Literature Review on the Use of Harvested Coal Ash as a Supplementary Cementitious Material with Recommendations for ASTM C618

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1.0 Introduction

1.1 Coal fired power generation in USA

Coal-fired power generation in the USA and in North America is diminishing. In some states, the amount of coal power production is diminishing rapidly and has already resulted in fly ash shortages and shortages are expected to become increasingly more severe. As a result, the availability of fly ash is also diminishing and this will result in a significant problem for concrete producers in terms of concrete durability and in reducing concrete's carbon footprint. Without other significant commercially available sources of supplementary cementitious materials (SCMs) in some parts of the USA, there is an urgent need to broaden the ASTM C618 specification to address the growing practice of using harvested fly ash stored in properly evaluated landfills or ponds. Landfilled fly ash is typically moistened with 10 to 15 % water and compacted in layers. When full, landfills are typically capped with soil or clay. Ponded fly ash is first slurried with water and then pumped into lagoons, which are later dewatered. In some cases, fly ash is stored separately as a monofill, but in many cases, bottom ash may be comingled with the fly ash in the coal ash landfill or lagoon.

In some cases, the landfilled ash was originally deemed non-suitable for uses as a SCM due to high LOI, but in most cases, the fly ash was of good quality, but there was insufficient market for it at the time of production. Also, with recent environmental regulations governing coal power plants requiring low NOx burners, SOx scrubbing, or mercury capture, fly ash in older landfills may be of better quality for use as a SCM than currently produced fly ash.

It should be noted that harvested fly ashes would almost always need to be processed before use to reduce moisture content and to ensure that the ash is of appropriate fineness.

This paper provides a review of the literature on the properties of harvested fly ashes as well as bottom ashes and co-mingled ashes when used as a ASTM C618 compliant SCM or in blended hydraulic cements in ASTM C595. Current requirements in standard specifications are also reviewed.

1.2 Coal Ash Properties and Utilization

The principal by-products produced from the burning of pulverized coal in a coal-fired electrical generation station are fly ash (FA), bottom ash (BA) and in some cases, flue-gas desulfurization

(FGD) material (see Figure 1). The use of fly ash as a pozzolanic material in concrete is well established and, also, widely practiced in the USA and worldwide. The use of bottom ash in concrete has, historically, been restricted to its use as a fine material (sand) predominantly in the manufacture of concrete masonry units. FGD material, which is principally gypsum, is not generally suitable for use in concrete although it is used in the manufacturing of portland cement where it is interground with cement clinker in place of natural calcium-sulfate minerals. FGD products will not be discussed further in this report as they can be avoided by proper site characterization as described in ASTM E3183 *Standard Guide for Harvesting Coal Combustion Products Stored in Active and Inactive Storage Areas for Beneficial Use*, and are not being considered as part of the harvested coal ash proposal. The 5.0% limit on SO₃ also provides protection from excess sulfate contents.

While fly ash monofills exist at some locations, in many landfills the fly ash is comingled with bottom ash from the same power plant. In some cases, FGD products are also landfilled together with bottom ash, so adequate site characterization (see ASTM E3183) need to be conducted to determine areas of landfills that are suitable for harvesting coal ash. The chemical composition of bottom ash is very close to that of the fly ash from a given boiler, but the particle size will be larger and there may be a difference in glass content. Given the larger particle size of bottom ash, in such cases, in addition to drying, the comingled ash would also have to be air classified and/or ground to the fineness of fly ash to meet ASTM C618 requirements.

Quality control procedures would need to be implemented when sourcing harvested fly ashes to prevent the inclusion of potentially deleterious materials such as coal rejects and flue gas desulfurization products.



Figure 1 Typical layout of a coal-fired generation station showing coal combustion byproducts (Sani et al. 2010)

2.0 Utilizing Harvested Coal Combustion Products

2.1 Processing Harvested Fly ash

Where power plants have created monofills consisting of exclusively fly ash, the main issues, after removal of any cover layer, would be to dry the ash as necessary to meet the maximum 3.0 % moisture limit in ASTM C618, to break up agglomerated particles and ensure that other limits are met, especially the +45 μ m (+Number 325 mesh) residue and the LOI limit.

McCarthy et al (2018) obtained three low calcium fly ashes from two drained lagoons and a stockpile and tested them for use in concrete after processing. The sources were described as follows: "LFA1 was from a lagoon where material had been deposited over the previous 30 years. LFA2 had been introduced to its lagoon about 3 years prior to sampling. SFA1 was kept in a stockpile at the site for 4 to 5 years. The lagoons had been drained at the time of recovery, enabling access for this to be carried out by hand auger. Samples were taken at a small distance from exposed fly ash surfaces. The typical moisture contents of LFA1 and 2 on receipt at the laboratory were 43.8 and 19.3 % respectively, while that of SFA1 was 27.5 %." The properties of these three ashes after drying at 110C were as shown in Table 1. Two of the raw ashes exceeded the ASTM C618 limit of 34 % retained on a 45 μ m (Number 325 mesh) sieve, while SFA1 was right at the limit. Microscopic examination of the ashes showed mostly spherical particles but with some agglomerated particles.

		Fly Ash Samples				
Property	PC	Lagoo	n Ash	Stockpile Ash		
	-	LFA1	LFA2	SFA1		
Fineness, 45µm sieve retention, %	364*	48.2	44.0	33.8		
LOI, %	1.4	6.4	10.3	15.1		
Particle Density, kg/m ³	3140	2120	1970	1980		
Particle Size Distribution,	μm					
d_{10}	-	6.2	4.6	2.6		
d ₅₀	-	46.1	40.6	21.9		
d ₉₀	-	133.6	139.0	95.7		
Bulk Oxide Composition, % by mass						
SiO ₂	21.5	48.3	46.9	49.8		
Al ₂ O ₃	5.4	27.2	28.7	23.9		
Fe ₂ O ₃	2.6	6.2	5.1	5.7		
CaO	64.2	2.9	1.8	2.4		
MgO	2.6	1.6	1.7	1.2		
TiO ₂	0.3	1.5	1.4	1.4		
K_2O	0.7	1.2	1.5	2.1		
Na ₂ O	0.3	1.4	0.8	0.5		
P_2O_5	0.1	0.6	0.4	0.8		
Cl	0.0	2.1	1.0	0.0		
SO_3	2.8	0.5	0.5	0.6		
Main Mineral Compositio	n, % by ma	ISS				
Quartz	-	10.8	4.6	3.8		
Mullite	-	16.6	18.0	8.0		
Non-crystalline+	-	65.3	66.8	72.7		

Table 1. Properties of Raw Harvest Fly Ashes (McCarthy et al 2018)

* Specific surface area, m^2/kg (Blaine method)

+ By difference

As shown in Table 2, after processing by either sieving, air classifying or grinding, the fineness, LOI and density of these ashes are shown in Table 2 (for different samples than shown in Table 1) The grinding was performed in a small laboratory ball mill. It is noted that SFA1 had LOI in excess of the ASTM C618 limit both before and after physical processing, therefore that source would need to undergo further processing to reduce LOI.

		Characteristics of Fly Ash			
	Samples	Fineness, 45 µm Sieve Retention, %	LOI, %	Particle Density, kg/m ³	
	Reference*	26.8	6.1	2120	
IEA1	63 µm sieved	12.0	3.2	2210	
LFAI	Air classified	6.1	5.8	2120	
	Ground	8.1	5.3	2310	
	Reference	33.4	9.7	2010	
1542	63 µm sieved	8.7	5.1	2130	
LFA2	Air classified	8.1	7.6	2020	
	Ground	6.3	10.8	2170	
	Reference	23.8	14.2	2060	
SEA 1	63 µm sieved	10.2	10.7	2160	
SFAI	Air classified	12.9	13.1	2100	
	Ground	0.6	14.1	2230	

 Table 2. Properties of Processed Ashes (McCarthy et al 2018)

* Recovered material screened at 600 µm

When used at 30% replacement of cement in concrete at w/cm = 0.53, it was found that slump increased as the $+45\mu$ m fraction reduced, as shown in Figure 2 (the "Reference" mentioned in Figures 2 to 4 refers to the unprocessed ash). Grinding the ashes had the most positive impact on increasing their reactivity as indicated by heat of hydration and strength development. The impact of fineness on 28-day strength is shown in Figures 3 and 4. Note that in these figures, 'Reference' refers to the unprocessed ashes.



Figure 2. Effect of ash fineness on concrete slump (McCarthy et al 2018)



Figure 3. Effect of +45 μm fraction of ash on 28-day cube strengths of concretes cast at w/cm = 0.53 (McCarthy et al 2018).



Figure 4. Relation between 28-day concrete strength and fraction of particles less than 10 um (McCarthy et al 2018).

Similar positive relationships were found for the % of -10 μ m particles and air permeability, chloride diffusion and rate of carbonation of these concretes.

Kaladharan et al (2019) examined harvested fly ashes from Pennsylvania, including processing and testing in concrete. They summarized the potential challenges with using harvested fly ash as:

1) high moisture content;

2) high unburned carbon (LOI) content;

3) presence of free lime (calcium oxide or calcium hydroxide), or excess alkalis or sulfur (for Class C ashes);

4) contamination of fly ash with salts, soil, and organic materials, or co-mingling with other coal combustion products (CCPs);

5) heterogeneity in fly ash properties within a landfill or pond; and

6) reduction in fly ash reactivity due to agglomeration and partial reaction as a result of long-term exposure to moisture.

While moisture contents can be controlled by drying and agglomerations can be removed in an air cyclone or by grinding, potential variability of ash within a landfill requires statistical sampling and evaluation to determine if the fly ash is of acceptable uniformity and quality for use in concrete. The authors discuss methods for the required statistical sampling.

