Chemical Composition and Engineering Properties of Solid By-products Collected from the Ohio State Carbonation and Ash Reactivation (OSCAR) Process

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ABSTRACT

Ohio state carbonation and ash reactivation (OSCAR) process was installed as a slip-stream at the McCracken Power Plant located on the Ohio State University main campus to test the efficiency of a new dry FGD system to remove SO_2. In this study, the chemical composition including heavy metals and polycyclic aromatic hydrocarbons (PAHs), leaching characteristics, and physical and engineering properties of solid by-product samples collected during the testing of the OSCAR process were examined to assess potential re-use opportunities for this material. Generally, trace element (i.e., arsenic, selenium, and mercury) concentrations were detected in mg/kg level. Measurement results for polycyclic aromatic hydrocarbons (PAHs) on selected cyclone and baghouse samples showed low concentrations (e.g. μg/kg). From the results, trace element concentrations in OSCAR samples were enriched compared to LSD ash. However leachate results indicated that ashes collected from the cyclone were not hazardous material. Arsenic concentration in cyclone ash was as much as 95 mg/kg, which is above the limit at 75 mg/kg for land application (EPA 503 Rule). For baghouse ash, arsenic and selenium concentrations were above the land application limits especially arsenic which was as high as 673 mg/kg. Bulk chemical and engineering properties indicated that OSCAR ash can be utilized in construction, agricultural and other civil engineering applications.

INTRODUCTION

A new dry FGD process was developed, called the Ohio State Carbonation and Ash Reactivation (OSCAR) Process, which improves the sulfur capture efficiency of calcium-based sorbents. Two types of reactivated sorbents were tested: (1) "regenerated sorbent" produced by utilizing lime spray dryer ash from the existing baghouse at the McCracken Power Plant and, (2) "supersorbent" generated from fresh lime. By-product samples were collected from the OSCAR process during injections of these two sorbents.

1

The primary purpose of this paper was to test by-products generated from the OSCAR process and to assess potential re-use opportunities for this material. To this end, the chemical composition (both organic and inorganic), leaching properties, bulk chemical properties, as well as physical and engineering properties were examined.

MATERIALS AND METHODS

Solid OSCAR by-product samples were collected from the cyclone and baghouse (if available). In addition, sorbent material was collected from the belt press prior to the drying process. Lime spray dryer (LSD) ash from the McCracken Power Plant was also collected to compare the properties of the by-product.

The collected samples were tested for mineralogical analysis by using X-Ray Diffraction (XRD) and Scanning electron microscopic (SEM).

INORGANIC ANALYSIS

In order to analyze OSCAR samples and LSD ash for elemental composition, solid samples were dissolved by microwave digestion (EPA method 3052). Leachate analyses were conducted by using the toxicity characteristic leaching procedure (TCLP) test (EPA method 1311). A Vista Pro simultaneous inductively coupled plasma optical emission spectrometer (ICP-OES) system (Varian, Walnut Creek, CA) and a SpectrAA 880Z Zeeman graphite furnace atomic absorption (AA) spectrometer (Varian, Walnut Creek, CA), were used to determine elements in the digested acid solution. Anions were measured by a DX-500 ion chromatography system (Dionex, Sunnyvale, CA) (EPA method 300.0). All analyses included controls (duplicate, blank, and check standards) for every fifteen samples or less.

ORGANIC ANALYSIS

For organic analysis, a 20 g sample was ultrasonic extracted with toluene (EPA 3540B) and concentrated to 1mL using a Kuderna-Danish concentrator and high purity N_2 gas for gas chromatography mass spectrometry (GC/MS) analysis (EPA 8270C). Duplicate extractions were conducted for all samples collected to ensure reproducibility.

BULK CHEMICAL, AND ENGINEERING AND PHYSICAL PROPERTIES

Bulk chemical characteristics relevant to agricultural applications determined by titration (ASTM C 25-96a), included available lime index (ALI) and calcium carbonate equivalence (CCE). Total neutralization potential (TNP) was measured by ASTM method C1318-95.

A number of standard ASTM test procedures were used for the evaluation of physical and engineering properties of the LSD ash and OSCAR by-product samples such as Moisture content (ASTM D2216, D4643), Specific Gravity (ASTM D854), Particle Size Analysis (ASTM D422), Standard Proctor Compaction Test (ASTM D698), Unconfined Compressive Strength (ASTM

D2166), Hydraulic Conductivity (ASTM D5084, D5856), Consolidation (ASTM D2435), and One Dimensional Swell Potential (ASTM D4546).

