Viability of a Heterogenous Fly Ash Disposal Site for Use in Concrete

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Abstract

Disposal of significant quantities of CCR has occurred for decades, resulting in massive total quantities of stored material - more than 895 million yd^3 of CCR is stored in the top five US states alone. With continued plant closures resulting in decreased availability of fly ash for use in concrete infrastructure, interest in utilization of alternative sources, such as ash that has been impounded in disposal sites, is increasing, but these materials are underutilized due to uncertainty regarding properties, material variability, and effects of contaminants such as flue gas desulfurization products that may be comingled with the fly ash. Although a topic of great interest, little data currently exists detailing the properties of impounded fly ash. Of the data that is available, most comes from monofill sites composed of a relatively stable single source material where site disposal history is well documented. Data from less controlled environments is rare. This work will increase understanding of the properties and variability innate within a heterogenous ash disposal site, located in the Midwest U.S., highlight differences between stored fly ash and high-quality virgin materials, and explore simple treatments that may improve materials not currently meeting ASTM C618 specification limits. Testing showed that variability across and through the depth of the ash impoundment was not problematic for parameters including water requirement, density, and adsorption. Most of the as-received samples, however, did not meet fineness, nor strength requirements.

Keywords: reclaimed fly ash; harvested fly ash; concrete; sustainability; ASTM C618; performance; reactivity; adsorption

Introduction

In the past two decades the supply of high-quality, virgin fly ash has declined considerably due to the downward trends of coal-powered electricity [1], leading to shortfalls in fly ash availability and supply chain uncertainties for construction applications. Utilization of reclaimed fly ash, or fly ash that has been disposed of into ponds or landfills, is one approach to addressing fresh fly ash availability shortfalls. Disposal of significant quantities of CCR has occurred throughout the US for decades, resulting in massive total quantities of stored material - 895 million yd^3 of CCR is stored in the top five US states alone [2]. Based on current rates of fly ash consumption in cement and concrete applications, this volume of material could supply the full U.S. ash market for more than 131 years! Yet reclaimed materials continue to be underutilized due to fears of consumers around uncertainty regarding properties, source material variability, and possible comingling with contaminant materials such as flue-gas desulfurization products, bottom ash, organics, or other materials that may decrease quality of concrete in which they are used. Increasing access to publicly-available data on the quality of ash stored in ponds or landfills throughout the U.S. will help mitigate fears surrounding use of ash from disposal sites, and spur innovation into methods to improve quality for materials not meeting current specification requirements. Towards that end, this study evaluates samples from a heterogenous fly ash landfill, tracking properties and overall quality across, and through the site depths. Samples were analyzed for chemical composition and phase analysis, moisture content, adsorption, fineness and grain size, specific gravity, water requirement, reactivity, and setting time. In addition, several simple beneficiation methods were preliminarily investigated to evaluate the ability to improve ash properties.

Materials & Methods

Ten landfilled fly ash samples, obtained using sonic drilling methods, were analyzed for conformance with the ASTM C618 Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete [3] and compared to a standard, high-quality Class F fly ash. Samples were taken from a landfill site located on the grounds of

a previous coal strip mine located within the Midwestern U.S.. The former mine area, a 58m (190 ft) deep valley, was infilled with layers of CCR from 1995 until 2018. Although the constituent materials were supplied primarily from one large utility, over the course of the landfill's operation as many as 30 different sources supplied materials to the site within each given year, creating a high likelihood of heterogenous ash properties throughout the site. Anecdotal history available suggested that the site contained primarily fly ash, intermixed with small quantities of bottom ash materials, and layers of shale, which were placed approximately every 6 – 7.5 m (20-25 ft) throughout the depth of the site as cover material, to minimize material drift from wind. Ash for the study was obtained from five boring sites within the landfill footprint and from two sample depths, between the surface and 24 m (~80 ft) depth for each material, in order to increase understanding both of the properties and variability in the fly ash samples across the site as well as through its depths. Samples in this manuscript are named by their site (S1, S2, etc…) and according to their depth ('a' indicating the shallower, lower depth sample at the site, and 'b' indicating the deeper sample).

All tests requiring use of portland cement utilized a Lehigh Type I/II ordinary portland cement (OPC). Ottawa sand (Humboldt Manufacturing) was used for production of all mortars. Samples were collected from a sonic drilling rig and transported to the lab in 19L (5-gal.) buckets. Moisture content samples were stored in sealed plastic bags and not removed until just prior to testing. Materials for all other tests were dried in metal bowls at 105 °C for 24 hours, lightly reground to break up agglomerated particles, and remixed prior to application of other test methods.

Chemical analyses of each sample were performed according to ASTM D6357 [4]. Crystalline and amorphous phase content for each ash was determined using quantitative x-ray diffraction (QXRD). For QXRD analysis, fly ash samples were dried at 105 °C, reground and sieved to pass the #325 sieve, then interground with a zincite internal standard (at 10 wt%) using an isopropanol dispersant. XRD scans (Bruker D8, Johannsson mode using a copper x-ray source producing CuKα radiation) were run from 5 to 60 degrees 2θ with a step size of 0.02°. Profex Rietveld analysis software was used to quantify phase content [5]. Particle size analysis was performed on the samples utilizing a Beckman-Coulter LS13-320 laser particle size diffractometer

with fly ash samples analyzed in air. Fineness of the ashes was tested using the ASTM C311 and C430 [6] methods.

The effect of fly ash substitution in cement pastes on hydration kinetics was evaluated through isothermal calorimetry (TAM AIR) using 5g paste samples. Pastes were composed of 20% substitutions of fly ash for OPC, and mixed with DI water at a w/c of 0.4. The cementitious materials were mixed by hand with a metal spatula until homogenous, combined with water and mixed for two minutes using a hand-held mixer (Hamilton Beach), then placed into glass ampoules, sealed and placed in the calorimeter. Heat release of the samples at 25 °C was tracked over 72 hours following insertion into the calorimeter. Initial and final setting times of 20% fly ash pastes at normal consistency (ASTM C187 [7]) were tracked using the Vicat set time method ASTM C191 [8].

Longer-term reactivity of the ashes was tracked through several methods. First, the strength activity index (SAI), or ratio of strength of fly ash-cement mortars utilizing a 20% substitution of fly ash for ordinary Portland cement (OPC) compared to a reference cement mortar, were tracked according to the procedures of ASTM C311. The quantity of water used, water-cement ratio (w/c), and resulting flow diameter of all mixtures used for SAI testing are shown in Table 1. Compressive strength was measured for the mortars following 7 and 28 days of curing in a limewater bath.

Second, R^3 calorimetric methods were utilized to determine the extent of pozzolanic reactivity of the samples [9]. In this method, (similar to ASTM C1897-20), 11.11g of fly ash is combined with 33.33g $Ca(OH)_2$, 5.56g $CaCO_3$, and 60g of a potassium solution created by mixing 4g of potassium hydroxide with 20g of potassium sulfate in 1.0L of DI water. Dry mixture and potassium solution were stored overnight at 60°C in air-tight containers. About 110g of pastes were mixed for 2 minutes, using a magnetic stir plate at 400 rpm. Following mixing, approximately 15g of the sample and high pH mixture are placed into an isothermal calorimeter at 40 °C and heat release was tracked for 7 days.

