Harvested Landfilled Fly Ash in Concrete: A Case Study

Technical Brief — *Coal Combustion Products Management*

Introduction

Pozzolans have been used to enhance contrete durability since Roman times. Since the 1930s, coal fly ash has been the primary pozzolan in US concrete. The beneficial use of fly ash in concrete forms an important market for ash produced at electric power plants. Data from the American Coal Ash Association (ACAA) indicates that the percentage of fly ash beneficially used continues to increase (Figure 1).

Coal-fired electricity generation has decreased from 1.9 terawatt hours (TWh) in 2010 to just 0.9 TWh in 2021 (Figure 2) according to the US Energy Information Administration (EIA). As a result, total fly ash production has declined by more than 50% in the US since 2010 (Figure 1). The downward trend in coal generation and associated fly ash production is projected to continue as an additional 59 GW of coal-fired electric generating capacity is set to retire by 2035 (EIA).

As a result of the overall decline in fly ash production due to the retirement of coal generation and the flexible operations of the remaining generation fleet, fly ash use has not kept pace with growth in portland cement use (Figure 3). Based on ACAA and United States Geological Survey (USGS) data, fly ash replacement of portland cement peaked in 2015 at about 16% of total portland cement used.

Although beneficial use accounts for much of the coal ash produced today, limitations associated with local coal ash markets, in-plant ash handling technology, and ash quality historically resulted in much of the fly ash going unused. Instead, the unused fly ash was stored in surface impoundments and landfills. However, changing market conditions and the increasing focus on the decarbonization of concrete (Shah 2022, Hafez 2020) are anticipated to increase the demand for coal combustion products (CCPs).

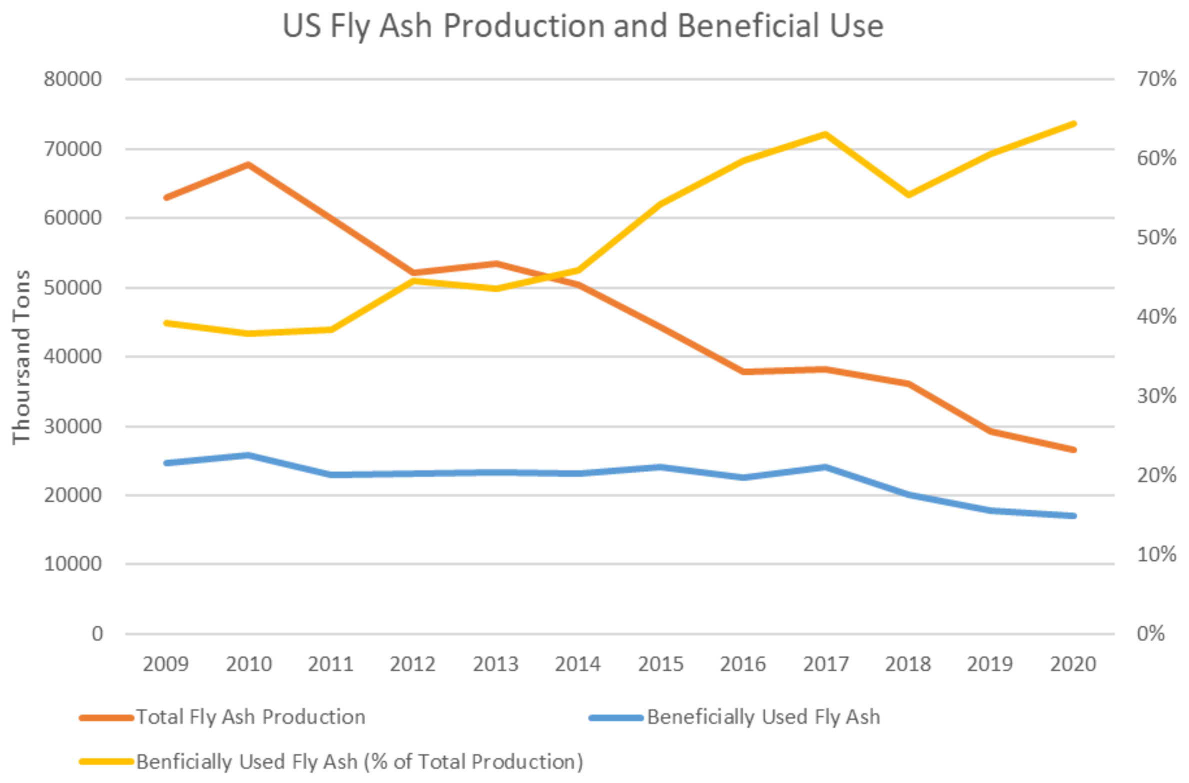

Figure 1. Fly Ash Production and Beneficial Use, 2009-2020 (ACAA 2021)

