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Disclaimer

Approximate Conversions to SI Units (from FHWA)

Symbol	When You Know	Multiply By	To Find	Symbol
Length				
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
Area				
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
mi^2	square miles	2.59	square kilometers	km^2
Volume				
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE: volumes greater than 1000 L shall be shown in m^3				
Mass				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
Temperature (exact degrees)				
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
Illumination				
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
Force and Pressure or Stress				
lbf	pound-force	4.45	newtons	N
lbf/in^2	pound-force per square inch	6.89	kilopascals	kPa

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16. Abstract

Recent coal-fired power plant closures resulted in limited availability of fresh fly ash in some regions of the United States of America. This combined with stricter environmental regulations has led to national specifications being modified to allow the use of coal bottom ash in addition to coal fly ash as a supplementary cementitious material in making concrete. Coal bottom ash is different from coal fly ash in its chemical, physical and mineralogical composition. The literature review conducted in this study identified variability in performance of coal ash that can be related to variability in the available sources of the collected coal ash; namely, landfills, lagoons or freshly collected bottom ash. The findings indicate that the work is needed to ensure consistent performance of coal ash collected from variable sources. It is recommended that a study on coal ash performance be initiated to ensure adequate and consistent performance and durability of structural concrete elements in the state of Florida using coal ash as a supplementary material.

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Executive Summary

E.1 Background

Fly ash governing specifications in the United States (ASTM C618) have been modified recently (March 2023) to accommodate the use of coal combustion products. The recent change in specification C618 allows the use of coal ash defined as “fly ash and bottom ash resulting from combustion of ground or powdered coal obtained from the current power plant production or harvested from landfills or impoundments.” Additionally, the specifications changed the term “Coal Fly Ash” to “Coal Ash” to accommodate this modification.

Landfilled or ponded fly ash has higher moisture content and can be comingled with bottom ash as well as flue-gas desulfurization materials (FGD) and fluidized bed combustion (FBC) fly ashes. Due to comingling, there is a tendency to have an increase in SO_3 content; however, ASTM limits SO_3 content to 5%. Comingled sources may be more difficult to process and beneficiate for use in concrete. One could think that such limits would be adequate to control the presence of FGDs or FBCs in harvested ash; however, the form of sulfur present in the harvested coal ash, such as calcium sulfate ($CaSO_4$), calcium sulfite ($CaSO_3$) or sodium/alkali sulfate (Na_2SO_4), has a substantial effect on performance. Also, the form(s) of sulfur is not identified by the chemical analyses prescribed in ASTM C618. An additional issue that can exist is excess alkali content. Excess alkali content can be of significance on the rate of reaction of the cementitious system as well as concrete durability.

While the chemical composition of bottom ash is similar to fly ash, the mineralogical composition and therefore pozzolanic activity can be substantially different. Heterogeneities or pockets of impurities that might be present should be identified in landfill maps, however this may be difficult because of changes in material within short distances in the landfill. This can negatively affect quality and reliability of performance of concrete containing coal ash. This can be mitigated by blending ash or homogenizing it in silos.

Prior to the recent specification changes, fly ash was considered a reliable pozzolanic material in the state of Florida structural concrete mixtures. Currently, the state does not have any scientific data to accommodate such a change in its specifications.

The state of Florida has substantial concrete durability concerns due to its coastal location and therefore it is imperative to update the relevant specifications to ensure that expected changes in the quality of coal ash have no negative impact on durability, performance and longevity of structural concrete elements in the state of Florida. Current concerns can be summarized as follows:

1. Adequacy of landfill records/survey, age of landfill and hydration/chemical reactions within landfill.
2. Alkalis, chlorides, sulfates and forms of sulfates, lime, and hydrated lime among other elements and compounds.
3. Comingled coal combustion products in landfills and their effect on structural concrete performance and durability.
4. Leachability of hazardous components

In order to allow the use of this new supplementary material, it is critical to assess its performance and durability to maintain the safety of Florida infrastructure concrete elements.

E.2 Research Objectives

The objectives of this investigation were:

1. Review the existing literature on the procedures needed to produce concrete-quality pozzolanic materials from coal ash.
2. Identify any components of coal ash that could negatively affect the reactivity or long-term durability of concrete.
3. Prepare a test matrix for Phase II to follow completion of the current work order. The matrix is to provide the testing protocol, number of samples as well as the cementitious materials constituents in order to ensure the safety and durability of the state of Florida structural concrete.

E.3 Main Findings

The findings indicated that the current state specifications don't address coal ash potential variability. As such, research is needed to determine the performance of coal ash as a supplementary cementitious material in Florida structural concrete. It is important to initiate a research study to address the effectiveness of coal ash on controlling temperature rise in massive concrete elements, enhancing sulfate and chloride durability in structural concrete as well as minimizing shrinkage and delayed ettringite formation.

E.4 Recommendations

Based on the findings of this study, the following recommendations can be made:

1. Research on coal ash from different sources including landfills and lagoons should be performed before being used in Florida structural concrete.
2. Modify current specifications to limit the use of coal ash to fresh production until research is conducted on the performance of harvested coal ash for Florida structural concrete. Once scientific data is collected to prove the appropriate use of coal ash for structural concrete, through conducting scientific research, specifications can be further modified to allow its proper use in different structural applications

E.5 Recommendations for Future Study

Based on the findings of this study, it is recommended that a research study should be initiated to address concerns identified in this report on the use of coal ash as a supplementary cementitious material in Florida structural concrete elements.

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Chapter 1 Literature Review

1.1. Background

The purpose of this review is to consider the inclusion of coal ash as a supplementary cementitious material for use in Florida structural concrete. Coal-powered electrical plant retirements over the past decade have reduced the supply of fresh fly ash. Pollution control measured implemented over the last two decades have also changed the nature and composition of fresh fly ash. Specifications governing the use of coal combustion products in the United States (ASTM C618) have been modified recently (March 2023) or are in the process of modification (AASHTO M295) to accommodate the use of unconventional coal combustion products in concrete. The recent change in specification C618 allows the use of coal ash defined as "fly ash and bottom ash resulting from combustion of ground or powdered coal obtained from the current power plant production or harvested from landfills or impoundments". Additionally, ASTM C618 changed the term "Coal Fly Ash" to "Coal Ash" to accommodate this modification.

While the chemical composition of bottom ash is similar to fly ash, the mineralogical composition and particle size distribution and therefore pozzolanic activity can be substantially different. Bottom ash can be ground to increase the reactivity and meet reactivity requirements for use as a supplementary cementitious material (SCM) in concrete.

Landfilled or ponded coal ash may have a different composition than the traditionally used fresh fly ash. Reclaimed coal ash has higher moisture content and can be comingled with bottom ash as well as flue-gas desulfurization materials (FGD) and fluidized bed combustion (FBC) fly ashes or off-specification coal ash. Due to comingling, some coal ashes could have a high SO_3 content; however, ASTM limits SO_3 content to 5%. The form of sulfur present in harvested coal ash such as calcium sulfate ($CaSO_4$), calcium sulfite ($CaSO_3$) or sodium/alkali sulfate could have substantial effect on concrete performance. Sodium carbonate could also affect the concrete performance. Another process, flue gas denitrification, can result in a wide range of nitrogen compounds with contents ranging from 0.1-6% in coal ash, including ammonium sulfate or ammonium hydrogen sulfate with negative implications on durability, rate of strength gain, air-entraining admixture dosage for a desired air content and setting properties. Though the current specifications identify a limit for maximum SO_3 content, it does not identify the sulfur form(s) by the prescribed chemical analyses (Kaladharan et al., 2019; Shearer et al., 2024). An additional issue that can exist in coal ash products is excess alkali content. Excess alkali content can be of significance on cementitious materials reaction kinetics, and fresh and hardened concrete properties and performance. Even if landfill mapping is done to exclude heterogeneities, there are concerns that heterogeneities or pockets of impurities present could be missed (Kaladharan et al., 2019). This can negatively affect quality and reliability of performance of concrete containing coal ash. Adequate quality control sampling should be considered when harvesting a landfill.

Prior to the recent specification changes, fly ash was considered as a reliable pozzolanic material in the state of Florida structural concrete mixtures. The state of Florida has substantial concrete durability concerns due to its coastal location and therefore it is imperative to update the relevant specifications to ensure that expected changes in the quality of coal ash have no negative impact on durability, performance and longevity of structural concrete elements in the state of Florida.

In order to allow the use of this new supplementary material, it is critical to assess its performance and durability to maintain the safety of Florida infrastructure concrete elements. Towards these objectives, an extensive literature review will be presented in the following paragraphs to identify the state of knowledge pertaining to the characteristics and use of coal ash, fresh and hardened concrete properties of coal ash blended concrete, durability studies on cementitious mixtures incorporating coal ash, coal ash components that could negatively affect concrete reactivity or long-term durability, and coal ash impact on health and environment.

1.2. Coal Combustion Product Types

Coal combustion generates large amounts of waste. These waste materials are referred to collectively as coal ash by-products as depicted in Figure 1. Combustion occurs at very high temperatures, usually above 900°C. During the burning of pulverized coal in coal-fired power plants, bottom ash (BMA) is generated at the bottom of the boiler when the the boiler operates under dry conditions and boiler slag (BS) when the boiler operates under wet conditions. These “heavy” particles settle at the bottom, and the remaining products are carried away in the flue gas. Particulate emission control devices like electrostatic precipitators are used to collect fly ash from the flue gas. Desulfurization material is added to the remainder of the flue gas to remove SO_x present and the insoluble precipitate formed is collected as flue gas desulfurization material (FGD).

In a more energy-efficient combustion method, fluidized bed combustion, coal is burned in a boiler containing a fluidized bed of inert particles usually at lower temperatures compared to the traditional pulverized coal combustion. The coal ash generated from this combustion technology is termed fluidized bed combustion ash (FBC) which is currently not allowed to be used as a supplementary cementitious material per standard specifications. FBC ash has much lower amorphous content and has a different particle morphology than fly ash produced in conventional pulverized coal combustion power plants because most of the material does not melt or volatilize at the lower combustion temperature used in FBC processes. FBC also contains calcium sulfate because calcium carbonate is injected with the coal to calcine and absorb sulfate in the boiler (Pei et al., 2023).

In addition to reduced SO_x emissions, recent EPA rulings have required NO_x reductions. Reduction of NO_x can be done using several techniques. Qin et al. (2019) reported that the most commonly used technique is selective catalytic reduction of NO_x with NH_3 (NH_3-SCR). This results in the adsorption of NH_3HSO_4 and $((NH_3)_2SO_4)$ on coal ash particles. During cement hydration and the high pH environment, ammonium salts can affect cementitious paste properties. The implications of ammonium salts presence in coal fly ash on cementitious mixtures performance will be discussed later in this review. Other air emission controls for power plants include controls for mercury, arsenic, and selenium in addition to other heavy elements. When considering using reclaimed coal ash in concrete, it is important to keep in mind that pollution control measures have been strengthened and evolved with technology and regulations over the last several decades, resulting in different ash properties and concerns depending on when it was generated.

