabView and a USB data acquisition module (National Instruments, Austin, TX). All tests were sheared to at least 15% the specimen diameter at a displacement rate of 0.08 mm/min. This horizontal displacement rate was conservatively selected based on ASTM International (2011b) such that drained conditions persisted during shear.

2.6. Vane shear testing

Vane shear testing was conducted in laboratory cells that allowed consolidation and shearing under a target σ'_v . Two different-sized cells were constructed for this study: the small-scale vane shear (SS-VS) cell was 63 mm in diameter, and the large-scale (field-scale) vane shear (LS-VS) cell was 292 mm in diameter. A minimum cell diameter-to-vane diameter ratio of 5 was observed in accordance with ASTM International (2016). All CCP specimens tested in vane shear were prepared from slurry in a similar manner to the direct shear test specimens.

2.6.1. SS-VS testing

A schematic of the SS-VS apparatus is shown in Figure 2. The cell consisted of an acrylic cylinder with an inside diameter of 63 mm and height of 90 mm. The cylinder was attached to an acrylic pedestal that was bolted to a steel base plate. Silicon was used between the cylinder, steel base plate, and bottom pedestal to create a watertight seal. A drain line in the side-wall of the cylinder at the bottom of the cell allowed drainage and pore pressure monitoring. A porous plastic disk and filter paper were placed at the base of the cell to prevent clogging of the drain line.

A dead-weight loading system consisted of a top acrylic load platen placed on the specimen, a circular riser tube, and a square acrylic plate attached to the riser tube (Figure 2a). Filter paper was placed between the specimen surface and top load platen. Holes in the center of the top load platen, load plate, and dead weights allowed the vane to be inserted into the specimen without removing the vertical load. Aluminum foil was used to cover the hole at the base of the top load platen to prevent slurry from squeezing out during loading. The vane could easily penetrate the aluminum foil and filter paper for testing.

Vertical displacement of the top load platen was measured using a dial gauge and measuring tape adhered to the side of the cell. Pore pressure at the bottom of the specimen was monitored using a manometer. An ELE International vane apparatus (Figure 2b) was used to measure shear strength. Shear stress (τ) was applied to a given test specimen through a 12.7-mm-diameter $\times$ 25.4-mm-tall vane using one of four calibrated springs with torques that were calibrated to shear strength. An electric DC motor was retrofit to the apparatus to provide a constant rate of vane rotation. Three interchangeable 12-V DC motors were used to achieve vane rotation rates between $5^\circ/\text{min}$ and $300^\circ/\text{min}$.

Fig. 2. Schematics of the small-scale vane shear consolidation cell and apparatus used for (a) consolidation and (b) small-scale vane shear.

The SS-VS tests were conducted in accordance with ASTM International (2016) under σ'_v values ranging from 17 to 94 kPa. The SS-VS test procedure was as follows: (1) consolidate under the target σ'_v for 24 hours; (2) insert vane to one vane height below the specimen surface and allow 1 minute to elapse between inserting the vane and beginning rotation; (3) shear at a constant rotation rate of $60^\circ/\text{min}$ until a peak torque was measured; (4) rapidly rotate ($\approx 280^\circ/\text{min}$) the vane five revolutions to then measure residual shear strength at the same rate used to measure peak shear strength; and (5) record final specimen

height and measure water content on exhumed specimen to compute a final void ratio ($e = w \cdot G_s$ for 100% saturation). Loading of a SS-VS specimen began immediately after self-weight consolidation was complete, and load increments were added approximately every hour up to the target σ'_v . Residual shear strength was measured immediately after the five vane revolutions as recommended in ASTM International (2016).

Aside from the standard test procedure described in the previous paragraph, the following test variables were evaluated: (1) rate of vane rotation; (2) time delay between vane insertion and beginning rotation (t_d); and (3) elapsed time under the final σ'_v before shearing (t_c). Rate of rotation varied between 5°/min and 300°/min; t_d varied between 0.1 and 60 min; and t_c varied between 1 hour and 7 days. These variables were evaluated to assess their potential influence on shear strength and identify a vane shear methodology(s) that yielded comparable undrained shear strength in triaxial and/or drained shear strength in direct shear.

2.6.2. LS-VS testing

Cross-section and plan-view schematics and a photograph of the LS-VS apparatus are shown in Figure 3. The apparatus was developed with a similar objective as the SS-VS apparatus, whereby specimens could be consolidated and sheared under a target σ'_v without removing applied load. The cell was an acrylic cylinder with an inside diameter of 292 mm and height of 610 mm. The cylinder was attached to a steel base plate by using silicon caulk to provide a watertight seal. A hole in the side-wall of the cylinder at the bottom of the cell allowed drainage. A non-woven geotextile was used as a filter layer at the base to prevent material from migrating into the drainage line.

A loading frame was constructed from prefabricated square steel tubes that were 50 × 50 mm in cross section (Figure 3). Buckets of sand were hung from the 1.8-m-long moment arm to generate force that was transferred to the specimen at a 9-to-1 ratio. A 20.5-kg counterweight was used to offset weight of the moment arm. Vertical load was transferred to the specimen through four 9-mm-diameter steel rods positioned on the upper load platen. The load platen was a 290-mm-diameter × 12-mm-thick plastic plate that had a 54-mm-diameter hole in the center to allow vane insertion. A thin non-woven geotextile with a 54-mm slit was used as a filter layer between the specimen surface and load platen. Aluminum foil was placed over the hole in the load platen to prevent material loss during loading. The vane easily penetrated the aluminum foil and slit in the geotextile for testing. Vertical displacement was monitored during consolidation using an adhesive-backed measuring tape affixed to the side of the cell.

