Short and Long Term Variability of Flue Gas Desulfurization By-Product

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ABSTRACT

Over 20 million metric tons of flue gas desulfurization (FGD) by-product are generated in the United States every year. Currently, a number of applications for these materials exist. A major obstacle effecting utilization, however, is the potential variability in the chemical composition, leaching behavior, and engineering properties of these materials. Although this variability has an impact on effective utilization, little is known about how the physical, chemical and engineering properties of FGD by-product change over the course of different time periods. In this study, we examine the variability of FGD by-product generated at the McCracken Power Plant on The Ohio State University campus. To examine variability, samples of FGD by-product were collected from the power plant on a daily, weekly, and monthly basis and analyzed for chemical composition, leaching potential, and engineering properties. These new data also are compared to data for similar samples collected at the McCracken Power Plant in 1991 to examine long-term trends in FGD by-product properties.

INTRODUCTION AND BACKGROUND

In 1998, 22.7 million metric tons of FGD by-product was produced in the United States, with 90% being disposed in landfills or surface impoundments[1]. To lower the amount of FGD by-product entering landfills, the reuse of FGD by-product in a number of applications has been studied, including highway/road applications[2], mine reclamation uses[3,4], agricultural applications[5], and other civil engineering applications[6,7]. For effective utilization and marketing, the physical, chemical and engineering properties of FGD by-product must be thoroughly characterized.

It is also important to understand how the physical, chemical, and engineering properties of FGD by-product change with time. For example, variations in engineering properties of the FGD by-product could result in problems for applications requiring consistent strength, such as structural fills. Variations in

the levels of trace elements in FGD by-product may result in applications that are not environmentally sound.

In this study, we examine the variability of FGD by-product produced at the McCracken Power plant, located on The Ohio State University campus. The McCracken Power Plant is capable of generating approximately 9.5 megawatts of electricity and supplies steam, hot water, chilled water, and compressed air for campus use. Coal is used as fuel in a spreader-stoker boiler (boiler #8), which produces 115,000 lbs per hour steam at 600 psi and 750 ºF. There are two storage buildings for coal, a main storage of 500 tons or 4 day supply and a 175 ton overhead bunker. Sulfur oxides are removed from flue gas leaving boiler #8 using a dry scrubber. A lime slurry mist is injected into the scrubber to react with sulfur oxides and the by-product, along with fly ash, is collected by woven fiberglass filter bags in a pulse jet baghouse.

Samples of FGD by-product were collected on a daily, weekly and monthly basis from the McCracken Power Plant in order to characterize the variability of these materials over different time scales. Samples of coal and lime were also collected in order to determine how raw material properties may influence FGD by-product variability. Following sample collection, the physical, chemical (organic and inorganic), and engineering properties of FGD by-product samples were determined. In addition, these data are compared to similar data collected at the McCracken power plant in 1991[8,9,10]. The resulting information is used to assess the variability in specific properties of FGD by-product over a number of different time intervals, from days to years.

MATERIALS AND METHODS

FGD By-Product Sampling

Sampling of FGD by-product, lime (unslaked), and coal in the McCracken Power Plant was accomplished by an approach designed to provide statistically significant (representative) material for measurements of physical and engineering properties and chemical composition. For purposes of chemical characterization, our goal was to acquire a small fraction of the total mass of these granular materials with equal probability of capture for every particle size present in the original mass of material. Streams of lime or coal transported on the surface of a belt were sampled at release locations to avoid non-statistical fractions[11]. Freshly accumulated FGD by-product in bag house hoppers were the only sites available for sampling of FGD by-product for this investigation.

Specially designed devices for collection of coal and lime samples were constructed from stainless steel (SS) at The Ohio State University. Following each sampling event, the SS sampling devices were cleaned with liquid Alconox®, rinsed with high-purity water (18.2 megohm-cm), and wiped dry with Kimwipe®. These devices enabled both acquisition and transfer of each

collected sample into a metal-free high density polyethylene (HDPE) container or into a brown glass container free of PAHs and semi-volatile organic compounds (containers cleaned by EPA procedures). Labeling for each container identified the sampled material, site, date, sequence number, type of analysis required, and name of the team member who actually collected the sample.

All precleaned tools and sampling containers were transported to the sampling site inside a ziplock® type plastic bag, wrapped in polyethylene film, or enclosed within some other appropriate protective container. Following the sampling process, the outer surface of each labeled sample container was rinsed with high-purity water to remove dust and surface contaminants, wiped dry with a Kimwipe®, and subsequently stored in an environmental room (4 to 12 °C) until the appropriate chemical measurement procedure was started.

FGD by-product material was sampled through an 11-cm circular port in a hopper module that collects particles removed from the flue gas stream by filters located in the "bag house". Just prior to sampling, the level of FGD by-product in the hopper was increased for approximately 2 hours by closing the exhaust valve on the hopper.

