TECH BRIEF

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Advancing Concrete Pavement Technology Solutions

USE OF HARVESTED FLY ASH IN HIGHWAY INFRASTRUCTURE

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Summary and Disclaimers

The purpose of this Tech Brief is to describe the characteristics of harvested coal fly ash and identify considerations for its use in highway infrastructure. The document is intended for highway agency and contractor engineers.

The contents of this document do not have the force and effect of law and are not meant to bind the public in any way. While this is non-binding guidance, compliance with applicable statutes and regulations cited is required.

ASTM International and American Association of State Highway and Transportation Officials (AASHTO) standards are private, voluntary standards that are not required under Federal law. These standards, however, are commonly cited in Federal and State construction contracts and may be enforceable when included as part of the contract.

Introduction

Coal fly ash is an integral part of durable concrete for use in highway infrastructure. Historically, fly ash has been obtained directly from coal-fired power plants as it is being produced. Recent changes in fly ash production and availability, however, have resulted in challenges regarding both the supply and quality of fly ash in some markets, which in turn has caused providers to turn to a new source for the material, harvested fly ash.

Harvested fly ash is ash that was not used as it was produced but was instead deposited in landfills or impoundments for disposal. In many cases, the disposed ash is good-quality ash; there simply was not sufficient market demand for it to be used beneficially at the time of production. Harvested fly ash is becoming a principal source of fly ash for the concrete industry in some geographic areas and is soon expected to become a significant portion of the total fly ash supply.

Background

Fly ash is the airborne, non-combustible residue that results from coal-fired electric power production. Its use in concrete was first described in 1937 (Davis et al. 1937), but despite the compelling research presented in that early publication, fly ash was initially used only to replace the most expensive part of a concrete mixture (i.e., the portland cement) as a less expensive filler, not as a supplementary cementitious material (SCM).

Over time, largely in the last 50 years, concrete engineers have come to understand how to improve the properties of concrete by including fly ash in a concrete mixture, and fly ash has now become a common component in concrete.

Benefits of Fly Ash in Concrete

Workability – Replacing, on a weight basis, portland cement with fly ash, which typically has a lower specific gravity than cement, increases the paste volume if the water-to-cementitious material mass ratio (w/cm) is held constant. The volume of the concrete mixture typically is corrected by withholding an equal volume of fine aggregate. Increased paste content improves concrete workability.

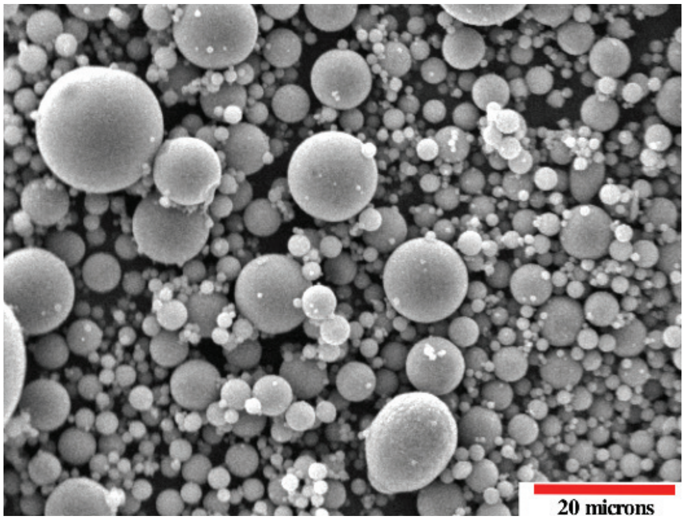

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Figure 1. SEM micrograph of fly ash particles illustrating the spherical particle shape typical of coal fly ash

In addition, the spherical shape of fly ash, illustrated by the scanning electron microscope (SEM) micrograph in Figure 1, imparts a "ball bearing" effect to fresh concrete that also contributes to workability improvements.

Bleeding – Fly ash generally reduces the amount of water needed to obtain a given slump or flow in a concrete mixture. This results in reduced bleed water.

Pumpability – The spherical particle shape of fly ash improves pumpability by reducing friction between particles as well as between the mixture and the pump line. The water-reducing effect of fly ash also reduces segregation while concrete is being pumped.

Set Time – Partially replacing portland cement with fly ash generally extends concrete set time, and this effect can become more pronounced as the percentage of cement replaced is increased. Fly ash with CaO contents greater than 18 percent (i.e., Class C fly ash as defined by AASHTO M 295 or ASTM C618) can have a greater influence on extending set times than fly ash with lower CaO contents (i.e., AASHTO M 295 or ASTM C618 Class F). In concrete containing fly ash, set time can be adjusted using accelerating admixtures.