Table 1 *– Water and w/c used in SAI mortar cubes to achieve equivalent flow of the OPC mortar.*

Sample	OPC	S1a	S1b	S2a	S2b	S3a	S3b	S4a	S4b	S5a	S5b

w/c	0.48	0.50	0.51	0.51	0.52	0.50	0.50	0.53	0.51	0.52	0.51
Flow diameter	13.0	13.0	15.0	11.0	16.0	16.0	15.5	12.0	8.0	14.0	10.0

Two tests were used to understand adsorption of the fly ash samples: loss on ignition (LOI) and the Foam Index Test (FIT) - ASTM C1827 [10]. The loss on ignition of the ashes (up to 750 °C) was determined using a Thermogravimetric analyzer (Mettler Toledo), with a ramp rate of 10 °C/min. Foam index testing was performed according to ASTM C1827 and using a AE200 (BASF) air entraining admixture and Lehigh Type I/II portland cement.

Results & Discussion

The primary chemical makeups of the fly ashes are shown in Table 2. Low calcium content of the ashes (<18%) indicates all samples can be classified as “Class F” fly ashes. All fly ash samples meet the chemical requirements of ASTM C618, namely, all ashes exceeded the 50% minimum composition of SiO_2, Al_2O_3, and Fe_2O_3, and had less than the 5% maximum allowed sulfate content. Low sulfate levels suggest that samples have minimal intermixing with other high sulfate coal combustion products, such as flue gas desulfurization products, and that these samples will not have significant delays in setting time and strength development that can result from high sulfate contents.

Similar to what has been shown in other studies [11], all samples considerably exceeded the 3% maximum moisture content allowed by ASTM C618. This is unsurprising, due to addition of water during the drilling process. Despite this, it is still very likely all ashes would require drying prior to sale for use in concrete.

Quantitative phase content, shown in Table 3 did not identify any abnormal phases present in the ashes, which were composed primarily of mullite and quartz. The amorphous content of the ashes was found to be on the low-to-average side of what is typical for fly ash samples.

Table 2 *- Fly ash chemical composition. ASTM C618 requires a minimum 70% SiO_2 + Al_2O_3 + Fe_2O_3 (%) content and a maximum of 5% SO_3.*

Sample	Moisture Content, %	SiO_2 + Al_2O_3 + Fe_2O_3, %	SiO_2, %	Al_2O_3, %	Fe_2O_3, %	CaO, %	MgO, %	Na_2O, %	K_2O, %	SO_3, %	Density (g/cm^3)
C618	-	83.35	55.57	17.40	10.38	5.38	1.43	1.17	2.59	0.41	
S1a	15.2	86.80	55.20	18.60	11.80	1.40	0.47	1.15	1.92	0.68	2.27
S1b	20.4	88.00	53.00	20.30	10.60	1.10	0.52	0.99	1.93	0.49	2.29
S2a	29.3	91.00	54.50	17.90	15.00	1.57	0.51	1.15	1.94	1.30	2.20
S2b	23.4	94.00	55.70	18.20	16.00	1.62	0.51	1.16	1.99	1.30	2.28
S3a	21.1	90.00	60.00	18.10	7.60	1.20	0.60	2.50	2.50	0.40	2.20
S3b	24.7	84.00	54.00	21.70	5.80	0.73	0.60	0.51	1.86	0.37	2.20
S4a	31.2	83.00	52.00	16.50	12.00	2.50	0.91	1.48	1.76	1.31	2.24
S4b	36.0	78.40	54.00	15.40	7.50	2.62	0.84	1.24	1.85	0.96	2.19
S5a	25.9	77.80	56.00	12.20	8.30	3.13	1.20	1.45	1.46	1.18	2.26
S5b	33.2	89.00	59.60	17.00	6.90	2.60	1.10	1.59	1.80	0.8	2.23

Table 3 *– X-ray diffraction phase content.*

	Phase Content (%)								
Sample	**Hematite**	**Mullite**	**MgO**	**Anhydrite**	**Magnetite**	**Maghemite**	**Calcite**	**Quartz**	**Amorphous**
C618	1	2	0	1	0	2	3	7	84
S1a	1	18	0	1	1	1	0	9	68
S1b	1	15	0	1	1	1	0	7	74
S2a	3	13	0	1	2	2	0	11	68
S2b	4	13	1	1	3	2	0	11	65
S3a	1	18	0	1	0	1	0	9	70
S3b	1	21	0	0	0	1	0	9	68
S4a	2	8	0	1	2	2	1	9	75
S4b	1	11	0	0	0	1	0	11	75
S5a	1	11	0	0	0	1	0	11	75
S5b	1	10	1	0	0	1	0	10	75

Grain size analysis of the ashes is shown in Figs. 1 and 2. Samples taken at the shallower depth at each site are shown with a solid line, samples taken from a deeper depth are shown with a dashed line. The fly ashes tested herein were generally coarser than typical of other standard virgin fly ashes, primarily due to the presence of larger particles in each sample, shown in Fig. 2, which shows an increased volume of 100 micron and 800 micron-sized particles. These particles were visible in some samples, and were believed to be fragments of the shale layers placed intermittently through the site depths. As a result of the presence of these coarse particles, most samples exceeded the maximum coarseness allowed by ASTM C618 fineness limits (maximum 34% of the sample retained on a 45-micron sieve) with only one set of ashes, S3a and b, meeting initial fineness limits (Fig. 3). Coarser particle size distributions are generally believed to translate to lower overall reactivity and strength development [12]. Correction of this specification nonconformance may lead to greater ash sample reactivity and greater strength development in the ash samples.