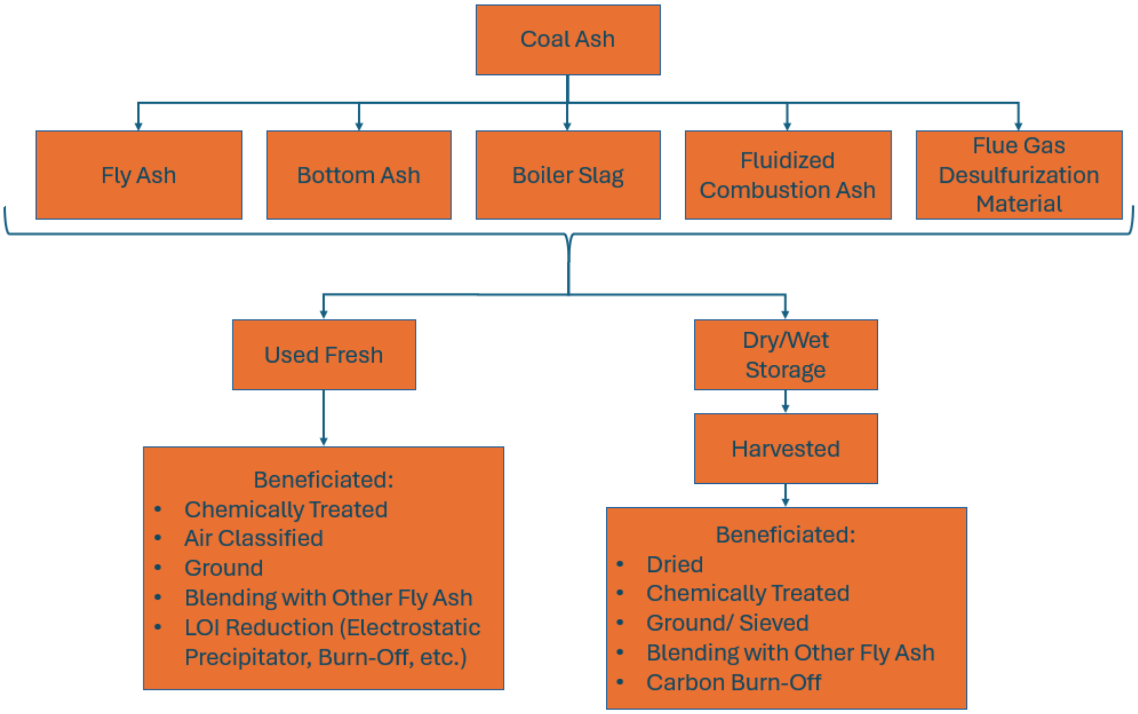

Figure 1: Flow Chart on Types of Coal Combustion Products and Beneficiation Methods

1.2.1. Fly Ash

Coal-fired thermal power plants generate electricity by producing steam from the burning of pulverized coal. The steam produced under high pressure in the boiler turns the turbines to generate electricity (Siddique, 2008). Once the coal gets to the power plant, it is ground into fine powder by coal mills to produce pulverized coal. The pulverized coal is then placed into the combustion chamber of the boiler, where it ignites immediately, and while generating heat, a molten mineral residue is produced. The boiler tubes then extract heat from the boiler, causing the molten residue to harden and form ash. The coarse ash particles, which could be either bottom ash or boiler slag, fall to the bottom of the combustion chamber, while the lighter fine ash particles, known as fly ash, remain suspended in the flue gas. Before the flue gas is exhausted, particulate emission control devices like electrostatic precipitators, filters, or scrubbers then remove the fly ash as shown in Figure 2. It can be very similar to volcanic ash and has special properties that make it great for making concrete. Since the discovery of (Davis et al., 1937) that fly ash contains large amounts of aluminosilicate glass, it has become the most used supplementary cementitious material in the United States and the world at large. According to (Hooton & Thomas, 2021), the first significant use of fly ash was in the construction of the Hungry Horse Dam in Montana, built between 1948 and 1953, where it replaced up to 32% of portland cement (Rafieizonooz et al., 2016).

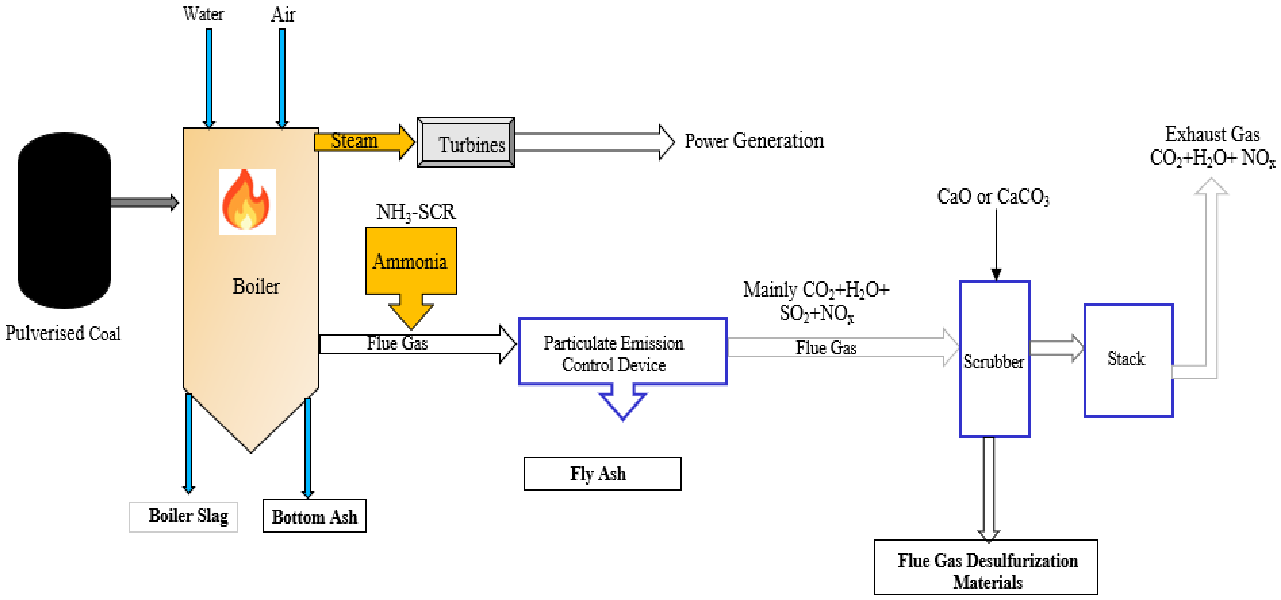

Figure 2: Main stages involved in the generation of coal combustion products

In coal-fired power plants, particulate separators like baghouses or electrostatic precipitators are used in the collection of fly ash from the flue gases produced during coal combustion. The collected fly ash is usually transported pneumatically by pressure-driven pumps from the particulate separators to storage silos where it is kept dry to be utilized immediately, further processed, or sent to a system where the dry ash is mixed with water and stored for future use or disposal. The moistened fly ash is often stored in landfills or lagoons where it is later collected as harvested fly ash (McCarthy et al., 2018). The addition of water to the dry fly ash allows for easy stockpiling or landfilling or washing down into a lagoon depending on the storage method. Moistening the dry fly ash also reduces blowing during transport and makes it easier to recover for use (FHWA, 2016). Hooton and Thomas (2021) found in their investigation that landfilled fly ash is typically compacted and moistened with about 10-15% water.

Fly ash generally consists of a complex blend of silica (SiO_2), alumina (Al_2O_3), iron oxide (Fe_2O_3), and calcium oxide (CaO). When used in concrete production, fly ash is classified as either Class C or Class F with the difference in these two classes emanating from the CaO content of the fly ash. CaO content of more than 18% is classified as Class C, while CaO content of 18% or less is classified as Class F (ASTM C618-23). The mineralogical composition typically includes phases such as quartz, mullite, and glassy materials, which contribute to its pozzolanic properties (Chuo et al., 2024). The variability in mineralogy and chemical composition can significantly influence how fly ash behaves when used as a supplementary cementitious material (SCM). The high silica and alumina content of fly ash allows it to react with calcium hydroxide (produced during the hydration of Portland cement), forming additional cementitious compounds (Sharma et al., 2012). The higher CaO content of Class C fly ash gives it a higher reactivity compared to Class F fly ash, with many Class C fly ashes showing hydraulic and pozzolanic reactivity. The pozzolanic activity is influenced by factors including the fineness and amorphous content of the fly ash, which can differ based on the coal source and combustion conditions. The amorphous content of fly ash usually ranges from 60 – 90% with the remainder being crystalline and usually inert and does not contribute to its cementitious properties (Sharma et al., 2012). Smaller particle sizes result in better reactivity and improve the packing density within the concrete matrix, thus enhancing its mechanical properties. The fineness also improves the fresh properties of concrete; finer fly ash can improve the flowability of fresh concrete without the need for additional water, which is beneficial for achieving high-performance concrete (Theerthananda & Naveen, 2021). When it comes to hardened properties, fly ash enhances long-term strength and durability while reducing permeability due to the formation of additional calcium silicate hydrate (C-S-H) gel, which fills voids between aggregate particles (Zheng et al., 2023). However, the initial strength might be lower than that of conventional concrete without fly ash, necessitating careful consideration of curing conditions and mix designs to optimize performance during early hydration. Fly ash may also contain "heavy" elements such as arsenic, cadmium, and mercury in higher concentrations than in the original coal (Chen et al., 2024). As compared to other coal combustion products, fly ash contains more aluminosilicate glass due to the higher temperatures it experiences during combustion. As shown in Table 1, fly ash consists of finer particles, with diameters ranging from 0.1 μm to 100 μm (3.9×10^{-6} in. to 0.0039 in.). Hooton and Thomas (2021) found this to result in a larger specific surface area for fly ash, making it more suitable for use as a supplementary cementitious material (SCM) in concrete without beneficiation than other materials. Other properties of fly ash that make it a good SCM are its skin of glassy or amorphous calcium-aluminosilicate glass that makes it a very reactive component as well as its hollow spheres (cenospheres), which contribute to its lower specific gravity (Safiuddin & Zain, 2006).

When stored in lagoons, the ash is mixed with water and pumped into large water-filled areas that are later dewatered. Harvesting fly ash (especially from older landfills or lagoons) often requires drying to reduce moisture content, break up or remove agglomerated particles, and ensuring the material meets ASTM C618-23e standards for supplementary cementitious materials (SCMs). The method of storage of the fly ash (dry or wet) has an effect on its reactivity; the ability of fly ash to be cementitious or pozzolanic. McCarthy et al. (2018) studied the reactivity of wet-stored fly ash (held in wet condition for 730 days) compared to dry fly ash based on their lime consumption and activity index and observed that the former had a gradual reduction in reactivity from initial storage to 730 days. They attributed this to the agglomeration of fine fly ash particles during the wet storage. The dry-stored fly ash gave better reactivity. The challenges with harvesting stored fly ash include: excess moisture level, high level of unburned carbon (LOI), presence of free lime, excessive alkalis, excessive sulfur in Class C ashes, fly ash contamination with salts, soil, organic matter, mixing with other coal combustion products, inconsistent fly ash properties within a landfill or pond, diminished fly ash reactivity due to clumping, and partial reaction from prolonged moisture exposure (Hooton & Thomas, 2021). Free lime and calcium-aluminate bearing phases in Class C fly ash that reacted with water hydraulically during storage can carbonate with time. The heterogeneity arises due to differences in how the ash was deposited, its exposure to environmental conditions over time, and its co-mingling with other materials. For instance, older landfilled fly ash can have higher quality due to fewer environmental regulations at the time of its storage, which contrasts with freshly produced ash from modern plants with stringent environmental controls (Diaz-Loya et al., 2019).