The LS-VS test was conducted in accordance with ASTM International (2018) on CCP at $\sigma'_v = 40$ and 90 kPa. Two LS-VS tests were conducted for each σ'_v . A Humboldt handheld field vane (25.4 mm in diameter, 50.8 mm in height) was used to measure shear strength. The Humboldt field vane allowed a τ between 0 and 65 kPa to be measured with an accuracy of $\pm 10\%$.

For all LS-VS tests, the vane was inserted to approximately the mid-depth of the specimen. The specimen height was sufficient such that the top of the vane was deeper than one vane height (50.8 mm) below the specimen surface. A 5-minute delay was allowed between the vane reaching the final position for shearing and beginning rotation. The handheld vane was rotated “as slow as possible” as

Table 1

Summary of the three seepage-induced consolidation tests (SICTs) conducted on coal combustion product (CCP)

Test	e_i	e_0	H_i (mm)	H_0 (mm)	H_s (mm)
SICT-1	3.53	1.50	67	37	15
SICT-2	3.18	1.41	92	53	22
SICT-3	2.00	1.27	99	75	33

Note: e_i = initial void ratio of slurry; e_0 = void ratio at zero effective stress; H_i = initial height of slurry sample; H_0 = height at zero effective stress; H_s = initial height of solids in sample.

per manufacturer instructions, which was approximately 10°/min. ASTM International (2018) suggests a rate of rotation of 6°/min, with a permissible range of 3°/min to 7°/min. Peak shear strength was measured, and then the vane was rapidly rotated (i.e., $\approx 180^\circ/\text{s}$) five revolutions to measure residual shear strength at the same rate of rotation used to measure peak shear strength. A final height of the specimen was recorded, the average w was determined via exhumed material, and the final e was computed assuming complete saturation.

3. Results and Discussion

3.1. Compressibility and hydraulic conductivity of CCP

A summary of the SICTs conducted on CCP is in Table 1 and includes the following: e_i , e_0 , initial height of the slurry specimen (H_i), height of the settled specimen at e_0 (H_0), and height of soil solids (H_s). Three SICTs on CCP were conducted with slurries prepared to different initial water contents to confirm the premise that regardless of the initial slurry consistency, compressibility and hydraulic conductivity results were repeatable. A c_v was computed from SICT data to determine appropriate elapsed times for excess pore pressure (u_e) dissipation during specimen preparation for the shear test specimens and to assess drainage conditions during vane shear.

3.2. Seepage-induced consolidation

A summary of the SICTs conducted on CCP is in Table 1. Relationships of e - σ'_v from the three SICTs on CCP as well as a single logarithmic regression of all data are shown in Figure 4. The SICTs were performed to a final $\sigma'_v = 80$ kPa, and all e - σ'_v data displayed a decreasing trend of e with increasing σ'_v . Comparing e_i and e_0 in Table 1, a considerable reduction in e occurred as water was released from the CCP during sedimentation and self-weight consolidation. Subsequent loading during the seepage and vertical loading phases of the SICT produced smaller changes in e . The average compression index (C_c) was 0.142, which agreed with CCP compressibility reported by Bachus and Santamarina (2012).

The k for CCP measured in the three SICTs decreased from 6×10^{-7} to 2×10^{-7} m/s, which corresponded with the increase in σ'_v from 1.5 to 80 kPa. This magnitude of k was typical of CCP, as was the observed relative insensitivity of k to σ'_v (Bachus and Santamarina, 2012). In general, there was good agreement of compressibility and k behavior between the three SICTs on CCP.

3.3. Time-rate of consolidation

An example of time-rate of consolidation behavior observed in SICT-2 is shown in Figure 5a as temporal trends of u_e and vertical

Fig. 3. Cross-section schematic (a), plan view schematic (b), and photograph (c) of the large-scale vane shear consolidation cell and load frame.

deformation (δ_v) for the load increment from $\sigma'_v = 20$ kPa to $\sigma'_v = 40$ kPa induced via vertical loading. The average specimen height was 43 mm, and drainage was only allowed via the top boundary such that u_e was monitored at the bottom. At time = 0, $u_e = -1$ kPa because seepage had been induced at the end of the previous load increment to measure k . The u_e due to loading immediately increased and then dissipated to approximately 0 kPa after 150 seconds. Only 22% of the applied vertical load was measured as u_e due to the high k and rapid drainage of CCP. The square-root-of-time method was used to determine $c_v = 1.25$ m²/day for data in Figure 5a. The c_v was relatively consistent across the entire range of σ'_v

used to evaluate compressibility due to the narrow range of k (6×10^{-7} to 2×10^{-7} m/s).

Relationships of δ_v vs. the square root of time for load increments during consolidation of CCP specimens in direct shear, SS-VS, and LS-VS are shown in Figure 5b. The c_v values determined using the square-root-of-time method for the shear data in Figure 5b ranged between 0.89 and 1.2 m²/day. These c_v values computed for the shear specimens and SICT were comparable, which indicated that time-rate of consolidation behavior was consistent across all laboratory experiments conducted on CCP.

Fig. 4. Relationships of void ratio vs. vertical effective stress for seepage-induced consolidation tests (SICTs) on coal combustion product. Data points are representative of the mid-depth of a specimen at the end of consolidation during the seepage and loading phases.

The c_v of CCP was relatively high compared with most natural fine-grained materials. A high c_v indicates rapid dissipation of u_e and rapid settlement. A $c_v = 1.25 \text{ m}^2/\text{day}$, based on SICT data, was used to approximate the time required for 99% consolidation for a given load increment of a given shear test specimen (e.g., LS-VS specimen with height = 600 mm and double-drainage yielded $t_{99} = 3.08$ hours). This time-rate of consolidation analysis ensured suitable elapsed times yielded complete consolidation for load increments applied during test specimen preparation.