RESULTS
CHARACTERIZATION OF INORGANIC COMPONENTS IN OSCAR BY-PRODUCTS

For experiments using regenerated sorbent injection, the range in concentrations of major elements in samples collected from the baghouse were similar to ranges in concentrations observed for samples collected from the cyclone, except for S and organic carbon, which had consistently greater concentrations in samples from the baghouse for all experiments (See Table 1 and 2). When supersorbent was used in the OSCAR process, Ca was generally greater in samples from the cyclone than in the baghouse. The concentrations of all other major elements examined, however, were generally greater in samples collected from the baghouse or of similar concentration. Organic carbon was similar in samples collected from the baghouse and cyclone, which was different from the samples collected when using regenerated sorbent. For the regenerated sorbent, the carbon content of samples from the baghouse and cyclone varied.

For trace elements such as As, Hg and Se, higher concentrations were generally observed in samples from the baghouse compared to cyclone samples in experiments with both regenerated sorbent and supersorbent. Previous studies suggest that the capture of trace elements is influenced by the specific surface area of sorbent particles, temperature, and carbon content [Sakulpitakpol, et al., 2000, Dunham, et al., 2003]. Higher specific surface area, higher carbon content and lower temperature favors the sorption of volatile trace elements like As, Se, and Hg on solid particle surface. In our study, although the concentrations of trace elements in the baghouse samples increased up to an order of magnitude compared to the samples collected from cyclone, the specific surface areas of samples collected from baghouse did not show a significant change compared to values found for samples from the cyclone. For example, in experiment 38, the specific surface area increases from 11.4 m^2/g in the cyclone sample to 19.5 m^2/g in the baghouse sample, while the As concentration increased by an order of magnitude. Thus, capture of trace elements was not controlled by the specific surface area. As for the carbon content, for experiments using regenerated sorbent, samples collected from the cyclone were found to have a significantly greater level of organic carbon than samples collected from the baghouse for a given experiment (Tables 1 and 2). However, for experiments using supersorbent, levels of organic carbon in samples from the cyclone and baghouse were similar or only slightly different. Thus, organic carbon content does not appear to be the major factor responsible for the elevated levels of trace elements in by-product samples collected from the baghouse. More likely, the lower flue gas temperature in the baghouse compared to the cyclone is the major reason resulting in the capturing of trace elements on ash in the baghouse. The flue gas temperature in the cyclone of 1200 to 1400 ºF was significantly greater than the temperature in the baghouse of around 500 to 700 ºF.

CHARACTERIZATION OF TRACE ORGANIC COMPONENTS IN OSCAR BY-PRODUCTS

PAH concentrations on lime and LSD ash before activation and formed supersorbent and regenerated sorbent were measured to establish background levels of PAHs on the solid by-products. As shown in Table 5, the raw material before activation showed lower PAH concentrations compared to the sorbents produced by the OSCAR process. Although more PAH homologs (e.g., naphthalene, phenanthrene, and fluoranthrene) were detected on the LSD ash, the concentrations remained at μg/kg concentrations. However, regenerated sorbent had much higher PAH concentrations than those of the LSD ash. In addition, compared to the supersorbent, regenerated sorbent had much higher PAH concentrations.

The PAH concentrations increased for both sorbents during the activation process possibly due to the sorption of PAHs from the flue gas. Flue gas in the McCracken Power Plant was used to activate the sorbent in a slurry tank at a temperature around 150 ^{o}C. It is possible that PAHs in the flue gas are sorbed onto the LSD ash or lime particles. The increase in PAHs after activation indicates that LSD ash and lime are able to capture PAHs from flue gas under appropriate conditions.

PAHS ON OSCAR SOLID BY-PRODUCTS

With the supersorbent injection, the PAH speciation and concentrations in sample No.37 and 38 are listed in Table 3. Small molecular weight PAHs such as naphthalene and phenanthrene were dominant in most of the samples. Larger molecular weight PAHs including benzo(b)fluoranthene and/or benzo(k)fluoranthene were detected in several cyclone samples (e.g., No.38). However, no PAHs larger than benzo(a)anthracene could be detected in baghouse samples. On all the samples collected during supersorbent injection, the concentrations of PAHs detected were generally at sub-ppm levels but varied in different samples. For the baghouse samples, the concentrations of naphthalene and phenanthrene were much higher than in the corresponding cyclone samples, while the concentrations of other PAHs detected on the baghouse samples were similar.