To reduce high unburned carbon, Kalahdharan et al (2019) reviewed several of the techniques including thermal processing, electrostatic separation, and chemical passivation. It was found thatfly ash reactivity can be improved by grinding, thermal processing, and chemical activation.

Concretes were cast using 25 % of a monofill source of reclaimed fly ash in Pennsylvania. As shown in Table 3, there was no problem obtaining workability or air entrainment with the harvested fly ash mixture. Figure 5 indicates that the fly ash is starting to have an influence on strength beyond 28 days of age, as expected with Class F fly ash.

In addition, tests showed that 25 % harvested fly ash was effective in mitigating ASR expansion (see Figure 6).

	OPC mixture	Fly ash-blended mixture
Cement, kg/m ³	365	274
Water, kg/m ³	175	175
Coarse aggregate, kg/m ³	1020	1020
Fine aggregate, kg/m ³	676	654
Fly ash, kg/m ³	0	91
Air entraining admixture, mL/m ³	475	475
Slump, mm	165	171
Plastic air content, vol %	6.12	6.72
Hardened air content, vol %	5.98	6.65
Spacing factor, mm	0.126	0.142

Table 3. Concrete Mix Proportions and Properties with 25 % Harvested Fly ash(Kaladharan et al 2019)



Figure 5. Concrete Strength Development of Mixtures Shown in Table 3 (Kaladharan et al 2019)



Figure 6. Mitigation of ASTM C1567 ASR Expansion with 25 % Harvested Fly Ash (Kaladharan et al 2019)

To evaluate uniformity of fly ash extracted from this landfill, eleven samples of ash from one landfill were tested and the average and standard deviations of the chemical and physical properties are shown in Table 4. The authors (Kaladharan et al 2019) then determined the probability of the ash not meeting ASTM C618 requirements using a 5% probability as a criterion for concern. The only property of concern was meeting the 3 % moisture content limit. This could be solved by drying. They also suggested modifying the 45- μ m sieve test by using a 25g sample of harvested fly ash instead of the 1g sample normally used in ASTM C311. This allowed for determining of agglomerates.

Property	Mean	Standard deviation	Minimum-Maximum	ASTM limit for Class F	Probability of not meeting ASTM limit
Sum of SiO ₂ , Al ₂ O ₃ , and Fe ₂ O ₃	87.28%	0.0161	85.42% to 89.40%	> 70%	<0.001%
Sulfur trioxide	0.81%	0.0013	0.70% to 1.05%	< 5%	<0.001%
Moisture content	15.93%	0.0091	14.3% to 16.8%	< 3%	~100%
Loss on ignition	2.81%	0.0027	2.49% to 3.14%	< 6%	<0.001%
Carbon	2.1%	0.0029	1.80% to 2.41%	N.A.	NA
Fineness, % retained on No. 325 sieve	26.90%	0.0309	24.6% to 32.7%	< 34%	0.122%
Strength activity index 7-day	81.78%	0.0817	72% to 93%	> 75%	4.883%
Strength activity index 28-day	93.15%	0.0664	84% to 100%	>75%	0.056%
Water requirement	97.30%	0	97.3% to 97.3%	< 105%	NA
Soundness	-0.02%	0.0001	-0.03% to 0%	<±0.8%	<0.001%
Fineness uniformity, maximum % variation from average	2.49%	0.0161	0.4% to 5.2%	< 5%	0.610%
Density uniformity, maximum % variation from average	0.87%	0.0054	0.4% to 1.9%	< 5%	<0.001%

Table 4. Properties of Fly Ash sampled from a Landfill (Kaladharan et al 2019)

9

Note that mean values in Table 4 are expressed as percentages but standard deviations are expressed as decimals. Probability calculations are provided in the cited paper.

Diaz-Loya et al (2019) compared the properties of harvested low-calcium Class F fly ash from a site landfilled in the 1970s-1980s to currently produced (2016) fly as from the same power plant. After drying the harvested (landfill-recovered) fly ash to a similar moisture content, and air classifying, the ASTM C618 properties are shown in Table 5. It was noted that because this was a low-calcium fly ash, there was little agglomeration and the chemical composition had not changed during the period of landfill. It was also noted, as shown in Table 6, that the composition of the older harvested ash was better (in terms of higher silica and alumina content, lower alkali content, reduced LOI and higher fineness) than the ash currently being produced.

Table 5. Comparison of ASTM C618 properties for currently produced and harvested flyash from the same power plant (Diaz-Loya et al 2019)

STALCOTO Class E results for sub-stored and landini-recovered by ash.							
Class F fly ash criteria	Current production/Stored in silo (%)	Landfill-recovered fly ash (%)					
SiO ₂ +Al ₂ O ₃ +Fe ₂ O ₃ (%) [70% min] SO ₃ % [5.0% max] Moisture content (%) [3.0% max] LOI (%) [6.0% max] Fineness (%) [34% max] SAI, 7 day (%) [75% min] SAI, 28 day (%) [75% min] Water requirement (%) [115% max]	81.99 2.55 0.21 8.80 28.65 76 77 101	90.84 0.19 0.16 3.05 11.90 79 78 100					

Table 6. Comparison of chemical composition and fineness for currently produced and
harvested fly ash from the same power plant (Diaz-Loya et al 2019)

Constituent	Current production/Stored in silo (%)	Landfill-recovered fly ash (%)
SiO ₂	41.08	51.16
Al ₂ O ₃	21.12	28.06
Fe ₂ O ₃	19.79	11.62
SO ₃	2.55	0.19
CaO	9.38	2.21
Na ₂ O	1.08	0.21
MgO	0.94	0.90
K ₂ O	1.43	2.35
d ₅₀ (μm)	26.23	18.17
Specific Surface Area (m ² /g)	3.39	3.62

Oxide compositions (measured by combustion infrared detection technique), median particle sizes, and specific surface areas of silo-stored and landfillrecovered fly ashes.

McCarthy et al (1999) made concrete using fly ashes that had been stored in lagoons and in simulated lagoons. They noted that the amount of agglomerated ash increased with the storage period in the lagoon. The chemical properties did not change except for formation of a small amount of calcium sulfate due to leaching of calcium, alkalis and sulfate. The concrete strengths were slightly lower with increasing periods of lagoon storage. This was attributed to fewer -6µm particles, lost to the formation of agglomerates. This likely would not have happened if the ashes had been air cycloned or ground before use.

2.2 Summary on Processing Harvested Fly Ash

It will be up to the supplier of harvested fly ash to process the ash so that it meets all the requirements in ASTM C618 and that the ash meets uniformity requirements related to performance. At the very least, it appears that the harvested ash will most likely need to be dried and then de-agglomerated. Relative to freshly produced ash, the reactivity of an ash will not be impacted as long as the fineness of the processed ash is similar to that of freshly produced ash, at least for low-CaO ashes. While intuitively it might be expected that reactivity of high-CaO ashes could be reduced after prolonged periods of wet storage, we are not aware of data to determine if this is a real concern.

2.3 Coal Combustion Products: A Comparison of Bottom Ash and Fly Ash

In many landfills and lagoons, both fly ash (FA) and bottom ash (BA) are comingled and may require additional processing beyond simply drying and breaking up fly ash agglomerates. FA and BA are both forms of coal ash. Coal contains detrital minerals, predominantly aluminosilicates (from clays and shales), silicates (quartz) and lesser amounts carbonates (from limestone) and sulfides that were deposited contemporaneously with the organic material that formed the coal. During the burning of pulverized coal in the furnace (or boiler) temperatures reach 1500°C and most of the carbonaceous matter is combusted and escapes as CO₂ (or CO). The inorganic minerals melt and either escape as fine liquid droplets with the flue gases or form larger agglomerations and fall by gravity into a hopper at the bottom of the furnace. The fine material is removed from the flue gases by a particulate separator (baghouse or electrostatic precipitator) by which time it has quenched and formed spherical particles composed of both amorphous glass and crystalline

compounds; the collected material is termed fly ash (FA). The heavier coarser particles that fall by gravity are collected in a hopper at the bottom of the boiler and are termed bottom ash (BA). Approximately one fifth of the ash falls to the bottom of the furnace (Helmuth, 1987) although this will vary depending on the nature of the pulverized coal, the air flow, the boiler configuration, and the burning conditions.

Since FA and BA are formed from the same inorganic minerals that were associated with the coal, the chemical composition of the ashes produced in the same furnace from the same coal is very similar. However, the physical properties can be quite different in terms of particle size and shape (Table 7). The average diameter of FA particles is typically two or three orders of magnitude smaller than BA resulting in a much larger specific surface area. FA is dominated by spherical particles that form from molten droplets whereas BA consists of agglomerated angular particles (Figure 7). The specific gravity of FA is lower than that of BA because of the presence of hollow spheres (cenospheres) that form together with solid spheres in the flue gases. Furthermore, the materials (FA and BA) may differ somewhat in mineralogy mainly because the larger BA particles will cool more slowly allowing more crystalline phases to form compared to FA.

Table 7. Physical characteristics of fly ash and bottom ash from coal combustion (from
Tishmack and Burns, 2004)	

Property	Fly ash	Bottom ash
Particle size range (mm)	$10^{-4} - 10^{-1}$	$10^{-1} - 10^{1}$
Mean particle diameter (µm)	20-80	500-700
Saturated hydraulic conductivity (cm/s)	$10^{-6} - 10^{-4}$	$10^{-3} - 10^{-1}$
Specific gravity	1.59-3.1	2.17 - 2.78
Dry bulk density (g/cm ³)	1.0-1.6	0.74-1.6
Surface area (m^2/g)	0.2 - 3.06	0.4

Sources: Summers et al. (1983); Valkovic (1983); Hostetler et al. (1989).