3.4. Shear strength of CCP

Shear strength of CCP was evaluated via direct shear, triaxial compression, and vane shear. Furthermore, vane shear was conducted in SS-VS and LS-VS. Triaxial compression tests were used to determine drained and undrained shear strength. Direct shear tests were conducted to provide a second measure of drained shear strength and compare with triaxial compression. These measurements of CCP shear strength were used to establish drained and undrained shear strength to assess measurements of shear strength from vane shear.

3.5. CU triaxial compression

A summary of the CU triaxial tests conducted on CCP is in Table 2. The data compilation includes the following: σ'_c , B-value, final void ratio at the end of shear (e_f), axial strain at failure ($\epsilon_{a,f}$), deviator stress at failure ($\Delta\sigma_{a,f}$), effective major principle stress at failure (σ'_{1f}), effective minor principle stress at failure (σ'_{3f}), p'_f and q_f at failure ($p'_f = (\sigma'_{1f} + \sigma'_{3f})/2$ and $q_f = (\sigma'_{1f} - \sigma'_{3f})/2$), excess pore

Fig. 5. (a) Temporal relationships of excess pore water pressure and vertical deformation the seepage-induced consolidation test (SICT) on SICT-2 based on vertical loading from vertical effective stress (σ'_v) of 20–40 kPa on coal combustion product (CCP). (b) Relationships of vertical deformation vs. square root of time for select σ'_v loading increments in small-scale vane shear (SS-VS), large-scale vane shear (LS-VS), and direct shear test on CCP.

water pressure at failure ($u_{e,f}$), secant friction angle (ϕ'_{sc}), and the ratio of undrained shear strength at failure to initial effective confining stress (S_u/σ'_c). A definition of failure for CU triaxial tests is needed to determine shear strength parameters that can represent a given engineering scenario. Brandon et al. (2006) describe six potential failure criteria, of which two were considered in this study (Table 2): (1) the point at which an effective stress path for a given CU triaxial test reached the K_f line in q - p' space and (2) the point at which the effective principal stress ratio (σ'_1/σ'_3) reaches a maximum. Selection of these failure criteria for evaluation was based on recommendations in Brandon et al. (2006) and previous work (e.g., Jehring and Bareither, 2016; Hamade and Bareither, 2019).

Relationships of $\Delta\sigma_a$, u_e , and σ'_1/σ'_3 vs. ϵ_a for CU triaxial tests are shown in Figure 6. Solid symbols included in Figure 6 identify failure as interpreted from the three criteria tabulated in Table 2 (i.e., reaching K_f line and max σ'_1/σ'_3). The CCP exhibited a tendency to contract on initial loading followed by a tendency to dilate with continued axial deformation. Contractive behavior and development of positive u_e was more pronounced at higher σ'_c ,

Table 2

Summary of consolidated undrained triaxial compression tests conducted on coal combustion product (CCP) with failure conditions define based on (1) reaching the K_f line and (2) maximum principal effective stress ratio (σ'_1/σ'_3)

Target cell pressure (kPa)		10	20	50	100
σ'_c (kPa)		9.7	20.0	50.3	100.0
B-value		0.97	0.96	0.95	0.96
e_f		0.98	0.96	0.92	0.90
Failure definition: reaching K_f line	$\varepsilon_{a,f}$ (%)	2.5	2.2	2.2	3.1
	$\Delta\sigma_{d,f}$ (kPa)	20.1	35.8	54.1	108.3
	σ'_{3f} (kPa)	7.6	14.8	25.0	41.9
	σ'_{1f} (kPa)	27.7	50.6	79.1	150.2
	p'_f (kPa)	17.6	32.7	52.1	96.1
	q_f (kPa)	10.0	17.9	27.1	54.2
	$u_{e,f}$ (kPa)	2.1	5.2	25.0	58.1
	ϕ'_{sc}	34.7	33.1	31.3	34.3
	S_u/σ'_c	1.0	0.89	0.54	0.54
Failure definition: maximum σ'_1/σ'_3 ratio	$\varepsilon_{a,f}$ (%)	10.1	10.0	10.1	10.0
	$\Delta\sigma_{d,f}$ (kPa)	44.2	83.7	140.1	194.2
	σ'_{3f} (kPa)	13.3	28.4	52.9	65.0
	σ'_{1f} (kPa)	57.5	112.1	193.0	259.1
	p'_f (kPa)	35.4	70.2	122.9	162.0
	q_f (kPa)	22.1	41.8	70.0	97.1
	$u_{e,f}$ (kPa)	-3.6	-8.4	-2.9	35.0
	ϕ'_{sc}	38.7	36.6	34.7	36.8
	S_u/σ'_c	2.3	2.1	1.4	1.0

Note: σ'_c = effective confining stress; B-value = b-check for saturation; e = final void ratio that corresponded to the void ratio during undrained shear; $\varepsilon_{a,f}$ = axial strain at failure; $\Delta\sigma_{d,f}$ = deviator stress at failure; σ'_{3f} = minor effective principal stress at failure; σ'_{1f} = major effective principal stress at failure; $p'_f = (\sigma'_{1f} + \sigma'_{3f})/2$ and $q_f = (\sigma'_{1f} - \sigma'_{3f})/2$ from Lambe (1964); $u_{e,f}$ = excess pore water pressure at failure; ϕ'_{sc} = secant friction angle; S_u/σ'_c = ratio of undrained shear strength to initial effective confining stress.