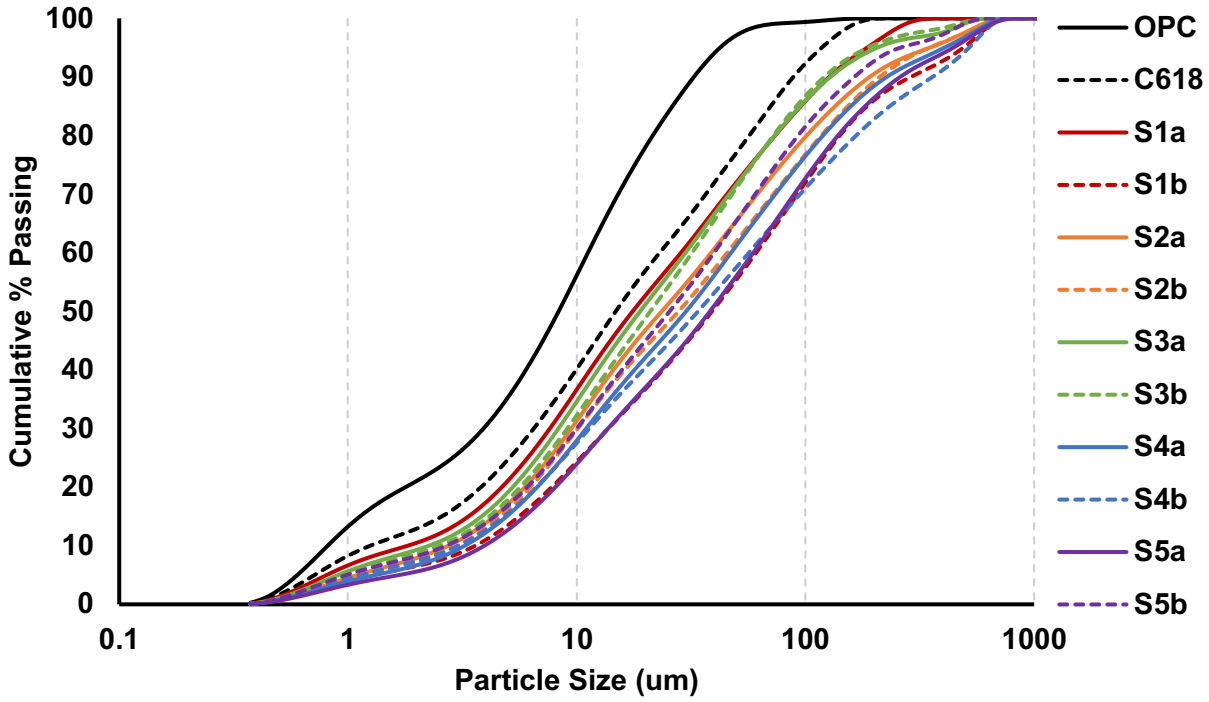

Figure 1 *- Cumulative percentage of fly ash particles smaller than a given size for the fly ash samples, a typical OPC, and an ASTM C618 Class F fly ash.*

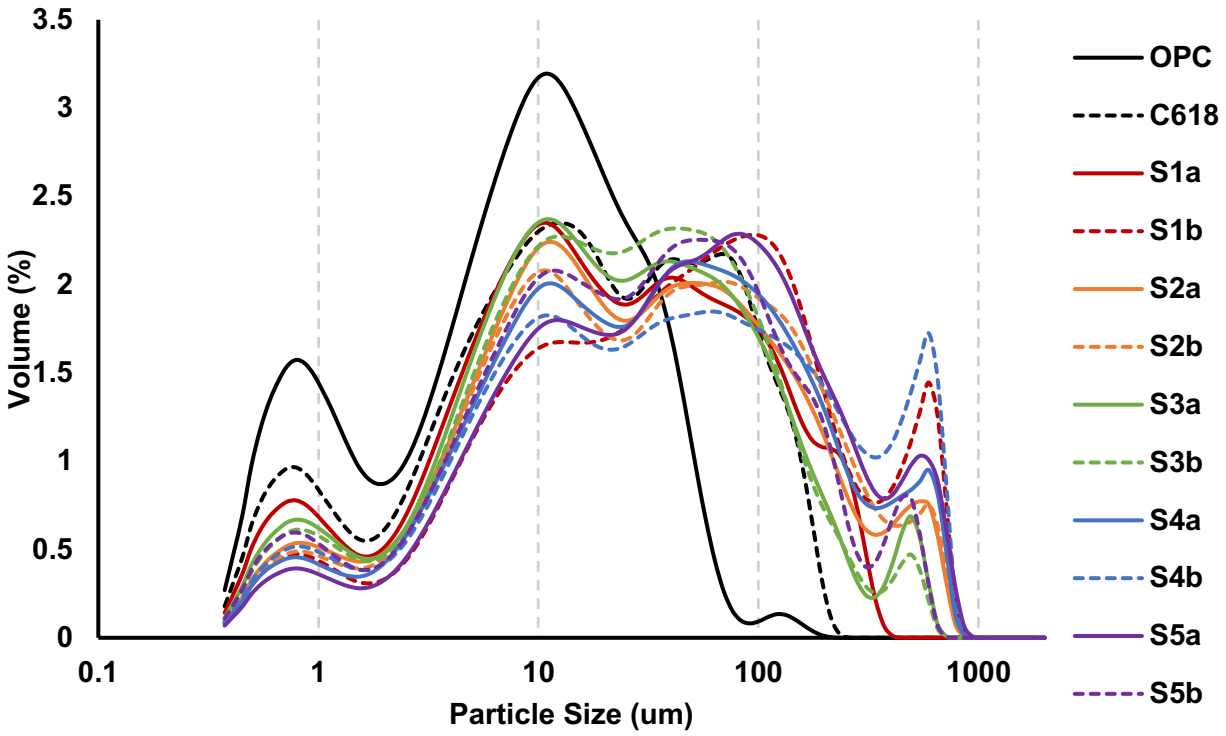

Figure 2 *- Distribution of particles sizes for each of the fly ash samples, a typical OPC, and an ASTM C618 Class F fly ash.*

In order to explore the extent to which samples would need to be sieved to obtain adequate fineness, all samples were sieved through a #100 (0.149 mm) or a #60 (0.25 mm sieve) and fineness was remeasured. After sieving through the #60 sieve, eight out of the ten samples met fineness requirements, with only the samples originally having the greatest original coarseness, S4b and S5a, in nonconformance. Following sieving through the #100, all samples met the fineness requirement. This suggests first, that the samples' coarse particles are predominantly greater than 0.25 mm in size, and second, that simple sieving procedures to remove the largest segment of particles, likely fragments of shale intermixed into the ash, may correct the fineness deficiencies of the fly ash samples.

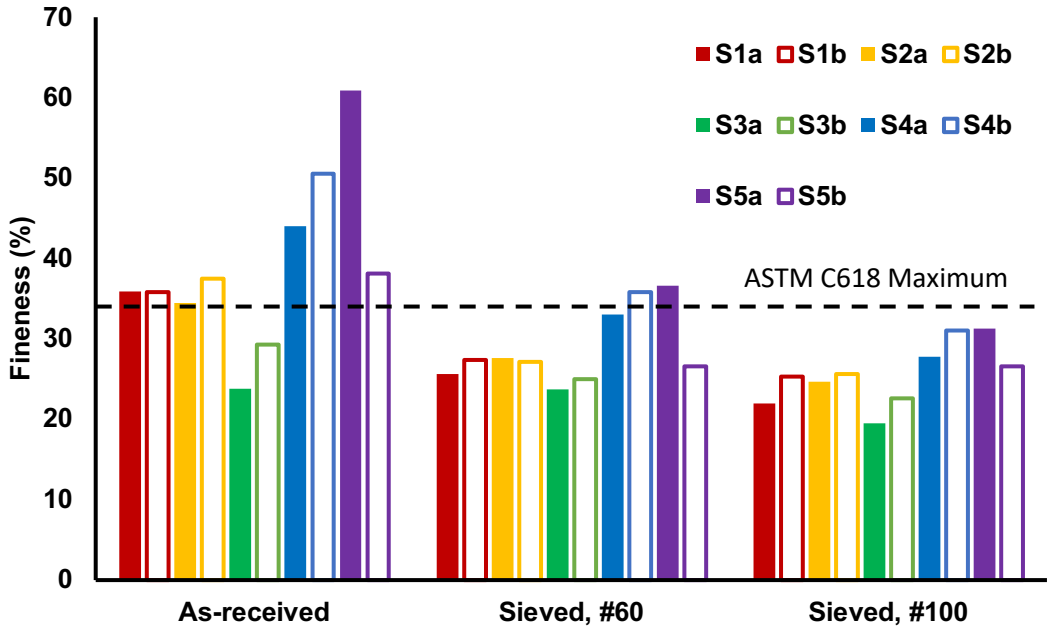

Figure 3 *- Fineness of the fly ash samples before and following sieving. ASTM C618 allows a maximum fineness of 34%. This value corresponds to the proportion of the mass of material in a sample greater than 45 μm in diameter.*