Width of view approx. 60 μm

Width of view approx. 26 µm

Figure 7. SEM images of (a) coal bottom ash and (b) coal fly ash (from Argiz et al. 2017)

Fly ash has been used as a supplementary cementing material for concrete since the pioneering work of Davis et al (1937) demonstrated that it was an efficient pozzolan owing to its high content of aluminosilicate glass and fine particle size. The first major use was in the construction of the Hungry Horse Dam in Montana (constructed between 1948 to 1953) where it was used to replace up to 32 % of the portland cement and, since that time, fly ash has displaced natural pozzolans, which were widely used in concrete during the first half of the last century, as the predominant pozzolan used in concrete construction in most countries worldwide. However, as discussed in this report, the forecast reductions in coal-fired electricity and therefore fly ash production have led to renewed interest in both natural pozzolans and in harvesting fly ash from storage ponds and landfills.

Raw bottom ash, because of its coarse particle size (0.1 to 10 mm) compared to fly ash (0.0001 to 0.1 mm), is not an effective pozzolan despite its similar chemical composition and the presence of aluminosilicate glass. Consequently, its uses have been restricted to a replacement for sand in masonry products.

Coal ashes (FA and BA) are frequently disposed together in the same landfill; that is, the two materials are comingled. Harvesting FA from landfills for use as a pozzolan in concrete has, generally, required use of fly ash monofills or the separation of FA and BA based on particle size, for example by air classification. However, as discussed in detail below, research over the past two to three decades has shown that the pozzolanic reactivity (pozzolanicity) of bottom ash can be greatly enhanced by grinding the material to a finer particle size, thereby increasing the surface area available for pozzolanic reaction with lime. The commercial viability of this process was first exploited by Hopkins and Oates (1997) who filed a patent for cements produced with ground bottom ash as a pozzolan. Grinding comingled FA and BA to reduce, predominantly, the particle size of the BA negates then need for separation of the two materials and allows all of the landfilled coal ash to be reclaimed for use a pozzolan.

Also, in some cases, the harvested coal ash will need to be dried to meet the maximum 3.0 % moisture content allowed in ASTM C618.

Data from a range of published and ongoing (unpublished) studies on the use of ground bottom ash as a cementing material are presented below. In many of these studies, the performance of the ground bottom ash in mortar or concrete is compared directly with that of fly ash produced from the same coal burned in the same furnace.

2.4 Published Studies on Ground Bottom Ash

2.4.1 Effect of Grinding on the Pozzolanic Reactivity of Bottom Ash

Cheriaf et al (1999) were the first to report on the pozzolanicity of bottom ash and the influence of grinding. They tested a relatively fine BA (average particle diameter of 35 μ m) in pastes produced from 50:50 lime:pozz and 0.42 water/binder to determine both lime consumption and strength with age. A summary of these results is shown in Table 8. At early age (up to 7 days) there was little chemical reaction but the pozzolanic reaction accelerated with age and was particularly evident between 28 to 90 days. The strength activity was tested according to EN 450 using mortar bars produced with 75 % reference cement and 25 % bottom ash and exceeded the required indices of 0.75 and 0.85 at 28 and 90 days, respectively.

Table 8. Pozzolanic activity of bottom ash with lime and strength activity of bottom ash with cement (Cheriaf et al. 1999)

	Age (days)				
	7	14	28	90	
Pozzolanic Activity of bottom ash with lime					
Compressive strength (MPa)	1.8	3.2	6.4	17.3	
Calcium hydroxide consumption (%)	5	15	37	60	
Strength activity in mortar (according to EN 450)					
Strength (% control)	72 76 88 97				

To study the impact of fineness, the bottom ash was ground in a ball mill from 1 to 6 hours. At hourly intervals the physical properties of the ash were determined and the pozzolanic activity was determined according to Brazilian Standard NBR-5752 (28-day strength of mortars with 65 % cement and 35 % ash cured for 26 days at 38°C). Results are shown in Table 9. The increase in specific gravity with grinding is attributed to the breakdown of porous particles. After 6 hours grinding, the 28-day compressive strength of the mortar produced with 35 % BA was 108 % of the control mortar produced with 100 % portland cement (note mortars were cured at 38°C for 26 of 28 days).

	Time of grinding (h)						
	0	1	2	3	4	6	
Physical properties of ground bottom ash							
Specific gravity	2.00	2.02	2.11	2.14	2.21	2.25	
Mean particle size (µm)	35	33	25	20	16	13	
Particles < 1µm (%)	2	2	5	8	12	15	
Strength activity (according to NBR-5752)							
Water/binder	0.62	0.60	0.58	0.58	0.57	0.57	
Activity (% control)	81	81	92	93	95	108	

Table 9. Physical properties and strength activity of ground bottom ash (Cheriaf et al.1999)

Arun et al (2020) determined the pozzolanic activity of ground bottom ash using a lime-reactivity test (Indian Standard IS-1727-1967) which is based on the 8-day strength of mortar cubes produced with 1:2 lime:pozzolan blends and cured for 7 days at 50°C. This test is similar to the pozzolanic activity with lime test ASTM C311-87 (now withdrawn) and in CSA A3004-E1, Annex A. The unprocessed ash (BA0) was ground for 1 h (BA1), 2 h (BA2) and 4 h (BA4) in the Los Angeles abrasion apparatus and the performance compared with fly ash (FA) from the same source. Figure 8 shows results from particle-size analysis and the lime-reactivity test. The particle size distribution for the unprocessed ash (BA0) was only slightly finer than the sand and the 8-day strength was just 0.74 MPa. The strength value indicated some limited pozzolanic reaction as inert materials do not set in this test and cannot be tested (i.e. strength = zero, 0 MPa). After 4 hours grinding, the particle size distribution of the BA4 ($D_{50} = 11 \mu m$) was similar to FA ($D_{50} = 12 \mu m$) and the 8-day strengths are very close.



Figure 8. Particle size distribution (left) and lime-reactivity results (right) for ground bottom ash and fly ash (Arun et al. 2020).

2.4.2 Strength and Durability of Mortars and Concrete Produced with Ground Bottom Ash

Argiz and coworkers (Argiz et al. 2017) compared the strength development of mortars produced with ground bottom ash (GBA), fly ash (FA) and various combinations of GBA and FA (presumably to represent comingled BA and FA). In this study the GBA (CaO = 2.4 %, LOI =3.8 %, Sum of oxides = 86.5 %) was ground in a ball mill to produce a Blaine fineness ($346 \text{ m}^2/\text{kg}$) that was similar to both the portland cement ($405 \text{ m}^2/\text{kg}$) and the FA ($398 \text{ m}^2/\text{kg}$). The bottom ash and the fly ash had almost identical chemical properties as shown in Figure 9.



Figure 9. Comparisons of compositions of fly ash and bottom ash from the same source. (R.I. = insoluble residue) (Argiz et al 2018)

They utilized cement replacement rates of 10 %, 25 % and 35 % to represent European EN 197 cement types CEM II/A-V, CEM II/B-V and CEM IV/A (V), respectively. Only the data for mortars produced with the highest cement replacement level (35%) are presented here as comparisons between different pozzolans become more evident at higher replacement levels. The CEM IV/A (V) mortars were produced with 65 % portland cement and five combinations of FA:GBA, these being 35:0 (β), 31.5:3.5 (γ), 28:7 (δ), 17.5:17.5 (λ) and 0:35 (Ω). The Greek letters shown in parentheses are the symbols used by the authors to differentiate between the various FA:GBA blends; α was used to denote the CEM I control which was produced with 100 % portland cement. Figure 10 shows the strength development curves for the five FA:GBA blends compared to the CEM I control. As expected, the early-age strength of the mortars with 35 % coal ash was significantly lower but there was considerable strength gain of these mixtures between 28 and 90 days such that 90-day strengths were between 82 % and 93 % of the control CEM I (portland cement) mix. As concluded by the authors, "it can be said that the differences between coal fly ash and coal bottom ash are not significant."



Figure 10. Compressive strength development of mortars produced with 35 % coal ash with various blends of FA and GBA (Argiz et al. 2017)

In a follow-up study (Argiz et al. 2018), the impact of ground bottom ash on the chloride resistance of concrete was evaluated using chloride migration (NT Build 492), chloride diffusion (NT Build 492 – similar to ASTM C1556) and bulk electrical resistivity (using Giatec RCON device). Coal fly ash (FA) and bottom ash (BA) from the same power plant in Spain were used to replace either 10 % or 25 % of a sulfate-resistant portland cement. The ground bottom ash (GBA) was produced in a laboratory ball mill to achieve a 45- μ m sieve retention value of 3%. It is noteworthy that the FA used in this study was unusually coarse and had a reported median particle size of 104 μ m compared to 10 μ m for the GBA.

The results from the tests are summarized in Figure 11. It is apparent that both the FA and the GBA had a very profound effect on improving chloride resistance, especially at a replacement level of 25 %. The electrical resistivity results show the impact of age and the importance of testing mature concrete if the full benefits of pozzolans are to be realized. At an age of 132 days the concrete with 25 % GBA had an electrical resistivity more than 6 times higher than that of the control mix. Electrical resistivity is a good measure of cement reaction, whether hydraulic or pozzolanic, and is able to discriminate between reactivity and filler effects. As will be shown later in the report, finely ground inert fillers will invariably decrease the resistivity of concrete whereas pozzolans universally increase the resistivity of mature concrete.