which was attributed to suppressed dilatancy with increasing σ'_c . All specimens did exhibit a modest tendency to dilate with increased axial deformation that led to strain-hardening behavior, whereby $\Delta\sigma_d$ increased before becoming approximately constant near the end of shearing. Although $\Delta\sigma_d$ increased modestly throughout axial deformation, the σ'_1/σ'_3 reached a maximum at approximately 10% axial strain for all CU tests (Figure 6c). The small increase in $\Delta\sigma_d$ and σ'_1/σ'_3 for the CU test at $\sigma'_c = 20$ kPa at an axial strain of 12% was not observed in the other triaxial tests and was not considered representative of undrained shear behavior that would influence selection of a maximum σ'_1/σ'_3 . The undrained shear behavior of CCP agreed with that of loosely prepared, low-plasticity silts (Wang and Luna, 2012) and slurry deposited mine tailings (Jehring and Bareither, 2016).

Effective stress paths in p' - q space for the four CU triaxial compression tests on CCP are shown in Figure 7. Failure conditions based on the two criteria tabulated in Table 2 (i.e., reaching K_f line and maximum σ'_1/σ'_3) are included in Figure 7, along with linear regressions for the strength envelopes. In this study, all CCP specimens were normally consolidated such that the strength envelopes were assumed to pass through the origin (i.e., $q = 0$ at $p' = 0$). Effective stress paths in p' - q space theoretically reach the K_f line at failure and maintain a constant q/p' ratio for the remainder of axial deformation in a CU triaxial test. The consistency of this interpretation can be observed in Figure 7 as failure points identified for criteria of reaching the K_f line and the maximum σ'_1/σ'_3 align to form approximately a single strength envelope. However, there was a modest difference in effective stress friction angles (ϕ') of 34° and 36° for the two failure criteria. The main difference in defining

Fig. 6. Relationships of (a) deviator stress, (b) excess pore water pressure, and (c) principal effective stress ratio vs. axial strain for consolidated undrained triaxial compression tests on coal combustion product conducted at different effective confining stress (σ'_c).

failure in the CU triaxial tests based on reaching the K_f line and the maximum σ'_1/σ'_3 was that the stress state at failure corresponding to the maximum σ'_1/σ'_3 yielded larger p'_f and q_f . These larger effective stress states at failure were attributed to the tendency to dilate (Figure 6b) and the development of negative excess pore pressure at failure for the CU triaxial tests conducted at $\sigma'_c = 10, 20$, and 50 kPa (Table 2).

The difference in the stress states at failure based on defining failure as reaching the K_f line or maximum σ'_1/σ'_3 had a pronounced effect on the magnitude of undrained shear strength. The tendency to dilate and negative excess pore pressure at failure led to considerably larger ratios of S_u/σ'_c for failure defined at maximum σ'_1/σ'_3 compared with reaching the K_f line (Table 2). These implications are discussed subsequently in comparison to direct shear and vane shear.

Fig. 7. Effective stress paths in p' - q space for consolidated undrained triaxial compression tests on coal combustion product conducted at different effective confining stress (σ'_c). Failure conditions are shown that correspond to failure criteria of the effective stress paths reaching K_f line and maximum principal effective stress ratio (σ'_1/σ'_3). The slope of the strength envelope in p' - q space (α) and effective stress friction angle (ϕ') are included for both failure criteria.

3.6. Consolidated drained direct shear

A summary of the consolidated drained direct shear tests conducted on CCP is in Table 3. The data compilation in Table 3 includes σ'_v , peak shear strength (τ_p), e_i , and e_f . Multiple direct shear tests were conducted at a single σ'_v to account for minor inconsistencies between specimens and to assess repeatability.

Relationships of τ and e vs. horizontal displacement (δ_h) for the direct shear tests are shown in Figure 8. In all direct shear tests the CCP exhibited contractive behavior and a strain-hardening response under drained conditions, whereby specimens became denser with increasing δ_h and τ increased and remained approximately constant.

Relationships between the ratio of τ to σ'_v (τ/σ'_v) vs. δ_h for the direct shear tests are shown in Figure 9. Nearly all direct shear tests achieved a similar ratio of τ/σ'_v , which indicated similar secant friction angles and that a linear strength envelope could be developed

Table 3
Summary of consolidated drained direct shear tests conducted on coal combustion product

Test	σ'_v (kPa)	τ_p (kPa)	e_i	e_f
DS-1	32.7	22.7	1.05	1.01
DS-2	32.7	20.3	1.05	0.96
DS-3	32.7	28.7	1.06	0.97
DS-4	48.2	29.3	1.03	0.94
DS-5	48.2	26.7	1.02	0.97
DS-6	48.2	30.7	1.03	0.95
DS-7	48.2	30.0	1.02	0.96
DS-8	110.1	69.1	1.00	0.93
DS-9	110.1	69.0	0.99	0.93
DS-10	110.1	62.0	1.00	0.93
DS-11	110.1	65.9	1.00	0.90
DS-12	110.1	69.2	1.01	0.96

Note: σ'_v = vertical effective stress; τ_p = peak shear stress; e_i = void ratio before shear; e_f = void ratio after shear.

Fig. 8. Relationships of (a) shear stress and (b) vertical deformation vs. horizontal deformation for consolidated drained direct shear tests on coal combustion product conducted at different effective vertical stress (σ'_v).

Fig. 9. Relationships of the shear stress to vertical effective stress ratio vs. horizontal displacement for consolidated drained direct shear tests on coal combustion product.