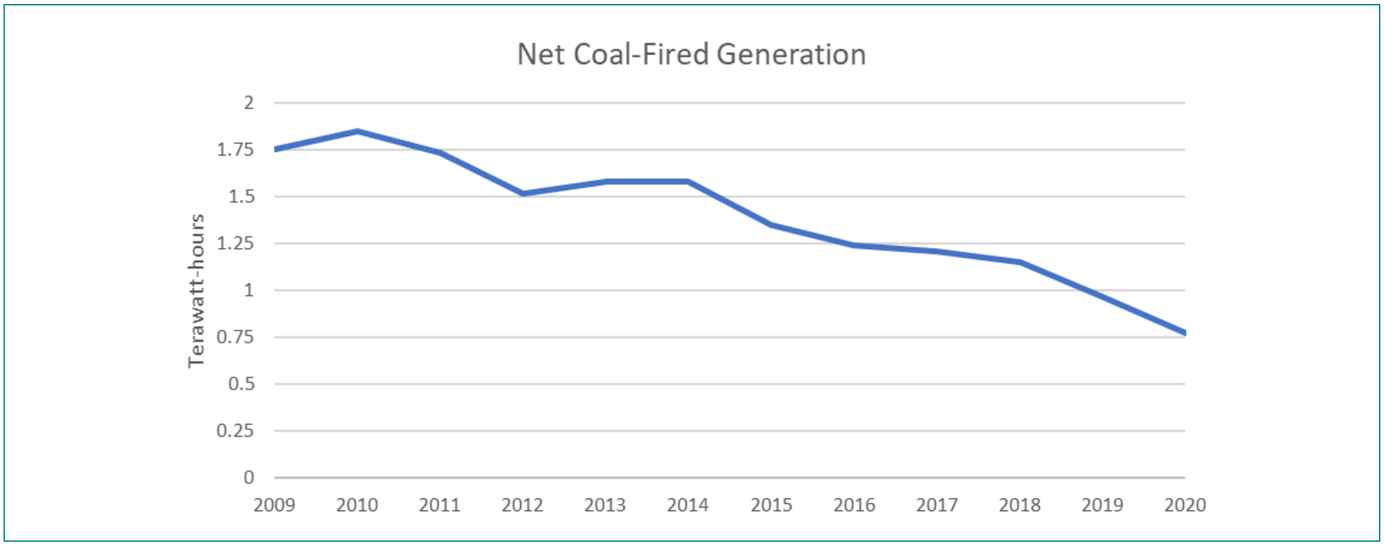

Figure 2. U.S. Coal-fired Electric Generation, 2001-2020

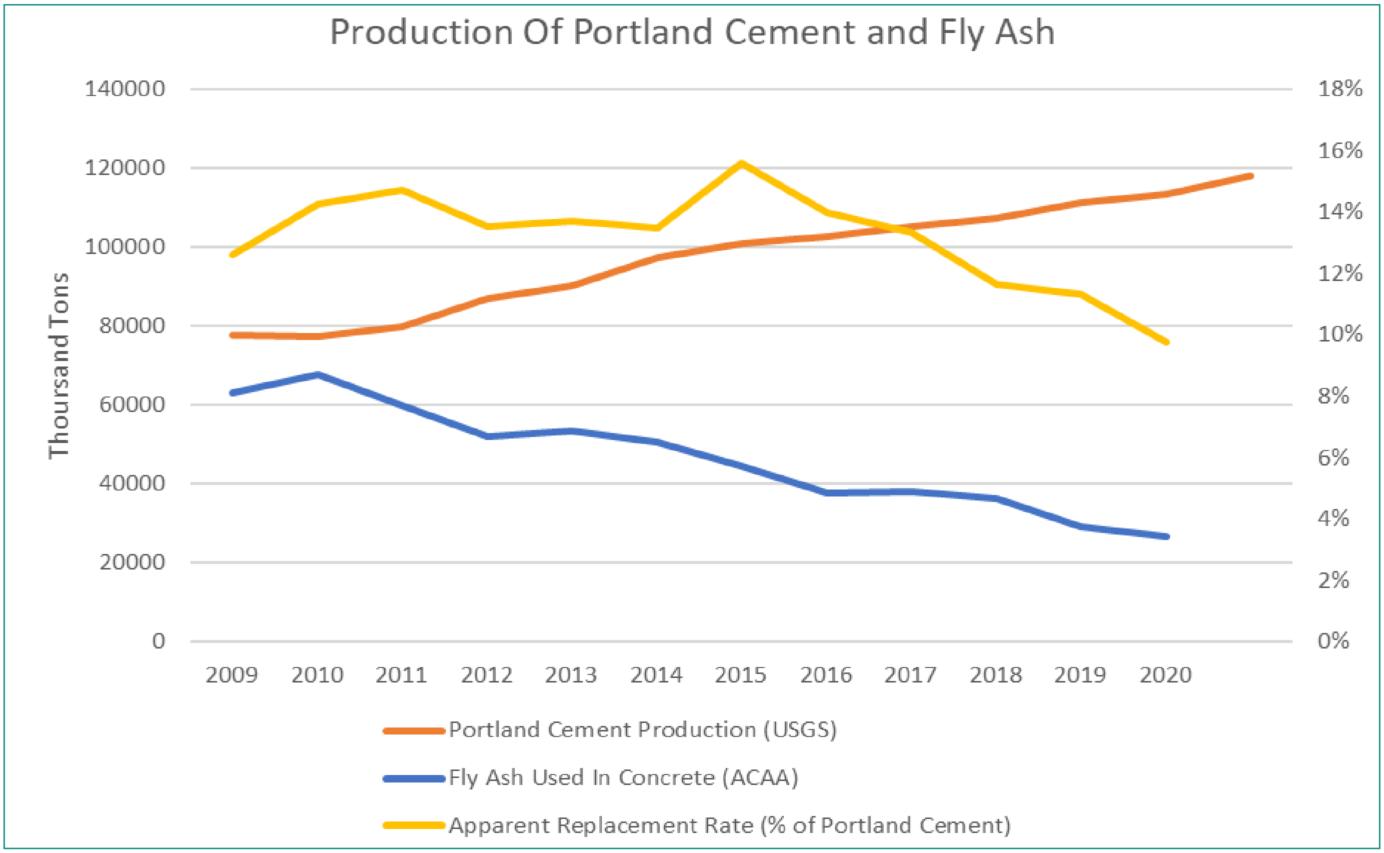

Figure 3. Production of Portland Cement and Fly Ash, 2009-2020

Before the 2015 passage of the US Coal Ash Disposal Rule (40 CFR 257), the US Environmental Protection Agency estimated that 310 landfills and 735 surface impoundments nationwide were being used to store CCPs. One estimate based on extrapolation from production and use surveys puts total US fly ash reserves at about 2 billion tons (Minkara 2020). Some storage units have already been closed, but an abundant and widespread distribution of stored CCP remains across the country. In addition, based on public announcements, several ash harvesting projects, amounting to more than 1M tons per year, have already begun (Figure 4).

Since fly ash was often stored without future beneficial use in mind, concerns about the potentially poor quality of the stored fly ash are a possible barrier to harvesting. These concerns commonly include the following:

- Excess vegetation in the ash, particularly in surface impoundments
- Excess unburned carbon measured by loss-on-ignition (LOI)
- Poor fineness
- Comingling with bottom ash, gypsum, or other products

A range of academic publications have characterized impounded and landfilled fly ash (Tyra 2003, McCarthy 2013, Kaladharan 2019, Wirth 2019) and demonstrated that it could serve as cement replacement in concrete (McCarthy 1998, Robl 2017, Diaz-Loya 2019, Rajabipour 2020, Wang 2022). Researchers used a range of techniques to characterize the ponded and landfilled ash and identified several processing approaches to produce fly ash that meets specifications for use in concrete (Robl 2008, Jones 2009, McCarthy 2018, Innocenti 2021).

To enable the fabrication of uniform products, rapid characterization is an important component of the successful harvesting of fly ash for beneficial use. This brief summarizes some of the technologies and management approaches that have been used or proposed in the characterization and processing of stored CCP, focusing on the rapid characterization tools that can potentially be used at a fly ash harvesting site. An example of the successful utilization of harvested CCPs is then discussed.