Figure 11. Results from testing for chloride migration at 132 days (top left), bulk chloride diffusion after 400 days immersion (top right) and electrical resistivity at ages from 7 to 132 days (bottom) - (Argiz et al. 2018)

Figure 11 also indicates that the GBA significantly outperformed FA in terms of both chloride resistance and electrical resistivity. However, this can be largely attributed to the considerable differences in the fineness of these materials. The chemical composition of the FA and GBA are very similar and this includes the amount of "SiO₂ reactive" which is reported to be 45.2 % for FA and 42.7 % for GBA (Argiz et al. 2018). SiO₂ reactive is the arithmetic difference between the total SiO₂ by XRF and the SiO₂ found in the insoluble residue of the ash.

Miligre-Martins et al (2010) compared the performance of concrete containing FA and GBA (physical properties in Table 10) both at cement replacement levels of 25 % and 33 %. To compensate for the increased water demand of concrete with GBA versus FA, which was due to the differences in the particle shape, two series of GBA mixtures were cast, one with the same water content (and w/cm) as the FA mixes but increased doses of water-reducing admixture, and the second with the same admixture content but an increased water content (and w/cm) to maintain slump. The concrete properties measured included compressive strength, accelerated carbonation, chloride diffusion (NT Build 492), permeability to oxygen, capillary absorption, and porosity. The authors concluded that, provided the w/cm is maintained, the performance of GBA concrete is similar to FA concrete both in terms of strength and durability. Only the chloride diffusion results are shown here (Figure 12) as the very significant reduction in the diffusion coefficient between 35 days and 365 days (365-d values are 15 to 18 % of 35-d values) is typical of concrete containing reactive pozzolans.

Procedure	BA	FA
Residue on 45 μ m sieve (%)	4.0	17.3
Blaine specific surface (cm ² /g)	3480	3500

Table 10. Fineness of fly ash (FA) ground bottom ash (BA)(Miligre-Martins et al. 2010)



Figure 12. Chloride diffusion coefficients for concrete with FA and GBA; note (w/b) indicates mixes cast at the same w/cm. wra indicates mixes cast with the same admixture content and varying w/cm to maintain slump (Miligre-Martins et al. 2010)

Oruji et al (2019) studied the impact of the fineness of GBA on the strength of mortar using a FA and GBA ground to two different levels in a high-energy vibratory ball mill; Table 11 shows the physical properties of the cementing materials: portland cement (PC), fly ash (FA) and processed

(ground) bottom ashes (PBA(I) and PBA(II)). Table 12 shows the strength of mortar cubes at 3 different ages (7, 28 and 90 days) and 4 levels of replacement 9, 23, 33 and 41 %). The strength activity (% control strength) was a function of the age, the replacement level and the fineness of the coal ash. The strength activities for mortars produced with PBA(I) were higher than those of comparison mortars produced with FA. The finer PBA(II) produced even higher strength and by 91-days the strength activity was above 100 % for all levels of replacement even 41 %.

Property	PC	FA	PBA(I)	PBA(II)
Blaine fineness (m ² /kg)	388.3	379.6	858.6	1101.9
Mean particle size, D ₅₀ (µm)	11.8	14.7	6.3	4.5

Table 11. Fineness of cementing materials (Oruji et al. 2017)

Table 12. Strength Activity of FA and PBA blends at 7, 28 and 90 day (Oruji et al. 2017)

Mix ID	Cement Replacement	Cement Replacement Strength activity (%)								
	(% Binder)	7-day	28-day	90-day						
FA-1	9.1	80.4 ± 5.3	94.5 ± 5.7	108.0 ± 2.7						
FA-2	23.1	69.0 ± 1.4	82.9 ± 5.3	101.1 ± 5.8						
FA-3	33.3	56.1 ± 0.9	70.7 ± 3.4	91.5 ± 3.5						
FA-4	41.2	44.9 ± 3.8	61.9 ± 3.7	81.0 ± 5.3						
PBA(I)	9.1	93.4 ± 0.9	104.3 ± 3.3	113.4 ± 7.6						
PBA(I)	23.1	77.1 ± 3.9	92.5 ± 4.9	105.6 ± 2.0						
PBA(I)	33.3	65.7 ± 4.1	85.7 ± 2.3	98.3 ± 0.8						
PBA(I)	41.2	57.3 ± 3.3	76.2 ± 2.0	88.4 ± 2.1						
PBA(II)	9.1	96.6 ± 4.2	110.7 ± 1.7	120.9 ± 3.4						
PBA(II)	23.1	92.3 ± 2.6	108.5 ± 1.9	119.6 ± 1.5						
PBA(II)	33.3	83.8 ± 5.6	104.8 ± 2.1	115.5 ± 4.0						
PBA(II)	41.2	79.6 ± 4.1	96.0 ± 4.1	110.3 ± 1.0						

Oruji et al (2019) conducted tests to determine the efficacy of these same materials (Table 11) in controlling expansion due to alkali-silica reaction (ASR). The materials were tested using the accelerated mortar bar test (ASTM C1260/C1567) using highly-reactive Jobe sand from El Paso, TX. The expansion of mortar bars stored in 1 M NaOH at 80°C for up to 28 days is shown in Figure 13. Both FA and GBA were effective in controlling expansion of the mortar bars but slightly higher expansion (approximately 10 %) was observed for mortars with GBA. The authors (Oruji et al. 2019) conjectured that this was a result of lower amounts of reactive silica and alumina in the GBA compared to FA but these quantities were not actually reported. Figure 14 shows the 14-

day expansion of the mortars as a function of the replacement level of the different coal ashes. Also shown is the commonly-used expansion limit of 0.10 % at 14 days. This graph indicates that ground bottom ash would have to be used at an increased level of replacement compared to fly ash to reduce expansion to an acceptable level.



Figure 13. ASR Expansion of mortar bars with reactive Jobe sand and varying amounts of fly ash (FA) or ground bottom ash (PBA(I) or PBA(II)) - Oruji et al (2019)



Figure 14. ASR Expansion of mortar bars at 14 days as a function of the level of coal ash (plotted from the data in Figure 13 reported by Oruji et al. 2019)

Jaturapitakkul and Cheerarot (2003) studied the impact of GBA on the strength of mortars and concretes. The properties of the cementing materials are shown in Table 13. Results from mortar tests conducted on both the original bottom ash (OB) and the ground bottom ash (GB) at replacement levels of 10, 20 and 30 % are shown in Figure 9 in terms of strength activity (strength as a % of control). The very coarse original bottom ash mortar (OBM) reduced the strength compared to the control above and beyond the level of replacement and it is assumed that the large strength reduction (e.g. 30 % OBM reduced the strength by slightly more than 60 % at 90 days) is attributed not just to the lack of reactivity of the coarse material but also to a significant increase in water demand of the mortar, leading to increased w/cm. The ground bottom ash mortar (GBM) showed strength activities below 100 % at 7 and 28 days but by 60 and 90 days the strength of the mortar with 10 to 30 % was greater than the control mortar.

Table 13. Physical Properties of Portland Cement, Original, and Ground Bottom Ashes(Jaturapitakkul and Cheerarot, 2003)

Sample	Specific gravity	Retained on Sieve 325 (%)	Blaine fineness (cm²/g)	Mean particle size (micron)
Portland cement type I	3.14	4.8	3,270	13
Original bottom ash	2.13	94.5		290
Ground bottom ash	2.70	2.8	6,355	7



Figure 9. Results of mortar strength activity tests (Jaturapitakkul and Cheerarot, 2003)

In the same study (Jaturapitakkul and Cheerarot, 2003), concrete mixes were produced with and without the ground bottom ash (at 20 % replacement) at three different strength grades (25, 35 and 45 MPa (3,625, 5075, and 6525 psi)). Table 14 shows the strength of the concrete from 3 days to 90 days. At 3 and 7 days the strength of concrete with 20 % ground bottom ash (GBC) was less than the control concrete of the same strength grade. However, the differences between mixes with and without ground bottom ash diminished with age and by 90 days concrete with 20 % ground bottom ash was stronger than the equivalent control concrete.

Table 14. Compressive Strength and Percentage Compressive Strength of Concrete
(Jaturapitakkul and Cheerarot, 2003)

		Compressive Strength (MPa)—(Percentage Compressive Strength)											
Type of concrete	3 day	7 day	14 day	28 day	60 day	90 day							
CC25	12.3-(100)	17.3-(100)	21.0-(100)	25.5-(100)	26.7-(100)	27.0-(100)							
GBC25	9.8-(80)	15.5-(90)	19.2—(91)	23.6-(93)	26.7-(100)	27.8-(103)							
CC35	19.7-(100)	28.4-(100)	33.0-(100)	36.6-(100)	38.1-(100)	38.9-(100)							
GBC35	16.4-(83)	24.4-(86)	31.5-(95)	37.1-(101)	40.1-(104)	40.8-(105)							
CC45	26.2-(100)	34.3-(100)	40.4-(100)	45.8-(100)	46.7-(100)	46.9-(100)							
GBC45	22.6—(<i>86</i>)	31.1—(91)	40.5-(100)	46.2—(101)	49.4—(106)	50.1-(107)							

Note: CC= cement concrete; GBC= ground bottom ash concrete; Design strength (in MPa) of cement concrete at 28 day=25, 35, and 45 Note: 1.0 MPa = 145 psi.