Fig. 10. Relationships of shear strength vs. normal stress from direct shear tests and (a) effective stress and (b) total stress failure conditions using consolidated undrained (CU) triaxial compression tests on coal combustion product. Failure in the triaxial tests was defined based on reaching the K_f line and the maximum principal effective stress ratio (σ'_1/σ'_3). The effective stress friction angle (ϕ') and total stress friction angle (ϕ) are shown for the strength envelopes.

that passed through the origin. Test direct shear (DS)-3 at $\sigma'_v = 32$ kPa was a single outlier in the data set that achieved a higher τ/σ'_v ratio than all other tests. Although this test was included in the analysis, the dissimilarity in shear behavior relative to all other direct shear tests suggests that DS-3 may not be an effective assessment of the drained shear strength.

3.7. Comparison of triaxial compression and direct shear

The effective and total stress strength envelopes for CCP established from CU triaxial tests are shown in Figure 10, along with τ_p vs. σ'_v points representing failure conditions in the direct shear tests. The drained strength envelope for the direct shear data yielded $\phi' = 32^\circ$, which was comparable but slightly lower than the strength envelopes and corresponding ϕ' determined from triaxial tests ($\phi' = 34^\circ$ and 36° , respectively). The modestly higher shear strength and corresponding ϕ' in triaxial may be attributed to denser initial test specimens (i.e., lower e) and tendency to dilate relative to direct shear test specimens. Total stress strength envelopes for the two failure criteria in triaxial are shown in Figure 10b, along with direct shear data reproduced for comparison. The total stress strength envelope based on reaching the K_f line yielded a total stress fric-

Fig. 11. Relationships of void ratio vs. effective normal stress for initial and final specimen conditions of the coal combustion product in direct shear (DS) and consolidated undrained (CU) triaxial (TX) tests. Drained effective stress paths are shown for direct shear and undrained effective stress paths are shown for CU triaxial. The critical state line (CSL) was regressed through all data points identified as the final state of the specimens.

tion angle (ϕ) of 21° . By contrast, the total stress strength envelope based on maximum σ'_1/σ'_3 yielded $\phi = 32^\circ$.

A critical state analysis was conducted to compare density and effective stress states in direct shear and triaxial. Relationships between e and effective normal stress (σ'_n) in direct shear and triaxial are shown in Figure 11 at initial and final conditions. Stress and density at the end of the direct shear and triaxial experiments were used in the critical state analysis because modest changes existed throughout shear deformation that precluded determination of a true critical state (Jefferies and Been, 2006). The drained effective stress paths for direct shear indicate downward movement corresponding to contractive behavior and decrease in e during shear. Initial σ'_n values for triaxial specimens were taken as σ'_c (Table 2) because specimens were consolidated isotropically in the triaxial cell, and final σ'_n at critical state corresponded to σ'_n on the failure plane at the end of the tests. The undrained effective stress paths for triaxial test specimens exhibit movement to the right (i.e., increasing σ'_n) and terminate in the same critical state region as direct shear. Dilative tendencies in the triaxial specimens were due to initially denser specimens and position below the critical state line, whereas the contractive behavior for direct shear was due to initially looser specimens and position above the critical state line.

Strength envelopes for the drained direct shear tests compared favorably to the effective stress state from the CU triaxial tests (Figure 10a); however, defining failure based on the maximum σ'_1/σ'_3 yielded failure conditions approximately representative of the end of the tests (Figure 6), which compared favorably to direct shear in the critical state analysis. By contrast, defining failure in triaxial compression based on reaching the K_f line did not agree well with direct shear failure conditions in the critical state analysis (data not shown). Thus, effective and total strength envelopes based on

Fig. 12. Relationships of (a) peak shear strength vs. rate of rotation, (b) peak shear strength vs. the time delay before shearing (t_d), and (c) peak shear strength and residual shear strength vs. time in the consolidation cell (t_c) under the final vertical effective stress (σ'_v) for small-scale vane shear tests on coal combustion product consolidated under $\sigma'_v = 95$ kPa.

maximum σ'_1/σ'_3 were believed more representative of drained and undrained strength for the CCP evaluated in this study.

3.8. Vane shear tests

A summary of all SS-VS and LS-VS tests conducted on CCP is in Table 4. The data compilation in Table 4 includes the following: σ'_v , τ_p , residual shear strength (τ_r), rate of vane rotation, t_d , t_c , and e_f .

3.8.1. Effect of rate of rotation

The relationship between τ_p vs. rate of vane rotation for SS-VS specimens consolidated to $\sigma'_v = 95$ kPa is shown in Figure 12a. In general, the rate of vane rotation changes the time to failure, which controls the available time for u_e dissipation during shear (Reid, 2016). The standard rate of rotation for a miniature vane is between 30°/min and 60°/min. Shear rates of 5°/min, 60°/min, 150°/min, and 240°/min were considered, and τ_p was essentially constant with

varying rate of rotation. The negligible influence of rate of rotation on τ_p was attributed to the high c_v and small vane diameter, which likely promoted drained conditions during shear.

Blight (1968) developed a relationship between degree of drainage during vane rotation and a dimensionless time factor that is a function of c_v , time to failure (measured from the start of rotation), and vane diameter. Blight assumed undrained conditions when the degree of drainage was less than 10%. Dimensionless time factors for SS-VS tests based on Blight (1968) for the varying rate of rotations yielded a degree of drainage substantially higher than 10%, which suggested that partially drained to fully drained conditions developed in the SS-VS tests. The presences of the side-wall of the specimen cell to act as an impermeable drainage boundary and alter drainage conditions was a possibility in the laboratory tests; however, excess pore water pressure was not measured laterally around the cell and the impact of the cell wall was unknown.