Compressive Strength – Concrete containing fly ash generally develops a higher ultimate strength than a portland cement-only mixture with the same total cementitious material content. The addition of fly ash may, however, result in a slower rate of strength development, especially when using Class F fly ash. Class C fly ash has a lower impact on the rate of strength development.

Freezing and Thawing – Fly ash itself has little effect on the ability to entrain air in concrete or a concrete's resistance to freezing and thawing cycles. However, unburned carbon in fly ash can adsorb air-entraining agents (AEAs), thereby reducing their effectiveness in producing an adequate air void system.

Most fly ashes contain unburned carbon from the coal combustion process. In addition, some plants inject powdered activated carbon (PAC) into the flue gases to control emissions. The PAC is intermingled with the fly ash and captured as part of the particle collection system used to capture the fly ash in the power plant. These PAC particles have a much greater specific surface area than regular unburned carbon particles and typically impact air entrainment through AEA adsorption.

Fly ash sources with high carbon contents, regardless of the type of carbon, can be beneficiated to mitigate the impact of the carbon on AEA adsorption. These beneficiation technologies include the following:

1. Removal of carbon by electrostatic separation (Bittner and Gasiorowski 2005).
2. Reburning the fly ash to burn off residual carbon (Knowles 2009).
3. Chemically passivating the carbon surfaces, thereby mitigating their capacity to adsorb air entraining agents (Minkara 2015, Plunk 2015).

In general, care should be taken when proportioning air-entrained concrete containing fly ash to ensure the formation of an adequate air void system.

Deicing Salt-Induced Scaling – The risk of concrete scaling typically increases with increasing fly ash content, largely due to the need for extended curing times resulting from the slower rate of strength development. This effect is typically more pronounced with low-CaO Class F fly ashes.

Research has shown that slip-formed concrete has much greater resistance to scaling than expected for a given cement replacement level (Thomas 1997). Fly ash, predominately Class F fly ash, has been shown to improve a concrete's resistance to chemical attack by deicers due to calcium oxychloride formation (Sutter et al. 2008, Monical et al. 2016, Suraneni et al. 2017).

Permeability and Corrosion of Reinforcing Steel – Fly ash reduces concrete permeability by reacting with calcium hydroxide in the concrete to generate additional hydration products. This is referred to as the pozzolanic reaction, and the products of the reaction refine the concrete's pore structure, which lowers the rate of ingress of fluids.

The pozzolanic reaction rate is relatively slow when compared to portland cement hydration and continues over the course of many years. Therefore, at early ages there is little difference in permeability between concrete with and without fly ash. But after a year or more, the permeability of concrete containing fly ash can be significantly less than that of a comparable cement-only mixture (ACI Committee 232 2018).

Alkali-Silica Reaction (ASR) – This deleterious reaction occurs between certain reactive siliceous aggregates and alkalis in concrete, causing expansion and eventually widespread cracking (Thomas et al. 2008). Fly ash can mitigate ASR-induced expansion in concrete by reacting with alkalis and binding them within pozzolanic reaction products and by reducing the concrete's permeability, thereby limiting the mobility of alkalis and water within the concrete.

Both Class C and Class F fly ash can mitigate ASR, but Class F fly ash is more effective; for the same aggregate and total cementitious material content, the amount of a typical Class C fly ash used to mitigate the ASR-induced expansion of a given aggregate is larger than the amount of a typical Class F fly ash used.

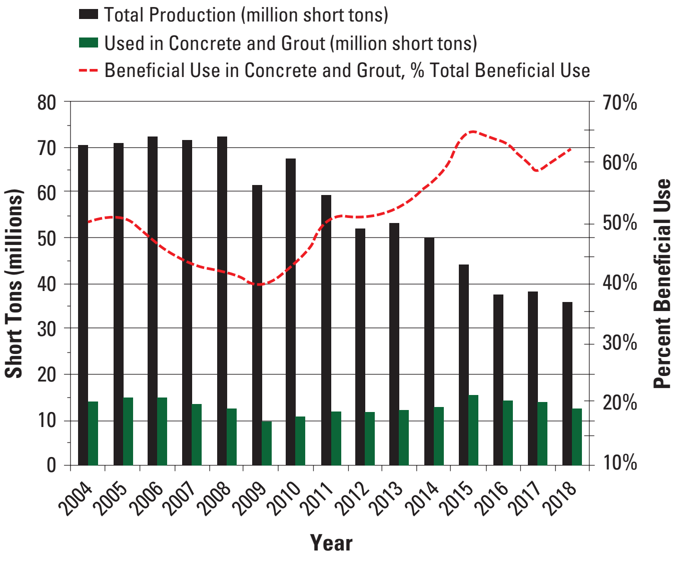
In total, the effects of fly ash in concrete have made it a common component in concrete mixtures when improved durability is desired. This is reflected in the new performance engineered mixtures (PEM) approach for designing durable concrete mixtures, described in AASHTO PP 84, Standard Practice for Developing Performance Engineered Concrete Pavement Mixtures.