All of the harvested fly ash samples generated mortars requiring higher water dosages than the OPC mortar (>100%) with half exceeded the ASTM C618 maximum water requirement limitation of 105% (Fig. 4). In comparison, the standard C618 ash obtained a water requirement equal to that of the OPC mortar. Water requirement evaluates the impact of particle size, shape, and surface texture, on workability, or flowability, of a cement mortar mixture. Values greater than 100% show that greater quantities of water per quantity of cementitious materials (cement + fly ash) will be required to obtain similar levels of flowability when fly ash is substituted in the mixture in the place of portland cement. Values lower than 100% show that less water will be required to obtain similar flowability. Scanning electron microscopy images of sample S4a (Fig. 5) suggest that high water requirement may be a result of non-spherical particles (indicated by arrows a and b) and the presence of what appear to be hydrated materials, both on the surface of the fly ash grains (c), and also independent from them (d).

In order to mitigate high water requirement levels, a simple wet-milling technique was explored. Approximately 100g of dried S4a fly ash was combined with 55g of water, for a w/c of 0.55. The ash was ground by hand for 5 minutes in a ceramic mortar and pestle, then re-dried. After milling, the water requirement was reduced from 108.5% to 100%, now within the requirement of ASTM C618, and indicating that the wet-milled sample would not alter the flowability of mixtures in which it was incorporated. This suggests that deficiencies in the sample affecting water requirement could be corrected with minimal mechanical grinding effort and time. Wet milling has also been shown in other studies to also reduce sample particle size distribution, and increase strength and pozzolanic reactivity of fly ash samples [13,14].

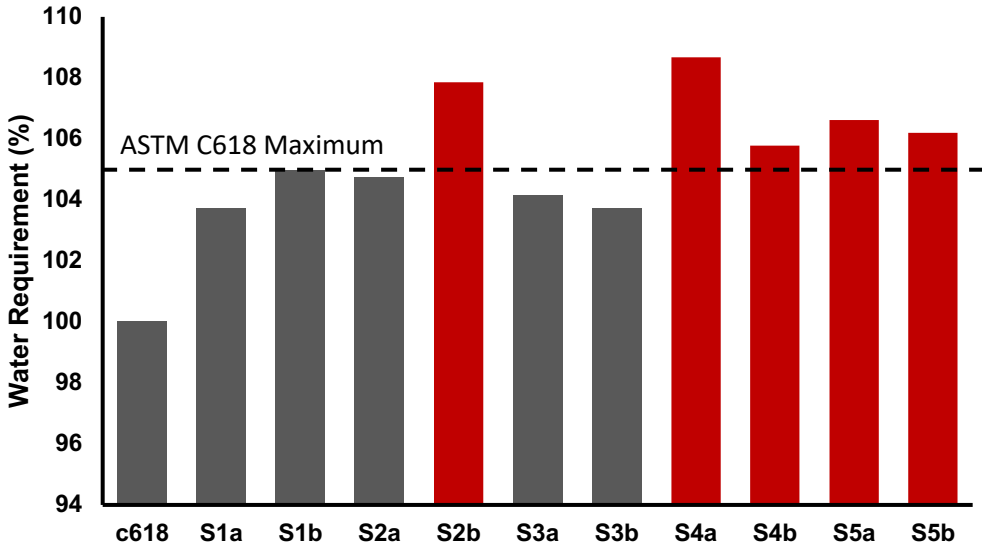

Figure 4 - *Water requirement, or the relative effect of the ash samples on flow of a fly ash-cement mortar compared to the OPC mortar. ASTM C618 allows a maximum water requirement of 105% of the control.*

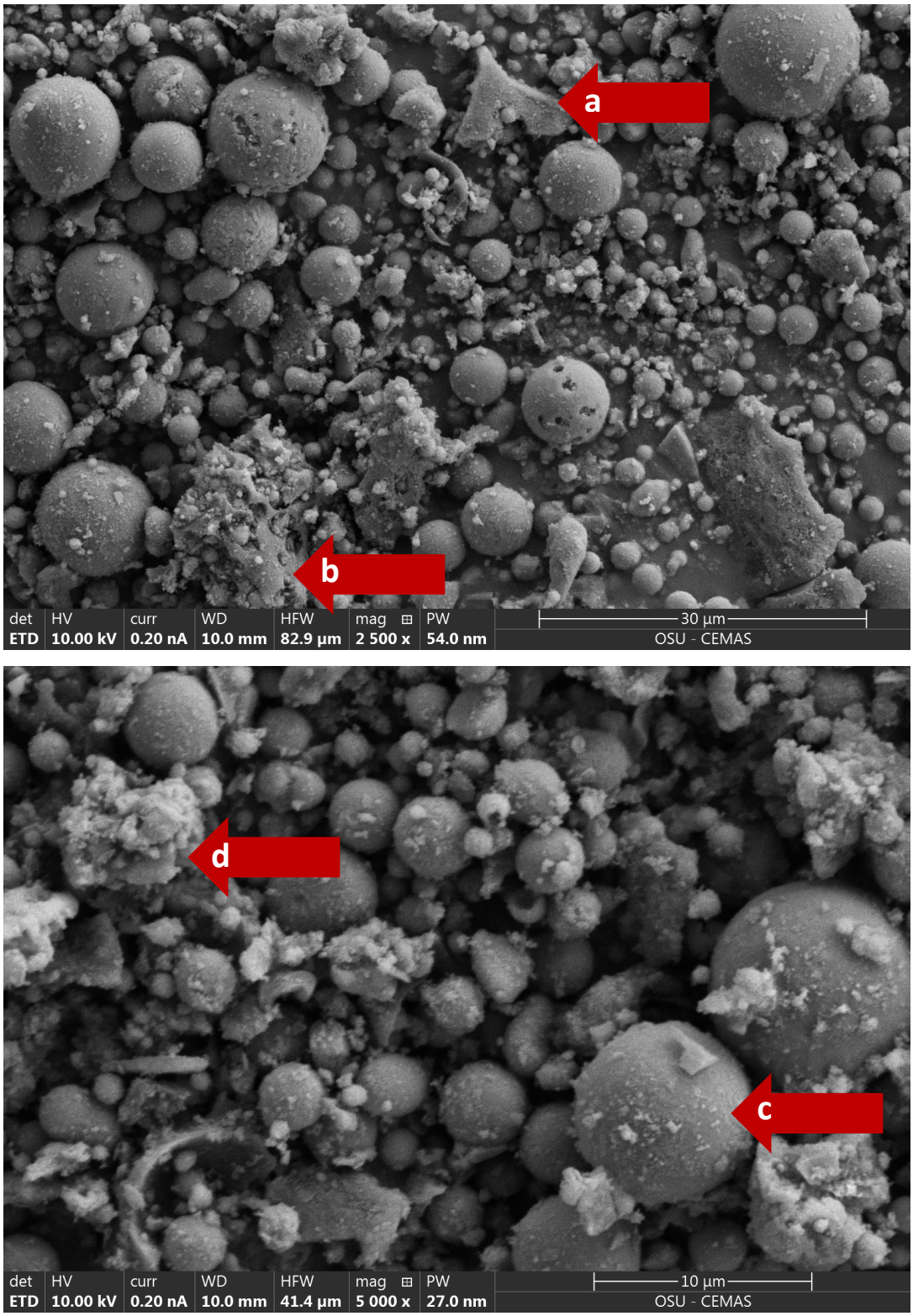

Figure 5 *- SEM images of sample S4a showing the presence of non-spherical particles, and possible hydrated components, both independent of the fly ash particles and on the surface of the fly ash.*