3.8.2. Effect of delay before shear

The relationship of τ_p vs. t_d for SS-VS specimens consolidated to $\sigma'_v = 95$ kPa is shown in Figure 12b. The standard t_d was 1 minute, and t_d was varied between 0.1 and 60 minutes. Similar to rate of rotation, there was no defined trend between τ_p and t_d across the range of elapsed times evaluated. Furthermore, the collection of SS-VS tests presented in Figures 12a and 12b illustrate that τ_p for CCP consolidated to $\sigma'_v = 95$ kPa and maintained under σ'_v for 24 hours ranged between approximately 16 and 22 kPa, with an average $\tau_p = 18.4 \pm 1.7$ kPa.

Morris and Williams (2000) reported that vane insertion can lead to development of positive u_e up to 75% of σ'_v during a given vane shear test. Subsequent dissipation of positive u_e after vane insertion and during shearing yields an increase in effective stress and corresponding increase in vane shear strength. Vane shear tests on materials with c_v lower than CCP and with larger vane diameters than what was used in the SS-VS tests showed an increase of measured shear strength up to 126% with increasing t_d (Morris and Williams, 2000). However, the high c_v of CCP combined with the relatively small vane diameter used in the SS-VS tests meant that even after the shortest delays, u_e developed due to vane insertion had dissipated. The similarities in τ_p measured in SS-VS with varying rate of rotation and elapsed time after vane insertion support that CCP was readily drained and τ_p can be assumed to represent drained shear strength.

3.8.3. Effect of elapsed time under constant effective stress

Relationships of τ_p and τ_r vs. elapsed time under a constant σ'_v (i.e., t_c) for SS-VS specimens consolidated to $\sigma'_v = 95$ kPa are shown in Figure 12c. Both τ_p and τ_r were observed to increase with increasing t_c up to an approximately constant shear strength after 72 hours under a constant σ'_v . These trends suggest that time-dependent diagenesis may have influenced shear strength of CCP. Diagenesis is defined as a change in mineralogy due to chemical reactions that occur after disposal of CCP into a surface impoundment (McCarthy et al., 1999). Changes in mineralogy during diagenesis can lead to an increase in stiffness with increased time (Bachus and Santamarina, 2012), which may lead to higher shear strength of in situ or undisturbed CCP. Disturbance of CCP, for example, via static loading (Bachus and Santamarina, 2012) or shearing that can break

Table 4

Summary of small-scale vane shear (SS-VS) and large-scale vane shear (LS-VS) tests conducted on coal combustion product

Test type	σ'_v (kPa)	σ'_h (kPa)	τ_p (kPa)	τ_r (kPa)	Rate of rotation ($^\circ$ /min)	t_d (min)	t_c (h)	e_f
SS-VS-1	38.6	15.9	1.7	0.4	60	1.0	24	1.01
SS-VS-2	38.6	15.9	4.9	1.0	60	1.0	24	1.02
SS-VS-3	63.3	26.1	14.2	1.7	60	1.0	24	0.98
SS-VS-4	63.3	26.1	13.1	1.4	60	1.0	24	0.99
SS-VS-5	94.3	38.9	19.3	1.6	60	1.0	24	1.00
SS-VS-6	94.3	38.9	16.8	1.2	60	0.0	24	1.01
SS-VS-7	94.3	38.9	21.4	2.5	60	20.0	24	0.97
SS-VS-8	94.3	38.9	17.5	1.2	60	60.0	24	1.00
SS-VS-9	94.3	38.9	18.3	0.8	5	1.0	24	0.98
SS-VS-10	94.3	38.9	15.5	1.2	150	1.0	24	0.97
SS-VS-11	94.3	38.9	2.2	0.8	60	1.0	1	0.98
SS-VS-12	94.3	38.9	3.3	0.4	60	1.0	6	1.02
SS-VS-13	94.3	38.9	11.0	1.3	60	1.0	12	0.99
SS-VS-14	94.3	38.9	19.3	1.7	200	1.0	24	1.00
SS-VS-15	94.3	38.9	19.3	2.2	280	0.0	24	1.01
SS-VS-16	94.3	38.9	26.1	1.7	60	1.0	72	0.97
SS-VS-17	94.3	38.9	24.4	2.3	60	1.0	168	0.99
LS-VS-1	87.9	36.2	25.0	3.0	12	5.0	120	0.95
LS-VS-2	87.9	36.2	21.0	2.0	12	5.0	120	0.95
LS-VS-3	40.0	16.5	9.8	1.5	12	5.0	120	0.96
LS-VS-4	40.0	16.5	7.5	1.0	12	5.0	120	0.95

Note: σ'_v = vertical effective stress before shear; σ'_h = horizontal effective stress before shear; τ_p = peak shear stress; τ_r = residual shear stress; t_d = time delay between vane insertion and beginning rotation; t_c = time in cell; e_f = void ratio after consolidation and before shear.

chemical bonds, can eliminate the beneficial strength gain from diagenesis.

The magnitudes of τ_p and τ_r in Figure 12c demonstrate that CCP is a sensitive material, whereby a considerable loss in strength occurred between τ_p and τ_r . The ratio of τ_p/τ_r increased with increasing t_c to 72 hours and ranged between 8 and 16 for all $t_c > 1$ hour. The strength loss due to disturbance and remolding suggests that shearing eliminated any strength gain potentially attributable to diagenesis in the CCP (i.e., increase in τ_p from 1 to ≥ 72 hours under load) and that completely remolded CCP can have very low τ_r .