The higher PAH concentrations on the baghouse samples compared to the cyclone sample may due to the low temperature in the baghouse (.300 ^{o}C, compared to 600 ^{o}C at cyclone). Sorption of gas phase PAHs onto solid particles will be enhanced at lower temperature and lead to higher PAH concentrations on baghouse samples. In addition, longer residence time in the baghouse may enhance contact time between gas-phase PAHs and sorbent resulting in more sorption of PAHs onto solid particles.

With regenerated sorbent injection, PAH homologs and concentrations detected in selected cyclone and baghouse samples are also listed in Table 3. Similarly, the PAHs identified in cyclone samples were small molecular weight PAHs. Interestingly, the concentrations of PAHs detected on OSCAR samples with regenerated sorbent injection were consistently low, ranging from a few to

tens of µg/kg. The baghouse sample had a slightly higher total PAH concentration than the cyclone samples.

As mentioned earlier, the PAH concentrations on supersorbent before injection were very low. Therefore, the higher PAH concentrations on solid by-products after supersorbent injection indicated the capture of PAHs from flue gas. Mastral et al. studied the effects of limestone on PAH emissions from coal atmospheric fluidized bed combustion and showed that limestone helped to control the PAH emissions in the gas phase by adsorption (Mastral, et al., 2001). Compared to the supersorbent, regenerated sorbent was not as effective at capturing PAHs from flue gas. The high PAH concentrations on the regenerated sorbent and the lower PAH concentrations on the cyclone and baghouse samples suggest release of PAHs from the solids or reactions of PAHs during SO_2 capture and particle removal processes.

LEACHING AND BULK PROPERTIES

Due to inadequate amounts of baghouse sample, leaching tests were only conducted on samples collected from the cyclone. Table 4 shows the results of TCLP tests of samples 4A, 5A, which were collected during experiments with regenerated sorbent. Selected results of TCLP tests of samples collected from cyclone during supersorbent experiments are also shown in Table 4. Leachate concentrations of by-products with supersorbent injection were similar to leachate obtained from regenerated sorbent samples, possibly due to similar final pH values (~6).

When compared with LSD ash, concentrations of most elements (Al, As, Ca, Ba, Fe, Mg, Mn, S, Se, Si, and Zn) in leachate from samples collected from the OSCAR experiments were greater, possibly due to the lower final pH of the leaching solutions. Samples were also compared with Resource Conservation and Recovery Act (RCRA) limits. For all samples, element concentrations did not violate RCRA limits, indicating that OSCAR cyclone samples are non-hazardous. Table 5 shows results of available lime index (ALI), calcium carbonate equivalent (CCE) and total neutralization potential (TNP) of samples collected from cyclone during regenerated sorbent and supersorbent experiment and LSD ash. ALI in LSD ash was 14.5% as $CaCO_3$, however, for samples collected from the OSCAR cyclone, all ALI results were less than 0.3% as $CaCO_3$ possibly due to lack of lime, which was spent to generate $CaCO_3$ sorbent. CCE results of samples collected from the OSCAR cyclone ranged from 22.4 to 59.41 % as $CaCO_3$, while CCE for LSD ash was measured as 64.9% as $CaCO_3$. In addition, results indicated that TNP of samples collected from the cyclone were small and varied with the sorbent feed rates from 4.1 to 27.4% as $CaCO_3$. The TNP in LSD ash was 16.3% as $CaCO_3$. The high level of TNP indicates the OSCAR by-product would be a good replacement for $CaCO_3$ in agricultural applications.

ENGINEERING PROPERTIES

Samples collected in experiment Nos. 2 (cyclone and baghouse samples combined) and 35 (cyclone sample) were used for engineering properties testing. The results are shown in Tables 6-7. Results indicate that the as received

moisture content, specific gravity, and percent finer than #200 sieve were similar for OSCAR ash and LSD ash. For the optimum moisture content, the results in LSD ash range from 61-69%, while the OSCAR ash had significantly lower optimum moisture contents (in the 40 to 44% range). The maximum dry density was found greater in the OSCAR samples (10.5 KN/m^3) than in LSD ash (7.7 - 8.5 KN/m^3) and much greater maximum dry densities were found when the OSCAR samples were compacted. The 7-day unconfined strengths of the OSCAR samples were also higher than the LSD ash strengths. The strengths (at 28, 60, and 90 days of curing) of the OSCAR samples are higher than that of LSD ash samples. The permeability and swell results show that the properties of the OSCAR sample are comparable to those of cohesive soils such as silts.