1.2.2. Bottom Ash

In the United States, about 15 million tons of bottom ash are produced each year, with 10 to 15% being recycled into useful products (Zhou et al., 2022). Bottom ash refers to the larger ash particles that form in coal furnaces and are too heavy to be carried away with the flue gases. It is produced during the burning of pulverized coal in a dry bottom boiler. During the combustion process, the ash particles that are heavy and are unable to be captured in the flue gas fall to the bottom of the boiler due to gravity. Bottom ash can be removed using conveyors in a dry system or in a wet system cooled with water in a hopper. When enough of the ash is collected, it is removed and deposited in a collection pond and stored for disposal or to be used later (FHWA, 2016). The coal ash generation stages depicted in Figure 2 show bottom ash is the first coal ash byproduct to be collected during the combustion of coal.

Historically, bottom ash has mainly been used as a fine material, like sand, in making concrete blocks and bricks (2021). Bottom ash is also used (1) as a base for roads, (2) for controlling snow and ice, (3) as structural fill, (4) in cement and grout, and (5) for filling mines (Kalyoncu & Olson, 2016). Recently, bottom ash has started gaining recognition as a supplementary cementitious material due to changes in ASTM C618-22, which renamed "coal fly ash" to "coal ash" to include bottom ash and harvested coal ash.

Bottom ash is collected on the walls and bottom of the boiler. It is regularly removed and either disposed of in landfills or reused as a useful byproduct of coal combustion. Long-term storage in impoundments or landfills can be problematic due to potential environmental contamination, especially if storage sites are not properly designed and maintained. There have been instances where coal ash spills have caused significant environmental damage, like in the Tennessee Valley Authority Kingston spill in 2008 (U.S. Environmental Protection Agency, 2012). When incomplete combustion occurs in the boiler, the resulting bottom ash may contain polycyclic aromatic hydrocarbons (PAH), which are carcinogenic to humans and have very low biodegradability (M. Ivanitskiy, 2022; M. S. Ivanitskiy, 2023). PAH are however bound by bottom ash, reducing the risk of PAH leaching from the bottom ash into ground water.

Bottom ash is generally coarser and heavier than fly ash, consisting of particles that are typically angular and porous. The size of these particles varies widely, often ranging from fine sand to small gravel, with a bulk density that can be higher than that of natural aggregates (Tishmack & Burns, 2004). The texture and particle size distribution make bottom ash with minimal processing required a potential substitute for sand and other natural aggregates in construction materials (Zhou et al., 2022).

Chemically, bottom ash is primarily composed of oxides of silicon (SiO_2), aluminum (Al_2O_3), and iron (Fe_2O_3), along with smaller amounts of calcium (CaO), magnesium (MgO), potassium (K_2O), and sodium (Na_2O) (Hooton & Thomas, 2021; Ramzi et al., 2016; Zahedi & Rajabipour, 2019). These oxides are similar to those found in fly ash, though the proportions can differ (Hooton & Thomas, 2021). The amorphous content of bottom ash, which is the main reactive phase, typically ranges from 30.8% to 81.3% by weight and is less than that of fly ash which ranges from 60% to 90% by weight (Alterary & Marei, 2021; Chen et al., 2024). The chemical composition of the amorphous phase (CaO, Al_2O_3, and SiO_2 content) further determines the reactivity of the ash (Provis & Van Deventer, 2009).

Bottom ash can contain trace amounts of toxic elements such as arsenic, lead, and mercury, which can pose environmental risks if not properly managed (Zhou et al., 2022).

Apart from the amorphous phase of the bottom ash, its mineralogical composition for Class F ash includes crystalline phases such as quartz, mullite, and magnetite, which are stable at high temperatures and do not participate in the pozzolanic reaction. However, for Class C fly ash, the crystalline content can incorporate reactive compounds such as tricalcium aluminate, anhydrite, and lime that have different durability performance than those in Class F ashes. The variability in the crystalline and amorphous composition and content depends on the source of the coal and the combustion process, and this can affect its performance in various applications (Hooton & Thomas, 2021; Zhou et al., 2022).

Table 1: Physical characteristics of fly ash and bottom ash from coal combustion from (Tishmack & Burns, 2004)

Material 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

1.2.3. Boiler Slag

Boiler slag is an incombustible byproduct of coal combustion that is only produced when the bottom boiler operates in wet conditions. Two types of wet-bottom boilers produce boiler slag: slag-tap and cyclone. The slag-tap boiler burns finely ground coal, while the cyclone boiler burns crushed coal. In both types, molten ash collects at the bottom of the furnace and flows into a hopper filled with water. When the hot ash meets the water, it cools rapidly, forming hard, glassy pellets called boiler slag. This slag is then washed out of the hopper with high-pressure water jets and transported to basins for drying, and sometimes further processing. The resulting boiler slag is a coarse, black, glassy material (Moulton et al., 1973). In slag-tap furnaces, up to 50% of the ash becomes boiler slag, while in cyclone furnaces, 70% to 85% of the ash turns into boiler slag (FHWA, 2016). Boiler slag is a smooth textured byproduct with a size generally ranging between 0.5 and 5.0 mm, but can develop a slightly porous texture if gasses become trapped in the slag during cooling. It is collected from the bottom of the boiler after the quenching process and is stored either in silos or on the ground before it is used or disposed (Benson & Bradshaw, 2011) either in landfills or lagoons (FHWA, 2016).

Boiler slag mainly consists of silicates and aluminosilicates, like other coal combustion byproducts. However, the exact chemical composition can vary depending on the type of coal used and the specific combustion conditions (Benson & Bradshaw, 2011). It also contains small amounts of iron, calcium, and magnesium. It is black and glossy, with a granular texture that resembles coarse sand or gravel. As compared to bottom ash in Table 2, boiler slag is often denser and harder, which makes it useful in various industrial applications, such as abrasive blasting or as an aggregate in asphalt.

Table 2: Physical properties of boiler slag compared with bottom ash (Benson & Bradshaw, 2011)

Material Property	Bottom Ash	Boiler Slag
Specific Gravity	2.1-2.7	2.3-2.9
Dry Unit Weight (kN/m³)	7.07-15.7	7.43-14.15
Absorption (%)	0.8-2.0	0.3-1.1

1.2.4. Fluidized Bed Combustion (FBC/CFB) Ash

The United States produces over 14 million tons of FBC ash every year (Zahedi & Rajabipour, 2019). CO_2, NO_x, and SO_x emission control during coal combustion have called for more efficient combustion methods; that is, fluidized bed combustion. The boilers of FBC contain beds of inert material (sand) which is fluidized by combustion air that comes from the bottom of the boiler. The flow of air causes the particles of the inert material to become suspended. The fuel (coal) is introduced into the fluidized bed, where it mixes with the hot bed material and air. The fuel particles combust rapidly due to the high heat transfer rates and turbulence within the bed. The combustion process occurs at lower temperatures (800-900°C) compared to the traditional pulverized coal combustion method, reducing the formation of nitrogen oxides (NO_x) and allowing for better control of emissions (Pei et al., 2023). Limestone is added to the combustion to capture the SO_x present and nullifies the need for a separate desulfurization method. During combustion, coal particles in the FBC boilers undergo drying, devolatilization, and fragmentation, combining with the bed materials and the limestone during collisions in the fluidized bed to form ash. The ash generated can be classified into two main types: bed ash (coarse ash that remains within the fluidized bed) and fly ash (finer ash particles that are carried by the flue gases and are collected in electrostatic precipitators or fabric filters).

Currently, there is no global standard specifically for FBC ash, which hinders its widespread adoption as a supplementary cementitious material. Instead, it is used as a construction material for embankments, and roads, filler for bituminous mixes, material for anti-filter screens and a substrate stabilizer. In the definition of coal combustion products, FBC ash is not included (ASTM E3183-24). Zahedi and Rajabipour tested (2019) FBC fly ashes from two different circulating FBC (CFBC) power plants on their compliance with the ASTM C618 requirements and observed that the fly ashes met all other physical and chemical requirements with the exception of exceeding LOI and SO_3 limits. The high levels of SO_3 didn't appear to affect the slump and strength development properties of the concrete that was prepared using these ashes. The SO_3 content is mostly in the form of anhydrite ($CaSO_4$) which sheaths the limestone particles to form layers (Pei et al., 2023). The high levels of SO_3 (> 5 wt%) in FBC ash disqualify it from being sold as coal ash under ASTM C618 and adopted as a supplementary cementitious material. However, (Pei et al., 2023) is of the view that FBC ash should be considered an SCM due it its high amorphous phase that greatly enhances its pozzolanic and cementitious properties. They classified FBC fly ash into three categories based on its calcium oxide (CaO) and sulfur trioxide (SO_3) content:

1. High calcium and sulfur: FBC fly ash with CaO and SO_3 content higher than 20 and 5 wt%, respectively.
2. Low calcium and sulfur: FBC fly ash with CaO and SO_3 content lower than 20 wt% and 5 wt% respectively.
3. Low calcium but high sulfur: CaO content lower than 20 wt% and SO_3 content greater than 5 wt.%

They found low calcium and low sulphur FBC fly ash behave similarly to pulverized coal combustion fly ash, hence their proposal that it is suitable for use as supplementary cementitious material. However sulfates in the FBC fly ash react with calcium in cement in the hardened concrete to form ettringite, which causes expansion and cracking in concrete. Based on the specifications of ASTM 618-23e, fluidized bed combustion ash has been excluded and will not be considered further in this report.

1.2.5. Flue Gas Desulfurization Materials

Flue-gas desulfurization (FGD) materials are the solids produced from the removal of SO_x from the exhaust gases in coal-fired power plants before such gases get into the atmosphere (Punshon et al., 1999). According to Ladwig and Blythe, “FGD systems represent the second-largest coal combustion product (CCP) stream by volume, exceeded only by fly ash”. Due to environmental restrictions on the release of gases into the atmosphere, flue gases are always “cleaned” at the power plants before being released to the environment. There are two widely used methods of cleaning flue gas: wet and dry. The choice of cleansing depends on the composition of the parent coal used in the combustion (Grutzeck et al., 2006). The cleansing is usually done by using a slurry of calcium-containing materials, like slaked lime or calcium carbonate, which is sprayed into the flue gas or used in a bubble tower. The calcium present in this calcium-containing material reacts with the SO_2 in the flue gas to produce an insoluble precipitate in the scrubber as shown in Figure 2. Other coal-powered plants also use a dry injection of these calcium-containing materials. In both methods, the final product mainly consists of hannebachite (calcium sulfite hemihydrate) ($CaSO_3 \cdot 1/2H_2O$) with smaller amounts of gypsum ($CaSO_4 \cdot 2H_2O$) (FHWA, 2016; Grutzeck et al., 2006). Whether dry or wet, the chemical composition of the gypsum or hannebachite depends mainly on the desulfurization material (Berland et al., 2012). FGD materials are similar to conventional fly ash in terms of particle size, particle density, and morphology (Berland et al., 2012). It is not regarded as a supplementary cementitious material due to its high content of CaO and $CaSO_4$.

Wet and dry FGD materials from scrubbers are thickened and dried for handling or recycling, with wet FGD materials being relatively difficult to handle or recycle due to desulfurization material used. FGD gypsum, particularly when used commercially, can be challenging to handle due to its abrasive, sticky, and fine nature (Berland et al., 2012). The United States generates more than 60 million tons of FGD materials every year with only a half being beneficially used (Butalia et al., 2017).