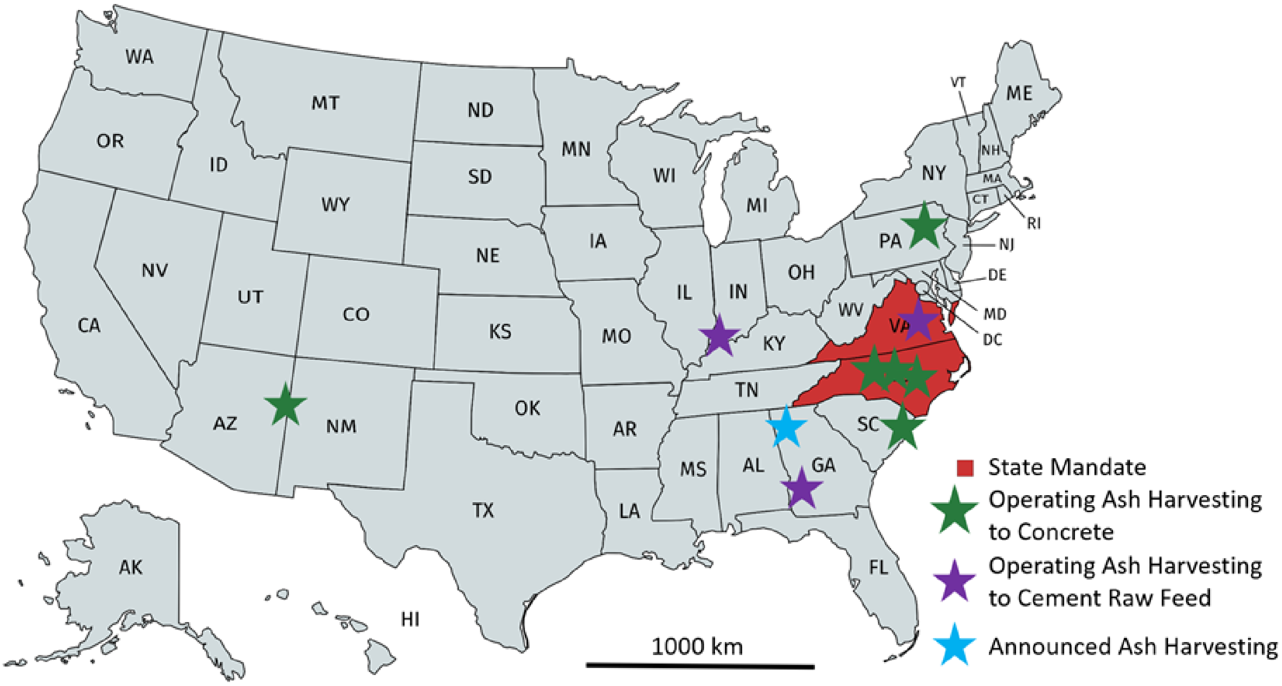

Figure 4. US Ash Harvesting Locations

Determining Ash Quality – Field, Laboratory, and Process Quality Monitoring

Despite the abundance of stored fly ash, ensuring the harvested fly ash meets specifications like ASTM C 618 is challenging for utilities and ash marketers. Operators often placed the ash in storage units without consideration for future beneficiation. As a result, much of it has been commingled over time with other byproducts of coal plant operation, such as gypsum, coal pile runoff, boiler slag, and various liquid waste streams. Furthermore, surface impoundments are often covered with vegetation, and landfills may utilize intermediate soil covers to protect non-working areas. Properly evaluating the nature of the deposits in each portion of a storage unit is the first step towards developing a successful harvesting plan.

Recent work has advanced the methods and standards for assessing and profiling CCPs in storage units. EPRI's 2018 *Guidance for Sampling and Mapping of Coal Combustion Products in Ponds and Landfills for Beneficial Use Applications* (EPRI report 3002013740) provides guidance and best practices for identifying and sampling CCP units. By combining historical information from plant operation records with in-situ testing, sampling, and conventional laboratory analysis, CCP units can be mapped and modeled three-dimensionally. Maps can focus on dominant material types, like fly ash, bottom ash, or gypsum, or delineate based on critical properties like fineness, LOI, or sulfur content. Cross-sections of the three-dimensional resource model, such as Figure 5, can assist in determining the economic viability of harvesting from a CCP unit and will allow design engineers to develop targeted harvesting plans that minimize exposure of CCP and maintain regulatory protections.

The resource model, informed by historical data and field testing, enables the review and identification of challenges in harvesting and critical influences on CCP quality. A harvesting strategy can be developed from this review, and measures to control quality can be selected. The resource model also informs further investigations of uncertainties in the resource.

Characterization of CCPs is possible through commercially available and emerging hand-held and benchtop analysis tools (Figure 6). Several tools can rapidly analyze composition, physical properties, and performance characteristics. The analysis speed of these devices allows almost continual characterization of the product as it goes to the storage unit, creating the potential for building a real-time map of the deposits and segregation of the highest quality material. Exploration of existing storage units can also be carried out rapidly and with a greater number of data points than would be feasible with laboratory testing alone.

