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Waste Minimization and Recycling

Fly Ash as a Replacement for Cement in Concrete Construction

Doug Midkiff

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INTRODUCTION

Fly ash has been used in the U.S. for many years as a substitute for portland cement. Improved strength and mobility are two major advantages due to the use of fly ash in concrete. Recovered gases from coal burning produce a fine glass like powder that is either dumped in landfills or collected and packaged as fly ash. The major compounds making up the chemistry of fly ash include silica, alumina, and iron. As these compounds combine, they form a pozzolan that reacts with water and lime and forms a cementitious material.

The shape of the fly ash particles is spherical and reduces internal friction. Along with the reduced internal friction, viscosity of the concrete mixture is decreased allowing for increased workability. [1] A traditional mixture of just portland cement would need a large amount of water to increase workability, however this excess water also decreases the strength of the mixture. Using fly ash as a substitute, the amount of water for workability is decreased and the strength is not compromised.

Fly ash produced from Eastern coal is covered in a thin layer of melted glass. This helps the particles against expansion due to sulfates which makes its use in fertilized soils and coastal areas ideal. The ash produced from Eastern coal is known as Class F Fly Ash. The other common type of fly ash is known as Class C Fly Ash. Produced from Western coal, Class C also protects against expansion, but has much higher calcium oxide content. Class C fly ash is generally preferred for structural concrete.

In the heavy civil construction industry, fly ash is commonly used as a replacement for cement to reduce weight and cost. The specific gravity of fly ash is generally $^{2}/_{3}$ that of cement. This allows for lower unit weights of structural components, reducing the design loads. With the lower design loads, the engineer has a greater freedom to choose the geometry of structural components.

Background and Origin

Fly ash is collected from the flue gas that comes from the burning of coal in a power plant.[a] A fine grained, powdery material accumulates in the electrostatic precipitators, baghouses, and cyclones that exhaust flue gases pass through. The fly ash is recovered from the machinery along the exhaust line and used either in the construction industry or landfilled.

The electric industry uses three different types of coal fired boilers, depending on the power plant. The most common type of these is the dry-bottom furnace. In the bottom ash furnaces, nearly 80% of all ash that leaves the furnace is fly ash. The remaining 20% of ash is considered bottom ash.[d] This ash is collected under the boiler in a hopper and consists of larger granular material that is disposed of. The other two types of boilers are the wet-bottom furnace and cyclone furnace. Both of these furnaces yield a lower percent of fly ash than the dry-bottom furnace.[d]

Chemical Composition

The most abundant element in the composition of fly ash is silica. Depending on the coal feedstock used, the concentration of silica can range from 40-60%. [2] Other elements include a fairly large portion of iron and aluminum oxides, 5-25% and 18-31% respectively.[d] Calcium oxide is also an important portion of fly ash, but is variable on its concentration. A portion of the coal used as fuel travels in small concentrations with the fly ash in the flue gas. This excess carbon is measured by loss of ignition. This measurement compares an amount of ash before and after it is burned in a small vessel; the carbon, and other volatiles, will burn off and the ash will be left.[a] A higher carbon content, and thus a higher loss of ignition, in the ash makes it unsuitable for structural purposes.

Ashes that contain a higher amount of calcium are generally collected from a subbituminous coal. This ash also has a reduced percentage of silica and iron oxide. A lower carbon content results in a lower loss of ignition.[e] The higher concentration of calcium makes the fly ash a Class C Ash which has its own cementitious properties. A Class C Ash can be mixed with only water to create a concrete, although the strength is not as high as a blended mixture of fly ash and cement.[a] The Class C Ash contains a high percentage of calcium oxide, approximately 30-

40%, whereas a Class F Ash contains 1-6% calcium oxide. The high amount of calcium oxide is what provides the Class C Ash with its own cementitious materials because of the pozzolanic nature of ashes to react with free lime. Table 1.1 shows the approximate concentrations of compounds in ash collected from different types of coals. [3]