The PEM approach considers six key metrics critical to concrete constructability and longevity: aggregate stability, concrete permeability, resistance to freezing and thawing, volume stability, strength, and workability. Fly ash plays an essential role in optimizing these key metrics, which has made it not only desirable to include in concrete but also, in many cases, required by highway agencies and other users.

Supply Issues Related to Fly Ash

Since approximately 2008, the electric power industry has undergone a major shift away from coal-fired electric power plants in favor of plants using natural gas or passive power production (e.g., through photovoltaic solar cells or wind turbines). This change has resulted in a dramatic reduction in coal fly ash production, as shown in Figure 2.

As seen in Figure 2, the total production of coal fly ash has diminished from a high of 72.5 million short tons in 2008 to 36.2 million short tons in 2018 (ACAA 2019).



Data from the American Coal Ash Association, Coal Combustion Products Production & Use Statistics, https://www.acaa-usa.org/publications/productionusereports.aspx

Figure 2. United States coal fly ash production and use for the period 2004–2018

Meanwhile, in 2018 the beneficial use of fly ash in concrete accounted for 12.5 million short tons of the material, which represented over 60 percent of its total beneficial use. Although the total tonnage of fly ash used in concrete has not increased significantly in the past 10 years, the concrete industry's demand for fly ash, as a percent of the material's total beneficial use, has increased by nearly 50 percent.

Because, as noted above, fly ash has historically been used in part to reduce the cost of a concrete mixture by replacing portland cement with a lower cost SCM, cost has always been a consideration affecting fly ash distribution. As a result, fly ash is, in general, used within proximity to its point of production. Transporting fly ash large distances significantly increases the cost, and the price point of fly ash in most markets does not support these added transportation costs.

The net result of these market pressures coupled with the overall decrease in supply has been spot shortages of fly ash in some markets and, in some cases, shortages of fly ash that has the performance attributes for use in concrete. Balancing supply and demand is limited by the cost of transportation, so to address demand in some markets, accessing disposed ash, referred to as harvesting ash, is an emerging solution.

Harvested Fly Ash as a Solution

Because the supply of freshly produced fly ash has been significantly reduced while the demand is increasing, harvested fly ash is likely to become a significant source for concrete-grade fly ash in the near and long terms. In many cases, ash disposed of in landfills and impoundments would have met the performance attributes for use in concrete, but it was disposed of due to a lack of demand in the available markets at the time of its production.

In the past 18 years alone, approximately 658 million short tons of fly ash have been produced with approximately 27 percent being beneficially used, the rest being disposed of (ACAA 2019). This leaves over 480 million short tons of ash in disposal that are potentially available for harvesting. At the current use rate of fly ash in concrete, that amount corresponds to over 50 years of reserves.

Not all ash in landfills and impoundments is suitable for use in concrete or available for harvesting. However, fly ash has been produced in the US since the early 1900s (Speight 2012), and much of the older material is also available for use.

Production and Beneficiation

Potential sites for harvesting fly ash vary in composition and quality throughout the site. To help ensure quality and consistency, as well as consensus, industry standards are being developed by ASTM International for identifying and commissioning harvesting sites.

A first standard is ASTM E3183, Standard Guide for Harvesting Coal Combustion Products Stored in Active and Inactive Storage Areas for Beneficial Use, which covers the harvesting of fly ash from landfills and impoundments. That ASTM standard provides a framework for characterization of the site, planning and scoping of a harvesting project, the design and approval process (as applicable), as well as the implementation of harvesting. That first standard, ASTM E3183, does not address processing the material to meet ASTM C618 or AASHTO M 295.

With very few exceptions, harvested ash will be processed for use in concrete. One processing operation that is involved is drying the harvested material to meet specification moisture content limits. The moisture in landfilled material results from the common practice of adding water to the disposed material for optimum compaction, from groundwater if the landfill is not lined, or simply from exposure to the environment.