Adsorption potential of the ash samples were measured through loss on ignition measurements and foam index testing. High fly ash adsorption levels will result in removal of air entraining admixtures from solution, and can prevent the entrainment of air in concrete, leading to rapid deterioration due to water movement during freezing and thawing events. The LOI values for the fly ashes, shown in Table 4, were relatively low for all samples and well within acceptable ASTM C618 limits (maximum 6%), with the highest values obtained for the S4 and S5 samples (highest value 4.26%). However, foam index adsorption testing indicated that several of the ashes will adsorb significantly more admixture than standard ashes - the standard ASTM C618 Class F fly ash generated a foam index number of 25 and adsorbed 29 microliters of air entraining admixture per gram of fly ash. In comparison, the other ash samples adsorbed between 41 and 329% more admixture. ASTM C618 does not (yet) place a limitation on FIT number or adsorption levels, but the results do indicate that several of the ashes will be more difficult to air entrain, despite LOI values well within acceptable ASTM C618 limits.

Table 4 *– Indications of fly ash carbon content and adsorption capacity: LOI, FIT, and Iodine Number values. ASTM C618 allows a maximum LOI% of 6%. No limits on FIT or Iodine number have yet been specified.*

Samples	LOI %	Foam Index Number	Absolute Volume of AEA (μL/g fly ash)	Difference from C618 Ash
OPC	-	23	27	-
C618	0.6	25	29	-
S1a	1.40	34	40	+38%
S1b	1.36	42	50	+71%
S2a	2.48	73	87	+199%
S2b	2.94	70	83	+187%
S3a	1.09	38	44	+53%
S3b	0.94	35	41	+41%
S4a	2.92	75	89	+206%
S4b	4.26	105	124	+329%
S5a	3.38	55	65	+123%
S5b	3.82	54	64	+120%

Early age hydration kinetics of 20% fly ash-cement pastes and mortars were evaluated for all samples using isothermal calorimetry and the Vicat setting time test, respectively. In isothermal calorimetry results (Fig. 6) the ashes showed no signs of significant hydration delays, nor accelerations to system hydration kinetics due to filler

effect, likely due to the coarse nature of the fly ashes. Vicat setting times of many of the fly ash-cement mortars (Fig. 7) exceeded that of the OPC mortar, but by only a maximum of 27 minutes for initial set, and 38 minutes for final setting time.

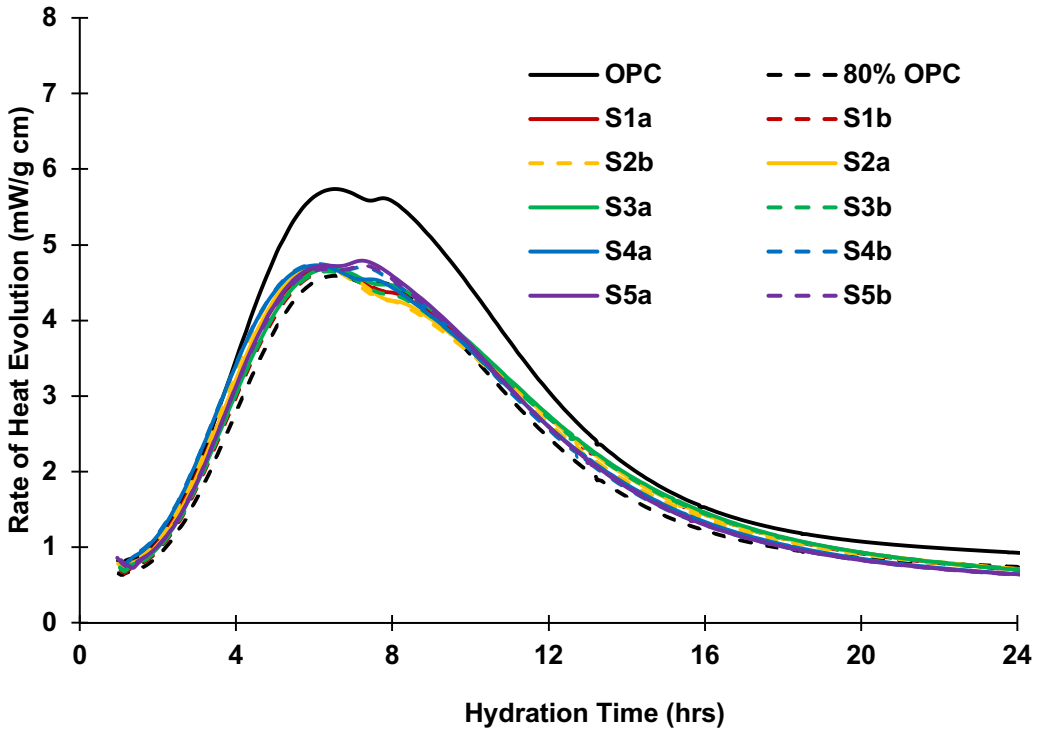

Figure 6 *- Hydration kinetics of 100% OPC or 80% OPC + 20% fly ash pastes at a w/c of 0.40.*