FGD by-product samples for which inorganic constituents were to be determined were collected in an acid-leached 250-mL polytetrafluoroethylene (PTFE) beaker (Fisher Scientific) attached to a 2-meter PTFE-coated steel rod. This beaker was pushed through the hopper port to contact the freshly accumulated FGD by-product powder and then, pulled through the powder toward the port to collect powder. This process was repeated until each 500-mL HDPE storage container was approximately 75% full.

FGD by-product samples for which organic constituents were to be determined were collected by the same methods used for the samples collected for inorganic analyses. However, these samples were placed in clean 950-mL brown glass bottles that were filled to minimize head space.

FGD by-product material used in characterization of engineering properties was collected from the bag house hopper through the 11-cm port described previously. Twenty-liter plastic containers were filled with FGD by-product collected in a precleaned "shop vacuum" device fitted with appropriate PVC hose and an inner paper filter. This approach enabled the rapid acquisition of the large quantities of material required for physical tests.

Lime was sampled from the falling stream of unslaked lime as it was fed by belt into the lime slaker. Each sample taken represented all of the lime going into the slaker for a short interval of the transport process. All samples were stored in containers described previously for FGD by-product samples.

Coal was obtained at the release point of the belt that feeds coal into the combustion chamber at an approximate rate of 4.5 metric tons per hour. Each sample (~ 3 kg) collected from the falling stream of coal was poured into a clean HDPE bucket that was immediately closed with a matching lid (Fisher Scientific). Samples for both inorganic and organic characterization were collected in the same fashion.

Powder samples contained in cylindrical bottles can be mixed effectively by rotation of the bottle around a tumbling axis[12]. A tumbling device was used in the laboratory to achieve homogeneity of powders in conjunction with sample reduction that was accomplished by a 24-chute stainless steel riffle.

Small subsamples, 250 mg to 10 g, needed for laboratory analyses required initial comminution of both coal and lime. Coal samples first were pulverized to -8 mesh (Holmes mill) and then split by SS riffle. Splits were homogenized by tumbling, and subsamples were ground to -100 to -200 mesh in a non-metallic environment of an impact pulverizer. Lime samples (~500 g) were ground to -8 mesh, split by SS riffle, and a 30 to 35 g subsample was pulverized to -100 mesh in a vertical plate grinder.

Inorganic Chemical Properties

Inorganic properties of FGD by-product measured in this study included elemental composition, leachate composition, and available lime index. Complete elemental composition was determined by digesting approximately 400 milligram (mg) of FGD by-product by microwave digestion with a combination of nitric acid, hydrochloric acid, hydrofluoric acid and boric acid as described in EPA method 3052[13]. The minimum quality of all acids used in the analysis was "trace metal" grade. Sample solutions after digestion were preserved at 4-12 °C in an environmental chamber. Standard reference material "coal fly ash" 1633b provided by the National Institute of Standards and Technology (NIST) was used for validation of the method. Leachate analysis was accomplished by the toxicity characteristic leaching procedure (TCLP), EPA test method 1311[13]. Each TCLP test was conducted in duplicate. After filtration, TCLP samples were acidified by nitric acid to pH less than 2 and preserved at 4-12°C until analysis.

The determination of Ag, Al, B, Ba, Ca, Cd, Cr, Mg, Na, Pb, S, Si, Sr, and Zn in sample solutions was conducted by EPA method 6010B[13] using a Vista Pro simultaneous inductively coupled plasma optical emission spectrometer (ICP-OES) system (Varian Instruments, Walnut Creek, CA). Arsenic and selenium were determined by EPA methods 7060A and 7740[13], respectively, using a SpectrAA 880Z Zeeman graphite furnace atomic absorption (GFAA) spectrometer (Varian Instruments, Walnut Creek, CA). A vapor generation accessory was added to the GFAA spectrometer for the determination of mercury by EPA method 7470A[13]. Anions, including sulfate and chloride, were determined by EPA method 300.1[14] using an ion chromatograph (IC) (model DX-

500, Dionex, Sunnyvale, CA) with an AS-11 anion column. A duplicate, blank, and check standard was analyzed for at least every ten samples for ICP, GFAA, and IC analyses. Available lime index (ALI) was determined by ASTM method C 25-96a[15].

Organic Chemical Analysis

The extraction of FGD by-product samples was accomplished by EPA method 3541[13] using a Tecator Soxtec (Model 1043) extraction system. For each sample, 10 g of FGD by-product was placed in an extraction thimble with 60 mL of methylene chloride. The solution from this extraction process was subsequently evaporated to 1 mL prior to analysis. EPA method 8270C[13] provided the basis for measurement of polycyclic aromatic hydrocarbons (PAHs) and other semi-volatile organic compounds. A Thermo-Finnigan GC/PolarisQ ion trap was used for GC/MS analysis. Samples (1 μL) were injected into the programmable-temperature injector, operated in splitless mode, onto a Restek RTX-5 fused silica capillary column (30m$\times$0.25mm$\times$0.25μm). Helium served as the carrier gas. The mass spectrometer was operated in full scan mode for both standards and extracts from FGD by-product. The PAHs and other semi-volatile compounds were identified secondarily using the integrated search program for the NIST 106,000 compound database. Retention times for the 16 EPA-specified PAH standards[16] provided confirmation of the presence of PAHs in extracts.

