BENEFICIAL USE OF PONDED FLY ASH IN STRUCTURAL CONCRETE

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ABSTRACT. This paper investigates the potential large-volume use of ponded fly ash for concrete applications in the United States. The use of fresh coal ash in concrete (meeting ASTM C-618 specifications) has become a stable revenue for coal-fired utilities and ash marketers. However with the decline in usage of coal in the US, the quantity and quality of coal ash available for structural concrete applications has seen a significant reduction. Harvesting ponded fly ash which after treatment can meet national specifications for concrete applications can provide an economic alternative to keeping the ash in the closed out ponds. The ash in closed out ponds can be a valuable resource that can be harvested in the future to provide a positive revenue stream for ponded ash while at the same time reducing the liability of the utility owning the closed out pond. The value of using fly ash in concrete is not limited to reducing waste stockpiles, however, as use of fly ash has been shown, through prolific amounts of research on the subject, to be highly beneficial to concrete – increasing workability and ease of placement, and resulting in increases in strength and dramatic improvements in durability, paired with reduced material costs. Further, use of fly ash represents the single most impactful method of reducing the environmental and energy impacts of concrete construction – in the US State of Ohio alone, replacement of 30% of the state's cement content in concrete mixtures would avoid nearly 1 million tons CO_2 emissions per year. Given current world trends of increasing interest in the 'greening' of technologies, especially those with high embodied greenhouse gas emissions and energy usage (as occurs in the production of cement), demand for use of coal ash in concrete is unlikely to subside.

Keywords: Fly ash, Concrete, Ponded, Off-Spec

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INTRODUCTION

Review of coal ash ponds in the United States has shown that there are hundreds of coal ash ponds across the US with a significant to high-hazard potential rating, and others may need to be closed due to potential groundwater pollution issues. These ash ponds are in the process of being closed and remediated. The ash in closed out ponds can be a valuable resource that can be harvested in next 5-10 years to provide a positive revenue stream for ponded ash while at the same time reducing the liability of the utility owning the closed-out pond.

The use of fresh coal ash in concrete (meeting ASTM C 618 specifications) has become a stable revenue for coal-fired utilities and ash marketer, and the concrete production industry is the single largest user of fly ash, consuming 38% of 2016 production [1]. However, with the decline in usage of coal in the US, the quantity and quality of coal ash available for structural concrete applications has seen a significant reduction. Harvesting ponded fly ash, which, on its own, or post-treatment can meet national specifications for concrete applications, may provide an economic alternative to keeping the ash in the closed-out ponds.

SUPPLY AND DEMAND OF FLY ASH

Coal combustion residues (CCRs) have a long history of use as a supplementary cementitious material in civil engineering infrastructure applications, having been used in roadways and interstate highways since the early 1950's. Between 1950 and 2006 over 15 million tons of CCRs have been diverted from storage sites (fly ash ponds or landfills) for beneficial use in concrete infrastructure. Still, the amount of fly ash currently impounded in fly ash ponds or landfills is extremely high – with 66 million pounds estimated to have been ponded or landfilled in 2016 alone (https://www.epa.gov/coalash/frequent-questions-about-coal-ash-disposal-rule#2).

The value of using fly ash in concrete is not limited to reducing waste stockpiles, however, as use of fly ash has been shown, through prolific amounts of research on the subject, to be highly beneficial to concrete – increasing workability and ease of placement, and resulting in increases in strength and dramatic improvements in durability, paired with reduced material costs [2]. Further, use of supplementary cementitious materials, with fly ash being the most commonly used, represents the single most impactful method of reducing the environmental and energy impacts of concrete construction. In the State of Ohio alone, replacement of 30% of the state's cement content in concrete mixtures would avoid nearly 1 million tons CO_2 emissions per year.

Given current world trends of increasing interest in the 'greening' of technologies, especially those with high embodied greenhouse gas emissions and energy usage (as occurs in the production of cement), demand for use of coal ash in concrete is unlikely to subside.

Concurrent with this increase in demand, the supply of high quality, virgin fly ash has declined due its association with the downward trends of coal-powered electricity generation resulting from the ever-increasing burden of U.S. Environmental Protection Agency (EPA) regulations, environmental concerns of the U.S. public, and competition from other energy sources (i.e. natural gas and renewable energy) [3]. This disparity between supply and demand is exasperated by the cyclical highs and lows of energy generation resulting from the nature of energy usage (consumers use less power in spring and fall, when the climate is more temperate, more in summer and winter, when power is required for heating and cooling). These seasonal energy industry highs and lows do not necessarily align with seasonal cycles of the construction industry, and lead to shortfalls in fly ash availability and supply chain uncertainties for construction applications in spring and fall, and production of large excesses of fly ash in winter that are currently deemed 'unusable' after being stored. Shortfalls also decrease the likelihood of concrete producers to continue using fly ash in concrete when it is not dictated by fly ash utilization minimums in specifications.