Screening or other size separation will also commonly be done. In disposal sites, fly ash is often comingled with bottom ash. Since bottom ash generally has a granular sand-like particle size, it can be screened from fly ash. Air classification using cyclone sizers or other technologies typically will be used to size the finest fractions. When grinding, sizing can be done in a closed circuit with grinding mills to achieve the desired size distribution or to re-expose pozzolanic material, especially if a certain degree of self-cementing has occurred.

Depending on the specific materials present at a given site, additional beneficiation may be involved. The most common reason for additional beneficiation is the presence of excessive carbon in the harvested material. This is not unexpected, because much of the ash placed in disposal sites was often disposed of simply because it had a high loss-on-ignition (LOI) content when it was produced. Many processes can be used to remove excess carbon, and they are the same processes used to beneficiate freshly produced ash. These include triboelectrostatic separation, carbon burnout, and passivation of carbon surfaces.

Triboelectrostatic separation is a process for separating unburned carbon from coal fly ash. The combined fly ash and carbon is fed into a separator, and the particles pass between two planar electrodes that charge the particles in an electrostatic field (Bittner and Gasiorowski 2005). The carbon assumes a positive charge, while the mineral species assume a negative charge. The charged particles are then attracted to oppositely charged electrodes and swept away by a moving belt in opposite directions to areas where they are collected (Bittner and Gasiorowski 2005).

Carbon burnout can be done in many ways. In one process, residual carbon is removed by combustion in a fluidized bed combustor (FBC). The FBC's temperature is raised to the point where carbon auto-ignition occurs (i.e., 860°F) but the mineral species in the fly ash are not altered (Keppler 2001).

More recently, a carbon burnout process has been developed that utilizes a turbulent flow reactor (combustor) with staged introduction of air to effect staged combustion. The process differs from one that uses an FBC in that it uses turbulent air flow to reduce agglomeration, thereby improving the particle-size distribution of the material while burning off the residual carbon (Knowles 2009).

In another approach to carbon burnout, high-carbon harvested fly ash is comingled with the coal fuel for an operating power plant combustor. The process both burns the residual carbon and provides the benefit of fuel recovery (Rosenmerkel and Ramme 2015).

Passivation refers to treatment of the ash with a chemical that preferentially adsorbs on the carbon, blocking the adsorption sites on the carbon particles' surfaces so that AEA cannot be adsorbed. Passivation processes are relatively low cost compared to physical treatment processes, and many technologies have been implemented by various fly ash producers (Minkara 2015, Plunk 2015).

In general, triboelectrostatic separation and carbon burnout involve significant capital investment and a steady supply of materials to be economically feasible. Therefore, a source of fly ash typically will be harvested only when there is a combination of sufficient market demand (i.e., limited access to other sources), adequate fly ash reserves at the harvesting site to sustain a long-term business plan for payback of the capital investment, and/or regulatory/legislative pressure to process a disposal landfill or pond for beneficial use.

Sites where fly ash has been comingled with desulfurization byproducts during the disposal process are currently not being considered for harvesting. However, processes to treat ash from these sites have been developed, and these materials could conceivably be utilized later.

Specific Considerations for Harvested Fly Ash

The primary performance benefits of using fly ash in concrete stem from the pozzolanic properties of the material. The pozzolanic reaction occurs between alkali ions, water, and the glassy phases in the fly ash. Fly ash landfills or impoundments, where harvested fly ash may be obtained, are typically not highly alkaline (Roy and Berger 2011). This means that harvested fly ash is expected to retain its pozzolanic properties. This has been confirmed through various research studies (Diaz-Loya et al. 2019, Al-Shmaisani et al. 2018).

Figure 3 shows SEM micrographs illustrating the similarities between freshly produced fly ash and harvested fly ash from the same power generation station.

In Figure 3, the harvested fly ash appears to have lost surface texture because of being landfilled, but the basic particle shape and integrity is retained. In harvested fly ash, the cementitious components would likely have reacted over time while the pozzolanic glass (amorphous, non-crystalline) phases would be retained.

Harvested fly ash will almost always undergo some processing or beneficiation to meet applicable construction specifications. In addition to drying, sizing, and grinding, harvested fly ash may be blended to meet the uniformity requirements of those specifications. The blending could involve fly ash from different locations in the same harvesting site, harvested fly ash from multiple sites, or harvested fly ash blended with freshly produced fly ash.