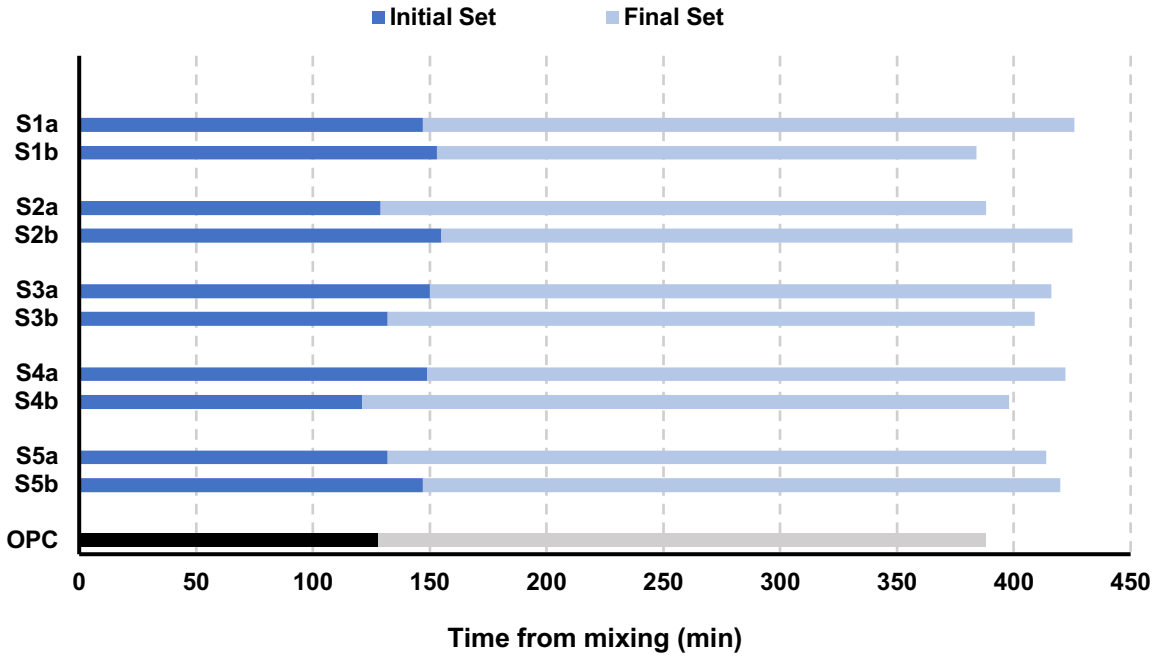

Figure 7 *- Effect of fly ash on mortar initial and final setting times.*

Reactivity of the fly ashes was further evaluated using the R^3 calorimetric method (Fig. 8). This method attempts to create conditions similar to those in the portland cement system, but that will accelerate pozzolanic reactions. This test method has been shown to correlate with long term strength development in SCM-cement mixtures with a variety of SCMs, including fly ash [15]. After 7 days of curing in the high pH solution, heat release from four of the ashes exceeded that of a standard Class F fly ash (sourced from Plant Bowen, GA. Note that this is a different ash than is designated as 'C618' and used for other tests). Snellings and Scrivener [16] showed that through this method an unreactive quartz powder will generate approximately a 50 J/g cumulative heat. All of the reclaimed ash samples well exceeded 50 J/g, suggesting at least low levels of reactivity.

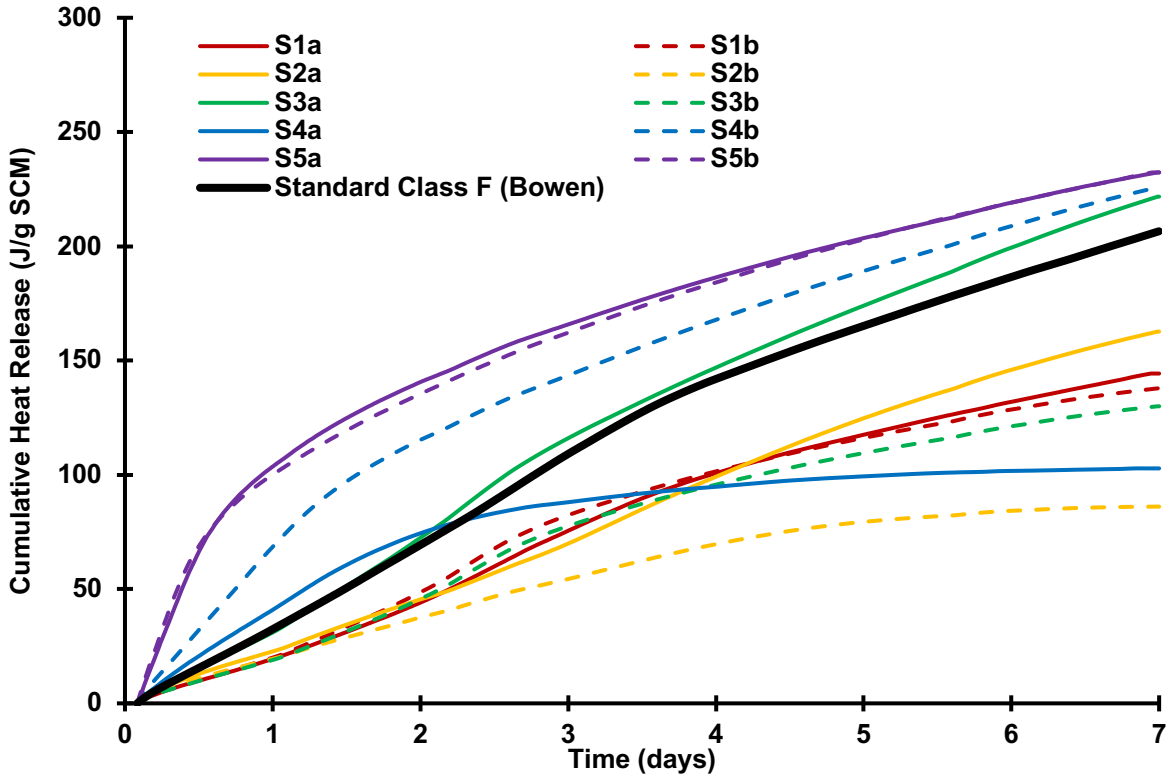

Figure 8 - R^3 calorimetric testing of fly ash pozzolanic reactivity.

Strength development and reactivity of the fly ashes was gauged through strength activity index (SAI) testing (Fig. 9), which compares the strength obtained by 20% fly ash, 80% OPC mortars to that of an OPC control at the same age. Of the samples tested, only one of the as-received (but dried) ashes, S3b, obtained >75% SAI

at 7 days. This is consistent with isothermal calorimetry results in Fig. 6, which indicated minimal additional early age reactivity was provided by the fly ash samples. After 28 days of curing, five additional samples (S1b, S2b, S3a, S4a, and S5a) had reached the threshold SAI limit, and several more surpassed the limit when accounting for sample variability. It is well known that effects of the fly ash's pozzolanic reaction (strength gain, reduced porosity, etc.) manifest slowly and may not be apparent until 28 – 90 days following production of samples. However, the positive growth in SAI from 7 to 28 days did evidence pozzolanic reactivity in the fly ash sources.

One aspect of SAI testing that must be noted, is that the test is conducted on mortars with similar *flow* to the OPC mortar. This means that mixtures using fly ashes with high water requirements will require more water to achieve similar workability levels. As w/c is well known to correlate inversely with strength, increased w/c in the fly ash samples will directly correlate with lower compressive strengths. Therefore, although an ash generated low strengths in the SAI test, the levels of strength generation are, to some degree, artifacts of the method. In concrete mixtures, where workability and flow can be changed through use of water reducing admixtures, rather than through increases in water content, strength generation may not be as depressed as shown in the SAI results.

Several methods of improving the strength development were investigated using the S4a and S4b samples: 1) sieving the sample through the #100 sieve to reduce particle size to within specification limits; 2) wet milling the sample (also used to reduce water requirement, discussed previously); and 3) blending the sample with a high-quality ash source. After 7 days, the success of attempts to decrease particle size through removal of larger particles was limited: S4a's SAI increased insignificantly (from 71.82% → 73.20%); while S4b's SAI increased from 57.30% to 67.07%, still significantly below the 75% minimum threshold of ASTM C618 (Fig. 10). However, by 28 days, the sieved samples' SAI far surpassed that of both the as-received companion samples, and the 75% minimum requirement of ASTM C618, with strengths equal to that of the control (100% SAI).