(Navarrete et al., 2021) found that hannebachite in FGD fly ash effectively controlled C_3A hydration like gypsum without causing harmful expansion in the concrete, making it a potential supplementary cementitious material (SCM). However, they were against the use of the fly ash generated from plants that operate on flue gas desulfurization (FGD) processes, since such fly ash could contain high amounts of sulfur oxides making it inappropriate for concrete application.

In another study (Zunino et al., 2018) the authors examined two commercially produced FA with high sulfur content. Analysis indicated that sulfur was present as calcium sulfite ($CaSO_3$, hannebachite) and not gypsum. Two ashes from power plants, with joint collection of FA and FGD, were investigated. X-ray diffraction of the as-received material identified the presence of hannebachite with no other calcium sulfate compounds in addition to the non-reactive mineral phases typically found in fly ashes such as mullite and quartz. Calcite and portlandite were also identified as consequence of the desulfurization process. Some nitrogen residue was also identified primarily as beta and gamma potassium nitrate due to NO_X reduction processes. When prewashing treatment was used, there was substantial reduction in the nitrates due to their high solubility contrary to calcium sulfite which has low water solubility at ambient temperatures. All phases present in the ashes prior to washing treatment were otherwise the same with the exception of calcium hydroxide which was also reduced. The study noted that in a reducing atmosphere, such as N_2, decomposition of anhydrous calcium sulfite ($CaSO_3$) to calcium oxide (CaO), calcium sulfide (CaS), oxygen (O_2) and sulfur dioxide (SO_2) did occur. Setting time studies on the as-received ashes at 30% replacement of cement (by volume), indicated 8.2 h and 7.5 h delay in the initial setting of the cementitious paste compared to the control for both ashes. The findings also indicated that pre-washing treatment of the ash was effective in reducing the delayed setting behavior due to hannebachite presence in fly ash. Pre-washing combined with calcium chloride can be an effective setting accelerator but in reinforced systems, use of limestone powder in combination with pre-washing helped alleviate the retardation effect of hannebachite due to its effect on extending the induction period.

1.2.6. Comingled vs. Single-Sourced Coal Combustion Product Storage

Freshly produced coal ash that exceeds demand is often stored in ponds or landfills for future usage or disposal. This stored coal ash is either single-sourced or comingled with other coal combustion products. In commingled storage, coal combustion products (CCP) from different sources are mixed in a single storage facility while single-sourced storage involves storing each CCP separately. Storing together CCPs from different sources can lead to inconsistency in both the chemical and physical properties of the resulting mixture as well as potential particulate contamination. This is because the composition of the fly ash, bottom ash, and other byproducts can vary significantly depending on the type of coal burned, the combustion process used, and any pollution control technologies applied. This may lead to higher variability in its performance attributes, making it less reliable as an SCM. On the other hand, single-sourced coal ash, derived from a specific coal-fired power plant, typically exhibits a more consistent mineralogical and chemical composition. This uniformity in properties helps to achieve predictable performance outcomes in concrete applications. Thus, for high-performance concrete applications that demand specific characteristics, single-sourced coal ash is often preferred over comingled variants, which would require more extensive beneficiation, altering its properties by processing to ensure quality compliance.

From the findings of (Hooton & Thomas, 2021), few fly ash monofills exist in the United States. A majority of landfills for storing coal ash products consist of fly ash comingled with bottom ash and other coal combustion products. This implies that caution must be taken to exclude potentially deleterious materials such as coal rejects and FGD materials from comingled landfills when harvesting coal ash. They also found that the main tasks when harvesting coal ash from single-sourced storage would be to dry the ash to meet the 3.0% moisture limit required by ASTM C618 and remove or grind large particles to meet reactivity and fineness specification. Comingled storage may require additional production steps. This is in addition to issues pertaining to the implementation of consistent procedures in storage facility and record keeping. Recent studies (Al-Shmaisani et al., 2019; Shearer et al., 2024) found variation in impoundments due to FGD contamination of bottom ash or off-specification ash can generate variation in performance and durability.

1.3 Coal Combustion Product Harvesting and Beneficiation

Coal combustion products (CCPs) produced at the power plants are often transported to storage sites and harvested for various uses. CCPs harvested from landfills or ponds require some beneficiation to obtain well refined products, especially when the primary purpose of such products is to be used as supplementary cementitious materials (Gardner et al., 2017; Hooton & Thomas, 2021) Beneficiation involves the removal of contaminants from the CCPs to turn them into useful products that would improve concrete durability and do not pose any environmental challenge. Some of these contaminants include excess carbon (unburned carbon), organic compounds, ammonia, and excess water. At comingled storage sites, coal ash may be contaminated with sand, gravel, and other impure CCPs like FBC products (Kaladharan et al., 2019). The larger particle size of the bottom ash and the agglomeration of coal ash particles during storage under wet conditions also pose issues with harvested coal ash usage.

While drying and grinding (or sieving) may solve the issues of particle size and moisture content, high unburned carbon content, the presence of activated carbon, and deleterious sulfates must be dealt with to consider harvested coal ash suitable SCMs. Harvested fly ash usually is made up of about 2 to 12% and in some special instances more than 20% unburned carbon (Ahmaruzzaman, 2010). The amount of this unburned carbon is often due to the nature of the parent coal, the particle size distribution of the pulverized coal, the culture of maintenance at the electrical power plant, and the efficiency of the production process (Bartoňová, 2015; Dindarloo & Hower, 2015; Yan & Li, 2009). The unburned carbon reduces concrete durability by absorbing air entraining admixtures thereby causing irregular distribution of the air content in concrete. ASTM standards have not provided direct and accurate measures to determine this unburned carbon content. Loss of ignition (LOI) specified by ASTM 618-23e is an indirect measurement and may not give a proper indication of unburned carbon content. LOI measurements are affected by more than just the unburnt carbon content. The change in mass due to the decomposition of carbonates, the oxidation of iron and sulfur compounds and sometimes even bounded water in clays will affect the LOI (R. Hill et al., 1998; R. L. Hill et al., 1997; Mohebbi et al., 2017). There is therefore the probability that harvested coal ash may meet the LOI requirements but still contain levels of unburned carbon that would be detrimental to concrete durability. For example, activated carbon can absorb large amounts of chemical admixtures. Unburned carbon in freshly produced fly ash is usually removed by methods like sieving, electrostatic separation, froth flotation, oil agglomeration, chemical passivation, and thermal processing (Hower et al., 2017). However, these neutralization techniques are not directly applicable to harvested coal ash, especially coal ash stored under wet conditions (Ghafoori et al., 2024; Kaladharan et al., 2019). Methods for removing unburned carbon as well as standard specifications on the acceptable levels of unburned carbon that would have no impact on concrete durability need to be determined and specified.

The simple beneficiation methods needed for most harvested ash are drying and de-agglomeration. Other beneficiation methods to reduce the impact of unburnt carbon include thermal beneficiation, electrostatic separation, air classification, and chemical passivation, with thermal beneficiation being the widely used commercial technique are discussed below.

Thermal beneficiation

Thermal beneficiation treatments involve processing coal ash at elevated temperatures to alter its physical and chemical characteristics (Castleman, 2017). This method primarily serves to improve the overall quality and uniformity of the coal ash by reducing the loss of ignition (LOI) and eliminating ammonia (Gardner et al., 2017). Additionally, the process enhances its strength and performance in concrete. Candidate ashes for thermal beneficiation must have a moderate unburnt carbon content. If the unburnt carbon content is too low, there will not be sufficient fuel in the ash to power the heating to dry and ignite the carbon. If the unburnt carbon content is too high, the ash could be heated to too high of a temperature and recrystallize, reducing reactivity its concrete.

Electrostatic separation

Electrostatic separation is a dry technique designed to remove unburned carbon from coal ash by utilizing the differences in electrical conductivity between the carbon particles and the ash particles (Hrach et al., 2022). This method involves charging the coal ash particles and then separating them based on their polarity within an electric field.

Air classification

Air classification is a technique that separates coal ash based on particle size using aerodynamic forces as opposed to mechanical sieves. This method enhances the fineness and reactivity of the fly ash by selectively removing coarse particles or concentrating fines (Lanzerstorfer, 2015). The process involves passing air through a stream of ash particles, with the finest particles being carried with the airflow to a collection point while coarser particles fall out due to gravity or centrifugal forces (FHWA, 2016).

Chemical passivation

Chemical passivation involves treating harvested coal ash with chemicals to reduce the effects of contaminants, particularly reducing the admixture absorption potential of residual carbon when added to the concrete. This process creates stable surface layers on the ash particles, minimizing their chemical activity and making the ash safer and more effective for use (Chen et al., 2024). This method ensures that the treated ash has more predictable performance characteristics, especially in concrete production where high carbon content can affect durability and strength (FHWA, 2016).

1.4 Coal Ash Combustion Products Characteristics and Concrete Fresh Properties

1.4.1 Characteristics of off-specification coal ash

Fly ash is known to affect the air-entrainment capability of concrete and dosage demand for a required air content. This effect is primarily controlled by the carbon content of fly ash as well as the nature of the carbon particles. Unburnt carbon content in fly ash originates from power plants operation efficiency as well as variation in the loading conditions. Variation in carbon content of fly ash generated from the same power plant using the same coal source has been documented in the literature for several decades. Recently, stricter measures to enhance air quality imposed by regulatory agencies such as US Environmental Protection Agency (EPA) effectively exacerbated this issue further. Currently, to minimize and control particulate emission from coal burning power plants, activated carbon injection is applied for mercury control (Ladwig & Blythe, 2017b). Carbon injection can be implemented in several locations and involves injection of activated carbon in the flue gas path. Activated carbon has high absorption capacity and typically mercury, available in the flue gas, is adsorbed by the activated carbon particles. The efficiency of activated carbon to adsorb mercury is affected by many factors, depending on the flue gas particulate capturing process location as well as its characteristics including availability of other constituents such as sulfur trioxide, hydrochloric acid as well as nitrogen dioxide.

Activated carbon inclusion in fly ash affects the air entrainment dosage required to attain a specified air content in blended concrete mixtures. This is due to the preferential attachment of the chemical admixture to activated carbon particles. Additionally, activated carbon particles in fly ash can limit its use as a feed addition in clinker manufacturing process due to mercury release which is expected to occur at high temperatures typically used in the kiln operation. One of the additional concerns is that the effect is not necessarily correlated to the carbon content, as the degree of carbon activation is of significance on the degree of adsorption of air-entrainment admixtures.

As indicated in the previous paragraphs, activated carbon can be injected at several locations in the flue gas path. It can be injected in the gas following electrostatic precipitators (Ladwig & Blythe, 2017b) which renders fly ash of high quality and generates disposable waste of high activated carbon concentration. Another location can entail injection of activated carbon during the flue gas desulfurization process which can effectively affect the gypsum quality generated as a by-product of FGD process. Mercury capture if conducted as co-removal with FGD by-products is affected by the chloride content of the coal ash as well as the type of particulate control devices. Chemical additions of halogen salts can occur in this process to enhance mercury capture. Examples of chemical additions include calcium chloride and bromide. It is expected that this process of co-removal of mercury during FGD process, will affect FGD solids. Concerns in regard to halogen additions, especially chlorides, is the fact that current specifications for coal ash acceptance do not require chloride content measurements.