Abdulmatin et al (2018) produced mortars with and without 20 % bottom ash (CaO = 18.7 %, Sum of oxides = 70.1 %, and LOI = 3.6 %) in accordance with ASTM C311 (water content adjusted to produce constant flow). The bottom ash was tested after sieving on a 5-mm sieve (OBA) or after grinding for various periods of time. The grinding time was varied to achieve samples such that the mass retained on a 45-µm sieve was 5 ± 2 , 15 ± 2 , 25 ± 2 , 35 ± 2 , 45 ± 2 %; these samples were designated as 5BA, 15BA, 25BA, 35BA and 45BA, respectively. The physical properties of bottom ash samples tested are shown in Table 15. The 28-day strength activity index (SAI) is plotted against the 45-µm sieve retention value for the ground bottom ashes in Figure 10. The ground bottom ash samples with ≤ 24 % material retained on a 45-µm sieve met the ASTM C618 requirement of SAI \geq 75 %; the sample with just 3.7 % retained produced a compressive strength higher than the control at 28 days (SAI = 102%). However, the ground bottom ash samples with \geq

34 % sieve retention did not. Note that the unground sample (OBA) achieve a SAI of just 49 % at days.

Materials	Retained on a No. 325 Sieve (% by weight)	Specific Gravity	Median Particle Size, d ₅₀ (µm)				
OPC	16.8	3.14	14.7				
5BA	3.7	2.88	4.3				
15BA	14.5	2.85	15.4				
25BA	24.0	2.83	24.2				
35BA	35.3	2.76	39.8				
45BA	43.7	2.72	72.3				
OBA	96.3	2.33	400				

 Table 15. Physical properties of bottom ashes (Abdulmatin et al. 2018)

Also shown on Figure 10 are SAI data for fly ashes from various published studies. The data suggest that for a given 45- μ m sieve retention value, fly ash can be expected to provide a slightly greater 28-day SAI. Much of the difference probably results from differences in the water content (w/cm) of the mortars. The ground bottom ashes tested by Abdulmatin et al (2018) all showed increased water demand (101 to 108 %) compared to the control with the exception of the finest sample (5BA) which had the same water demand (100 %). Although the data were not provided by Abdulmatin et al (2018) it is expected that fly ash would typically reduce the water demand and, thus, be tested at a lower w/cm.



Figure 10. Strength activity index (at 28 days) plotted as a function of the 45-µm sieve retention for fly ashes and bottom ashes (Abdulmatin et al. 2018)

They concluded that to use BA as a pozzolanic material, the chemical properties should follow ASTM C618 for fly ash Class F or Class C and the BA must be ground until the particles retained on a 45 μ m sieve is no more than 25 % to show good performance (87 % strength activity at 28 days). In a related study (Jaturapitakkul et al 2003), bottom ash from the same plant was ground to 5 % retained on a 45 μ m sieve and used to make concretes with 20 % bottom ash pozzolan and with w/cm = 0.75, 0.56, and 0.45 and cementitious contents ranging from 260 to 440 kg/m³ (438 to 742 pcy). Equal strengths with the portland cement control mixtures were obtained at 60, 28 and 14 days of age, respectively.

There are other published studies available on ground bottom ash that have not been included in this review because either samples were not ground sufficiently or only early-age data were available making interpretation of the data difficult with regards to the reactivity of the bottom ash.

A wide range of pozzolans were tested at the University of New Brunswick as part of a study aimed at making improvements to the strength-activity-with-lime test. Some of the details and early results have been published (Kasaniya, 2019; Kasaniya et al. 2019; 2021a; 2021b) and these data together with more recent unpublished data are summarized here.

A wide range of cementing materials including one portland cement (PC) and seventeen pozzolans (five pumices (PM-A through PM-E), one low-alkali ground glass (G-E), two high-alkali ground glasses (G-F and G-G), one high-CaO fly ash (FA-C), one low-CaO fly ash (FA-D), one ground bottom ash (GBA), one metakaolin (MK-E), one silica fume (SF-B), one perlite (PR), one lassenite (LSN) and one blend of fly ash/lassenite/limestone 60/20/20 (FAB)), and two inert fillers (ground quartz (GQ) and limestone (LMS-B)) were investigated in this study. In addition, an unprocessed bottom ash sample (BA) from the same source as the ground bottom ash (GBA) was used. The amounts retained on the 45-µm sieve were 13.9 % and 96.6 % for, respectively, the ground bottom ash (GBA) and unprocessed bottom ash sample.

Figure 11 shows the 7-day strength results for mortars produced with lime-pozzolan mixtures and stored at 40°C; details of the test can be found in Kasaniya et al (2019). Results are shown for 16 different pozzolans, the two inert materials (LMS-B and GQ) and the raw (coarse) bottom ash (BA). The error bars shown represent twice the standard deviation of the compressive strengths of three specimens. The inert materials, ground limestone (LMS-B) and ground quartz (GQ), recorded a strength of 0 (zero) MPa as the cubes were still soft and friable at 7 days. The raw bottom ash, which is composed largely of sand-sized particles, did gain sufficient strength to be tested but the strength at 7 days was very low (< 0.5 MPa). The 16 remaining materials, which are all considered to be pozzolans, showed a wide range in strength values from about 3 to 23 MPa.

Reactivity Class	7-day Strength (MPa)	Materials
	in lime-pozzolan test	
Low reactivity	3 - 5	PR, PM-C
Moderate reactivity	5 - 10	G-E, G-F, G-G, FA-C, FA-D, FAB, PM-A,
		PM-D, PM-E
High reactivity	10 - 20	GBA, PM-B, LSN
Very high reactivity	> 20	MK-E, SF

For the sake of discussion in this report, the reactivity of the materials will be categorized as follows:



Figure 11. Results of Lime-Pozzolan Strength Tests (Kasaniya et al. 2021a)

Ground glasses, both low-alkali and high-alkali, perform in a similar manner to fly ash, being of moderate reactivity. The five pumices tested show a wide range in performance from low to high reactivity. The ground bottom ash (GBA) showed excellent performance in this test, the level of reactivity being significantly higher than the two commercially available fly ashes (FA-C and FA-D) tested. Comparison of the data for the unprocessed sand-sized bottom ash (BA) and the ground bottom ash (GBA) show the impact of particle size on the pozzolanic reactivity of bottom ash.

Figure 12 shows the results of bound water tests conducted on lime-pozzolan pastes. The bound water was determined as the mass loss exhibited when a sample pre-dried at 40°C was heated to 350°C. The test is similar to one of the two "R3 protocols" developed by RILEM for testing pozzolans; both of these R3 methods are now standardized in ASTM C1897. There is generally broad agreement between the 7-day strengths (Figure 11) and bound-water data; the more reactive

pozzolans producing larger amounts of bound water in 7-day-old lime-pozzolan pastes and higher 7-day compressive strengths in lime-pozzolan mortars. The ground bottom ash again shows improved performance over the two commercially available fly ashes and many of the other natural pozzolans.



Figure 12. Results of Bound-Water Tests (from Kasaniya et al. 2019)

These same materials were used to produce concrete mixtures with a total cementing materials content (PC+ pozzolan/inert material) content of 400 kg/m³ and a 0.45 water-to-cementitious materials (w/cm) ratio. Most pozzolans and the inert materials were used at a replacement level of 25 %, the exceptions being silica fume (SF-E) and lassenite (LSN) which were used at 8 and 20 %, respectively. Metakaolin was used at both a 15 % and a 25 % replacement level. Concrete testing included compressive strength, "rapid chloride permeability" (RCPT, ASTM C1202), chloride migration (Nordtest NT Build 492), bulk electrical resistivity (ASTM C1876), surface electrical resistivity and bulk electrical conductivity (ASTM C1760). There were strong correlations between the electrical resistivity and conductivity tests, the chloride permeability test (essentially an electrically conductivity test) and the chloride migration tests, and these results are discussed in detail in a forthcoming paper (submitted for publication). Only the strength and chloride permeability data are presented in this report.

The results of strength and RCPT testing are shown, respectively, in Figures 13 and 14. Generally, the pozzolans that gave the best performance in lime-pozzolan strength (Figure 11) and bound water (Figure 12) tests also provided the largest improvements in concrete. The concrete containing 25 % ground bottom ash (GBA) showed increased 91-day strength and a significantly reduced 91-day Coulomb value relative to the control concrete and, performed better than the concretes that were produced with the same amount (25 %) of Class F or Class C fly ash.



Figure 13. Results of Strength Testing (Kasaniya et al. 2021a)



Figure 14. Results of Chloride Permeability Testing (from Kasaniya et al. 2021a)

The same pozzolans and inert materials were also tested in mortars to determine their efficacy in controlling (i) alkali-silica reaction (ASR) using ASTM C441 (Pyrex mortar bar test) and (ii) sulfate attack using ASTM C1012. Only the data for the coal ashes, that is ground bottom ash (GBA) and two fly ashes (FA-C and FA-D), are included in this report. The results are shown in Figure 15. The ground bottom ash (GBA) is effective in suppressing expansion in both tests. In the sulfate resistance test the performance of the GBA and Class F fly ash (FA-D) are very similar, whereas GBA affects a bigger reduction in expansion in the Pyrex mortar bar test. The high-CaO Class C fly ash performs poorly in both tests.



Figure 15. Results of ASR tests (left) and sulfate-resistance tests (right) (from Kasaniya et al. 2021b)

In summary, the testing at UNB indicates that ground bottom ash tested is a highly reactive pozzolan and produces the performance expected of good quality Class F fly ash in terms of improved resistance to chlorides, ASR and sulfate attack.