CONCLUSIONS

Both regenerated sorbent and supersorbent experiments removed trace elements (e.g. As, Se, and Hg) from the flue gas especially in the baghouse. Significantly higher levels of these elements were observed on OSCAR baghouse samples compared to LSD ash samples. TCLP tests indicated that OSCAR by-product samples were not hazardous based on RCRA regulations.

PAHs on solid by-products were primarily small molecular weight compounds at low concentrations (e.g. from a few µg/kg to hundreds µg/kg). Baghouse samples had higher PAH concentrations than cyclone samples. PAH composition and concentration were found to be influenced by the sorbent type.

Engineering properties exhibited by OSCAR by-products are similar to or superior to those exhibited by natural cohesive soils. The potential uses of OSCAR solid by-products will be in the highway and construction industry, reclamation, agricultural, manufacturing, and other civil engineering uses.

Table 1 Elemental composition of LSD ash, OSCAR baghouse samples using regenerated sorbent (4A and 5A), and supersorbent (37 and 38).

Sample		4A	5A	37	38	LSD ash	EPA 503
Al	%	5.27	5.38	5.9	5.0	2.67	
Ca	%	17.6	18.1	11.0	15.9	25.3	
Fe	%	5.04	5.84	4.1	3.4	1.76	
K	%	0.94	0.94	0.9	0.8	0.44	
Mg	%	0.39	0.40	0.3	0.3	0.42	
S	%	10.4	10.5	7.9	7.4	10.2	
Si	%	7.68	7.93	9.2	7.5	4.70	
Org C	%	11.7	11.8	10.0	10.2	11.7	
Ag	mg/kg	UDL	UDL	1.1	0.7	1.38	
As	mg/kg	502	502	673	583	28.1	75
Ba	mg/kg	1300	1300	195	168	100	
Be	mg/kg	2.5	1.9	5.6	5.0	2.01	
Cd	mg/kg	2.9	3.0	4.3	4.0	UDL	85
Co	mg/kg	52.6	56.6	38	30	15.1	
Cr	mg/kg	395	286	597	288	28.1	3000
Cu	mg/kg	138	144	129	112	21.8	
Hg	mg/kg	3.59	3.41	2.4	2.7	0.42	57
Li	mg/kg	84.0	84.0	85	81	24.7	
Mn	mg/kg	506	513	254	213	99.6	
Mo	mg/kg	45.0	36.6	68	35	1.20	75
Na	mg/kg	3291	3345	1925	2007	882	
Ni	mg/kg	283	224	435	192	24.2	420
P	mg/kg	714	715	732	741	172	
Pb	mg/kg	174	156	142	169	18.0	840
Sb	mg/kg	10.4	9.80	5	7	2.06	
Se	mg/kg	101	101	120	117	16.2	100
Sn	mg/kg	19.9	21.1	16	17	UDL	
Sr	mg/kg	364.2	364.8	324	354	228	
Zn	mg/kg	N/A	N/A	511	520	23.2	

UDL – Under detection limit
N/A – Not available

Table 2 Elemental composition of LSD ash, OSCAR cyclone samples using regenerated sorbent (4A and 5A), and supersorbent (37 and 38).