For bulk elemental composition, central labs commonly use X-ray fluorescence (XRF) analysis. Hand-held XRF devices are also commercially available and may provide similar functionality in the field. Portable laser-induced breakdown spectroscopy (LIBS) and ramen spectroscopy equipment are emerging analysis techniques and may become useful field analysis tools in the future. EPRI is currently evaluating the applicability of hand-held and portable devices for bulk elemental composition of fly ash.

For mineralogical composition, lab-based X-ray diffraction (XRD) and thermogravimetric analysis are commonly used (EPRI 2019a). However, the expertise required to operate and interpret the results limits the application to central labs. Prediction of mineral phases from lab-observed elemental associations from scanning electron microscopy is a promising alternative to conventional mineralogical analysis, but it also requires an expert operator and capabilities found in a central lab.

For physical properties, laser diffraction methods provide a rapid alternative to sieve-based particle size distribution analysis and may be especially valuable in monitoring size separation and size reduction processes. Unburned carbon content can be quickly evaluated using a device like a LECO analyzer, which can also identify the inorganic carbon fraction

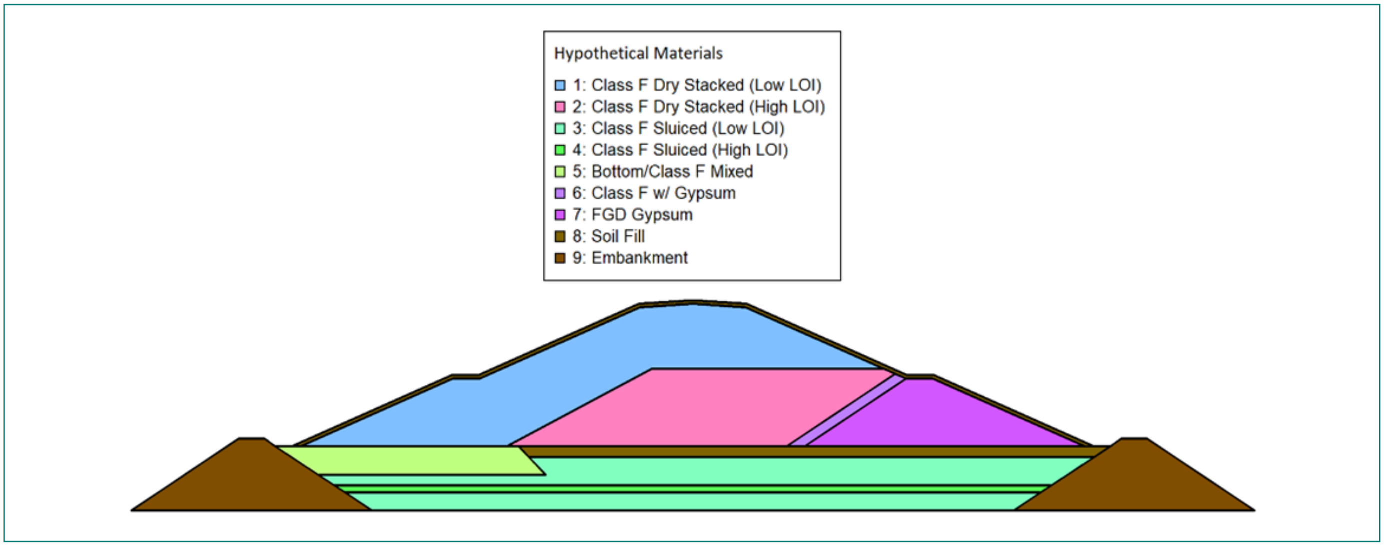

Figure 5. Example Cross Section of Material Type Delineated Resource Model

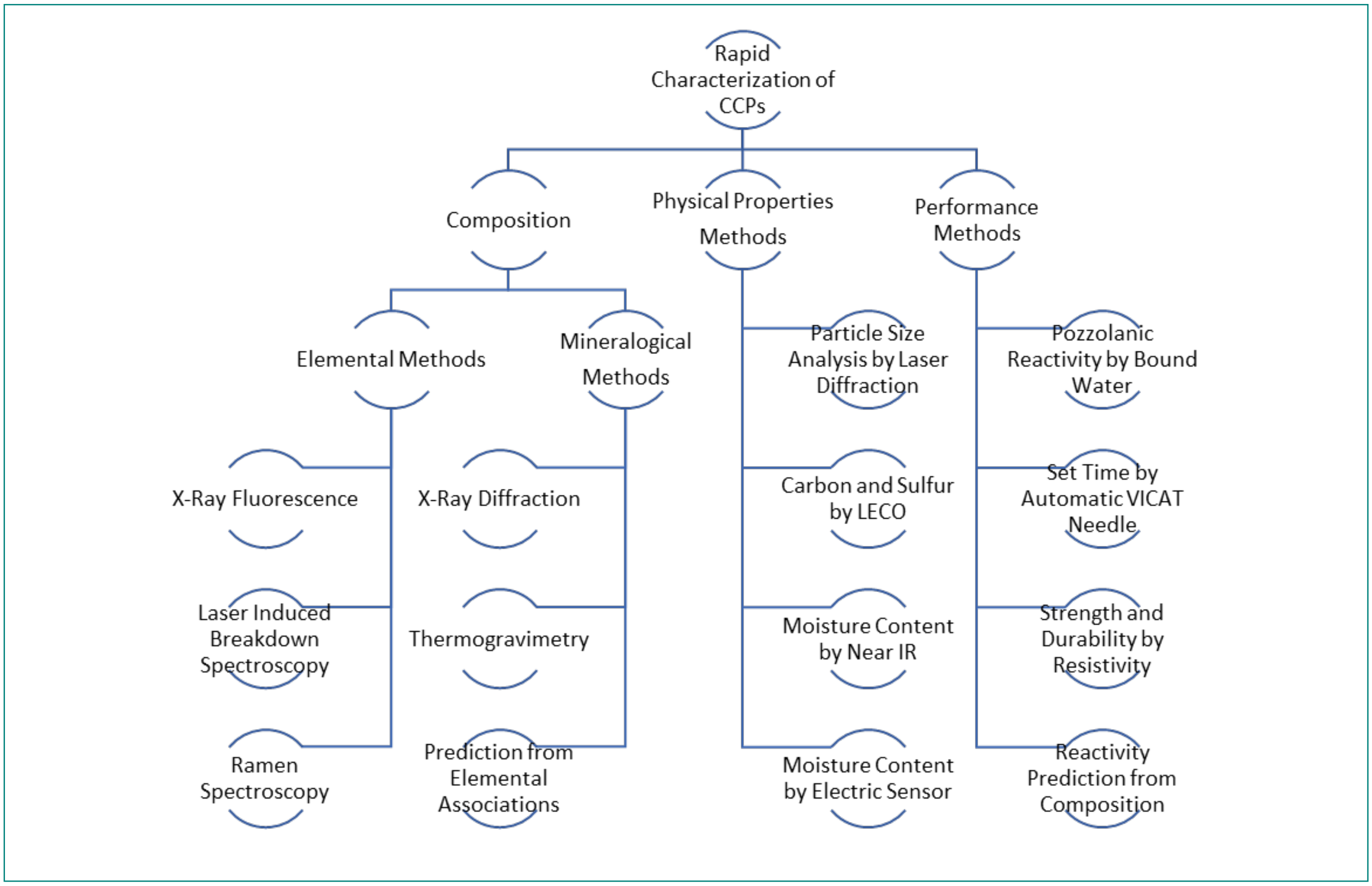

Figure 6. Commercial and Emerging Tools for Rapid Characterization of CCPs

from hydrates and carbonates that formed during weathering of the CCP. Rapid moisture sensors using near infrared (IR) emissions or electrical properties have been proposed, but their reliability in measuring CCPs has not been well documented.

For performance, fly ash used in concrete is routinely evaluated by the strength activity index, a test that often requires four weeks to complete (EPRI 2019). However, rapid evaluation of pozzolanic reactivity using the bound water method (ASTM C1897-19) offers faster assessment of reactivity using deployable field equipment (EPRI 2020a). Fly ash impact to set time can be evaluated in the field using automated equipment. The resistivity of cured mortar or concrete mixtures also has the potential to rapidly determine the CCPs' contribution to strength and durability. Finally, research suggests that fly ash composition may predict reactivity (EPRI 2020b, Song 2021, Kang 2020).