Wet milling of the sample resulted in even greater improvements in strength development than sieving. Shown in Fig. 11, at both 7 and 28 days of curing wet milled

samples generated SAI values of 87%, and 107% of the control, respectively, compared to 73% and 67% in sieved samples. This suggests that wet milling may increase overall reactivity through a mechanism separate from that of simple particle size reductions, leading to both earlier strength gains and greater percent reaction and strength gain, as was shown in previous studies [13,14]. However, additional testing should be done in order to confirm that this theory holds true with respect to reclaimed ash sources.

Blending of fly ash sources is an approach that is not yet widely accepted, but has been shown to improve overall sample properties by researchers [17] and has been utilized by ash suppliers seeking to improve lower quality ash sources. In this method, a high-quality fly ash (in this case, the ASTM C618-meeting class F fly ash discussed throughout this report) was blended, in the dry state, with either sample S4a or S4b, at a 25 or 50% replacement rate. For example, the mortar recipe for SAI cubes calls for 400g OPC, 100g fly ash. In the 75/25 cubes the 100g sample of fly ash consisted of 75g S4a and 25g C618 ash. Shown in Fig. 12, substitution of only a quarter of the original source with a high-quality ash resulted in significant increases in SAI, increasing the SAI of both samples nearly 20% at 7 days. Both ashes easily surpassed the 75% minimum by 28 days. Greater substitution (50%) of the high-quality ash lead to further, and earlier, gains in strength compared to the 25% substitution rate. Given the success of this approach, it is also possible that in lieu of blending with a high-quality virgin source, some of the higher performing *on-site* ash could be blended with less reactive ash to average overall properties throughout site materials, rather than through introduction of outside materials.