Samples		BG FA[†]	4	5	37	38	LSD ash[‡]	EPA 503
Al	%	7.60	9.45	9.45	4.6	3.5	2.67	
Ca	%	0.42	7.39	7.39	19.0	23.7	25.3	
Fe	%	5.93	6.60	6.60	3.3	3.1	1.76	
K	%	0.83	1.12	1.12	0.7	0.5	0.44	
Mg	%	0.33	0.45	0.45	0.3	0.3	0.42	
S	%	0.40	2.17	2.17	1.4	2.5	10.2	
Si	%	13.1	16.2	16.2	8.2	6.2	4.70	
Org C	%	33.5	26.5	26.5	15.5	13.1	11.7	
Ag	mg/kg	5.3	UDL	UDL	0.4	0.2	1.38	
As	mg/kg	69.3	95.5	95.5	72.8	52.3	28.1	75
Ba	mg/kg	200	1400	1400	182	133	100	
Be	mg/kg	0.4	1.19	1.19	2.7	1.8	2.01	
Cd	mg/kg	UDL	2.68	2.68	0.9	0.5	UDL	85
Co	mg/kg	35.9	47.2	47.2	18	13	15.1	
Cr	mg/kg	157	188	188	58	44	28.1	3000
Cu	mg/kg	36.5	45.7	45.7	28	23	21.8	
Hg	mg/kg	UDL	UDL	UDL	UDL	0.23	0.42	57
Li	mg/kg	71.6	91.3	91.3	51	39	24.7	
Mn	mg/kg	64	130	130	70	58	99.6	
Mo	mg/kg	14.2	17.2	17.2	6.1	5.0	1.20	75
Na	mg/kg	1163	1357	1357	803	764	882	
Ni	mg/kg	97.0	100	100	37	29	24.2	420
P	mg/kg	274	306	306	272	181	172	
Pb	mg/kg	31.5	47.8	47.8	27	20	18.0	840
Sb	mg/kg	1.4	UDL	UDL	0.0	0.0	2.06	
Se	mg/kg	0.9	7.60	7.60	9.0	16.2	16.2	100
Sn	mg/kg	0.0	4.33	4.33	1.8	UDL	UDL	
Sr	mg/kg	276	373	373	367	365	228	
Zn	mg/kg	44.5	N/A	N/A	96.9	79.7	23.2	

*Sorbent sample was collected from belt press
[†] Background fly ash
[‡] Lime spray dryer ash
UDL – Under detection limit
N/A – Not available

Table 3. Measured PAH concentration on cyclone samples with supersorbent injection. #-7 are cyclone sample, #-8 are baghouse sample. Nap: naphthalane; Ace: acenaphthene; Phe: phenanthrene; Ant: anthracene; Py: pyrene; Flu: Fluoranthrene; Chy: chrysene; Ben(a): Benzo(a)anthracene; Ben(b): benzo(b)fluoranthene; Ben(k): benzo(k)fluoranthene

Samples	Sites	Nap	Ace	Phe	Ant	Py	Flu	Chy	Ben(a)	Ben(b)	Ben(k)
Lime		2.4±1.3	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D
SS		28.3±7.4	N/D	6.6±0.3	4.0±0.6	N/D	2.0±0.2	N/D	N/D	N/D	N/D
LSD ash		48.7±7.3	N/D	4.1±0.4	N/D	12.2±0.7	11.5±0.7	N/D	N/D	N/D	N/D
RS		373.2±106.8	18.9±4.1	95.7±7.4	13.7±1.1	16.4±2.3	36.5±6.6	13.9±2.9	62.8±8.0	N/D	N/D
4	CY	1.3±0.4	N/D	4.2±0.3	2.2±0.5	4.6±0.3	3.8±0.3	N/D	N/D	N/D	N/D
5	CY	19.5±0.6	N/D	3.1±0.4	1.6±0.2	5.8±1.0	5.6±1.6	N/D	N/D	N/D	N/D
1	BH	13.4±1.5	N/D	3.7±2.2	N/D	1.5±0.6	2.8±0.1	3.9±0.2	4.4±0.2	N/D	N/D
37	CY	58.5±18.1	N/D	22.5±2.4	10.9±0.9	15.0±2.3	9.5±1.9	N/D	N/D	N/D	N/D
38	CY	61.3±8.9	N/D	20.8±1.6	9.1±0.9	12.4±1.7	7.4±1.3	4.5±0.8	7.3±0.3	N/D	N/D
37	BH	241.9±19.8	10.4±1.0	26.9±12.0	5.7±1.9	17.6±1.5	3.0±1.0	N/D	N/D	N/D	N/D
38	BH	512.6±116.6	N/D	54.7±3.5	9.3±2.1	26.7±1.5	9.9±0.8	N/D	N/D	N/D	N/D

N/D – not detected, SS – Supersorbent, RS – regenerated sorbent

Table 4 Elemental compositions in leachates collected from TCLP test for LSD ash, OSCAR cyclone samples using regenerated sorbent (4A and 5A), and supersorbent (37 and 38).