2.5.2 Studies by Boral

The data reported in this section was provided to the authors of this report by Ivan Diaz-Loya, Director of Research, Boral Resources LLC. Boral have tested a number of sources of fly ash and ground bottom ash collected from the same source. Table 16 shows the chemical analysis of two such coal ashes. Differences in chemical composition for ashes (FA and BA) produced from the same coal are small. Figure 16 shows X-ray diffraction (XRD) patterns for the same four materials and the results from quantitative XRD Rietveld analysis are shown in Table 17. There are clearly differences in the mineralogical content of coal ashes from the same source. Class F fly ash is dominated by quartz, mullite and amorphous glass. The bottom ash from the same source contains a similar quartz content but the alumina is present as anorthite rather than mullite and the glass content is lower. Class C fly ash contains more crystalline phases including anhydrite and merwinite. The bottom ash from the same source also contains diopside and albite. With significantly less glass. Despite there being less glass in BA compared with FA from the same source, the amorphous content still dominates the ash being greater than 60 %.

	Plant Producing	Class F Fly Ash	Plant Producing	Class C Fly Ash		
	Fly Ash	Bottom Ash	Fly Ash	Bottom Ash		
SiO ₂	57.10	59.99	39.38	48.32		
AL ₂ O ₃	20.83	18.43	20.32	17.91		
Fe ₂ O ₃	4.75	6.48	6.94	5.85		
Sum of Oxides	82.68	84.90	66.63	72.08		
SO ₃	0.41	0.48	1.66	0.32		
CaO	10.30	9.44	21.58	18.30		
Na ₂ O	0.30	0.26	1.47	1.02		
MgO	2.46	2.15	4.65	4.46		
K ₂ O	1.03	0.91	0.66	0.49		

Table 16. Chemical analysis of fly ash and ground bottom ash collected from plants producing Class F fly ash and Class C fly ash (Diaz, 2020, private communication).



Figure 16. X-ray diffraction patterns for fly ash and ground bottom ash collected from plants producing Class F fly ash and Class C fly ash (Diaz-Loya, 2020, private communication).

	Plant Producing	class F Fly Ash	Plant Producing Class C Fly Ash				
	Fly Ash	Bottom Ash	Fly Ash	Bottom Ash			
Amorphous	72.73	64.01	86.41	66.84			
Quartz (SiO ₂)	13.88	13.71	7.95	14.55			
Mullite (3Al ₂ O ₃ ·2SiO ₂)	11.40	1.98	0.61	-			
Hematite (Fe ₂ O ₃)	0.41	0.26	0.21	2.46			
Periclase (MgO)	0.03	0.16	1.52	0.56			
Lime (CaO)	0.02	-	-	-			
Anorthite (CaAl ₂ Si ₂ O ₈)	-	18.63	-	-			
Anhydrite (CaSO4)	-	-	0.57	0.23			
Merwinite Ca ₃ Mg(SiO ₄) ₂	-	-	2.54	0.17			
Diopside (MgCaSi ₂ O ₆)	-	-	-	8.85			
Albite (NaAlSi ₃ O ₈)	-	-	-	6.31			

Table 17. Mineralogical analysis of fly ash and ground bottom ash collected from plants producing Class F fly ash and Class C fly ash (Diaz-Loya, 2020, private communication).

Figure 17 shows the heat output from calorimetry tests run on portland cement-ash blends using the ashes (FA and ground BA) from the two different plants (one producing Class F and the other producing Class C fly ash). For the plant producing the Class F fly ash, the differences in heat output between FA and GBA are small, with FA tending to retard the set time slightly more than the GBA. For the plant producing the Class C fly ash, the differences in heat output between FA and GBA are considerable. This particularly Class C FA results in very significant retardation in the set time of the blend, the amount of delay increasing with the amount of PC replaced by FA. This behaviour is not observed with the GBA produced from the same source; indeed, the set time seems to be unaffected by the amount of PC replaced.





Figure 17. Calorimetry results for portland cement-coal ash blends ash (Diaz-Loya, 2020, private communication)

Figure 18 shows the results of ASR testing using the accelerated mortar test (ASTM C1567) with highly-reactive El Indio reactive aggregate from Texas. The results for the FA and GBA from the plant producing Class F fly ash are consistent with the results of Oruji et al (2019) discussed earlier, with both ashes controlling expansion but FA being comparably more efficacious in this role. The case for the ashes from the plant producing Class C fly ash are quite different. In this case, the FA is not completely effective in controlling expansion to below 0.10 % at 14 days even when used at a replacement level of 45 %. This is typical for a Class C fly ash with a calcium content above 20

% CaO. However, the behaviour of the GBA from the same source is remarkable in controlling expansion (≤ 0.10 % at14 days) at a replacement level of 35%. Indeed, comparing the two graphs in Figure 18, it is apparent that the GBA from the Class C ash source, with 18. 30% CaO is more efficient than the lower-CaO GBA from the Class F ash source with 9.44 % CaO. This is somewhat surprising and counter to experiences with fly ash; further study of more high-CaO bottom ashes is required to see if this phenomenon is common to all such ashes.



Figure 18. Expansion (14-day) results for mortar containing coal ashes at different replacement levels (Diaz-Loya, 2020, private communication)

2.6 Testing by Ash Suppliers

There is considerable on-going work being conducted on both U.S. and Canadian sources of harvested coal ash and ground bottom ash and some of the preliminary data are presented here.

2.6.1 Amorphous (Glass) Content

Quantitative X-ray diffraction (QXRD) was performed on coal ashes from five different sources (source of ash for sample identified as UNB is unknown); for each source both a fly ash (FA) and a ground bottom ash (GBA) were tested. Samples from 3 of the sources were sent to a second laboratory for analysis. Figure 19 shows the results for the amorphous (glass) content which is calculated by subtracting the amounts of the various crystalline phases from 100%. The amorphous content of the bottom ash samples ranged from 44 to 83% with an average value of 60%. The amorphous content of the fly ash samples ranged from 68 to 91% with an average value of 80%. There was considerable variation between the results for the same materials tested at the two different laboratories. These data confirm the data from the Boral ashes (see section 2.5.2) and

indicate that, while the glass content of BA is likely to be less than that of FA, there are still significant quantities of reactive glass in ground bottom ash.



Figure 19. Comparison of amorphous (glass) content of fly ash and bottom ash collected from five different sources (Shogren 2020; Dobslaw 2020).

2.6.3 Bound Water Tests on Ground Bottom Ash Samples

Figure 20 shows the results of bound water tests conducted on lime-ash pastes for ground bottom ash from two sources (see section 2.5.1 for a description of the test). The bottom ash from each source was ground to fineness levels as measured by the percentage of material retained on a 45- μ m sieve. The amount of bound water lies between 4 to 6%, which is within the range of values typically found for fly ash (see Figure 12).

2.6.4 Strength-Activity Index

Figure 21 shows the strength-activity index (SAI) at ages of 7 and 28 days for various blends of fly ash and ground bottom ash from the same source. In this case, the bottom ash was ground such that the average particle size was $D_{50} = 8.2 \mu m$, which compares with $D_{50} = 4.5 \mu m$ for the fly ash sample. The results indicate no consistent trend when the fly-ash-to-bottom-ash ratio ranged from FA/BA = 80/20 to 40/50 and that the blended FA-BA samples achieved at least comparable SAI values as the unblended fly ash.



Figure 20. Results of bound water tests on ground bottom ash samples (Shogren 2020)



Figure 21. Results of SAI tests on FA/BA blends (Babichuk 2020)

2.6.5 Prevention of Alkali-Silica Reaction

Figure 22 shows the results of testing a fly ash (FA with 17.7% retained on the 45-micron sieve) and a ground bottom ash (BA with 18.4% retained on the 45-micron sieve) from the same source in the accelerated mortar bar test (ASTM C1567) with a siliceous limestone (Spratt) as the reactive aggregate. The results indicate that the efficacy of BA is comparable to that of FA, with a 20% replacement of high-alkali cement by either material being sufficient to control the 14-day expansion to less than 0.10%.



Figure 22. Results from ASR tests conducted with FA and ground BA from the same source (Dobslaw 2020)

2.6.6 Sulfate Resistance

Figure 23 shows the results of sulfate-resistance testing (ASTM C1012) for ground coal ash samples retrieved co-mingled deposits of fly ash and bottom ash harvested from three different power plants. Each of the coal ash samples were combined with an ASTM C595 Type IL (CSA Type GUL) portland-limestone cement which met the performance requirement for high sulfate resistance (0.05%) at 6 months but failed the requirement (0.10%) at 1 year. All Type IL-coal ash blends met the 6-month requirement (0.05%) at 6 months and the 12-month requirement (0.10%) at 12 months. Two of the mixtures were measured to 18 months with one (20% Harvested CA)

having an expansion of less than 0.10% while the other ((20% Harvested SD) slightly exceeded 0.10%.



Figure 23. Results from sulfate-resistance tests (ASTM C1012) for coal ash samples harvested from co-mingled deposits of fly ash and bottom ash (Shogren 2021).

Figure 24 shows 6-month and 12-month results from sulfate-resistance tests (ASTM C1012) performed on two ASTM Type V (CSA Type HS) cements and on blends of ASTM Type I (CSA Type GU) cements together with either fly ash or ground bottom ash.



Figure 24. Results from sulfate-resistance tests (ASTM C1012) for Type V (HS) cements and blends of Type I (GU) cements with harvested ash or ground bottom ash (Shogren 2021).

Collectively the results from these tests indicate that harvested fly ash or ground bottom ash can be processed to provide adequate sulfate resistance (at least equivalent to Type V portland cement) when blended with Type I portland or Type IL portland-limestone cements.