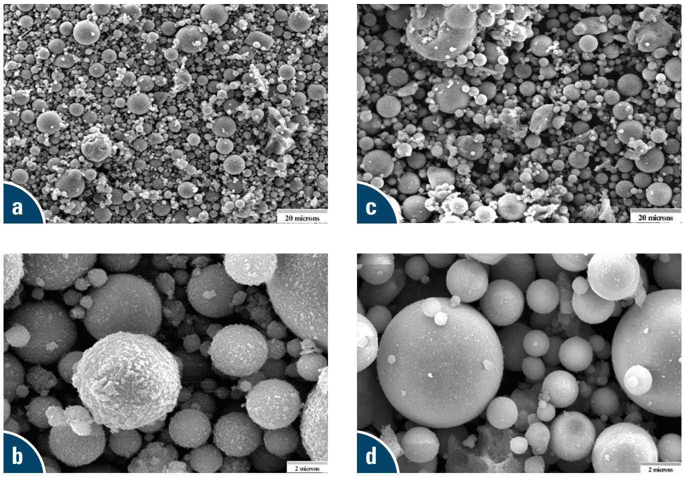


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Figure 3. SEM micrographs illustrating the similarities between freshly produced fly ash (a and b) and harvested ash (c and d) from the same power generation station

The process of harvesting fly ash will likely include more sampling and testing than is commonly done for fresh fly ash production. An increased frequency of testing should improve the consistency and uniformity of the harvested material compared to that of the freshly produced fly ash.

Harvested fly ash may be sourced from mono-fills in which only fly ash has been disposed or from landfills where the fly ash has been comingled with other coal combustion products, such as bottom ash and desulfurization byproducts. Given that landfills are in exposed conditions and many are unlined, there is a chance that clays, silts, and other materials may also become comingled with the ash due to infiltration, particularly at the base and boundaries of the deposit. Processing can separate most of these materials, but no beneficiation process is absolute, and some non-fly ash materials may remain comingled, albeit to a small degree. This factor should be addressed moving forward.

ASTM and AASHTO Specifications and Testing

ASTM C618 and AASHTO M 295 are the most common fly ash specifications cited in highway construction contract documents. Both are constantly being reviewed and improved to ensure these standards are applicable to harvested ash as well as fresh ash, and improvements in testing are currently being discussed. These improvements involve measurement of the following properties: (1) reactivity, both pozzolanic and hydraulic, (2) particle-size distribution, (3) adsorption, and (4) uniformity. Each of these limitations is discussed in more detail in subsections that follow.

Both ASTM C618 and AASHTO M 295 classify ash produced from coal combustion into one of two categories: Class F or Class C. The only distinction between the two classes is the bulk composition of the ash, where Class F fly ash has a CaO content of 18 percent or less and Class C fly ash has a CaO content greater than 18 percent. For both classes, the specification indicates that the cumulative percentage of silica, alumina, and iron oxides (i.e., $SiO_2 + Al_2O_3 + Fe_2O_3$) be 50 percent or greater.

Test methods for fly ash are specified in ASTM C311, Standard Test Methods for Sampling and Testing Fly Ash or Natural Pozzolans for Use in Portland-Cement Concrete. ASTM C311 references many other ASTM standards and modifies them as needed for use with fly ash.

Reactivity

Determining the bulk composition of a fly ash is a general method of classification, but the absolute reactivity, both pozzolanic and hydraulic, can vary within a specific class and is largely affected by the characteristics and abundance of glass phases in the ash. Class F materials tend to have a higher glass content than Class C materials.

Harvested fly ash will likely be blended to meet a specification, and for cases where harvested materials from different sites or sources are blended, the distinction between Class C and Class F materials based on composition may be less meaningful than for freshly produced fly ash. It is likely that all harvested fly ash will be richer in glass content because the hydraulic phases will have reacted in the landfill or impoundment, leaving only glass phases. Measuring the reactivity is the only definitive measure that can help characterize these materials.

Particle-Size Distribution

Current ASTM and AASHTO specifications only address particle-size distribution in terms of limiting the amount retained on a 325 mesh (45 micron) sieve to a maximum of 34 percent; this test measurement is referred to as fineness. The most reactive particles in fly ash are typically 10 microns or less, and the fineness test does nothing to quantify this finer particle size fraction.

The sizes of fly ash particles vary in landfills and impoundments due to settling, other transport within the disposal site (e.g., wind or currents), and temporal variations in the as-produced material. Moreover, material such as bottom ash or other diluents (e.g., sand) are coarser than 45 microns, and the existing ASTM and AASHTO specifications could permit up to 34 percent of these materials to be in the coarser fraction.

Attention should be directed to how particle-size distribution is measured and limited, and to the compositional and mineralogical properties of the material, particularly the fine fraction.

Adsorption Properties

The adsorption properties of fly ash are important, as mentioned above; unburned carbon or PAC in fly ash can significantly impact AEA adsorption and, in turn, air entrainment. The current approach to determining carbon content is to measure the LOI fraction of the ash. This test simply measures the mass loss from a sample when it is combusted at 750±50°C. The mass lost is assumed to be carbon, and, in freshly produced fly ash, it typically is.