Engineering Properties

The engineering tests were based on the assumption that the FGD by-product could be satisfactorily analyzed as a geotechnical material having specific and measurable properties. This allows for substitution of FGD by-products in place of natural soils. American Society for Testing and Materials (ASTM) standard procedures were employed to measure the desired engineering properties.

Hydrometer and dry sieving methods of ASTM 422 were used to conduct particle size analysis for the samples collected. The Coefficient of Uniformity (Cu), which is the ratio of D_{60} (the diameter at 60 percent) to D_{10} (diameter at 10 percent), was calculated from the particle size density curves. The specific gravity of the FGD by-product was used in calculating the phase relationships of FGD by-products, that is, the relative volumes of solids to distilled water and air in a given volume of FGD by-product. Calculation was achieved as described in ASTM D 854. Optimum moisture content and maximum dry density were determined using the Standard Proctor Test (ASTM 698). The engineering properties of a geotechnical material are strongly influenced by the density of the tested sample. Therefore, we chose the maximum dry density as defined in ASTM Standard D 698 as our reference condition for sample compaction. All the strength and permeability testing samples were compacted at the optimum moisture content and maximum dry density. Unconfined compressive strengths were determined on remolded specimens using a loading device as per ASTM D 2166. Hydraulic

conductivity, or coefficient of permeability, depends on the size of the void spaces, which in turn depends on the size, shape, and state of packing of FGD by-product samples. Saturated hydraulic conductivity measurements were conducted using replications for each sample as per ASTM D 5084. Testing of the daily samples nearly has been completed while testing for the weekly and monthly samples is in progress.

RESULTS AND DISCUSSION

Inorganic Chemical Properties

Figure 1 shows the variability in aluminum and arsenic concentration in TCLP leachate of FGD by-product collected over daily, weekly, and monthly time intervals. The aluminum concentration ranged from 4.5 to 8.0 ppb for daily sampling, from 5.0 to 7.0 ppb for weekly sampling, and from 7.0 to 8.0 ppb for monthly sampling. The analytical standard deviation for each measurement is also shown in Figure 1. Sampling dates for which no error bars appear had zero deviation for the two samples analyzed. The range of aluminum concentrations measured for daily TCLP tests was larger than the range observed for both weekly and monthly testing (Figure 1). The concentration of arsenic ranged from 2.0 to 3.0 ppb for daily sampling, from <1.0 to 2.5 ppb for weekly sampling, and from 2.0 to 3.0 ppb for monthly sampling. For arsenic, the most significant variability was observed over the monthly sampling period. While some variability in arsenic concentration was observed, all measured concentrations were well below the RCRA limit of 5 mg/L, and also significantly below the current primary drinking standard of 50 ppb and the proposed drinking water standard of 10 ppb.

Figure 2 shows the variation in calcium and silicon concentration of TCLP leachate for daily, weekly and monthly sampling periods. The measured calcium concentration in TCLP leachate was relatively high and showed low variation over the various sampling periods. The concentration of calcium ranged from 3376 to 3571 ppm for daily sampling, from 3398 to 3571 ppm for weekly sampling, and from 3376 to 3413 for monthly sampling. Like arsenic, the concentration of silicon varied significantly over all sampling periods. The concentration of silicon ranged from 85 to 246 ppb for daily sampling, from 55 to 154 ppb for weekly sampling, and from 154 to 177 ppb for monthly sampling.

In Figure 3 the variation of sulfate and chloride as a function of sampling period is shown. Similar to calcium, the concentration of chloride was high and showed little variation over the different sampling periods. The variation of chloride ranged from 34 to 46 ppm for daily sampling, from 35 to 41 ppm for weekly sampling, and from 38 to 40 for monthly sampling. Even though the sulfur concentration of TCLP leachate was high, similar to calcium and chloride, this species demonstrated greater variability. The sulfur concentration in TCLP

leachate ranged from 959 to 1360 ppm for daily sampling, from 924 to 1360 ppm for weekly sampling, and from 959 to 1105 ppm for monthly sampling.