3. Provisions for Use of Harvested Fly Ash and Comingled Ash in Specifications

3.1 CSA (Canadian) Specifications

In the 2021 amendment to the CSA A3001-18 standard, the definition of fly ash was changed and it now allows the use of harvested ash under the same categories as freshly collected fly ash (i.e. Class F, CI and CH). Given the likelihood of comingling of some proportion of bottom ash in many landfills and lagoons, this is also allowed under the definition of harvested fly ash. Harvested ash has to meet all the requirements of the appropriate fly ash category, and the only new requirement was the addition of a maximum limit of 5 % retained on a 160- μ m (Number 100 mesh) sieve. The additional fineness requirement was to help ensure that the processed harvested ash has sufficient fineness and also due to concerns that oversize amorphous ash particles could act as alkali-silica reactive aggregate. The amendment to CSA A3001 was made due to the imminent closing of almost all coal power plants in western Canada by 2023 and this would have left concrete producers with few options to mitigate alkali-silica reaction, chloride ingress, or sulfate attack. As a result of this recent change, harvested, comingled fly ash is now being processed and produced in Western Canada (primarily in Alberta) by several suppliers.

3.2 European Specifications

It is our understanding (Prof. R. Jones, University of Dundee, private communication April 27, 2020) that the next version on EN450 will include harvested fly ash and will likely require carbon reduction, drying, and fineness reduction to category N in EN450 (Note category N allows a maximum of 40 % retained on the 45 μ m sieve).

However, it is also interesting to note that the current EN450-1 (2012) as part of the definition of fly ash allows it to be "processed, for example by classification, selection, sieving, drying, blending, grinding or carbon reduction, or by combination of these processes, in adequate production plants, in which case it may consist of fly ashes from different sources, each conforming to the definition given in this clause." The EN450 definition of fly ash also allows fly ash that is from the co-combustion of pulverized coal with other fuels including wood and biomass up to 30 % by mass of the fuel. The allowable list of co-combustion materials is shown in the following table.

1	Solid Bio Fuels conforming to EN14588:2010 including animal husbandry residues as defined in 4.5 and excluding waste wood as defined in 4.52, 4.132 and 4.174.
2	Animal meal (meat and bone meal)
3	Municipal sewage sludge
4	Paper sludge
5	Petroleum coke
6	Virtually ash free liquid and gaseous fuels

3.3 Other Fly Ash Specifications

Australia, India Japan and China are not believed to be considering the use of harvested fly ash due to the considerable amounts of fly ash currently being produced at coal power plants.

While not addressing harvested fly ash, Tables 18a and 18b provide the requirements in different specifications for fly ash pozzolan. These tables are from a recent review in Japan (JCI 2016) but the data do not reflect the most recent changes in ASTM C618 and elsewhere. However, this may still be useful for comparison of specified limits on properties outside of North America. It can be seen that several specifications have multiple classifications for fly ash based on the percentage retained on the 45- μ m sieve and/or LOI.

		Table 5-1 Co	ompariso	n of specif	ied fly ash	1 between	Japan an	d other co	ountrie	s *4							
	Nai	_	JA	PAN		EU					USA						
		Standards			JIS A	A 6201		EN450-1					ASTM C 618				
	Year	of establishment			2	015			20	012	_		2008				
_		Types		I	II	Ш	IV	A	B	3		С	N	F	C		
		Silicon Oxide	%														
	5	Silicon Dioxide	%		2	≧45			-								
	5	Sulfur Trioxide	%						3	;≧	_		4≧		5≧		
	N	foisture content	%		1	≧								3≧			
		Ignition loss	%	3≧	5≧	8≧	5≧	5≧	72	2	9	2	10≥	6≥*2	62		
Chemical		Chloride ion	%						0.	$1 \ge 1$							
components	Fre	e Calcium Oxide	%						1.5	$j \geq 1$							
	Acti	ve Calcium Oxide	%		,				10	$\overline{\geq}$							
	M	agnesium Oxide	%						4	\geq							
	Total of S Oxide -	Silicon Dioxide + Ferric + Aluminum Oxide	%		2				≧	70			1 All	≧70	≧50		
		Alkali content	%							52							
	Density																
	Specific surface area			$\geq 5000 \geq 2500 \geq 2500 \geq 1500$													
	Fineness Percentage retained			10≧	40≧	40≧	70≧	Div	Division by fineness N: $40 \ge .5$: $40 \ge$			34≧					
DI		7 days	%							≥75*3							
Physical	Activation	28 days	%	≧90	≥80	≥80	≥ 60	≥75				≥75*3					
properties	index	91 days	%	≥100	≥90	≥ 90	≥ 70	>85				= 75					
	Ra (Rati	tio of flow value o of water content)	%	≧105	≧95	≧85	≧75	(S: 95≧)				(115≧) (105≧)					
Soundness Expansion ratio by autoclaye %										10mm≧					0.8≧		
Other specified items				Specific surface area: ±450 cm ² /g Percentage retained over 45µm sieve: ±5%				Density: ±0.15 g/cm ³ Percentage retained over 45µm sieve: ±10% *1: In the case of Free Calcium Oxide over 1.0%			%	Density: ±5% Percentage retained over 45µm sieve: ±5% *2: In the case of user's approval, limit of 12% may be applied *3: The age of index should be prescribed by the specifications					

Table 18a. Comparison of Fly Ash Specifications-1 (JCI 2016)

*4: Japan Concrete Institute: Reduction in Shrinkage Cracks and Improvement of Durability in View of Admixture, Committee Report of the JCI, pp. 89-99, 2010

			Table	5-2 Comp	parison o	of specif	fied fly as	h betw	een Japa	in and of	ther cou	ntries *1					
Name of country			UK			AUSTRALIA							REPUBLIC of KOREA				
	Star	ndards			BS3892			AS	3582.1				GB159	6		KSL5405	
	Year of es	tablishment			1993			19	998b				2005			20	09
	T	ypes		PART I	PART II A B Special		Special*2	*2 Normal Fine Medium Coarse		F C	II F C	Ш F С	For cement mix	ture C	Туре 1	Туре2	
	Silicon (Oxide	%														-
	Silicon I	Dioxide	%													2	45
	Sulfur T	rioxide	%	2≧	2.	5≧			3≧			3≧		3.5≧			-
	Moisture	e content	%	0.5≧	0.	5≧			_1≧			12		1≧	_	1.	2
	Ignition	loss	%	6≧	7≧	12≧	4≧	4≧	5≧	5≧	5≧	8≧	15≧	8≧		3≧	5≧
Chaminal	Chloride	e ion	%	0.1≧		-			7.557							22	5
Chemical	Free Cal	cium Oxide	%	$10 \ge$		-				_	$1 \ge 4 \ge$	$1 \ge 4 \ge$	1≧ 4≧	1≧ 4≧	2		-
components	Active C	Calcium Oxide	%			-	242		1000								
	Magnesi	ium Oxide	%		4	2					3. 						
	Total of Silicon Dioxide + Ferric Oxide + Aluminum Oxide		%													-	
	Alkali c	ontent	%														
-	Density		g/cm ³	≥ 2												≧1.95	
		Specific surface area				-										≧4500	≧3000
	Fineness	Percentage retained over 45µm sieve	%	12≧	30≧& ≧12.5	60≧& ≧30	25≧	25≧	35≧	50≧	12≧	25≧	45≧			10≧	40≧
Physical properties	Activation	7 days	%	≧80 (8days)		-											
	index	28 days	%											≧70	_	≧90	≧80
		91 days	%			-	-									≧100	≧90
	Ratio of flo	ow value vater content)	%	(95≧)	-						(95≧)	(105≧	(115≧)			105≧	95≧
	Soundness	Expansion ratio by autoclave	%			•											
Other specified items			For structural concrete	For	grout	*2: Re	lative s	trength >	► 105%						-		

Table 18b. Comparison of Fly Ash Specifications-2 (JCI 2016)

*1: Japan Concrete Institute: Reduction in Shrinkage Cracks and Improvement of Durability in View of Admixture, Committee Report of the JCI, pp. 89-99, 2010

4. Summary on Potential Inclusion of Harvested, Comingled and Bottom Ash in ASTM C618

This review of the literature and recent data indicates that coal fly ash and bottom ash from the same furnace will be very similar in chemical composition, and both will contain amorphous phases that react as a pozzolan. The main difference is that unground bottom ash particles are coarser than fly ash. So, with adequate grinding, comingled ash should be as acceptable for use as fly ash. Data from several studies showed that if not ground to a sufficient fineness, the water demand of mortars made with 100 % unground bottom ash is increased and strength activity is reduced; however, when sufficiently ground there is no increase in water demand and strength is equal to that of fly ash from the same source. Bottom ashes are also able to improve chloride penetration resistance, mitigate ASR and improve sulfate resistance similar to fly ashes from the same source. Therefore, harvested coal ashes, whether from fly ash, bottom ash, or comingled ash, should also be suitable for use.