Samples		LSD ash	4	5	37	38	RCRA
Ag	mg/L	0.031	0.037	0.034	0.002	0.002	5.0
As	mg/L	0.004	0.251	0.556	0.119	0.118	5.0
Ba	mg/L	0.081	0.109	0.205	0.105	0.074	100
Cd	mg/L	<0.001	<0.001	0.002	<0.001	<0.001	1.0
Cr	mg/L	0.004	0.005	0.006	<0.001	<0.001	5.0
Pb	mg/L	0.016	0.005	0.005	<0.006	<0.006	5.0
Se	mg/L	0.022	0.467	0.230	0.083	0.331	1.0
Hg	mg/L	<0.0001	<0.0001	<0.0001	<0.0003	<0.0003	0.2
Al	mg/L	0.009	1.32	2.56	0.155	0.336	
B	mg/L	7.7	10.4	7.6	4.862	11.243	
Be	mg/L	<0.001	0.001	0.001	<0.001	<0.001	
Ca	mg/L	3141	2867	2634	2560	2780	
Co	mg/L	0.019	0.052	0.053	0.020	0.014	
Cu	mg/L	0.032	0.038	0.059	<0.002	<0.002	
Fe	mg/L	0.008	9.4	15.3	0.008	0.010	
K	mg/L	14.8	10.6	11.1	10.08	6.664	
Li	mg/L	0.112	0.148	0.297	0.246	0.134	
Mg	mg/L	0.105	63.8	34.1	65.28	68.61	
Mn	mg/L	<0.0003	1.84	1.28	0.335	0.343	
Mo	mg/L	0.059	0.058	0.069	0.107	0.097	
Na	mg/L	63.4	57.6	53.2	22.60	21.00	
Ni	mg/L	0.055	0.183	0.198	0.058	0.059	
P	mg/L	<0.008	0.022	0.043	0.006	<0.008	
S	mg/L	219	668	999	455.9	548.5	
Si	mg/L	0.259	29.3	26.4	27.14	31.56	
Sn	mg/L	<0.001	<0.001	0.001	0.003	0.002	
Sr	mg/L	2.23	2.00	1.85	2.890	2.601	
Zn	mg/L	0.008	0.581	0.691	0.219	0.211	
pH*		12.74	6.02	5.88	6.010	5.970	
Cl$^-$	mg/L	171	49.4	35.6	16.72	21.63	
SO$_4^{2-}$	mg/L	541	702	1157	1298	1541	

* pH measured after 18 hours of rotation

Table 5 Available lime index, calcium carbonate equivalent and total neutralization potential results of samples collected from cyclone at OSCAR process and LSD ash

Samples	Available lime index	Calcium carbonate equivalent	Total neutralization potential
	% as CaCO3	% as CaCO3	% as CaCO3
4	0.14±0.01	36.8±0.3	10.3±0.0001
5	0.08±0.01	22.4±2.1	4.1±0.2
LSD ash	14.5±0.4	64.90±0.2	16.3±0.4
37	0.15±0.01	38.57±0.26	21.11±0.37
38	0.26±0.03	59.41±0.61	27.44±0.09

Table 6 Moisture Content, Standard Proctor Compaction test, Percent Finer than #200 Sieve, and Specific Gravity and Percent Finer than #200 Sieve of LSD ash and OSCAR samples

Sample		LSD ash	2	35
Moisture Content (%) as received	Bucket 1	0.3-1.3	0	0.1
	Bucket 2	0.4-1.3	0.2	N/A
	Small jar	N/A	0.1	N/A
Specific Gravity		2.36-2.54	2.45	2.59
Sieve analysis	% finer than #200 (0.075 mm)	80-96	81	94
Standard Proctor Test	Optimum Moisture Content (%)	61-69	41.3	43.5
	Maximum Dry Density (kN/m^3)	7.7-8.5	10.77	10.86

N/A – Not available

Table 7 Unconfined Compressive Strength and Permeability of LSD ash and OSCAR samples

Sample		LSD ash	2	35
Unconfined Compressive Strength (psi)	7 day	23-52	71	67
	28 day	27-62	89	82
	60 day	32-66	85	88
	90 day	44-69	69	90
Permeability (10^{-5}cm/sec)	7 day	0.39-1.76	1.61	2.26
	28 day	0.67-1.64	2.65	2.11
	60 day	0.37-2.13	2.59	3.07
	90 day	0.59-2.02	3.63	3.33
Percent Swell (%)	50 day		<2.5%	<2.5%

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