However, it is not known whether that carbon is highly adsorptive. Given its adsorption capacity, a small amount of PAC could make a negligible change in the LOI test but significantly impact adsorption. In the case of harvested fly ash, carbon contents exceeding specification limits could be a concern because, historically, coal combustion produced fly ash that was high in unburned carbon, and that ash was commonly disposed of in landfills and impoundments. Therefore, when those deposits are harvested, the fly ash will require some processing to either remove the carbon or mitigate its adsorption potential.

An additional consideration for harvested ash is that infiltrating materials or other diluents could be either organic or other material that is lost in the LOI test but may have no impact on adsorption. In short, the LOI is an important component to measure in harvested ash, but, in addition, the adsorption properties of the material need to be established.

Uniformity

Uniformity can be a problem with fresh sources of fly ash and may also be an issue for harvested materials. Day-to-day or load-to-load variations in fly ash may go undetected using current ASTM and AASHTO sampling frequencies. For as-produced material, little can be done to effectively control the material other than blending various ash streams. This is typically hindered by a lack of on-site storage and the necessary blending facilities at power plants.

The processing of harvested fly ash provides an opportunity to test more frequently and blend materials to meet specification requirements. One focus of National Cooperative Highway Research Program (NCHRP) research project 10-104, Recommendations for Revision of AASHTO M 295 Standard Specification to Include Marginal and Unconventional Source Coal Fly Ashes, is to examine the adequacy of current ASTM and AASHTO specification sampling requirements when applied to harvested fly ash.

Changes and Trends in ASTM and AASHTO Fly Ash Specifications

Current tests and specifications for the use of fly ash in concrete are being reviewed by ASTM and AASHTO with special attention to the four areas described above.

Reactivity

At ASTM, many tests are being discussed to measure the reactivity of fly ash. The most recently proposed tests have been developed by RILEM (Li et al. 2018) and are referred to as rapid, relevant, and reliable (R3) tests. These tests react a test material with calcium hydroxide in a solution that simulates concrete pore water and measures either the heat evolution in that reaction through calorimetry or the amount of water bound in the reaction products. Other tests are also being considered, including a test like the lime-based pozzolanic activity index (PAI) test previously used in both AASHTO M 295 and ASTM C618.

For all reactivity tests, a primary challenge will be developing meaningful limits for the measurements or providing guidance to the user on how to interpret the reported results. Nonetheless, there is strong agreement in the industry as evidenced at their meetings that measuring pozzolanic and hydraulic reactivity is a high priority for inclusion into existing ASTM and AASHTO specifications.

Particle-Size Distribution

Determining the particle-size distribution and characterizing the presence of diluents in sized material is more problematic. Existing tests include laser-based particle size measurement to determine particle size and x-ray diffraction to characterize the mineralogy of sized material.

For daily assessment of fly ash quality, however, implementation of these advanced technologies has not occurred possibly due to the complexity of the measurements as well as the high costs associated with the advanced equipment. Likewise, particle size determination and mineralogical characterization have not been implemented for daily quality assessment. These advanced tests, however, may have value for troubleshooting materials-related problems, approving new fly ash sources, or assessing long-term quality trends such as those found through the analysis of 30-day composite samples.

Adsorption Properties

Measuring adsorption properties has been addressed in recent research (Sutter et al. 2013), and tests have been developed. The foam index test has recently been standardized by ASTM and could be a useful field test for assessing changes in fly ash adsorption properties. Other tests developed include measuring fly ash adsorption of standard solutions, such as dilute iodine solutions, or solutions of organic compounds that simulate AEAs.

These adsorption tests are available as either bench tests (i.e., manually performed tests) that can be performed with typical laboratory equipment or automated tests that involve acquisition of proprietary equipment. These tests have been shown to be effective in measuring the adsorption capacity of fly ash (Anzalone et al. 2019) and provide a solution for characterizing both freshly produced and harvested fly ash.

Uniformity

Uniformity could be addressed through more frequent sampling and through implementing tests that measure the important properties described here. Increasing the frequency of testing, however, adds cost and could slow delivery. If a more uniform material is desired, one approach might be to allow fly ash producers to use blending as a means of meeting the desired consistency.

Ongoing Research on Fly Ash Specifications and Testing

NCHRP is conducting research project 10-104, Recommendations for Revision of AASHTO M 295 Standard Specification to Include Marginal and Unconventional Source Coal Fly Ashes. The objective of the project is to examine AASHTO specifications and tests for fly ash with special attention given to harvested fly ash. The research will evaluate the emerging tests and provide recommendations for changes to AASHTO M 295.