The ranges of concentrations observed for aluminum, arsenic, calcium, silicon, chloride, and sulfate, as well as other inorganic parameters, over the different sampling periods are summarized in Table 1. Also shown in Table 1 is the daily variability of the available lime index. The range of values observed for the five-week sampling period includes all values for the seven-day sampling period. Similarly, the two-month sampling period includes all data for within the five week and seven-day sampling periods. Based on these data, the range of concentrations for Ag, Al, B, Cd, Cr, Hg, Se, Zn, and chloride were controlled by the variability over the seven day sampling period. In contrast, the range in levels of As, Ba, Ca, K, Mg, Na, Pb, S, Si, Sr, sulfate and pH were controlled by variability over either the five week or two month sampling period. The available lime index varied from 10.37% to 13.32% over a seven-day period. Data for ALI for the five-week and two month sampling periods were not yet available.

It is also interesting to compare the data described above to previous data collected at the McCracken Power Plant. On April 1, 1991, FGD by-product from McCracken Power Plant was taken for measurements of a host of chemical properties[8]. Comparing the TCLP data from 1991 to the data described above provides a measure of the variability FGD by-product leachate over a 10-year period. The concentration of most inorganic elements in TCLP leachate in 1991 data were similar to the values observed over the 2-month period in 2001, except for Al, Mg, and Na. The aluminum concentration decreased from 200 ppb in 1991 to around 4.5 ppb in 2001. The magnesium concentration increased from 0.05 ppm in 1991 to 49 ppm in 2001, and the Na concentration increased from 3.6 ppm in 1991 to 24.6 ppm in 2001.

While variability was observed for most RCRA elements over the 10-year period, the range of values observed over all sampling periods was below regulatory limits. In fact, the concentrations of Ag, As, B, Cr, Pb, and Se were at least two orders of magnitude below the RCRA limit. The concentrations of Cd and Hg were below the limit of detection for all samples analyzed in both 1991 and 2001. The concentrations of all RCRA elements in the TCLP leachate were also below the primary drinking water standards.

Organic Chemical Properties

In our preliminary identifications from daily samples, only three U.S.EPA specified PAHs were confirmed using the retention time from a PAH standard mixture. These three PAHs were naphthalene, fluorene and phenanthrene. No four and five-ring PAHs were found in FGD by-product materials.

Two- and three-ring aromatic compounds were identified in FGD by-product from McCracken Power Plant. In previous studies, Liu et al. found both small ring and

large ring PAHs, such as chrysene and pyrene[17,18]. However, in our study no large ring PAHs were found.

Generally, two major mechanisms result in PAH formation during coal combustion. One is pyrolysis, and the other is pyrosynthesis[19]. During pyrolysis, the macromolecular aromatic compounds are broken into different size fragments, and these fragments then decompose and form small organic compounds. In the process of pyrosynthesis, these fragments undergo chemical and physical reactions to form polycyclic compounds. With increased combustion temperatures, intermolecular cyclization among the fragments produced during pyrolysis is expected to be more important[17,18,20]. However, high temperature will also produce more energy to break the bonds in large ring PAHs.

In addition to boiler temperature, a number of other operational factors may also influence the production of PAHs at the McCracken Power Plant, such as air ratio, combustion characteristics of the spreader stoker boiler, and coal characteristics, to name a few. Continued identification and quantification will be performed on the remaining FGD by-product samples, as well as work to elucidate the operational factors controlling PAH formation in this system.

Engineering Properties

The particle size distribution and compaction test results are summarized in Table 2. All the FGD by-product samples collected in 2001 were very fine, and the uniformity coefficients less than approximately 1.5 are indicative of very uniform particle size distributions. The uniformity coefficient for the 2001 daily samples varied from 1.11 to 1.33. For FGD by-products daily sampling in 2001, the optimum moisture content ranged from 61% to 66%, while the maximum dry density ranged from 8.05 kN/m^3 to 8.45 kN/m^3. FGD by-products tested in 1991, except the OSU01 sample, had similar optimum moisture content and maximum dry density values. Figure 4 shows the moisture content versus dry density curves for 1991 and 2001 samples. The slopes of the moisture-density curve are flat indicating that the range of moisture content over which maximum density can be achieved is fairly large. Therefore, the maximum dry density is not particularly sensitive to slight variations in the moisture content in the vicinity of optimum. All the FGD by-products tested in 1991 and 2001 would be considered as lightweight materials, i.e., compacted densities are lower than those of typical natural soils. Figure 5 shows the stress-strain curves for the 2001 daily samples tested at 7 days of curing. The 7-day curing unconfined compressive strength of 2001 samples ranged from 31 psi to 52 psi, while the failure compressive strain ranged between 0.9% and 2.3%. Similar to the 1991 samples, the material exhibited low compressive strength but comparable to that of natural soils. The hydraulic conductivity of the 2001 samples was in the 10^{-5} cm/sec range, which is very similar to that of OSU01. However, OSU03 has a lower hydraulic conductivity (7.7x10^{-6} cm/sec) as shown Table 3. Comparing the result with natural soils, the hydraulic conductivity of FGD by-product samples is similar to

that of silt, but higher than that of clay. Testing of samples up to 90 days of curing is in progress. An increase in curing time will result in increased compressive strength and lower hydraulic conductivity values for the FGD by-product samples.