Table 1.1: Percent of compounds in fly ash

Component	Bituminous	Subbituminous	Lignite
SiO_2	20-60	40-60	15-45
Al_2O_3	5-35	20-30	10-25
Fe_2O_3	10-40	4-10	4-15
CaO	1-12	5-30	15-40
MgO	0-5	1-6	3-10
SO_3	0-4	0-2	0-10
Na_2O	0-4	0-2	0-6
K_2O	0-3	0-4	0-4
Loss of Ignition	0-15	0-3	0-5

The color of fly ash can vary from tan to gray to black, depending on the amount of unburned carbon in the ash. The lighter the color is, the lower the carbon content. Subbituminous fly ash is usually light tan to buff in color, indicating relatively low amounts of carbon as well as the presence of some lime or calcium. Bituminous fly ashes are usually some shade of gray, with the lighter shades of gray generally indicating a higher quality of ash.[e]

Precast Concrete

The precast industry involves projects ranging from bridges to buildings. Typical structural components would include bridge girders, wall panels, and elevator and stair cores. These projects require an extensive amount of engineering and a concrete with a high strength to low weight/volume ratio.[b] A fly ash replacement of cement allows for a greater overall strength as the pozzolanic reaction continues with the free lime over a typical 28 day testing period. On average, 28 day compressive test yield higher values for fly ash concrete as cement concrete.[b]

Bridge girders generally need upwards of 10,000 psi concrete and prestressing to have the capacity for the loads that are placed on them.[c] To achieve these capacities, a replacement of fly ash is required. Typical portland cement concretes gain strength rapidly in the first 7 days after placing and slows following the initial water cement reaction. A fly ash concrete will gain strength slowly over the first 7 days and then continue to gain strength at a nearly continuous rate as the fly ash continues to react with the free lime resulting from the water cement reaction. Replacement with a Class C Ash will exhibit higher early strengths than Class F Ash because of the excess calcium oxide already in the ash. For high strength applications, a minimum of 15% by weight of cementitious materials is required to reach the specified strength levels.[b] Along with an increased compressive strength, the flexural capacity is increased. Although it is generally the case that flexural capacity increases with compressive strength, a fly ash concrete will still yield higher flexural capacities than an equivalent portland cement concrete.[b]

Permeable Concrete

Fly ash is an important part of creating a lightweight, porous concrete. The increase in concern for protecting the environment has lead to the development of permeable concretes for roads and parking lots. The intent of this concrete is to allow drainage of rain and snow water, along with the contaminants such as oil, through the concrete into a sub-base that filters the water and traps the contaminants. [4]

Permeable concretes are generally a high volume fly ash (HVFA) concrete. An HVFA concrete has, by definition, more than 50% replacement of fly ash to portland cement by mass. [5] In some cases, a mid-strength concrete can be obtained by using 100% Class C ash. The amount of fly ash used as a replacement also has an effect on the water-cement ratio of the mix. A higher replacement requires less water for the reaction. [6] The void structure of permeable concretes takes up between 18%-25% of the volume. Voids are achieved by various methods of air entrainment. A method of adding foam that does not break down in structure into the mix allows the void structure to be upwards of 67% of the volume.[a] While this decreases the strength of the mix, it also decreases the unit weight making mixes of 20-lb/ft^3 possible.[a] These very low density mixes are often used for pedestrian walkways in much larger structures such as stadiums. [8]

Concrete Rehabilitation

Much of the transportation infrastructure of decades past is deteriorating. Existing concrete structures, especially bridges, are in dire need of replacement or rehabilitation. Capital costs of replacement are extremely high and can also place a major impact on travel and commuting. While most bridges require replacement for structural elements, traffic volume is also increasing, so size is a consideration; some bridges can be retrofitted to be brought up to today's codes.[c]

The most rapidly deteriorating portion of a bridge is the deck. Concrete decks are preferred in Colorado because of the high temperature range for expansion and contraction, as are concrete girders.[c] These decks, although there is a sacrificial layer of asphalt on top of the concrete, are exposed to the elements, traffic and deicing chemicals. Spalling occurs at all of the sharp corners and continuing into the concrete until it reaches the layer of rebar. This spalling is designed to occur, however is very unpleasing to the general public and non-engineers. Once concrete cracks, it has no capacity in a tension state and the rebar carries the tension load.[c] The concrete within the rebar is confined and carries the full structural load. Using a fly ash concrete increases workability of the concrete allowing for ease of placement to spalled areas.