As another deliverable, the research will also provide suggestions to State highway agencies regarding the use of materials that do not meet applicable ASTM or AASHTO specifications. Often, these “off-spec” materials have only one or two characteristics that do not meet specification limits, and depending on how the material is used, the shortcomings may not cause performance issues. For example, if a fly ash has a high enough adsorption capacity to impact AEA adsorption, but the project does not require air-entrained concrete, the fly ash may be suitable for use in that application.

Harvested fly ash for use in concrete is currently specified under AASHTO M 295 or ASTM C618. There is also activity with ASTM International to develop a new performance-based specification for SCMs.

Closing

Harvested fly ash is new and is produced and marketed in only a few States; however, harvesting projects at multiple sites around the US are being considered by coal-burning electric utilities and the fly ash industry.

Harvested fly ash can offer two important benefits, among others, to concrete producers and specifiers:

- *Improved Consistency* – While silo-stored fly ash goes directly from the plant or terminal to market with limited processing, harvested fly ash will be the result of a process. Whether this process involves drying and sieving, reburning, or milling, it gives producers the opportunity to assess and ensure the consistency of certain quality metrics.
- *Improved Supply Reliability* – Fly ash production at power plants is subject to shutdowns due to preventive or corrective maintenance or seasonal flutuations driven by power demand. These issues often affect supply if fly ash storage is limited. In contrast, harvesting sites can generally provide many years worth of fly ash supply unaffected by changes in power generation. For these reasons, harvested fly ash offers significant opportunities to improve the reliability of fly ash supply.

Harvested fly ash, or excess fly ash produced and disposed of as waste at some point in the past, is being considered as a viable source of fly ash to supplement the dwindling supply currently being generated by operational coal-fired electric power plants.

With proper processing, harvested fly ash has been shown to match the chemical and physical properties of freshly produced fly ash and can be a viable source of supplemental cementitious material. Development of harvested fly ash sources would augment current fly ash production and help provide a consistent and reliable alternative fly ash supply for the foreseeable future.

Case Studies of Harvesting

Harvested fly ash is currently produced in Pennsylvania, South Carolina, and Wisconsin, as covered in more detail below. The processing at the Pennsylvania site involves drying and screening to produce consistent fly ash meeting ASTM C618 and AASHTO M 295 Class F, while the sites in South Carolina and Wisconsin use thermal processing on high-LOI fly ash to produce consistent specification-compliant fly ash. Additional harvesting projects are being considered by coal-burning electric utilities and the fly ash industry.

Boral Resources, Washingtonville, Pennsylvania

Boral Resources has commenced harvesting and making available approximately 2 million tons of Class F fly ash from a mono-fill in central Pennsylvania. The fly ash was produced by a coal-fueled generating station in the 1980s and 1990s, with the material placed in a covered dry stack on a 30-acre site.

Testing of numerous fly ash samples from 12 borings taken to characterize the site established that the harvested fly ash is of a consistently higher quality than the freshly produced fly ash from the plant across a range of criteria. These testing results are summarized in Table 1.

The harvested fly ash is concrete-grade fly ash with lower levels of LOI and sulfur than the freshly produced fly ash. Foam index testing indicates that the adsorption capacity of the fly ash is low (i.e., it has little to no impact on air entrainment), making the harvested fly ash suitable for applications that involve resistance to freeze and thawing.

Chemical and physical analyses of a boring composite sample of the landfilled fly ash were performed to assess it against both the ASTM C618 and AASHTO M 295 standard specifications. The sample met both standards. The harvested fly ash was also found to contain higher levels of silica and alumina and lower levels of calcium oxide than the freshly produced fly ash and is expected to outperform the freshly produced fly ash as a pozzolan.

Table 1. Comparison of key properties of freshly produced and harvested fly ash from the Washingtonville, Pennsylvania, power plant and harvesting site, respectively, with ASTM C618 specification limits for Class F fly ash for reference

Fly Ash	SiO_2 + Al_2O_3 + Fe_2O_3	SO_3	CaO	Moisture	LOI	Fineness	SAI 7 days	SAI 28 days	Water Req.
Freshly produced	81.99%	2.55%	9.38%	0.21%	8.8%	28.65%	79%	80%	101%
Harvested	90.84%	0.19%	2.21%	0.16%	3.05%	11.9%	79%	83%	100%
ASTM C618 Class F Limits	50.0% min	5.0% max	18.0% max	3.0% max	6.0% max	34% max	75% min	75% min	105% max