Other emission control measures imposed by the US Environmental Agency, entail NOx reduction as well as sulfur removal (desulfurization). The former generates ammonium salts while the latter entails limestone injection resulting in generating calcium sulfates. Using reclaimed/beneficiated ash from landfills or lagoons would therefore be expected to have potential for contamination from particulate waste and emission controlling procedures.

Current specifications for coal ash assess carbon content indirectly through measuring loss on ignition tests (LOI). (ASTM 618-23e). There has been concerns about the correlation between the carbon content and LOI as well as lack of any tests to identify or distinguish between activated and unburnt carbon content. This is exacerbated with the recent use of ponded and landfilled ashes.

1.4.2 Fresh Concrete Properties

1.4.2.1 Air Content

A study was recently conducted by Shearer et al. (2024) on the properties of 8 standard ashes and 14 unconventional ashes, with the latter including beneficiated ashes, reclaimed ash, blended C and F ashes, FGD ash, harvested impounded ash, ponded ash, bottom ash blend and cyclone collected ash. They measured the impact of the coal ashes on entrained air systems using the Foam Index Test, mortar air test, adsorption capacity for air-entraining admixtures, and hardened concrete air void analysis. Two air entraining admixtures were used; namely, sodium lauryl sulfate (SLS) and vinsol resin (VR). All ashes used satisfied the LOI ASTM 618-23e limit of max. 6% except one nonproduction unconventional ash with an LOI of 16.46%. The findings indicate that the mean and range of the LOI values for unconventional ashes were higher than standard ashes. Similarly, (ASTM C1827, 2020) (ASTM C1827-20) testing results for Foam index (FI) indicated off-specification/unconventional ashes had an increased range of FI values indicating potential of encountering higher than typical absorption values for unconventional coal ash sources.

For experiments conducted on air content in mortar, the results indicate that all ashes require higher air-entraining admixture dosage for the same air content compared to the control mixture. The results also indicate that there is not necessarily agreement between FI results and AEA demand for a specified air content. It was also observed that for unconventional ash blends of Class C with Class F ashes or Class C with bottom ash had higher AEA demand similar to cyclone collected ash.

Selected fly ashes were considered for further testing of air content in fresh and hardened concrete. The findings indicate for the selected ashes (7 ashes) tested whether conventional or off-specifications, appropriate air content and spacing factor were obtained provided air-entraining dosage adjustments were implemented. Material variability may be more important for concrete construction because if the material impact on the air entraining admixture changes while the chemical admixture dosage does not, the variability in air content and consequently the variability in strength will increase substantially.

1.4.2.2 Slump

Slump measurements of concrete mixtures using 7 ashes (2 standard and 5 unconventional) indicated that incorporation of standard ashes improved workability compared to the control mixture (Shearer et al., 2024). For unconventional ashes, slump measurements showed conflicting results where some sources increased workability (but not as conventional ashes) while others decreased it. The authors explained the reduction in slump to be due to the morphological aspects of the unconventional ash particles. The authors concluded that “Caution should be taken on an individual basis to safeguard against ashes that exhibited workability issues, notably unconventional ashes C, S, U, J and B”. To clarify, C ash is a circulating fluidized bed (CFB) ash, S ash is reclaimed ash which has undergone beneficiation using heat treatment and grinding, U ash is a high LOI ponded ash blend, J ash is cyclone collector ash and B ash is off-specification ash which undergone beneficiation using sieving and grinding.

In another study focused on the use of CBA (Ankur and Singh, 2021), where bottom ash was used as a fine aggregate replacement, workability was found to decrease with increasing replacement level. However, an increase in workability for replacement levels of up to 25% of portland cement was also reported when compared to portland cement mixtures or mixtures incorporating conventional fly ash. This was thought to be due to the coarser bottom ash particles.

1.4.2.3 Setting Time

As a result of stricter air emission regulations, several processes are currently implemented in coal fired electric power plants to enhance air quality. In addition to activated carbon injection discussed previously, flue gas denitrification as well as desulfurization are commonly used processes. Example of the former is selective catalytic reduction process of NO_x with NH_3 (Qin et al., 2019). The authors reported that this process can result in adsorption of ammonium hydrogen sulfate (NH_3HSO_4) and ammonium sulfate ($(NH_3)_2SO_4$) on fly ash particles which can result in a reaction between the ammonia salts with hydroxyl ions during cement hydration and subsequent release of ammonia gas with potential negative effects on cement and concrete performance. In their study, they evaluated the effect of ammonium hydrogen sulfate and ammonium sulfate at different concentrations on the cement paste properties at 20% fly ash replacement. Their findings indicate that the initial and final set of the cementitious paste were retarded, with the degree of retardation related to the concentration of the 2 compounds. Retardation ranged from 19.7%-41.3% compared to fly ash mixtures that did not include the ammonia compounds. In addition to the retardation effect, the 28-day strength was affected negatively.

Inclusion of bottom ash has different effects on setting behavior when used as a replacement for portland cement (Ankur and Singh, 2021). Increasing bottom ash content increases the setting time, while mortar incorporating up to 25% replacement decreased the initial and final set compared to plain mortar mixtures as well as mixtures blended with fly ash. The effect seems to depend on the fineness of bottom ash where increasing the fineness decreases setting times.

1.4.2.4 Chemical Admixtures Adsorption

Flue gas denitrification by selective catalytic reduction was also reported to affect chemical admixture adsorption of polycarboxylate-based superplasticizers (Qin et al., 2019). Increasing ammonium salts concentration to the range encountered as a result of denitrification increased adsorption of superplasticizers. Similar effects were noted for the AEA dosage with adsorption increasing with ammonia content. Compared to fly ash with no ammonia salts addition, ammonium hydrogen sulfate addition increased the superplasticizer adsorption rates by 50.1-169%, and for air entraining admixtures the increase was 47.5-226.8%, while ammonium sulfate addition increased adsorption by 69.4-88.3% for superplasticizer. The increase was more modest for AEA (29.4-50.6%). The authors hypothesized this could be due to chemical interaction between the ammonium salts and the admixtures molecules.

1.5 Coal Ash Effects on Concrete Mechanical Properties

In general, inclusion of specification-compliant fresh fly ash in concrete mixtures results in a decrease in the 7-day strength, (Siddique, 2008) The effect is dependent on the class of fly ash and is more apparent in Class F ashes. Class C ashes, however, have higher strength than F ash and can show similar strength values to the control mixtures at 7-days as they are cementitious as well as pozzolanic. In both classes, however, later strength is higher than the control mixtures. Similar effects are reported on the elastic modulus, where early-age elastic modulus is lower but at later age it is higher than the control mixtures. As for creep rates and strains, there are conflicting findings in the literature, with similar, higher or lower creep rates reported.

As a result of stricter US EPA rules for emission control, selective catalytic reduction process typically implemented for flue gas denitrification, can result in formation of ammonia compounds adsorbed by fly ash particles that can affect performance of fly ash in cementitious systems. In addition to their effect on the setting behavior of fly ash blended cementitious systems, it has been reported that early strength reduction (maximum of 10%) was observed (Qin et al., 2019). Strength reduction was believed to be due to the chemical reaction between ammonium sulfate or ammonium hydrogen sulfate and calcium hydroxide from the cement reaction. The chemical reaction resulted in the release of ammonia and a corresponding change in the pore structure of the hydrated cement paste. Mercury intrusion porosimetry measurements indicated an increase in pore coarseness due to the addition of ammonium compounds.

Strength is affected by several characteristics of unconventional coal ashes; namely, higher LOI, lower specific surface area or coarser particles, higher sulfate content, sulfate form, chlorides, or differences in particle morphology. It is therefore expected that bottom ash will have negative contribution to concrete strength as bottom ash particles are typically coarser even if they have the same amorphous content as its counterpart fly ash. Data on compressive strength of unground bottom ash indicate lower strength compared to its fly ash at the same cement replacement level (Shearer et al., 2024). Similar findings (Al-Shmaisani et al., 2019) on strength performance of milled bottom ash, where the strength activity index assessed using a constant w/cm ratio, was found to be lower than the control as well as Class F and C standard ashes mixes.

Bottom ash has a lower reactivity at early age and the effect is more pronounced with increasing the ash content, (Ankur and Singh, 2021). However, it appears that there is an optimum replacement level to maintain the required compressive strength, above which lower compressive strength can occur. Additionally, different processing options for bottom ash have substantial effect on its performance.

While there are several articles addressing the effect of bottom ash on compressive strength, very limited data is available on their effect on flexural strength, tensile strength and elastic and dynamic modulus and depends on the replacement level as well as replacement method (sand versus cement). For flexural and tensile strength, no significant effect reported with bottom ash replacement up to 20%; however, for higher replacement levels, a decrease in tensile strength was reported. Reduction in the dynamic modulus was also reported with bottom ash use (Ankur and Singh, 2021).

In conclusion, the effect of bottom ash and other coal ash products on the mechanical properties of concrete can be substantially different and dependent on the chemical composition, mineralogical composition, physical properties, beneficiation process used as well as replacement level and method.

1.6 Coal Ash Effects on Concrete Long-Term Durability

1.6.1 Fluid and Ion Transport

Chloride-induced corrosion, alkali-silica reaction, and sulfate attack are three of the most common causes of concrete deterioration and all involve fluid and ion transport into the concrete. Coal fly ash is the most used supplementary cementitious material in the United States because it can improve concrete durability by improving the concrete transport properties. Coal ash can improve the transport properties of concrete regardless of whether it has been stored and harvested or not, fly ash or ground bottom ash, and even in some cases not meet the requirements of ASTM C618 or AASHTO M 295, if it has sufficient pozzolanic reactivity (AASHTO M 295, 2021; Argiz et al., 2018; ASTM C618-23e1, 2023; Shearer et al., 2024).

A recent study on the performance of unconventional coal ashes examined 16 total coal ashes. Coal ashes studied included conventional fly ashes meeting ASTM C618, circulating fluidized bed (CFB) coal ash, loss on ignition (LOI) >6%, SO_3 >5%, >34% retained on No. 325 sieve (coarse ashes), reclaimed ashes, blends of Class F and Class C ashes, and bottom ash blends. Some ashes were beneficiated by particle size separation/ reduction, drying, heat treatment to lower carbon content and showed good reactivity and resistance to chloride penetration. Conventional coal fly ash vs unconventional coal ashes showed no statistically significant difference in the depth of chloride penetration for concrete samples after rapid chloride permeability tests. Concrete performance was more related to the ash properties than conventional or unconventional status. Ashes that are with coarse particle size distributions, very high SO_3 content, or high loss on ignition (LOI) tended to show low compressive strengths and smaller improvements in pore structure and resistance to chloride penetration compared to the control ordinary portland cement control mixture. All coal ashes studied reduced the penetrability between 28 and 91 days, indicating improvements in the pore system and better durability in marine environments important for Florida (Shearer et al., 2024).

A recent study compared the ASTM C1202 rapid chloride permeability measurements of concrete made with fly ash and ground bottom ash from the same power plant after 91 days of curing in a moist room. The mixtures containing fly ash had a minimum charge passed at 20% cement replacement with the charge increasing as the replacement level increased up to 60% cement replacement. The mixtures containing ground bottom ash however showed a continual decrease in the charge passed up to 60% cement replacement (Chuang et al., 2023). It is possible that the fly ash mixtures at a high replacement level could continue to decrease with additional curing. Another study examined the effects of blending Class F and Class C fly ash together on the charge passed in ASTM C1202. They compared the performance of Class F and Class C fly ash blends with 25, 50, and 75% Class F fly ash. Mixtures made with blended fly ash containing 25% and 50% Class F ash in the blend were measured to have charge passed at 91 days of 580 and 600 coulombs, respectively, while the mixture with 75% Class F fly ash had 1275 coulombs of charge passed. These were all better however than the reference OPC and the mixture containing 35% replacement with 100% Class C fly ash (Malisch, 1998).