Beneficiating Harvested CCP

Reclaimed CCP often meets required industry specifications such as ASTM C618 without processing beyond drying, as demonstrated by the Arkansas State University project highlighted later in this report. However, even CCP that does not meet specifications can potentially be economically processed and marketed. Sometimes the lowest cost approach to beneficially use an off-specification CCP deposit is to selectively mine materials that meet quality requirements or blend the off-specification materials with other on-specification materials. However, selective mining or blending approaches have downsides, requiring active quality control of mined materials, lower harvesting efficiency, and higher off-specification disposal volumes. As a result, several technologies to process off-specification CCP and bring it within the standards have been commercialized or developed. In particular, reducing the carbon content present in stored CCP from unburned coal, coal pile runoff, and vegetative growth can make previously undesirable ash marketable again (EPRI 2019b).

The SEFA Staged Turbulent Air Reactor (STAR®) technology is one approach that has seen commercial acceptance in ash beneficiation. Six STAR® plants are currently operating in North Carolina, South Carolina, and Maryland and can reduce the carbon content of coal ash from greater than 10% to less than 1%. Additional benefits of the STAR® process include an increase in fineness and a reduction in agglomerates. However, the main barrier to implementing STAR technology is the relatively significant capital investment required to construct the plant.

Triboelectrostatic separation is another technology that has shown potential for reducing the carbon content of stored fly ash. This process induces an electrical charge in the fly ash, which can then be used to facilitate separation from the carbon (Baltrus 2002). The separation of carbon and dry fly ash using triboelectrostatic separation has been commercially applied, and the separation of fly ash stored in moist conditions is being investigated at pilot scale. However, a potential barrier to implementing triboelectrostatic separation is the relatively stringent requirement for ash dryness before separation. The drying requirement constrains drying equipment selection and potentially increases operational costs.

Other processing technologies, including thermal processing, hydraulic separation, and pneumatic separation are discussed in EPRI's 2018 *Harvesting and Beneficiation of Coal Combustion Products from Landfills and Ponds: Workshop Proceedings*, Multiple processing technologies may be combined to treat target constituents. In addition to carbon reduction, many of these technologies result in smaller particle sizes for processed CCP. Greater fineness in fly ash has been shown to improve early concrete strength.

Guidance is also available for separating commingled ash and gypsum. Ash and gypsum are present in many CCP stacks due to handling operations or desulfurization products in the flue gas where fly ash is collected. EPRI's 2022 report *Technologies to Recover High-purity Fly Ash or Gypsum from Mixed Coal Combustion Products* discusses the significant challenges in separating fly ash and gypsum and potential approaches to recover fly ash suitable for use in concrete from comingled landfills and ponds.

Case Study: Landfill to Finished Concrete

The feasibility of beneficially using harvested CCP in concrete was successfully demonstrated by a recent project undertaken at Eco Materials, Louisiana State University (LSU), and Arkansas State University (ASU). Eco Materials excavated and processed fly ash from a landfill. Then researchers at LSU and ASU evaluated the harvested fly ash and other SCMs as part of a Transportation Consortium of South-Central States (Tran-SET) project.

The reclaimed fly ash for the project was sourced from a power plant landfill (EPRI ID 10164) in the southeastern United States. The power plant owner initially investigated the feasibility of harvesting ash for beneficial use by making exploratory test borings to obtain samples for laboratory characterization. The borings were performed at an approximate spacing of one boring per ten footprint acres using a rotary drill rig with hollow stem augers. The drill samples were visually characterized in the field by a geologist. Based on the history of ash production from plant operations and visual inspection, selected samples were tested for fundamental beneficial use properties in ASTM C 618 (bulk composition, fineness, loss-on-ignition, and moisture content). At the time of the investigation, rapid methods for characterizing pozzolanic activity (ASTM C1897) had not been standardized and were not available for use in the investigation.

The initial laboratory evaluation of the landfilled ash suggested that only drying of the fly ash would be required to meet specifications for use as an SCM. Therefore, the owner engaged an ash marketing contractor. A temporary pilot plant, nominal capacity of 10 tons per hour, was constructed to evaluate further the feasibility of beneficial use, including the cost to dry the landfilled ash. In the pilot plant, excavated ash passed through an initial vibratory screen for debris removal, a diesel-fired rotary dryer, and a vibratory screener with a #20 sieve (800 micron) prior to silo storage for future beneficial use (Figure 7). No other processing, carbon removal, gypsum separation, etc., was performed.

The pilot plant successfully dried several hundred tons of harvested landfill fly ash. The rotary dryer met the dryness requirement throughout the production run, but the manual process control required careful operator attention. An unexpected pocket of fly ash with slightly excessive SO_3 was encountered during harvesting, likely the result of a localized FGD gypsum handling activity in the landfill. The pilot plant operators first identified the off-specification material due to different color and poor handling behavior in the pilot plant. The dried, off-spec ash stored in the silo was ultimately blended with low SO_3 fly ash to produce on-specification material. Had an on-site characterization tool been available at the time of the pilot test, field characterization could have identified the off-spec material and limited the processing of poor handling material. Preemptively identifying unexpected materials enables blending prior to drying and reduces the chances of upsetting the drying process.