3.8.4. Shear strength

The evaluations of rate of vane rotation, elapsed time between vane insertion and shearing, and elapsed time under constant σ'_v before shear in SS-VS yielded two important observations: (1) CCP likely exhibited drained shear behavior, even at fast rates of rotation; and (2) diagenesis may have occurred to increase τ_p such that elapsed time under a constant σ'_v before shear needs to be accounted for in vane shear testing of CCP. Measurements of τ_p in LS-VS were conducted at $\sigma'_v = 40$ and 88 kPa and accounted for slow rates of rotation and $t_c = 120$ hours. The measured τ_p values in LS-VS-1 and LS-VS-3 were comparable to those of the SS-VS tests conducted under similar conditions (Table 4). For example, LS-VS-1 conducted under $\sigma'_v = 88$ kPa yielded $\tau_p = 25$ kPa, which was comparable to the maximum τ_p measured in SS-VS at elapsed times under constant σ'_v of 72 and 168 hours (SS-VS-16 and SS-VS-17 in Table 4). Thus, comparable measurements of τ_p were obtained in SS-VS and LS-VS under similar experimental conditions.

The tests labeled LS-VS-2 and LS-VS-4 were conducted on CCP that had previously been tested (i.e., used in LS-VS-1 and LS-VS-3) and subsequently air dried before being reused to prepare new slurry specimens. LS-VS-2 and LS-VS-4 exhibited lower shear strength

than the previous LS-VS tests under similar conditions (i.e., LS-VS-1 and LS-VS-3). The reduction in shear strength may have been attributed to a reduced effect of diagenesis caused by remolding and destruction of the initial bonds formed via diagenesis and a subsequent wet-dry cycle. Although only two LS-VS shear tests were conducted that assessed this phenomenon, the approximate 20% reduction in τ_p measured for CCP specimens subjected to remolding and another wet-dry cycle suggest diagenesis may reoccur in CCP and decrease with remolding and wet-dry cycling. Given that all materials tested in this study were first dried and rehydrated, the effect of diagenesis is hypothesized to have been greater in the as-disposed condition.

Relationships of τ_p vs. effective horizontal and vertical stress (σ'_h and σ'_v) in the SS-VS and LS-VS tests are shown in Figure 13 along with the upper and lower bounds of the drained and undrained strength envelopes determined from the CU triaxial tests (Figure 10). Vane shear data illustrate that τ_p plotted with respect to σ'_h provide a more appropriate comparison to the CU triaxial strength envelopes. The σ'_h was computed from σ'_v at the end of consolidation assuming (1) at-rest (K_0) conditions existed with $\phi' = 36^\circ$ and $K_0 = 1 - \sin(\phi')$ and (2) initial pore water pressure before shear was zero. Furthermore, u_e during vane shear was assumed negligible such that drained conditions were assumed and σ'_h computed before shear was representative of σ'_h during shear.

Shear strength measured in vane shear is derived from a cylindrical failure surface, with shear resistance provided by the vertical sides of the cylinder and the horizontal ends (Donald et al., 1977; Menzies and Merrifield, 1980). Assuming a vane height-to-diameter ratio of 2 and conventional stress distribution on the cylindrical surfaces, the vertical shear surface contributes 86% of the shear resistance (Chandler, 1988). Furthermore, Kouretzis et al. (2017) indicated that vane shear strength is analogous to direct simple shear conditions in the vertical plane with $\sigma'_h = K_0 \sigma'_v$. Therefore, strength

Fig. 13. Comparison between shear strength measured with small-scale vane shear (SS-VS), large-scale vane shear (LS-VS), and the drained and undrained strength envelopes developed from consolidated undrained triaxial tests on coal combustion product. Shear strength for SS-VS and LS-VS are plotted relative to the vertical effective stress (σ'_v) at the end of consolidation and the lateral effective stress (σ'_h) assuming no excess pore pressure development during shear.

conditions in vane shear were best represented as τ_p vs. σ'_h in a conventional Mohr–Coulomb assessment.

The LS-VS and SS-VS failure points plotted as τ_p vs. σ'_h in Figure 13 generally fall between the upper and lower bounds of the drained and undrained strength envelopes established in CU triaxial compression. Points plotting below the undrained strength envelope with $\phi = 21^\circ$ were for tests in which t_c was short and the potential effect of diagenesis only partially developed. Four tests were identified in Figure 13 in which test conditions likely captured the full potential effect of diagenesis (i.e., SS-VS-16, SS-VS-17, LS-VS-1, and LS-VS-3). In general, shear strength measured from these tests plotted on or closer to the drained strength envelope and upper bound total strength envelope relative to all other vane shear tests.

The potential influence of diagenesis evaluated in SS-VS was accounted for in the CU triaxial and direct shear tests. All CU triaxial tests were conducted after at least 48 hours had elapsed under the final σ'_c . In addition, direct shear tests were conducted at least 24 hours after applying the final σ'_c . Based on the direct shear results presented in Figure 10, the full potential of diagenesis in the CCP may not have occurred in the direct shear test specimens.

An additional comparison of shear strength measured in vane shear, direct shear, and triaxial compression as a function of effective stress before shear is shown in Figure 14. Vane shear data included in Figure 14 are the four tests identified in Figure 13 and are plotted as a function of σ'_h and σ'_v (i.e., σ'_h vs. τ_f/σ'_h and σ'_v vs. τ_f/σ'_v). Direct shear data are plotted as a function of σ'_v and drained shear strength. Triaxial data are plotted for failure identified at the maximum σ'_1/σ'_3 , and both drained and undrained strengths are plotted as a function of σ'_c . Shear strength measured in vane shear and related to σ'_h compare favorably to shear strength measured in direct shear. The normalized drained and undrained shear strengths measured in CU triaxial compression are considerably larger than the normalized shear strengths measured in vane shear and direct shear. These

higher shear strengths in triaxial were attributed to initially denser test specimens and the dilative tendencies of the specimens that led to higher undrained shear strength compared with drained shear strength (Figure 14). Consistency between shear strength measured

Fig. 14. Comparison between effective stress applied during specimen consolidation and the ratio of either drained or undrained shear strength (S_u) to effective stress applied during consolidation. Vane shear (VS) data shown for select tests identified in Figure 13 as a function of vertical effective stress (σ'_v) and horizontal effective stress (σ'_h). Direct shear (DS) data are shown as a function of σ'_v . Triaxial (TX) compression data are shown as a function of effective confining stress (σ'_c) before shear and plotted with regard to drained shear strength (τ_f) and S_u defined at the maximum principal stress ratio.

in vane shear and direct shear provides additional support that CCP in the vane shear was most likely drained.