Coal bottom ash can reduce the pore size distribution and improve fluid transport properties when finely ground. Concrete made with ground coal bottom ash at a 25% cement replacement showed 3.0 times lower chloride effective diffusion coefficient D_e than concrete made with 25% cement replacement by coal fly ash from the same power plant. The ground bottom ash was also found to increase the concrete resistivity by 6.7 times at 132 days compared to the control OPC and 3.1 times that of the mixture containing fly ash. The chemical composition of both ashes were similar, but because the coal bottom ash was able to be ground much finer than the fly ash, the reactivity was much higher (Argiz et al., 2018). Another study found that the ground bottom ash electrical resistivity correlated with the ash reactivity and chloride transport properties, with similar or better performance than fly ash (Kasaniya et al., 2021).

1.6.2 Chloride Binding

ASTM C618 does not contain a chloride content limit for coal ash. FDOT specification 934 however limits the total or acid-soluble chloride content of fresh concrete to 0.4 lb/yd^3 for concrete in moderately or extremely aggressive environments to help reduce the probability of reinforcing steel corrosion. Coal ashes with moderate chloride contents can fail this limit in concrete with coal ash contents between 18% and 50% as required by FDOT specification 346 and typical cementitious contents used in Florida concrete. For example, a concrete mixture made with 658 lb/yd^3 of cementitious materials and 30% by mass replacement of cement by coal ash with a chloride content of 0.2% would just meet the FDOT total acid-soluble chloride limit. Research on concrete made with coal ashes with varying chloride concentrations showed however that many of the chlorides from the coal ash are bound and not free to cause reinforcing steel corrosion, as shown in Figure 3. All concrete mixtures except that made with fly ash with very high chloride content at 50% fly ash were under ACI recommended water soluble chloride limits (Ortiz, 2020).

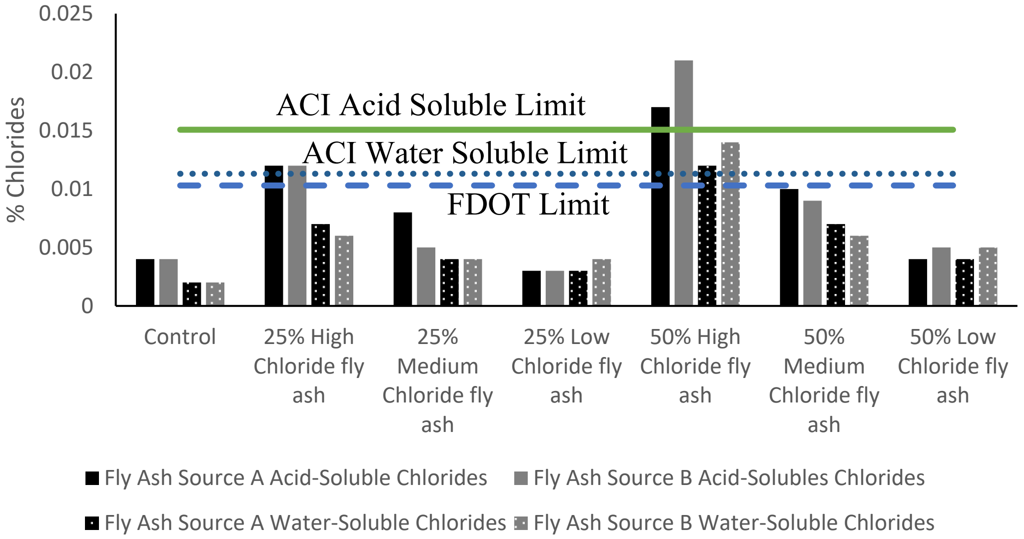

Figure 3: Acid and Water-Soluble Chloride Content for an FDOT Class IV Concrete Mixture (Ortiz, 2020)

1.6.3 ASR resistance

Ground bottom ash can be used to mitigate ASR. Some ground bottom ash may need a slightly higher cement replacement level with some Class F sources to control ASR expansion compared to fly ash because of slightly lower amounts of reactive silica and alumina that consume less calcium hydroxide and bind less alkalis (Hooton & Thomas, 2021; Oruji et al., 2019). Other Class F ground bottom ashes have performed as well or better than the comparable fly ash because they are able to bind more alkalis in hydration products (Kasaniya & Thomas, 2022). Class C ground bottom ash required a lower replacement level to mitigate ASR than the companion fly ash in one case, however more study is required (Hooton & Thomas, 2021). Because bottom ash particle size distribution and to some degree reactivity can be controlled through grinding, the ground bottom ash ability to mitigate ASR can be improved and have less variability than fly ash (Spencer, 2022). Harvested Class C coal ash, when ground, can help mitigate ASR. One study on three harvested and ground coal ashes measured the cement replacement level required to mitigate ASR according to ASTM C1567 (ASTM C1567, 2021). Coal ashes S1 and S2 had CaO contents of 26.4% and 26.5%, while S3 was right at the limit of Class F and Class C coal ash with a CaO content measured to be 17.6%. It found that Class C harvested and ground coal ash could effectively mitigate ASR with a very highly reactive fine aggregate, with higher replacement levels needed for the ashes with the higher CaO (S1 and S2) contents than lower CaO contents (S3), as shown in Figure 4. This is similar behavior as what is expected from fresh coal ash (Alaibani, 2021).

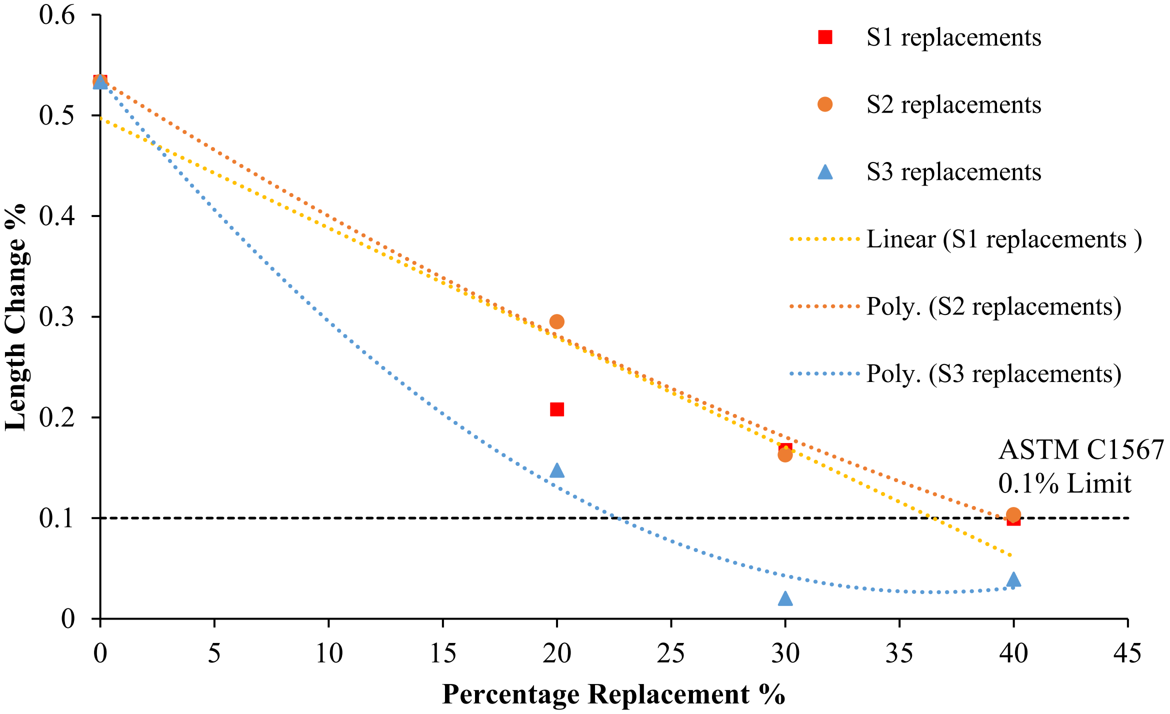

Figure 4: 14-Day Length Change Measured According to ASTM C1567 for Varying Replacement Levels of Harvested and Ground Coal Ash (Alaibani, 2021)

Coal ashes that blend material from two different power plants with different CaO contents can be used to mitigate concrete ASR. Testing however showed that a blended coal ash with a CaO content of 15.7 required a higher replacement level to mitigate the expansion than that of a reclaimed coal ash with a CaO content of 2.7% (Drimalas et al., 2023).

1.6.4 Dimensional Stability

Coal ash can cause some changes in the drying shrinkage performance of concrete mixtures; however, the difference may depend on the amount of curing provided, the coal ash properties, or other properties. One study compared a fresh fly ash with a ground bottom ash from the same power plant. Both materials were shown to increase the drying shrinkage at 91 days, with the ground bottom ash showing less shrinkage at early ages and slightly more shrinkage than the fly ash at 91 days. Detailed information on the curing provided for these mixtures was not provided, nor was the data analyzed statistically to determine the statistical significance of any differences seen. (Chuang et al., 2023). Another study showed that different Class F and Class C coal ashes had different effects on the drying shrinkage, with some showing higher shrinkage, and some lower than the control OPC. Blends of Class F and Class C fly ash showed similar results to binary mixtures, with some blends showing higher shrinkage and some showing lower shrinkage than the control mixtures (Okechi, 2019). A study performed on mortars showed that all coal ashes tested reduced drying shrinkage compared with the OPC mixture (Ghafoori et al., 2024).

1.6.5 Sulfate Attack

The sulfate attack resistance of coal ash, whether stored or fresh, is dependent mostly on the pozzolanic reactivity and chemical composition. High CaO contents in the ash that often correspond with high C_3A contents, coarse ashes with low reactivity, or high sulfate contents in the ashes can result in concrete expansion and disintegration when exposed to sulfates (Alaibani, 2021; Shearer et al., 2024).

Harvested coal ash performs according to the same general trends as fresh coal ash. Class F fly ash can reduce expansion in mortar tests. ASTM C1012 mortar bars made with PLC and harvested Class F fly ash showed improved performance over the control samples made with just PLC. ASTM C1012 mortar bars made with a Type I cement and harvested Class F coal ash or ground bottom ash showed lower expansion than those of mortar bars made with a Type V high sulfate resisting cement at 6 and 12 months (Hooton & Thomas, 2021). When impounded or landfilled, some of the phases of Class C coal ash can react hydraulically. This cements together large granules in the ash that either need ground or removed by sieving. The high porosity granules and reacted portions of the Class C coal ash are exposed to carbon dioxide during their storage. This can lead to high amounts of calcium in the ash reaction products carbonating, resulting in large quantities of calcium carbonate and alumina gel in the ash, as shown in Figure 5 Class C coal ash can be beneficiated by adding calcium sulfate and in some cases limestone fines to the cementitious system to improve sulfate attack durability. Some harvested Class C coal ashes contain their own source of calcium carbonate and may not need additional limestone fines. The combination of limestone fines and calcium sulfate additions to the cement helps promote the formation of carboaluminate phases and ettringite over monosulfoaluminate, improving sulfate attack durability, as shown in Figure 6 (Alaibani, 2021).