Utilization of ponded coal fly ash is one approach to addressing fresh coal ash availability shortfalls, with ponds providing an expansive supply of fly ash. Use of ponded ashes will also allow generators to reduce the size of current fly ash storage ponds and avoid future storage costs. However, the limited quantity of past research available on ponded fly ash suggests that considerable variations in chemical and physical properties exists both between different pond locations and even within ponds at the same location [4]. Changes in phase content and particle gradations can lead to considerable differences in concrete quality, and so these fly ash sources must be well characterized prior to sale as construction materials.

FLY ASH PROPERTIES

Fly ash, produced from the burning of pulverized coal in boilers is fine, non-combustible, silt-like particulate matter that is carried in the flue gases and is usually collected using electrostatic precipitators, baghouses, cyclones or other mechanical devices. Fly ash typically consists of spherical particles, either hollow or spherical, and ranging in size from 0.1 – 100 microns, with a bulk density of 0.54-0.86 g/cm^3, and a specific surface area typically between 0.3-1 m^2/g [5,6].

Two types of fly ash are produced, depending on the type of coal used. Class F fly ash, generally classified as such based on its composition of less than 70% of a combination of SiO_2, Al_2O_3, and Fe_2O_3, is created from the burning of anthracite or bituminous coal, prevalent in the Appalachian region of the United States. Class C fly ash originates from the burning of lignite or subbituminous coal, and consists of between 50-70% composition of SiO_2, Al_2O_3, and Fe_2O_3, due to its generally higher calcium composition [2]. The general oxide content ranges for both dry ash types are shown in Table 1. Also shown in Table 1 are the oxide contents of ponded fly ash available in literature for comparison with dry fly ash.

Table 1 Chemical Composition of Dry and Ponded Fly Ash

OXIDE (% BY WEIGHT)	DRY CLASS F FLY ASH	DRY CLASS C FLY ASH	PONDED CLASS C FLY ASH [8,9]
SiO_2	20-60	15-60	40-54 (generally on the higher end)
Al_2O_3	5-35	10-30	18-32 (generally on the higher end)
Fe_2O_3	10-40	4-15	4-22 (generally lower end)
CaO	1-12	5-40	1-5 (generally lower end)
MgO	0-5	1-10	0.5-2.8
SO_3	0-4	0-10	0-1.3
Na_2O	0-4	0-6	0-3.8
K_2O	0-3	0-4	0.7-3
Unburned Carbon	0-15	0-5	2-21
Amorphous Content	70-95	70-95	47-72
Quartz	2-17	2-5	3-14

Fly ash is deemed suitable for use in concrete if it meets the requirements set forth in ASTM C 618, which include limits on silica, alumina, iron oxide and sulfate contents, moisture content, loss on ignition, fineness, and consistency, as well as comparison of performance parameters of cement-fly ash mixtures compared to a 100% portland cement control mixture. These properties include compressive strength at 7 and 28 days, soundness, workability, and ability to control deleterious chemical reactions that can attack cement paste, including alkali-silica reaction and sulfate attack.

Table 2 ASTM C 618 Specification fly ash property requirements [10]

PROPERTY	CLASS F FLY ASH	CLASS C FLY ASH
SiO_2+Al_2O_3+Fe_2O_3, min%	70	50
SO_3, max %	5	5
Moisture content, max %	3	3
Loss on ignition, max %	6	6
Amount of material coarser than 45 μm, max %	34	34
Strength at 7 days relative to a 100% cement mortar, min %	75	75
Strength at 28 days relative to a 100% cement mortar, min %	75	75
Water requirement, max % of control	105	105
Thermal expansion or contraction, max %	0.8	0.8
Uniformity, max % variation of density and fineness from average	5	5
Increase in drying shrinkage, % difference from control	0.03	0.03
Control of alkali silica reaction (ASR), max % expansion	100	100
Contribution to sulfate resistance, max % expansion	0.1	0.1

During the process of collecting fly ash from coal combustion gases, mechanical collection devices generally collect larger particles from the flue gases while finer ash particles are collected by electro-static precipitators (ESPs) and baghouses. For all of these ash collection processes, the ranges of trace elements are quite similar except that arsenic, boron, lead, and selenium levels are slightly higher in ESP or baghouse ashes. Cadmium and fluorine may be present at higher levels in ash collected by mechanical devices such as a cyclones. In nearly all cases, the fly ash leachate levels meet the Resource Conservation and Recovery Act (RCRA) non-hazardous regulatory levels. In general, USEPA leaching potential tests conducted on fly ashes (Table 3) have shown that most fly ash leachates may even meet the national primary and secondary drinking water standards.