CONCLUSIONS AND FUTURE WORK

Inorganic elements and compounds found at relatively high concentrations (>1 mg/L) in FGD by-product leachate included B, Ca, K, Mg, Na, S, Sr, SO_4^{2-} and Cl-. Other trace elements found at trace levels (<1 mg/L) included Ag, Al, As, Ba, Cd, Hg, Pb, Se, Si and Zn. In addition, two-and three-ring aromatic compounds were identified in FGD by-product from McCracken Power Plant, though quantification has not yet been carried for these compounds. All inorganic elements in TCLP leachate were consistently well below the RCRA regulatory limits for all samples analyzed. The engineering characteristics of the FGD by-product samples were analyzed using standard geotechnical testing procedures. Further work will be carried out, including the determination of the elemental composition of coal and lime, in order to elucidate the cause of the variation in the physical, chemical, and engineering properties of FGD by-product over different sampling periods.

ACKNOWLEDGMENT

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Table 1. Variability of FGD by-product produced at the McCracken Power Plant.

Element /Parameter	Range of Values Observed		
	7 Days (5/14-5/20)	5 Weeks (5/17-6/14)	2 Months (5/14-6/14)
ALI (%)	10.37±0.13 – 13.32±0.12		
TCLP			
Ag (ppb)	8.1±0.1 – 9. 5±0.2	8.1±0.1– 9. 5±0.2	8.1±0.1– 9. 5±0.2
Al (ppb)	4.5±0.7 – 8.0±2.8	4.5±0.7 – 8.0±2.8	4.5±0.7 – 8.0±2.8
As (ppb)	2.0±0.0 – 3.1±0.1	<1.0 - 3.1±0.1	<1.0 – 3.1±0.1
B (ppm)	2.2±0.2 – 3.8±0.2	2.2±0.2 – 3.8±0.4	2.2±0.2 – 3.8±0.4
Ba (ppb)	159.5±0.7 – 330.5±6.4	121.0±4.2 – 330.5±6.4	121.0±4.2 – 330.5±6.4
Ca (ppm)	3376±65 - 3570±78	3376±65 - 3571±78	3376±65 - 3571±78
Cd (ppb)	<1	< 1	< 1
Cr (ppb)	<1- 2.0±0.0	<1 – 2.0±0.0	<1 – 2.0±0.0
Hg (ppb)	<0.2	<0.2	<0.2
K (ppm)	14.8±0.3 – 18.7±0.4	16.3±0.4 – 18.7±0.4	14.8±0.3 – 18.7±0.4
Mg (ppm)	28.0±1.4 – 41.0±1.4	28.0±1.4 – 49.0±12.7	28.0±1.4 – 49.0±12.7
Na (ppm)	20.1±0.4 – 24.6±0.8	18.9±1.0 – 24.6±0.8	18.9±1.0 – 24.6±0.8
Pb (ppb)	36.5±3.5 – 54.0±4.3	36.5±3.5 – 64.0±3.6	36.5±3.5 – 64.0±3.6
S (ppm)	332.1±3.9 – 479.2±89.0	328.7±15.7 – 479.2±89.0	328.7±15.7 – 479.2±89.0
Se (ppb)	6.4±0.7 – 15.4±1.0	6.4±0.7 – 15.4±1.0	6.4±0.7 – 15.4±1.0
Si (ppb)	85.0±0.0 – 245.5±19.0	54.5±68.6 – 245.5±19.0	54.5±68.6– 245.5±19.0
Sr (ppm)	2.03±0.01 – 2.27±0.04	2.03±0.01 – 2.74±0.24	2.03±0.01 – 2.74±0.24
Zn (ppb)	11.5±0.7 – 25.5±2.1	11.5±0.7 – 25.5±2.1	11.5±0.7 – 25.5±2.1
SO_4^{2-} (ppm)	959±16 - 1360±216	924±51 - 1360±216	924±51 - 1360±216
Cl^- (ppm)	34.0±1.0 - 46±0.7	34.0±1.0 - 46±0.7	34.0±1.0 - 46±0.7
pH	12.44 – 12.68	12.30 – 12.73	12.30 – 12.73

Table 2. Uniformity coefficient, optimum moisture content and maximum dry density for FGD by-product samples

Sample	Uniformity Coefficient (Cu)	Standard Proctor Test	
		Optimum Moisture Content (%)	Maximum Dry Density (kN/m^3)
Daily 05/14	1.2	66	8.05
Daily 05/15	1.11	63.5	8.45
Daily 05/16	1.21	62	8.12
Daily 05/17	1.13	61.5	8.3
Daily 05/18	1.33	61	8.45
OSU01*	-	50	8.92
OSU02*	-	68	8.04
OSU03*	-	63	8.13