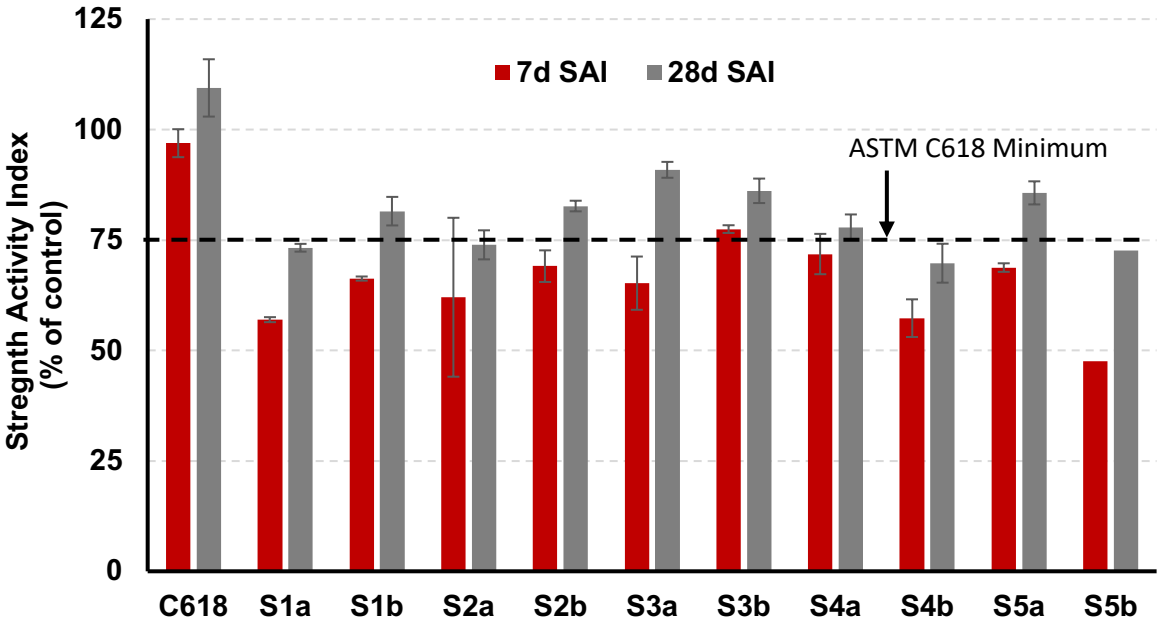

Figure 9 *- Strength activity indices of the fly ash mortars at 7 and 28 days.*

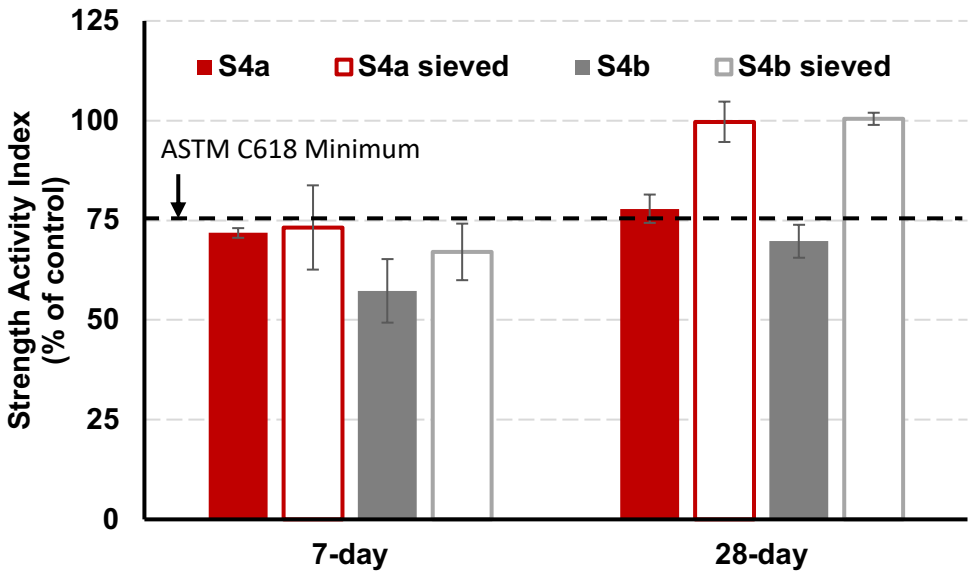

Figure 10 *- SAI of as-received and sieved S4a and S4b fly ashes.*

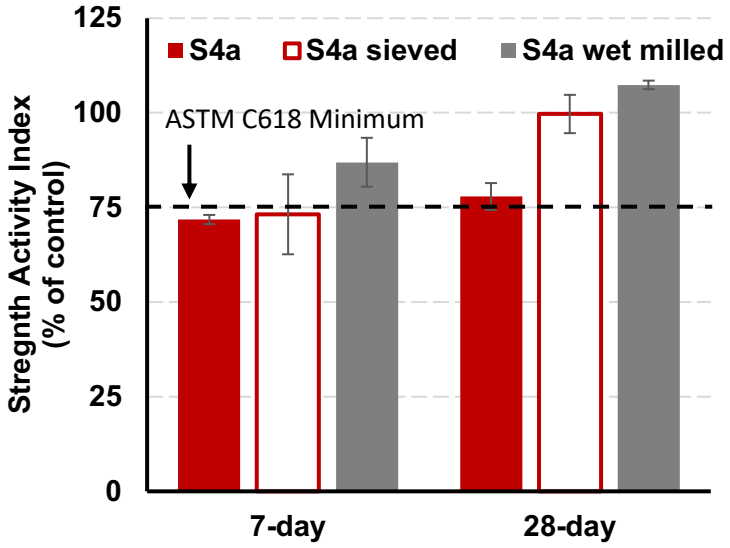

Figure 11 *- SAI of as-received, sieved, and wet-milled S4a fly ash.*

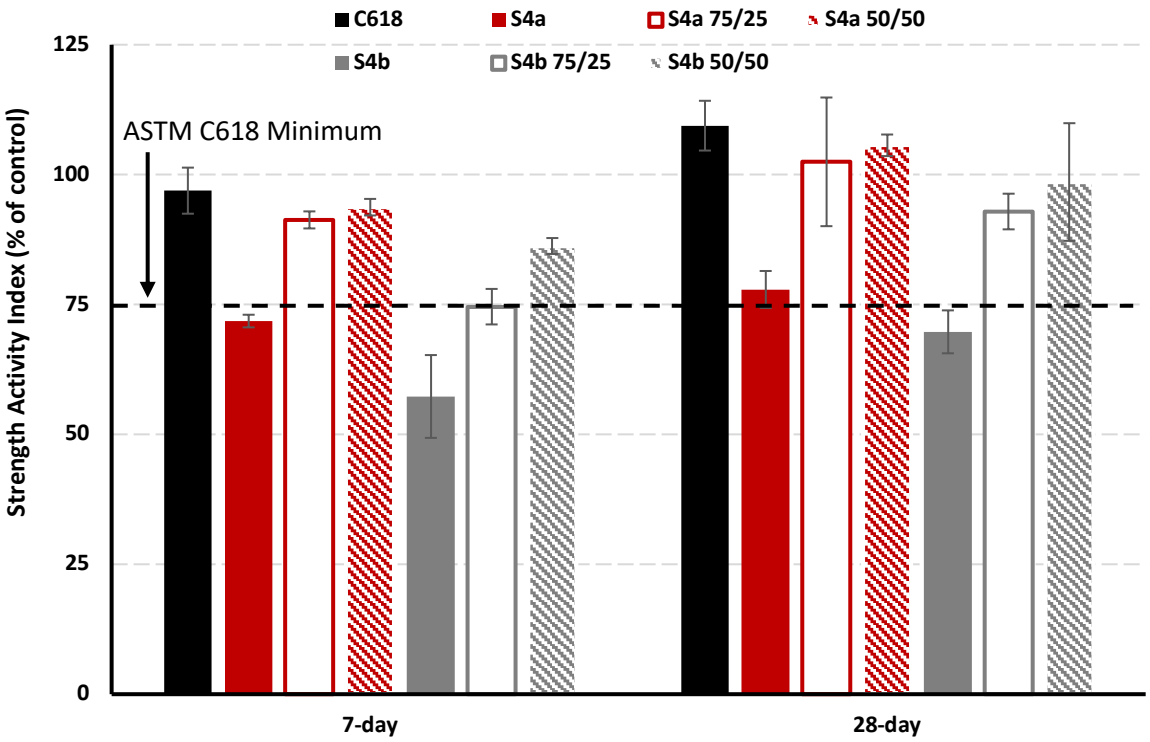

Figure 12 *- SAI of binary and ternary blends of fly ash-cement pastes.*

Uniformity, or variability within properties, is a significant concern of users interested in utilizing reclaimed ashes in concrete, due to the increasingly heterogenous nature of materials stored in landfill and pond sites. ASTM C618 uses density, along

with fineness, as a method of tracking uniformity of a sample source, and allows a maximum variation of 5% from the average value. Specific gravity of the ash samples is shown in Table 5, and ranged from 2.19 to 2.29. If we treat the ten ash samples obtained for this study as a single source, the total variation in density among the sample set is 2.40%, well within that allowable for the source by ASTM C618. In fact, ASTM C618 would permit density variations for this sample set to range from 2.11 – 2.34. It is likely that such a broad range of densities allows for variation in ash chemistry, mineralogy, and other factors which will translate to significant variability in property development of mixtures utilizing ash samples from different regions of the site, despite that the uniformity limits were met for density.

In contrast to what was observed with respect to density measurements, variation across the as-received sample finenesses significantly exceeded the 5% maximum limit, varying as much as 56% from the average fineness value. This is likely due to intermixing of multiple material types within the landfill (fly ash with shale, and/or bottom ash), or hydration of the materials that may have occurred over time. However, even following sieving through the #100 sieve, a process that brought fineness values into conformance with specification limits, and also significantly increased overall reactivity of the fly ash-cement mortars, uniformity values were still not met, with samples having as much as 24% variation from the mean. This suggests that meeting the uniformity requirements of ASTM C618 may be one of the more difficult hurdles to surpass, with sieving not sufficient to reduce variability between samples.

In traditional fly ash samples, changes in density and fineness typically indicated plant level changes in the coal or coal burning process. Fineness variation in reclaimed samples may result from a variety of causes, and may or may not lead to diminished performance of concrete in which they are used, therefore diminishing the ability of this parameter to identify meaningful changes in reclaimed ash properties. More work should be done to understand both the variability within fly ash landfills and ponds, as well as to discern the links between fly ash properties and concrete performance, to determine if gauging variability through density and fineness are appropriate indicators of changes in material performance.

Table 5 - Sample uniformity, based on density and fineness measurements for all ten site ash samples.

	Density (g/cm^3)	**Fineness** (%)	**Fineness of #100 Sieved Sample** (%)
S1a	2.27	35.9	22
S1b	2.29	35.8	25.3
S2a	2.20	34.5	24.7
S2b	2.28	37.5	25.6
S3a	2.20	23.8	19.5
S3b	2.20	29.3	22.6
S4a	2.24	44.0	27.8
S4b	2.19	50.5	31
S5a	2.26	60.9	31.3
S5b	2.23	38.1	26.6
Average	2.23	39.03	25.64
Max Variation from Mean (%)	2.40	56.03	23.95

Conclusions

Ten class F fly ashes obtained from a heterogenous fly ash landfill were characterized, and their performance evaluated through water requirement, adsorption, setting time, calorimetry, and strength development tests. The ASTM C618 chemical composition requirements were not problematic for the ashes, and all ashes were within limits on loss on ignition, despite showing indications of higher than typical adsorption through the foam index test. The as-received materials did not meet several of the ASTM C618 specification limits, including those for moisture content, water requirement, and fineness. Levels of variability in ash properties across the site were unclear, with samples meeting ASTM C618 uniformity requirements for density, but not for fineness (even following sieving to bring fineness levels within specification limits). About half of the fly ashes did not meet strength development minimum levels by 28 days, despite indications of reactivity shown through R^3 calorimetric test results. In attempts to improve ash properties, multiple simple beneficiation techniques were investigated including sieving, wet-milling, and blending of sources. All of these techniques were able to sufficiently increase strength development in strength activity

index samples to surpass the ASTM C618 minimum of 75% of the control mortar's strength. Wet milling was additionally shown to reduce high water demand, and increase reaction rates and strength development rates in fly ash-cement mortars. Overall, although initially many of the fly ash properties were less than ideal, with minimal beneficiation effort the materials were shown to be suitable for use in concrete.

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