Table 3 Fly Ash Leachate Analysis

CHEMICAL CONSTITUENT	FROM FLY ASH LEACHATE (MG/L)	USEPA DRINKING WATER MAXIMUM CONTAMINANT LEVEL (MG/L)
As	0.03 - 0.4	0.01
Ba	0.3 – 2	2.00
Be	<0.0001 - 0.015	0.004
Cd	0.0 - 0.3	0.005
Cr	0.023 - 1.4	0.1
Cu	0.0 - 0.43	1.3
Hg	0.0 - 0.003	0.002
Pb	0.0 - 0.15	0.015
Sb	0.03 - 0.28	0.006
Se	0.01 - 0.87	0.05

BENEFICIAL FLY ASH USE IN CONCRETE

Fly ash is typically used in concrete mixtures as a substitute for a portion of the cement component of the mixture. Through an extensive amount of research, fly ash has been proven to be extremely beneficial, improving the ease of placement of fresh mixtures, and also improving long-term strength and durability. Benefits of substitution of fly ash for Portland cement in concrete mixtures include [11-16]:

- Increased workability of fresh mixtures without addition of extra water
- Increased long-term compressive and flexural strengths
- Decreased permeability and diffusivity, resulting in slower onset of corrosion
- Increased resistance to alkali-silica reaction
- Increased resistance to sulfate attack
- Increased resistance to abrasion
- Increased resistance to carbonation
- Reduced heat of hydration
- Reduced shrinkage

The nature of changes in the properties of fresh (not hardened) concrete using fly ash are predominantly due to the small size and spherical shape, of the fly ash particle. In contrast, the effects of fly ash on long term strengths and durability (hardened properties) result from a chemical reaction that occurs between the fly ash and cement hydration products, known as the pozzolanic reaction, shown in the (simplified) equation [17]

$$Ca(OH)_2 + SiO_2 + H_2O \rightarrow \rightarrow C_x\text{–}S_Y\text{–}H_Z \qquad (1)$$

When cement reacts with water the two primary resultant products are calcium silicate hydrate (C_x-S_y-H_z) and calcium hydroxide ($Ca(OH)_2$). Of these two products, C-S-H is generally preferred over calcium hydroxide because it provides the strength of the hydrated solid material and resists dissolution by ionic solutions. In the pozzolanic reaction, silica (SiO_2) and alumina (Al_2O_3), from the pozzolanic material (in this case the fly ash) react with calcium hydroxide to form additional hydrate phases, primarily C-S-H. It is generally assumed that the pozzolanic reaction is a relatively long-term reaction, and can continue for up to 90 days after mixing. Conversion of calcium hydroxide to C-S-H through the pozzolanic reaction leads to considerable densification of the cement paste matrix and leads to the increases in mechanical and durability properties.

However, despite these benefits some potential pitfalls are associated with the use of fly ash, especially in high volume (>50%) replacement levels in concrete. The most significant of these problems includes inherent material variability, especially varying calcium, sulfate and unburnt carbon contents, which introduce variability both in mixture proportioning requirements (dosing of admixtures, water requirements, etc) and in property development in concrete containing these materials [18,19]. Additionally, high volume fly ash mixtures often induce considerable delays in set time and slowed strength gain. Both of these properties will serve to delay construction progression and dissuade potential users who are affected more by slowed construction rate than increased long-term durability (particularly contractors). Fly ash cement concrete has also been shown to be highly susceptible to curing – with improper curing having considerably a more reductive influence on concrete property development than in 100% portland cement concretes [20].

Many approaches have been suggested to help to minimize the impact on property development and constructability of fly ash-cement concrete mixtures, including physical and chemical treatments, and substitution schemes utilizing additional symbiotic materials, including additional pozzolans and microfine materials [12]. Tsimas [18] showed that grinding and intermixing of water into high calcium fly ash mixtures can reduce variability in property development. Hemmings showed that acid leaching of fly ash samples results in residues with high pozzolanic potential [21]. Tanesi et al. [22] showed that fine limestone additions can be used to decrease set time delays in high volume mixtures. Mixtures utilizing high calcium fly ash (Class C), which on its own has been generally been shown to be less beneficial with respect to improvements to concrete strength and durability than Class F, low calcium content, fly ash, showed significant improvements with silica fume additions.