*OSU01: McCracken Plant – baghouse (Jan. 11, 1991)
*OSU02: McCracken Plant – baghouse (Feb. 22, 1991)
*OSU03: McCracken Plant – baghouse (Apr. 1, 1991)

Table 3. Unconfined compressive strength and hydraulic conductivity for FGD by-product samples at 7days of curing

Sample	Unconfined Compressive Strength (psi)	Hydraulic Conductivity (cm/sec)
Daily 05/14	39.2	1.22×10^{-5}
Daily 05/15	51.9	1.14×10^{-5}
Daily 05/16	31.8	1.14×10^{-5}
Daily 05/17	45.6	1.13×10^{-5}
OSU01*	22.0	1.60×10^{-5}
OSU02*	37.4	-
OSU03*	38.0	7.70×10^{-6}

*OSU01: McCracken Plant – baghouse (Jan. 11, 1991)
*OSU02: McCracken Plant – baghouse (Feb. 22, 1991)
*OSU03: McCracken Plant – baghouse (Apr. 1, 1991)
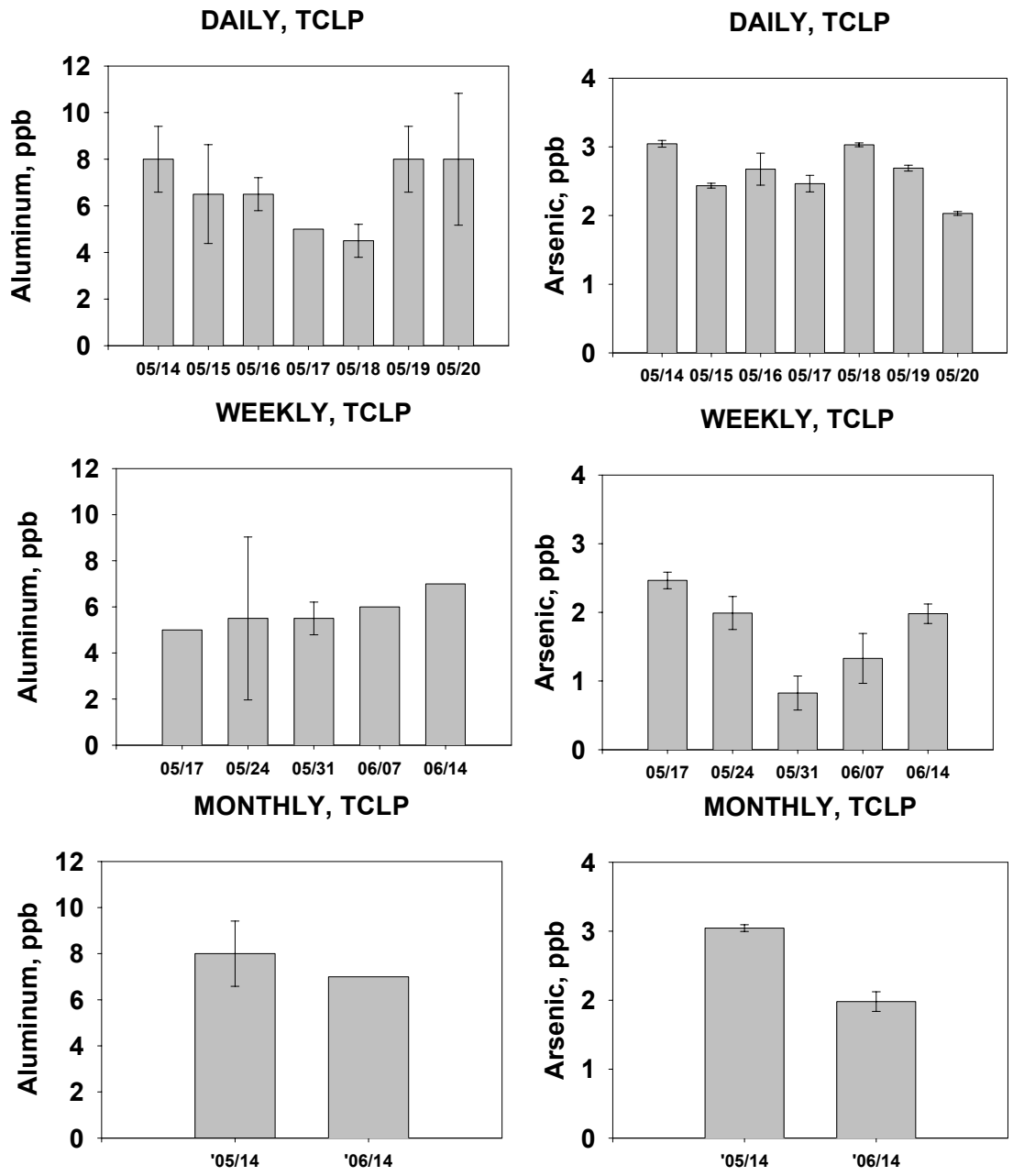
Figure 1. Variability in aluminum and arsenic concentration in TCLP leachate of FGD by-product material collected from the McCracken Power Plant, Ohio State University.
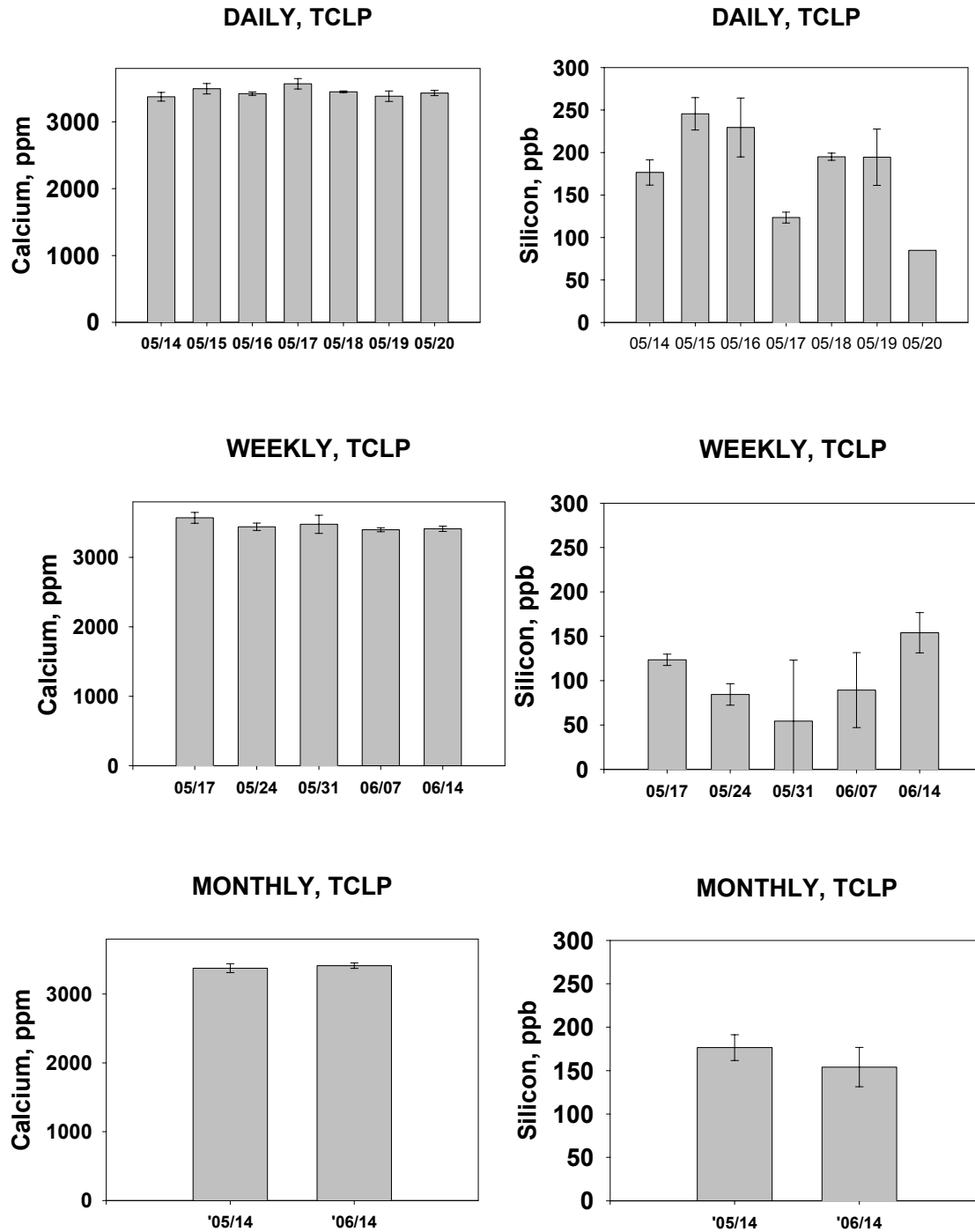
Figure 2. Variability in calcium and silicon concentration in TCLP leachate of FGD by-product material collected from the McCracken Power Plant, Ohio State University.