Samples of the dried harvested ash were shipped from the pilot test to LSU and ASU for testing and demonstration use. The chemical composition, moisture content, and loss on ignition (LOI) of the reclaimed fly ash were tested and compared to fresh production fly ash (Table 1). Both reclaimed and fresh fly ash met ASTM C618 requirements for Class F fly ash used in concrete (Arce 2021).

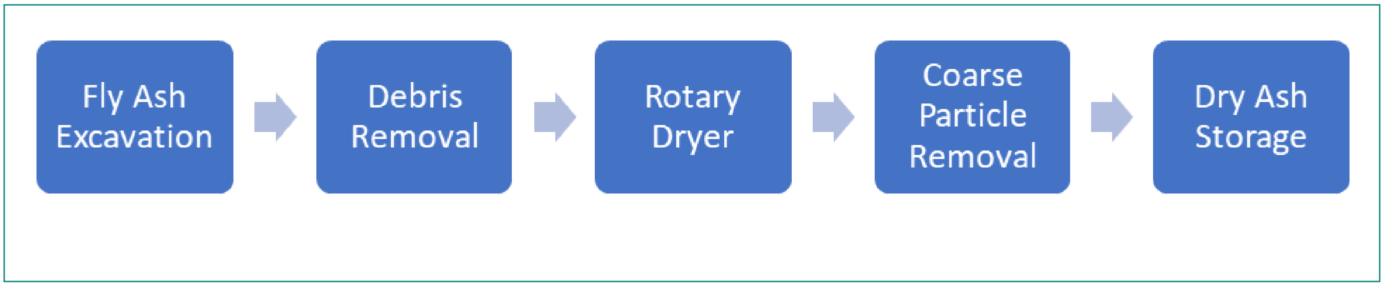

Figure 7. Processing of Fly Ash at the Harvesting Site

Table 1. Chemical Composition (Mass %), Moisture Content, and LOI. (Chowdhury et. al)

SCM Material	CaO	SiO_2	Al_2O_3	Fe_2O_3	SO_3	MgO	K_2O	Na_2O	$SiO_2 + Al_2O_3 + Fe_2O_3$	Moisture Content (%)	LOI (%)
RFA	**1.8**	**53.4**	**28.0**	**7.7**	**0.1**	**0.99**	**2.2**	**0.3**	**89.1**	**0.06**	**2.95**
FFA	8.4	57.2	20.2	10.2	1.2	1.6	2.7	1.1	87.6	0.40	1.42
ASTM C618, Class F	18.0 max	-	-	-	5.0 max	-	-	-	50.0 min	3.0 max	6.0 max

FFA – Fresh Class F Fly Ash; RFA – Reclaimed Fly Ash

Tested concrete mixes included SCMs at 10%, 20%, and 30% cement replacement values and a control mixture with no SCMs. After 28-days of curing, compressive strengths of all the reclaimed fly ash mixtures were lower than the control. However, after 90-days of curing, compressive strengths for the reclaimed ash mixtures showed no significant difference from the control mixture, even at 30% replacement. Shrinkage and alkali-silica reaction tests showed the reclaimed fly ash was effective at reducing drying shrinkage and reducing ASR-related expansion. These data indicate that reclaimed fly ash is a suitable replacement for fresh fly ash. (Arce 2021).

A field demonstration was developed to replace an existing 50-foot-long sidewalk on the ASU campus The ASU team selected the 20% replacement reclaimed fly ash mixture and the 20% replacement fresh fly ash mixture for demonstration. A 25-foot section of each mixture, about five cubic yards each, was poured on the morning of August 3, 2021. The mix designs were the same except for the SCM, and identical slumps were achieved during pouring. 14-day dry shrinkage from both mixes was nearly identical. The reclaimed fly ash mixture exhibited a higher entrained air content (6.7% vs. 2.0%) and a lower 28-day compressive strength (9020 psi vs. 9905 psi) than fresh fly ash (Chowdhury 2023).

After one year, the sidewalk with the reclaimed fly ash concrete performs as well as the fresh fly ash concrete. No cracking is present outside of the control joints, and there is no visible difference between the two sections. The durability of the sidewalk sections will continue to be observed over time, and additional publications on this Tran-SET project are anticipated.

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3002024166 November 2022

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