These past studies demonstrate that potential problematic properties of high volume fly ash usage, namely, variation in chemistry and physical properties, and slow reactivity leading to extended set times and low early age are possible to remediate. In order to address these issues investigation of several treatments and usage schemes to improve performance, and reduce variability associated with use of high-volume harvested fly ash mixtures needs to be built into the test matrix.

PONDED FLY ASH PROPERTIES

Fly ash impoundment have been one of the two primary fly ash disposal methods (the other method being landfilling) since the 1950s. In general CCR types are stored separately within ponds. However, some mixing is difficult to prevent, and additionally, standards and procedures for storage may have varied over the history of the pond. For these reasons, substantial variation in fly ash properties within the same pond are expected. These variations are further exasperated by changes induced in the ponded materials throughout their storage-life. Many factors may affect fly ash properties during ponding operations, including long term elemental exposure (sun, precipitation, pond water), settlement, mixing of fly ash with bottom ash, variations in ash chemistry and hydraulic reactivity (especially for Class C fly ashes) and the presence of sulfur or lime sorbents, used to help control mercury emissions from coal, in addition to the variations in properties inherent even in the virgin material.

Despite this, changes to fly properties ashes relative to virgin ashes have not been shown to be much more significant than typical variations in virgin ash properties. Changes often primarily include increased particle size and reduced amorphous content. Surprisingly little differences have been found in the chemical makeup of the ponded ashes relative to virgin ash [23] although concerns exist concerning harvested ash likelihood of high sulfate content, resulting from intermixing of fly ash and flue gas desulfurization (FGD) products.

It is not believed that ponding eliminates fly ash pozzolanic reactivity, as pond pH has been shown to rise no higher than 8.2 – not high enough to induce geopolymeric reactions [24]. However, significant increases in setting time have been shown to occur with use of ponded fly ash, as compared to both 100% portland cement mixtures and mixtures utilizing virgin fly ash meeting the ASTM C 618 specification [25]. Ponded fly ash substitution rates were also shown to correlate with decreased ultimate compressive strengths, resulting in a nearly 50% drop in strength with a 65% substitution rate [25]. It is theorized, however, that these changes in material properties with use of ponded ashes can be addressed through changes in fly ash sample particle size, as increased particle size is known to have a significant effect on reactivity and strength development. Erdogdu and Turker [26] established a strong relationship demonstrating the high dependency of compressive strength on fly ash average particle size. McCarthy [23] showed that grinding of ponded fly ash samples can increase total heat release and reduce setting time. Increasing fractions of material finer than 10 microns was associated with increased 28-day compressive strength and decreased permeability.

Another concern about the use of harvested fly ashes centers around the likelihood of environmental contamination from these ashes. Indeed, Lokeshappa and Dikshit [27] demonstrated, in simulated experimental fly ash ponds, that ponded fly ashes adsorb heavy metals from solution. This may indicate a higher potential to leach dangerous heavy metals into water sources later, even following encapsulation of the material in the cement binder matrix. Due to this concern, leaching potential of both the as-received harvested fly ashes, and concrete fabricated using harvested fly ash are needed.

Currently, understanding of ponded fly ash characteristics is limited due to very limited research on material characterization, and large variability in material properties depending on location. Reported ponded ash sample LOI varied between 2 to 8% in ponded ash samples studied in India: 4% and 8% in Ranganath et al. [28]; and 2.2% in Sofi and Phanikumar [29]. On the other hand, the LOI was 6.8% in ponded ash sample of Hwi et al. [30] in Korea, and 7.5% in Russia [30]. Jewell et al. [9] tested four ponded fly ashes from US Kentucky power plants and observed LOI varying from 1.8-7.2%. In these cases, LOI was almost always lower for the dry fly ash than the ponded ash samples in these studies. ASTM C 618 specifications (Table 2) limit the loss on ignition to maximum 6% for Class F and C fly ash, but states that the use of Class F pozzolan containing up to 12.0% loss on ignition may be approved by the user if either acceptable performance records or laboratory test results are made available. Limited previous research on ponded fly ash with more than 6% loss on ignition [9,28,30,31] did not show significantly different or adverse chemical or material characteristics in concrete. This suggests that testing to verify performance and property development of concrete produced using ponded fly ash may allow for its inclusion in future specifications.