4. Practical Implications

Understanding the shear strength of CCP in waste containment impoundments is important for safe construction and to avoid failures during construction activities. The data herein support that vane shear tests on CCP exhibited shear strength more similar to drained strength conditions. If undrained conditions develop during loading of CCP, particularly during construction, shear strength measured from vane shear and interpreted as undrained strength may not be representative.

Relating vane shear strength to σ'_h (e.g., Figures 13 and 14) was done to more effectively compare shear strength measured in vane shear to direct shear and triaxial compression. This assessment indicated that CCP in vane shear in this study was more representative of drained shear strength and in particular drained shear strength measured in direct shear. However, shear strength measured via vane shear in the field is conventionally represented with respect to vertical effective stress. The only potential limitation in relating vane shear strength to vertical effective stress and normalized vane shear strength to vertical effective stress is that these values may not be directly comparable to laboratory-measured strength. However, additional research is need on this topic, particularly a coupled field and laboratory investigation.

The potential impact of diagenesis can substantially improve the strength of CCP. However, data herein show that disturbance (i.e., progressive shearing) of CCP eliminated any potential strength gain due to diagenesis, and ultimately the residual shear strength of CCP was much lower than peak shear strength. Reliance on peak strength may also be unconservative if there exists the potential for disturbance due to construction equipment. Observations in the laboratory showed that material consolidated to relatively high stresses (i.e., $\sigma'_v = 100$ kPa) had reasonably high shear strength when undisturbed; however, disturbance via continued vane rotation reduced shear strength to <3 kPa in all vane shear experiments. This was attributed to the elimination of potential strength gain due to diagenesis, as well as the high retained water content under high vertical stresses.

The potential effect of diagenesis must be accounted for in preparation of laboratory CCP specimens to appropriately capture the range of shear strength. The results herein show that CCP gains strength with time and that testing materials at different elapsed times under constant σ'_v yields different results. A specimen preparation procedure that incorporates a time component is needed when testing CCP to ensure that if diagenesis develops the test specimens are more representative of anticipated in situ conditions.

5. Summary and Conclusions

Shear strength of coal combustion product (CCP) was evaluated with a series of CU triaxial compression, direct shear, small-scale vane shear (SS-VS), and large-scale vane shear (LS-VS) tests. Shear strength measurements from vane shear were compared with drained and undrained strength envelopes. Effects of the following variables on vane shear strength were evaluated using SS-VS: (1) rate of vane rotation, (2) time delay between vane insertion and

beginning rotation (t_d); and (3) elapsed time under the final σ'_v (t_c). The following observations and conclusions were drawn from this study:

- CCP had low compressibility and a single compression index of 0.142 captured the trend in void ratio vs. vertical effective stress (σ'_v) from three seepage-induced consolidation tests (SICTs). Hydraulic conductivity ranged between 6×10^{-7} and 2×10^{-7} m/s and was relatively insensitive to changes in σ'_v .
- Shear strength of CCP measured in CU triaxial compression and direct shear showed good agreement of drained shear strength. The effective stress friction angle (ϕ') determined from triaxial compression ranged between 34° and 36° . The total stress friction angle (ϕ) determined from triaxial compression ranged between 21° and 32° , whereby dilative tendencies in triaxial test specimens yielded higher undrained shear strength at larger magnitudes of axial deformation.
- A critical state analysis of end-state density and effective stress conditions in direct shear and triaxial compression supported the contractive nature of the direct shear specimens and dilative tendencies of the triaxial specimens. This analysis indicated that similar end-state conditions were achieved in both experiments.
- Results of SS-VS tests on CCP support that rate of vane rotation and time delay between vane insertion and beginning rotation had no influence on shear strength. This was attributed to the small vane diameter and high coefficient of consolidation (c_v) that led to drained conditions, even in tests with high rate of rotation ($280^\circ/\text{min}$) and short time delay between vane insertion and beginning rotation (0.1 minute).
- Data from SS-VS tests illustrated that CCP shear strength increased with time after consolidation. Shear strength increased an order of magnitude from $t_c = 1$ hour to $t_c = 72$ hours. This strength increase was hypothesized to be due to diagenesis, whereby chemical reactions within the CCP increased shear strength of the material.
- The SS-VS and LS-VS on CCP showed good agreement when similar experimental conditions existed. Peak shear strength measured in SS-VS and LS-VS compared favorably to the drained shear strength measured in direct shear. The close agreement with drained shear strength in vane shear tests further supported that drained conditions were present in the vane shear tests.

Acknowledgments

This work was supported by Colorado State University (CSU), the Tailings and Mine Waste (TMW) Conference, and Remedial Construction Services (RECON). The authors thank Dale Lane of RECON for thoughtful discussions of coal combustion residual management practices. The opinions, findings, recommendations, and conclusions are those of the authors and do not necessarily reflect CSU, the TMW Conference, or RECON.

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