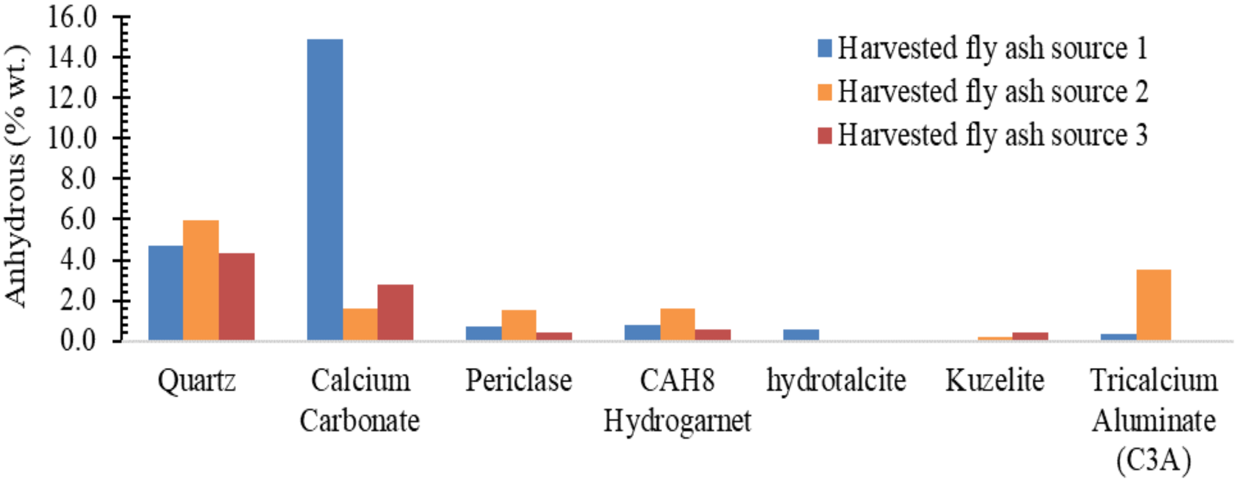

Figure 5: Crystalline Material Quantities in Harvested Class C Coal Ashes Measured Using Semi-Quantative X-Ray Diffraction (Alaibani, 2021)

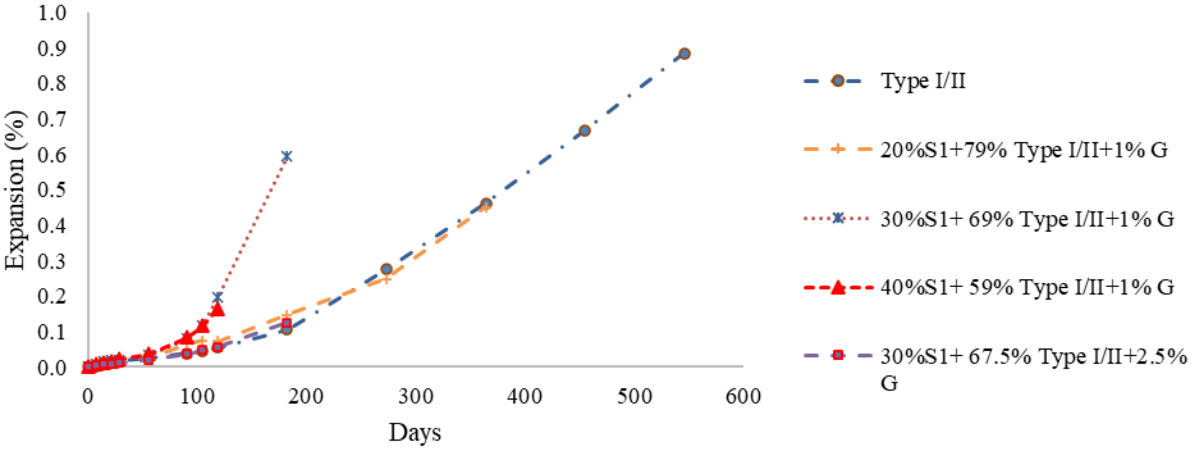

Figure 6: Effect of Gypsum Additions on Sulfate Attack Durability of Mortar Bars Containing Harvested and Ground Class C Coal Ash (Alaibani, 2021)

Some Class F coal ash is often blended with Class C coal ash to lower the CaO content and produce an ash that overall meets the requirements of a Class F coal ash. The resulting ash has been shown to have a sulfate attack durability in between that of the parent Class F and Class C fly ashes and can, when used in sufficient quantities, help the cementitious system meet the requirements of a moderate sulfate resistant cement (Franklin & Rhodes, n.d.).

When ground, fresh Class F bottom ash can mitigate sulfate attack as well as fresh Class F fly ash (Kasaniya et al., 2021). Conversely, coal ash with low CaO contents and low sulfate contents can have excellent durability in sulfate-rich environments even after ponding or landfilling (Shearer et al., 2024). The fineness and strength activity index requirements help protect against excessive amounts of coarse and inert or minimally reactive material increasing the system porosity and decreasing the sulfate attack durability. The 5.0% SO_3 limit given in ASTM C618 for coal ash helps prevent excessive calcium sulfate contents that can sometime come from intermingled flue gas desulfurization (FGD) material and cause sulfate attack in the concrete (Hooton & Thomas, 2021).

1.6.6 Frost and Salt-Scaling Resistance

Concrete frost protection is partially provided by the entrained air void system. Coal ash can contain carbon that can absorb air entraining admixtures that stabilize air bubbles during the mixing process. The carbon content and the carbon surface area both impact the ability of the carbon to absorb the air entraining agent. It is thought that the introduction of low NOx burners in the mid 2000s caused the surface area of carbon in fly ash to increase and absorb additional air entraining agent, and become more variable. Some power plants also started injecting powdered activated carbon (PAC) into the flue-gas duct to capture mercury (Ladwig & Blythe, 2017b). PAC can absorb air entraining agents and make it difficult to entrain air in the concrete and reduce the value of the fly ash, however the effect is greater when the PAC is added separately to the concrete than when found as a constituent of the fly ash collected directly from the power plant in lab tests designed to measure the impact of the PAC on the concrete properties (Mahoutian et al., 2015).

The impact of the coal ash on air entraining agent demand can be rapidly measured using ASTM C1827 "Standard Test Method for Determination of the Air-Entraining Admixture Demand of a Cementitious Mixture (ASTM C1827, 2020)." Tests on conventional and unconventional coal ash showed that most coal ashes had similar air entraining demand, and that differences were seen based on the carbon content and nature rather than whether the coal ash was conventional, from bottom ash or fly ash, or harvested (Shearer et al., 2024).

Coal ash can be beneficiated to improve the air entrainment and freeze-thaw performance. Carbon beneficiation methods include use of electrostatic separation, heating the ash to burn off carbon, and treating the coal ash with a passivating chemical to reduce the ash's ability to absorb admixtures

(Tritsch et al., 2021). A laboratory study on passivating chemicals for carbon showed that treated fly ash has lower concrete air content variability, but that as long as the concrete had at least 5% air content, the freeze-thaw durability was good (Ojo, 2018). Fly ash that was heated to reduce the carbon content prior to testing the air entraining agent demand showed much lower air entraining agent demand than before heating, indicating that the carbon was responsible for the high demand and that the ash could be beneficiated (Ley et al., 2008). Some coal ash that was produced and stored in the 20th century before the introduction of low NOx burners has been found to have lower LOI and sulfur content than ash currently being produced at the same power plant, producing concrete with lower air entraining agent demand than currently produced ash (ECO Material Technologies, 2022). Harvested coal ash with high loss on ignition is often treated by drying and igniting to reduce the carbon content. Because this operation is directed at improving the ash quality, low and consistent air entraining agent demand can be achieved, leading to high quality air void systems in concrete and good frost resistance. This is in contrast to how the ash is treated in the power plant, which is as a waste material where the ash quality is of little concern to the producer.

Blending Class F and Class C fly ash could alter the deicer salt scaling performance of concrete in laboratory tests. A study performed comparing the performance of different blends of Class F and Class C fly ash at 40% cement replacement found that as the percentage of Class F fly ash increased in the blended fly ash, the salt scaling durability worsened. Class C fly ash used at a 35% replacement level however showed no salt scaling damage after 50 freeze-thaw cycles, performing significantly better than the control OPC concrete mixture (Malisch, 1998). It is possible however that the results were influenced by problems finishing concrete containing high replacement levels of Class F fly ash in small laboratory specimens that are not representative of field performance in machine-placed concrete flatwork.

1.7 Health and Environmental Implications of Coal Ash Use in Concrete

1.7.1 Air Pollution

Coal-powered power plants produce electricity by combusting powdered coal in boilers that use the heat generated to produce steam from water that then turns a generator to produce electricity. During the coal combustion process, many materials are gasified or react to become gases. Other solid material in the coal such as inorganic materials may melt at the high boiler temperatures. Some material may agglomerate together and form larger particles that are removed from the bottom of the boiler as bottom ash. Other melted material may be small and lightweight enough to travel with the gasses out of the boiler. These small, melted droplets of material will cool as the gas cools after leaving the boiler, forming small particles with morphologies that approximate spheres. Hollow particles called cenospheres and nested hollow spheres called plerospheres can also form with the solid particles as part of the fly ash that is captured as part of the pollution control equipment using electrostatic precipitation and large filter bags. Materials that can change phase to a gas or form as part of the combustion reaction include mercury, oxides of nitrogen, sulfur dioxide, ozone, carbon monoxide, and carbon dioxide (Ladwig & Blythe, 2017b). The US Environmental Protection Agency (EPA) has established regulations that limit the release of some of these materials into the air from the power plant smokestack. As these regulations have come into effect, many coal-burning power plants have had to install air pollution control equipment to meet emission limits. The processes used to capture and reduce emission of air pollutants can impact the composition and ability to meet ASTM C618 for use of the coal ash as an SCM in concrete.

Sulfur dioxide emissions have been reduced significantly since the introduction of stringent limits by the EPA. Coal burning plants can use wet or dry sorbents such as limestone or lime to react with SO_2 and SO_3 in the flue gas and remove it from the air. Limestone or lime and water injected into the flue gas stream in forced oxidation processes react with sulfur-bearing molecules and form gypsum. This flue gas desulfurization material can be recycled and used in place of natural gypsum as a component in portland cement manufacturing or into dry wall (Gypsum Association, 2024; Ladwig & Blythe, 2017b). Wet systems can also capture fly ash particles in the system. If landfilled and comingled with coal ash, FGD will contaminate the ash and likely make it unsuitable for use in concrete.

Oxides of nitrogen quantities are reduced in the flue gas through selective catalytic reduction. In this process, ammonia or urea are injected into the flue stream reacts with the nitrogen oxides to form water and nitrogen gas that are not considered harmful pollutants (Ladwig & Blythe, 2017b). Some fly ashes will have residual ammonia present and a resulting strong smell.

Mercury is removed from the flue-gas stream by activated carbon injection (ACI), fabric filter and carbon injection, oxidation catalysts with electrostatic precipitation and flue gas desulfurization systems. ACI use is the most common and reliable method of removing mercury pollution from the flue gas. Calcium chloride or calcium bromide additives can be used for cases when particularly poor coal is used in the power plant (Ladwig & Blythe, 2017b).