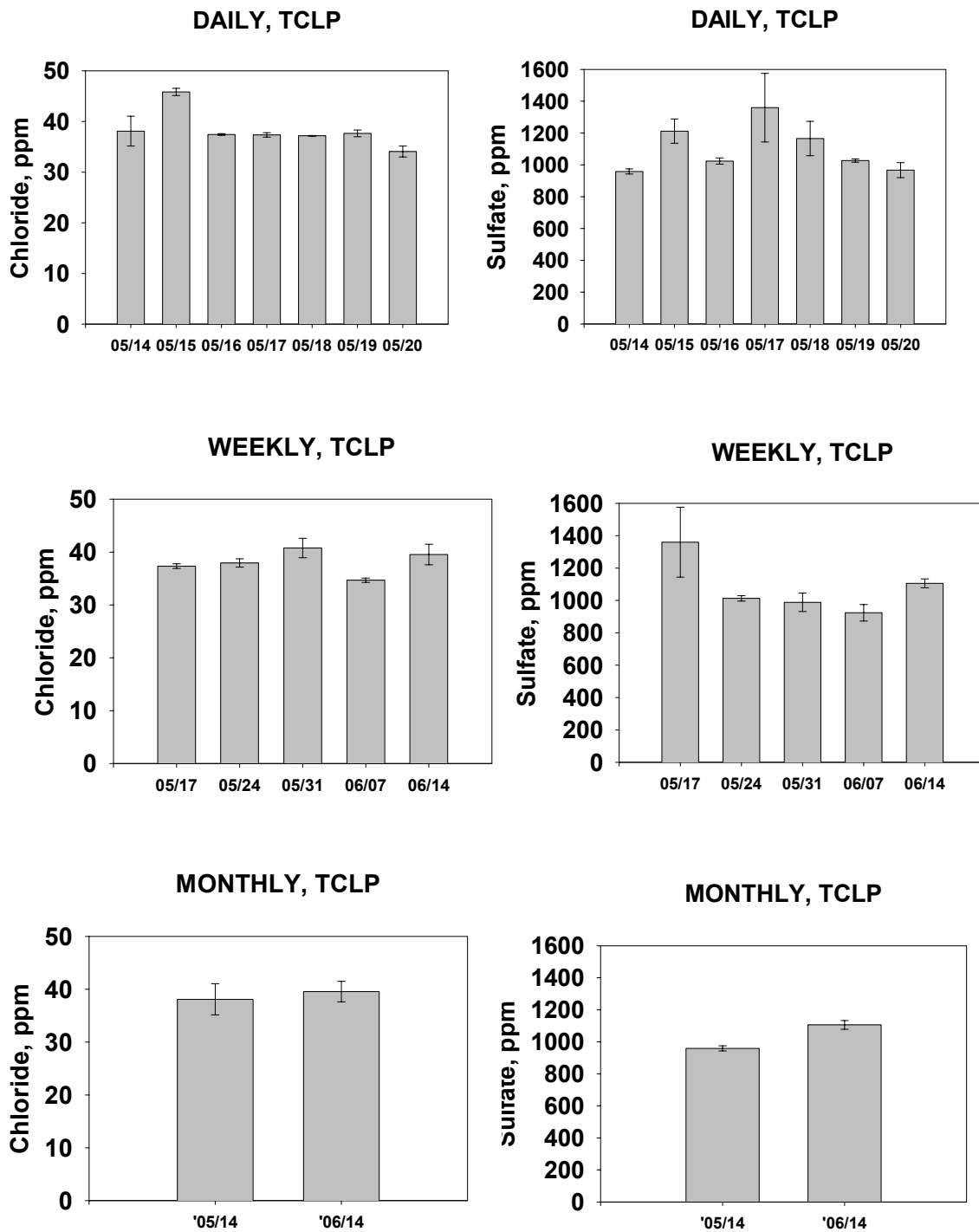
Figure 3. Variability in chloride and sulfate concentration in TCLP leachate of FGD by-product material collected from the McCracken Power Plant, Ohio State University.
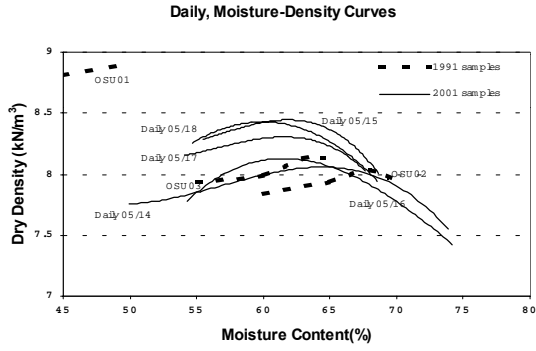
Daily, Moisture-Density Curves

Daily, Unconfined Compressive strength

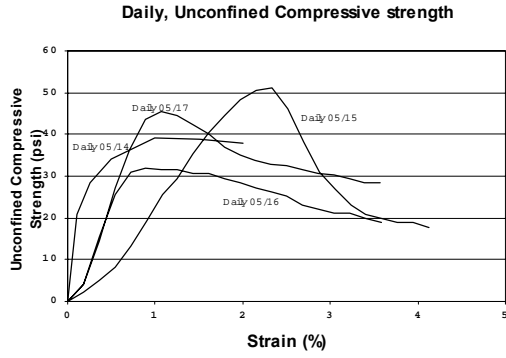**Figure 4.** Moisture content – dry density curves for FGD by-product samples

Figure 5. Compressive stress-strain response for FGD by-product samples at 7 days of curing