SAI=strength activity index

Source: Minkara 2019

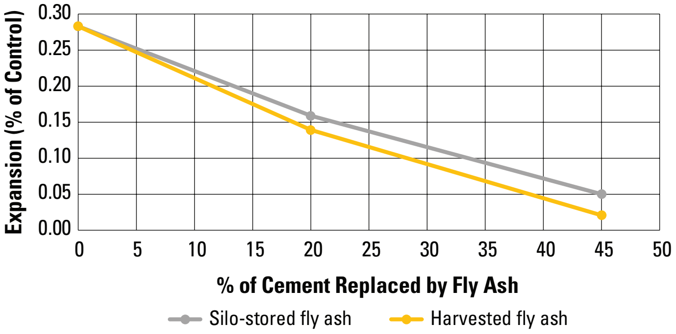

Figure 4. ASR mitigation results comparing the performance of the harvested fly ash and the freshly produced fly ash from the Washingtonville, Pennsylvania, site per ASTM C1567 using Spratt aggregate

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Figure 5. Fly ash harvesting site in Washingtonville, Pennsylvania, with a landfill containing approximately 2 million tons of fly ash (back) and a processing plant (front)

Figure 4 presents a comparison of the ASR mitigation results for both fly ash samples.

An on-site processing plant, shown in Figure 5, has been constructed to dry and beneficiate the harvested fly ash. The material also is tested to assure uniformity for use in ready-mixed concrete.

SEFA Group, Lexington, South Carolina

The SEFA Group originally developed its Staged Turbulent Air Reactor (STAR) process for beneficiating fly ash directly from the power plant, but the company has implemented the technology for processing harvested fly ash.

The first STAR facility was installed in 2008 at the McMeekin Generating Station near Columbia, South Carolina. This facility was designed with a maximum heat input of 35 million metric British thermal units (MM BTU)/hour and is permitted to process approximately 140,000 tons per year of dry fly ash (Fedorka et al. 2017).

The company later installed a modified system, called STAR II, at the Morgantown Generating Station near Morgantown, Maryland. The newer version was designed with a maximum heat input of 120 MM BTU/hour and has a nominal processing capacity of 360,000 tons per year assuming a 9% raw feed LOI (Fedorka et al. 2017).

Based on the experience at these two sites, the SEFA Group decommissioned an FBC carbon burnout system at the Winyah Generating Station near Georgetown, South Carolina, and installed its latest STAR facility, shown in Figure 6.

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Figure 6. STAR facility at the Winyah Generating Station

Although this STAR facility was originally designed to process both freshly produced and harvested fly ash, South Carolina's state-owned electric and water utility, Santee Cooper, recently announced that it is phasing out the four coal-fired combustors at the Winyah Generating Station (Brown 2019). As a result, a higher amount of on-site ponded ash than anticipated will be processed at the site.

This facility combines the STAR process with the technical flexibility to recycle coal ash stored in ash ponds. This plant is the first of its kind designed to remediate commercial quantities of coal ash from ponds, and fly ash produced using the STAR process has been approved for use by 12 state highway agencies. Three additional STAR facilities are planned for construction in North Carolina with the intent of processing harvested fly ash.

We Energies, Oak Creek, Wisconsin

We Energies has a long history of recovering ash for beneficial use and was one of the first producers to harvest fly ash for use in concrete. In 2018, the company utilized an overall total of 91% of its coal combustion products in a variety of applications, including fly ash for concrete.

Like the SEFA Group's process, We Energies' process for harvesting fly ash involves thermally reducing the LOI of the harvested material, but with a unique approach. At its now-closed Pleasant Prairie Power Plant, We Energies developed a reburning process for beneficiating high-LOI fly ash that involves blending a small portion of this material with delivered coal and using the blended fuel for power generation. This allows the company to take advantage of the fuel value of the carbon in the harvested fly ash while recapturing the mineral component as newly produced fly ash.

Since 2000, the use of this reburn strategy has displaced over 450,000 tons of coal while still producing a fly ash meeting ASTM C618 and AASHTO M 295. Based on the experiences at the Pleasant Prairie Power Plant, which closed in 2018, the design of We Energies' Elm Road Generating Station, which came online in 2010, included an investment in an ash reburn facility that feeds harvested ash onto the belts supplying coal to the generating station at a consistent, prescribed rate, yielding a specification-compliant fly ash.

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The mission of the National Concrete Pavement Technology Center is to unite key transportation stakeholders around the central goal of advancing concrete pavement technology through research, tech transfer, and technology implementation.