Replacement of structural elements is not advisable unless the same mix is used. Substituting a mix with more fly ash is only beneficial from a cost perspective. The change in strength and weight of structural members as a result of fly ash substitution can affect the camber, deflection and stiffness properties of the bridge.[c] These changes will not allow the bridge to act in the way it was designed and can lead to failure of the entire structure.

Conclusions and the Future

Fly ash will be used in more projects and in a greater quantity in the coming years. The global recession has caused projects to focus on economic advantages more than ever and fly ash is a major advantage. There are also chemical admixtures being developed that increase the amount of fly ash that can be substituted for portland cement.[a] There are advancements towards the use of concretes that are 100% fly ash. While these concretes don't have the capacity of other portland cement and fly ash blends, they still exhibit strengths high enough to be used in buildings with low importance factors.

Benefits of using 100% fly ash concrete reduce environmental impacts and the need for stockpiling of the waste material itself. Studies have shown that concrete mixes using a 100% replacement can exhibit characteristics very similar to those of standard portland cement concretes. Strengths of 4000-psi can be achieved using Class C ash and aggregates including sand and crushed glass. [10] Concretes of this kind are composed of nearly 100% recycled material and are suitable for structural components in small buildings. Using these components, a building is able to achieve a high score on a LEED test and is considered a “green” building by today’s standards.

The use of fly ash in the concrete industry has increased dramatically in recent years. Environmental impacts will be the largest result of this increase in use. While roughly the same amount of ash will be produced on a yearly basis, until population controls otherwise, more of the ash can be reclaimed and used rather than landfilled. Portland cement production will also slow will the increase in ash use. With the decrease in cement production, comes a decrease in CO_2 output. Whether the amount of CO_2 entering our atmosphere is an issue remains to be debated for years, outside the scope of this paper. Case studies and research at universities have shown that the replacement of portland cement with fly ashes increases strength, reduces cost and reduces weight. All of these are beneficial in the design of structural elements for today’s advancing infrastructure.

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Appendix

a. Brian Masloff
   Cellular Concrete
   Evergreen, CO
   (303) 908.9230
   - Brian is the head of research and development for Cellular Concrete. His main expertise is in the area of cellular concrete (permeable) for roadways and public facilities. He is also very knowledgeable in the chemistry and characteristics of cement and fly ash. His contributions to this paper include portions under the headings "Background and Origin", "Chemical Composition", "Permeable Concrete" and "Conclusions and the Future".

b. Jim Fabinski
   EnCon Colorado
   Denver, CO
   (303) 287.4312
   - Jim is the engineer in charge of the precast plant for EnCon Colorado. He assists engineers from design firms with the design of girders, wall panels, elevator cores and deck panels. His contribution to this paper is the section under the heading of "Precast Concrete".

c. Ray Nickle
   AECOM
   Denver, CO
   (303) 376.2900
   - Ray is a design engineer for AECOM. He is involved in the design of new bridges across the state of Colorado and also the retrofitting of existing bridges in the state. His contribution to this paper is the section under the heading of "Concrete Rehabilitation".

d. Bill Fedorka
   SEFA Group
   Lexington, SC
   (803) 520.9000
   - Bill is Director of Engineering for SEFA and manages all engineering activities related to development of new combustion technologies for fly ash beneficiation, as well as upkeep and improvements at existing facilities. His contribution to this paper are portions under the headings “Background and Origin” and “Chemical Composition”.

e. Rodney Cunningham
   Boral
   San Antonio, TX
   (210) 349.4069
   - Rodney is the Regional Manager for Boral Technologies in the Central Texas Region. He manages the production plants and new technologies for the products sold with the Boral name. His contribution to this paper is included under the heading “Chemical Composition”.

f. Jacob O’Brien
   VSL Structural
   Wheat Ridge, CO
   (303) 456.9887
   - Jacob is a post-tensioning design engineer for VSL Structural. He is responsible for understanding the behavior of structural concrete components under axial loads caused by tensioning steel after the components are erected. He could not comment on whether the use of fly ash in a component would affect the behavior of post-tensioning, therefore, there is no significant contribution to this paper.