This does not change when the coal ash is harvested from landfills or lagoons except the harvested ash will likely need to be dried and that potentially injurious levels of contaminants must be removed or eliminated through selective mining. Therefore, it is concluded that harvested ash should be suitable for use as a supplementary cementitious material in concrete under the current fly ash designations in ASTM C618, subject to the following provisions:

- a. As detailed in ASTM E3183, each landfill or lagoon site to be considered for harvesting ash needs to have adequate borehole logging including an evaluation of quality and consistency. This may require limiting extraction to only certain areas or depths of a deposit where the source meets the established criteria.
- b. For fly ash monofills, the ash will need to be (a) dried to meet the 3.0 % moisture content limit in ASTM C618, (b) agglomerates broken up or removed, and (c) limits on fineness, LOI and SO₃ be met. In addition to meeting the maximum limit of 34 % retained on the +45-µm sieve, to limit agglomerates, a maximum limit of 5 % retained on a 160-µm sieve was added to ensure adequate grinding of comingled bottom ash.
- c. For ash sources co-mingled with bottom ash, in order to meet the above listed fineness limits, additional production steps will be needed to increase fineness and limiting oversize particles through grinding and/or air cyclone classification.
- d. Note also that ASTM E3183 Standard Guide for Harvesting Coal Combustion Products Stored in Active and Inactive Storage Areas for Beneficial Use was published in 2018. This Guide states that, "Although many CCPs were placed in storage due to not meeting applicable specifications for use, many other CCPs were stored for lack of market. In either case, the CCPs retain the ability to be considered a wanted material that provides a functional benefit and a benefit to the environment. They can be harvested and lightly processed, if necessary, to meet relevant product specifications and substitute for the raw materials. Depending on the type and homogeneity of CCPs and the type of storage area from which the materials are being harvested (that is, dry or wet storage areas), this harvesting and processing may include, but is not limited to, excavating or dewatering/dredging, drying, milling, classifying and storing or transporting the material before they are beneficially used." This Guide outlines the steps that need to be taken when evaluating a CCP storage area and for obtaining environmental approvals.
- e. Finally, sources of suitable fly ash from coal power plants are diminishing and has resulted in shortages in certain regions of the USA; it is expected that these shortages will increase in the near future. Table 19 summarizes some of the risks and benefits of allowing or notallowing harvested, comingled and bottom ash into ASTM C618.

Table 19. Risks and Benefits of including Harvested Coal Ash in ASTM C618

<u>Risks</u> (Harvested ash including co-mingled and bottom ash is not adopted in ASTM C618)	<u>Benefits</u> (Inclusion of Harvested, co-mingled and bottom ash in ASTM C618)
 Significant reduction, if not elimination of access to supply Fly ash is often co-mingled with bottom ash in the ash deposit Requiring fly ash to be selectively removed from co-mingled ash sites will dramatically reduce the feasibility of harvesting ash Landowners will not want to disturb their land for a significant length of time to only remove 60-80% of the ash deposited there. The land will still contain ash and will be a future environmental liability to the landowner, impacting the value of that land. Increased costs to the ash marketer for mining and separation of fly ash from bottom ash Increased concrete durability issues With a lack of viable options, concrete producers will struggle to find economic solutions to mitigate Alkali Silica Reaction (ASR) and sulfate attack as well as reducing permeability Selectively mining fly ash from a comingled deposit will increase ash processing costs Concrete producers will be left to increase the cement content in mixes to meet performance requirements, increasing the CO₂ intensity 	 Reliable and abundant supply Allows for consistent, year-round ash supply, independent of power plant activities Adds long-term domestic resource of performing pozzolan Continued ability of the industry to efficiently mitigate concrete durability issues Long-term supply of economic SCM with comparable ability to mitigate Alkali Silica Reaction (ASR) and sulfate attack and to meet permeability limits. Environmental benefits Continued replacement of portland cement and corresponding reduction in GHG emissions Enables full removal of ash landfills and reduces associated environmental liabilities, including potential groundwater contamination Returns landfills to their natural state and unlocks redevelopment potential

5. Changes needed to ASTM C618

To allow for inclusion of harvested, co-mingled and bottom ash in C618, ASTM subcommittee C09.24 is being asked to consider the following changes:

1. Replace the word "coal fly ash" with "coal ash" in the title and throughout the document,

2. Add a top sieve requirement to ensure material does not include large particles (a maximum of 5% retained on a number 100 mesh sieve for harvested, comingled, and bottom ash. This matches the same requirement added to CSA A3001 in 2021 when harvested and comingled ash was included.),

3. Add definitions for coal combustion products, bottom ash and harvested ash (C125 already defines fly ash),

4. Add a materials and manufacture section stating that harvested ash and bottom ash require processing to meet the requirements of C618,

5. Add a reference to ASTM E3183-19, Standard Guide for Harvesting Coal Combustion Products Stored in Active and Inactive Storage Areas for Beneficial Use,

6. Add a requirement for disclosing the type of material (freshly produced or harvested coal ash, or a blend, and whether the coal ash includes bottom ash).

The wording of a draft proposed ballot is included in Appendix A.

5 Report References

5.1 Standards

ASTM E3183-19, Standard Guide for Harvesting Coal Combustion Products Stored in Active and Inactive Storage Areas for Beneficial Use, ASTM.

ASTM C618-19, Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete, ASTM.

BS EN 450-1:2012, "Fly ash for concrete Part 1: Definition, specifications and conformity criteria," The British Standards Institution.

CSA A3001, 2018 (with 2021 amendment), Cementitious materials for use in concrete, CSA Group, Toronto, Canada.

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Appendix A. Draft Proposed Changes to ASTM C618-19.

New wording is underlined and deleted text is stroked out. Note: The actual ballot wording may differ slightly from the draft shown here.

a. Modify the title to: Standard Specification for <u>Coal</u> Fly-Ash and Raw or Calcined Natural Pozzolan for Use in Concrete

b. Modify the Scope to:

1.1 This specification covers <u>coal fly</u> ash <u>resulting from the combustion of coal</u> and raw or calcined natural pozzolan for use in concrete where cementitious or pozzolanic action, or both, is desired, or where other properties normally attributed to <u>coal fly</u> ash or <u>natural</u> pozzolans may be desired, or where both objectives are to be achieved. Note 1—Finely divided materials may tend to reduce the entrained air content of concrete

Note 1—Finely divided materials may tend to reduce the entrained air content of concrete. Hence, if a <u>coal</u> fly-ash or natural pozzolan is added to any concrete for which entrainment of air is specified, provision should be made to ensure that the specified air content is maintained by air content tests and by use of additional air-entraining admixture or use of an air-entraining admixture in combination with air-entraining hydraulic cement.

- c. Add to cited standards: <u>ASTM E3193-19 Standard Guide for Harvesting Coal Combustion</u> <u>Products Stored in Active and Inactive Storage Areas for Beneficial Use</u>
- Add to Definitions: <u>3.2 Definitions of Terms Specific to This Standard</u>
 <u>3.2.1 coal combustion products</u>, n— all solid materials that result from the process of combustion of ground or powdered coal.

3.2.2.1 Discussion—Examples of coal combustion products include fly ash, bottom ash, flue gas desulfurization residue, and boiler slag. This definition of coal combustion ash does not include, among other things, the residue resulting from: (1) fluidized bed combustion, (2) the burning of municipal solid waste or any other refuse with coal, or (3) the burning of industrial or municipal solid waste in incinerators.

3.2.2 coal ash, n—fly ash and bottom ash resulting from the process of combustion of ground or powdered coal.

<u>3.2.3 *bottom ash, n*</u>-ash that results from the process of combustion of ground or powdered coal that is not transported by flue gases.

<u>3.2.3.1 Discussion</u>—To meet the fineness requirement of this specification, coal bottom ash shall be ground or sieved.

3.2.4 *harvested ash, n*—material extracted from deposits of coal combustion products stored in active or inactive disposal areas and processed for beneficial use in concrete.

e. Add to section 4 on classifications:

4.2 *Class F*—<u>Coal fly</u> ash that meets the applicable requirements for this class as given herein. This class of <u>coal fly</u> ash has pozzolanic properties.

4.3 *Class C*—<u>Coal</u> fly-ash that meets the applicable requirements for this class as given herein. This class of <u>coal</u> fly ash, in addition to having pozzolanic properties, also has some cementitious properties.

Note 2—Class F <u>coal</u> fly ash is typically produced from burning anthracite or bituminous coal, but may also be produced from subbituminous coal and from lignite. Class C <u>coal</u> fly ash is typically produced from burning lignite or subbituminous coal, and may also be produced from anthracite or bituminous coal.

4.4 Bottom ash and harvested ash shall meet either the Class F or Class C classification provided they are tested at the frequency required in this standard and that they conform to all requirements outlined in this standard for that class.

f. Add new section on Materials and Manufacturing:

5. Materials and Manufacture

5.1 Coal combustion products may be processed to meet the requirements of this specification.

5.2 Harvested Ash and Bottom Ash

5.2.1 The supplier shall certify the material being harvested or processed is not contaminated with any material that may deleteriously impact the products use in concrete.

Note 3—Examples of other materials that may impact use include coal rejects, flue gas desulfurization (FGD) materials, and organics.

5.2.2 Harvested ash and bottom ash each require processing to meet the requirements of this specification. Processing may include but is not limited to one or more of the following unit operations: grinding, drying, sieving, de-agglomeration, classification and carbon removal.

Note 4—For guidance on harvesting and processing ash from active or inactive storage areas see Standard Guide E3183.

- g. Change Note to Table 1: ^A The use of Class F coal ash pozzolan containing up to 12.0 % loss on ignition may be approved by the user if either acceptable performance records or laboratory test results are made available.
- h. Add new fineness requirement to Table 2 for Class C and F: <u>Amount retained when wet-sieved on 150-μm (No. 100) sieve, max, % ^A " 5%</u> where footnote A reads: <u>A. Limit only applies to harvested ash or coal ash containing, bottom ash.</u>
- i. Renumber all following sections, then delete wherever 'fly ash' appears, and change to '<u>coal ash'</u> in the rest of the sections of the document including the Appendices.
- j. Under Supplier's Certification, add a new section: <u>13.2 The manufacturer shall disclose</u> whether the source of the material represented in the certificate is coal ash, harvested ash from a monofill or a site co-mingled with bottom ash, bottom ash, or blends.

k. Change key words to: <u>coal ash;</u> fly ash, <u>bottom ash, harvested ash</u>, <u>natural pozzolan;</u> pozzolans.