Coal ash can contain quartz or other siliceous particles small enough to be considered respirable silica. As part of OSHA requirements found in 29 CFR 1910.1053(f)(2)(1), worker exposure to coal ash dust should follow exposure control plans to limit silica dust exposure and prevent silicosis or other preventable respirable illnesses (OSHA, 2019).

1.7.2 Water Quality

Coal ash contains small quantities of heavy metals and other pollutants that can leach out of the ash during long-term storage. These pollutants include "cadmium, chromium, lead, nickel, zinc, copper, vanadium, mercury, arsenic, and selenium (Schwartz et al., 2018)." Fly ash contains much more of these heavy metals than bottom ash because they can volatilize during coal combustion (Meij, 1994). FGD can contain water soluble compounds that can include "boron, carbon, sulfur, chlorine, bromine, nitrogen, mercury and selenium (Schwartz et al., 2018)." Modern landfills and impoundments are built with composite clay and at least 30-mil geomembrane liner meant to stop any harmful elements from leaching into the groundwater, a leachate collection system to capture and treat water before it can contaminate groundwater, and a groundwater monitoring system according to 40 CFR Part 257 Subpart D. The US EPA has long recognized that while stored coal ash may contain some heavy metals in trace amounts, the risk associated with using coal ash as a supplementary cementitious material or in wall panel products is very low and is considered non-hazardous. The US EPA has determined that when used in concrete or wall panel products, coal combustion products pose a similar or lower risk than similar alternative materials used in these products. Concrete and wall panel products tested "were found to be at or below all relevant regulatory and health-based screening benchmarks identified (US EPA, 2014)." When FGD is used in agriculture, it was determined that risks of selenium release into water could be managed by minor limits on use (US EPA, 2023).

A study was conducted on seven locations in four states (Minnesota, Wisconsin, Indiana, and Georgia) to determine the increased risk of groundwater contamination from the use of fly ash and bottom ash in roadway stability and fill applications. Leaching of 17 elements including Ag, Al, As, Ba, Be, Cd, Co, Cr, Cu, F, Hg, Ni, Pb, Sb, Se, Ti, and Zn were measured for the sites. All sections evaluated were found to either contain "no risk" because their trace element concentrations were below federal water quality limits, or "no additional risk" because element concentrations did not exceed that found at control sites that did not contain coal ash. This demonstrates that coal ash can be used in roadway unencapsulated applications without significant increase in health risk to the public (Brown, 2015).

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Chapter 2 Test Matrix for Phase II

2.1 Background

Based on the findings from the literature review, and discussions with the State Materials Office Engineers, cementitious materials proportions are proposed that will provide results to enable the safe use of coal ash as a new supplementary cementitious material in FDOT structural concrete. In addition, the Test Matrix includes a combination of all appropriate tests for the characterization of the as-received material, including physical, chemical and mineralogical testing. The Test Matrix also includes tests for the evaluation of fresh and hardened properties including long-term durability for potential aggressive marine exposures that are of concern due to the state of Florida geological conditions and geographical location. The ultimate objective is to ensure the safe use of coal ash as a new supplementary cementitious material in FDOT structural concrete. The matrix also provides necessary scientific testing that can correlate/corroborate performance test criterion to long term durability testing. This is very critical as previous research indicates that one performance criterion or limit does not necessarily apply for all different supplementary cementitious materials; however, with proper scientific testing such criterion can be modified/adjusted or confirmed for further implementation for this new coal ash.

2.2 Proposed Matrix

The proposed test matrix addresses concerns identified through the literature review; namely, potential elevated chloride content, potential contamination with different forms of sulfates, potential issues with setting behavior due to presence of ammonium bisulfate, and variation of air content due to injection of activated carbon. Performance of coal ash can also be complicated due to the current practice of blending high and low lime ash. This is of concern due to the presence of calcium aluminate and sulfates reactive compounds in the former. Blending can render concrete susceptible to sulfate attack in addition to unpredictable adiabatic temperature rise in massive concrete structural elements. The proposed matrix also addresses concerns related to blending of processed bottom ash with fly ash and its implications on concrete strength and durability performance. The proposed cementitious mixture proportions matrix is provided in Table 3.

Table 3: Cementitious Mixture Proportions

	Ash CaO Content		4	10	17	23	4	10	17
Mix #	Coal Ash Composite CaO	IL	Class F Fly Ash 1 (FFASH1) %	Class F Fly Ash 2 (FFASH2) %	Class F Fly Ash 3 (FFASH3) %	Class C Fly Ash 1 (CFASH1) %	Class F Bottom Ash 1 (FBASH1) %	Class F Bottom Ash 2 (FBASH3) %	Class F Bottom Ash 3 (FBASH3) %
1		100							
2	4	70	30						
3	10	70		30					
4	17	70			30				
5	23	70				30			
6	4	70					30		
7	10	70						30	
8	17	70							30
9	10	70	20.6			9.4			
10	17	70	9.4			20.6			
11	17	70		13.9		16.1			
12	10	70				9.4	20.6		
13	17	70				16.1		13.9	
14	4	70	10				20		
15	4	70	20				10		
16	10	70		10				20	
17	10	70		20				10	
18	17	70			10				20
19	17	70			20				10
20	8	70	10					20	
21	6	70	20					10	
22	12.7	70	10						20
23	8.3	70	20						10

Prior to blending of low and high lime fly ashes or bottom ash with fly ash, all as-received materials will be subjected to a battery of characterization tests as outlined in Table 4.

Table 4: As-Received Materials Characterization Tests

Material	Property to Measure	Method
Cementitious Materials	Fineness/particle size Bulk oxide composition Bulk mineralogy Specific gravity	Laser particle size analyzer, Blaine fineness X-ray florescence (XRF) ASTM C1365 (semi-quantitative XRD) Gas Pycnometer
Aggregates	Specific gravity Absorption capacity Particle size distribution	ASTM C127 &128 ASTM C127 & 128 ASTM C136

Accordingly, the proposed Tasks and Deliverables are as follows:

Task 1: Material Acquisition and Characterization

Concrete constituent materials will be acquired for this project. Cementitious materials and aggregates will be characterized to determine relevant material properties using the methods listed in Table 5. Laser particle size analysis, gas pycnometry, and X-ray florescence will need to be performed at the FDOT State Materials Office, with the rest of the tests performed at UF or USF.

Accordingly, for this part of the proposed work, and upon completion of Task 1, the university will submit a report in the form of a technical memo to the Research Center at research.center@dot.state.fl.us that contains a summary of materials acquired and their chemical and physical properties.

Task 2: Fabricate Test Specimens

Cement paste, mortar, and concrete specimens will be fabricated for FDOT performance tests and other tests for comparison to determine the performance of concrete made with different types of coal ash. Table 5 shows the specimen types and amounts anticipated to be made for each mixture using proportions identified in Table 3. The activation energy will be used to aid in calculating the concrete adiabatic temperature rise used in thermal control plans. Mortar mixtures will be made to measure sulfate attack and delayed ettringite formation durability. Concrete mixtures will be made to measure the impact of different coal ashes on setting time, compressive strength, and bulk resistivity. Semi-adiabatic calorimetry will be performed on concrete mixtures to measure the impact of different coal ashes on concrete adiabatic temperature rise.

Table 5: Cement paste, mortar, and concrete specimens

Material	Property to Measure	Method	Age	# Specimens/ Mixture
Cement Paste	Activation Energy	Isothermal calorimetry @ 23°C, 40°C, 50°C	72 to 168 hrs	2
Mortar	Sulfate durability	ASTM C1012	1,2,3,4,8,13,15,17,26,39, and 52 weeks	6
	Delayed ettringite formation		1,2, 3,6, and 12 months	4
Concrete	Compressive strength	ASTM C39	3, 7, 28, 56 days	12
	Bulk resistivity	ASTM C1876 (using limewater for curing)	28, 56, 91 days	3
	Surface resistivity	AASHTO T358	28, 56, 91 days	-
	Adiabatic temperature rise	Semi-adiabatic calorimetry	10 days	1
	Drying shrinkage	ASTM C157	455 days	3
	Shrinkage Ring Testing*	AASHTO T 334 modified for FDOT	35 days	3

*Modified AASHTO T 334 will be performed for concrete mixtures 1, 2, 5, and 10

Deliverable 2: Upon completion of Task 2 the university will submit a report in the form of a technical memo to the Research Center at research.center@dot.state.fl.us that contains details of the concrete mixtures made and their fresh properties.

Task 3: Cement Paste Performance

Isothermal calorimetry tests made in Task 2 will be completed during this task. Isothermal calorimetry measurements will be made at 23°C (73°F), 40°C (104°F) and 50°C (122°F). Activation energies will be calculated from the cementitious system heat of hydration measurements and used in calculating adiabatic temperature rises for concrete mixtures.

Deliverable 3: Upon completion of Task 3 the university will submit a report in the form of a technical memo to the Research Center at research.center@dot.state.fl.us that contains the results of cement paste performance tests for Florida mixtures containing coal ash.

Task 4: Concrete Mechanical and Durability Property Results

Concrete compressive strength tests started in Task 2 will be completed during this task. Sulfate attack and delayed ettringite formation tests started in Task 2 will be completed during this task. Sulfate attack and delayed ettringite specimen expansion will be measured until 12 months of age. Concrete bulk and surface resistivity, semi-adiabatic calorimetry, and drying shrinkage tests started in Task 2 will be completed during this task. Concrete shrinkage ring tests for mixtures 1, 2, 5, and 10 will be performed. The concrete adiabatic temperature rise for mixtures containing coal ash will be calculated using the results of the semi-adiabatic calorimetry and isothermal calorimetry tests using the procedures developed in the FDOT Next-Gen concrete performance testing initiative.

Deliverable 4: Upon completion of Task 5 the university will submit a report in the form of a technical memo to the Research Center at research.center@dot.state.fl.us that contains the results of concrete mechanical and durability property tests for Florida mixtures containing coal ash.

Task 5: Draft Final Report and Closeout meeting

Deliverable 5a: Thirty (30) days prior to the end date of the task work order, the university will submit a draft final report to research.center@dot.state.fl.us

The draft final report will contain the literature review, values for performance indicators, compilation of concrete mixes, and work plan for the second phase. The draft final and final reports must follow the Guidelines for University Presentation and Publication of Research available at https://fdotwww.blob.core.windows.net/sitefinity/docs/default-source/research/docs/t2/university-guidelines-2020285147769.pdf?sfvrsn=edd6df4d_2 and the FDOT Research Final Report Style Guide provided at https://fdotwww.blob.core.windows.net/sitefinity/docs/default-source/research/docs/t2/style-guide-2020.pdf

Deliverable 5b: Thirty (30) days prior to the end date of the task work order, the principal investigator will schedule a closeout teleconference. The principal investigator shall prepare a PowerPoint presentation following the template provided at https://fdotwww.blob.core.windows.net/sitefinity/docs/default-source/research/program_information/research.performance/closeout.meeting.reqs.pdf?sfvrsn=9b9774c1_2. At a minimum, the principal investigator, project manager, and research performance coordinator shall attend. The purpose of the meeting is to review project performance, the deployment plan, and next steps.

Task 6: Final Report

The project final report will be written based on feedback received on the draft final report from the project manager. The report will include recommendations for changes/additions to current state specifications based on the conducted research findings.

Deliverable 6: Upon Department approval of the draft final report, the university will submit the Final Report in PDF and Word formats electronically to the Research Center at research.center@dot.state.fl.us The Final Report is due by the end date of the task work order.