While general research on ponded fly ashes is limited the data required for structural concrete design is even more limited. The research team could find only one study on use of ponded ash in structural concrete [29], which tested 16 beam specimens by replacing 10%, 20% and 30% of cement by ponded fly ash. They demonstrated that if ponded fly ash is used in combination with steel fibers the flexural strength and ductility of reinforced concrete beams can be increased significantly and present no problems for use as structural concrete members.

US FLY ASH REGULATORY POLICIES

It is likely that limitations and requirements specified by the owners and other agencies may prevent or dictate the use fly ash. For example, may state departments of transportation restrict fly ash carbon content to 3% loss on ignition, limiting the use of high carbon content fly ash in bridge structures. LOI provides a measurement of the amount of unburnt carbon present in fly ash. Unburnt carbon is known to absorb air entraining admixtures and affect the air content of air entrained concrete, thus imposing lower LOI limits on fly ash is believed to ensure better control of the air content, an essential durability requirement for concrete subjected to cyclical freezing and thawing. Taylor [32] reported that large proportions of the fly ash generated in Ohio have unburnt carbon contents above the state's limit of 3% loss on ignition and must be discarded rather than used in concrete.

According to the NRMCA Research Engineering and Standards Committee, typical restrictions to fly ash seen in specifications for concrete include [33]: Restrictions on usage of Class C fly ash, and fly ash calcium oxide (CaO) contents, LOI, coarse material (retained on the 45 µm (No. 325) sieve), and alkali contents, all of which are more restrictive than the ASTM C 618 limits. After review of more than 100 specifications for private work, NRMCA notes these types of restrictions in 25% of U.S. specifications, 80% of which did not allow the use of Class C fly ash or had restrictions on the CaO content of the fly ash. While these strict restrictions are in place currently, as the industry moves towards performance-based mixture design in lieu of prescriptive specifications, it is likely that newer specifications will also shift to allow fly ash producers and marketers, and ready-mix concrete suppliers to instead justify off-specification material usage by providing material or performance data and monitoring installation quality and uniformity, rather than by dictating requirements based on singular material parameters.

ASH POND CLOSURE CONSIDERATIONS

An impetus for exploring usage of ponded fly ashes in concrete construction is the cost associated with closure or remediation of high-risk fly ash ponds. The fly ash pond closure process is arduous and expensive, often requiring processes such as: significant subsurface geotechnical investigations, removal of surface water; dewatering of the fly ash; re-grading contouring the fly ash with additional fill materials; constructing an engineered final cover; lowering constructed dam structures; installing new stormwater management controls; constructing overflow spillways and discharge channels, and ensuring that acid mine drainage does not occur [34,35]. Determining grading material requirements, soil stability parameters of the site, and construction processes for this rather uncommon project type represent considerable risks to both contractor and utility.

As a result of the immense amount of work and risk associated with these processes, cost of pond closures are immense. Costs associated with closure of one set of ponds at the Colstrip Steam Electric Station in Colstrip, Montana were approximated to be $65,700 per acre [36]. Therefore, creating a beneficial use stream for fly ash harvested from coal ash ponds can help utilities avoid considerable expenses associated with long-term storage of these products, expansion of facilities to house additional materials and costs of closing ponds, as storage transitions to facilities conforming to more restrictive environmental designs.

CONCLUSIONS

Re-evaluation of the safety of coal ash containment ponds in recent years has exposed the need to find beneficial uses for this material in order to prevent environmental problems from use of sites designed prior to regulation of disposal sites and protective liners, and also avert the immense costs associated with pond closure, when problems to occur.

While the use of dry fly ash in concrete infrastructure has been a relatively common practice for decades, the current utilization rate of fly ash concrete in concrete construction lags behind research recommendations and few mixtures venture into the high-volume fly ash substitution mixture arena. Challenges with increasing utilization of fly ash are more difficult for fly ash sources not meeting the ASTM C 618 specification. Still, these sources, which include ponded fly ashes, represent viable materials for use in concrete construction, potentially increasing strengths and durability of concrete, and reducing environmental impact of the concrete as well as costs, and providing supplements to current fly ash supplies during times when demand may outweigh fresh ash supplies. From the utility and fly ash marketer perspective, the immense amount of materials currently retained in ponds represent an enormous potential revenue stream, in addition to cost savings from reducing pond size, and deferring costs associated with remediation or closure of high-risk ponds. For these reasons it is essential to begin to work towards understanding and documenting the characteristics and performance of harvested fly ashes, and investigate options for economically-viable material improvements, if necessary.

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