Report on the Use of Fly Ash in Concrete

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Fly ash is used in concrete and other portland cement-based systems primarily because of its pozzolanic and cementitious properties. These properties contribute to strength gain and are known to improve the performance of fresh and hardened concrete, mortar, and grout. The use of fly ash typically results in more economical concrete construction.

This report gives an overview of the origin and properties of fly ash, its effect on the properties of hydraulic cement concrete, and the selection and use of fly ash in the production of hydraulic cement concrete and concrete products. Information and recommendations concerning the selection and use of Class C and Class F fly ashes conforming to the requirements of ASTM C618 are provided. Topics covered include a detailed description of the composition of fly ash, the physical and chemical effects of fly ash on properties of concrete, guidance on the handling and use of fly ash in concrete construction, use of fly ash in the production of concrete products and specialty concretes, and recommended procedures for quality control. High-volume fly ash concrete is covered in a general way in this report; readers can consult ACI 232.3R for more information.

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Keywords: alkali-aggregate reaction; controlled low-strength material; durability; fly ash; mass concrete; pozzolan; sulfate resistance; sustainability; workability.

CONTENTS

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CHAPTER 1—INTRODUCTION, SCOPE, SOURCES, AND SUSTAINABILITY

1.1—Introduction

Fly ash, a material resulting from the combustion of pulverized coal, is widely used as a cementitious and pozzolanic ingredient in concrete and related products. Fly ash is introduced in concrete either as a separately batched material (ASTM C618, Class C or F) or as a component of blended cement (ASTM C595/C595M; ASTM C1157/C1157M; ASTM C1600/C1600M).

Fly ash possesses pozzolanic properties similar to the naturally occurring pozzolans of volcanic or sedimentary origin found in many parts of the world. Two thousand years ago, the Romans mixed volcanic ash with lime, aggregate, and water to produce mortar and concrete (Vitruvius 1960). In modern concrete, fly ash combines with calcium hydroxide $Ca(OH)_2$, also known as portlandite, which predominately results from the hydration of portland cement, and with water to form additional cementing product. This process, called the pozzolanic reaction, creates a finer pore structure, which in turn increases the durability of mortar and concrete.

All fly ashes exhibit pozzolanic properties to some extent. However, some fly ashes also display varying degrees of cementitious properties without the addition of $Ca(OH)_2$ or hydraulic cement. The cementitious nature of the latter type of fly ash is primarily attributed to the presence of reactive constituents such as calcium aluminate and calcium silicate phases, and calcium oxide. The role of fly ash in concrete with hydraulic cement is summarized as:

a) Calcium and alkali hydroxides that are released into solution in the pore structure of the paste by hydrating cement combine with the pozzolanic phases of fly ash, to form additional calcium silicate hydrate (C-S-H) gel (cementing matrix)

b) The heat of hydration helps to initiate the pozzolanic reaction and contributes to the rate of the reaction

When concrete containing fly ash is cured, fly ash reaction products fill spaces originally occupied by mixing water but not filled by the hydration products of the cement, thus reducing the concrete permeability to fluids (Manmohan and Mehta 1981). The slower reaction rate of fly ash, when compared with hydraulic cement, limits the amount of early heat generation and the detrimental effect of early

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temperature rise in massive concrete structures. Concrete proportioned with fly ash can develop properties that are not achievable through the use of hydraulic cement alone.

1.1.1 *History*—Fly ash from coal-burning electric power plants became readily available in the 1930s and, shortly thereafter, the study of fly ash for use in hydraulic cement concrete began (Davis et al. 1937; Stanton 1940). This early research served as the foundation for initial specifications, methods of testing, and use of fly ash. Abdun-Nur (1961) covers much of the early history and technology of using fly ash in construction and includes an annotated bibliography (1934-1959). Since this early work, much research has been performed regarding alkali-silica reaction (ASR) mitigation using fly ash. A recent summary is provided by Thomas et al. (2013).

Initially, fly ash was used as a partial replacement of hydraulic cement, which is typically the most expensive manufactured component of concrete. As fly ash usage increased, researchers recognized that fly ash could impart beneficial properties to concrete. Additional research was done on the reactivity of fly ash with calcium and alkali hydroxides in portland cement paste, and the ability of fly ash to act as a mitigator of deleterious alkali-silica reactions was identified (Davis et al. 1937). Other research has shown that fly ash often improves concrete's resistance to deterioration from sulfates (Dunstan 1976, 1980; Tikalsky et al. 1992; Tikalsky and Carrasquillo 1993). Fly ash also increases the workability of fresh concrete and reduces the peak temperature of hydration in mass concrete. The beneficial aspects of fly ash were especially notable in the construction of large concrete dams (Mielenz 1983). Some major projects, including the Thames Barrier in the UK (Newman and Choo 2003) and the Upper Stillwater Dam in the United States (Poole 1995), incorporated 50 and 65 percent mass replacement of hydraulic cement with fly ash to reduce heat generation and decrease permeability, respectively. The Iraivan Temple, built in Kauai, HI, in 1999, has a foundation composed of high-volume fly ash (HVFA) concrete with an estimated service life of 1000 years (Mehta and Langley 2000). This concept of HVFA concrete was adopted for foundation construction of at least two additional temples in the United State: one located in Chicago, IL, and the other in Houston, TX (Malhotra and Mehta 2012). In addition, numerous projects in the United States have used HVFA concrete for sustainable construction. More information on HVFA usage is available in Chapter 7 and ACI 232.3R.

A new generation of coal-fired power plants were built in the United States during the late 1960s and 70s using efficient coal mills and state-of-the-art pyroprocessing technology. These plants produce fly ash with a smaller average particle size and lower carbon content. Fly ash containing high levels of calcium oxide became available because of the use of western U.S. coal sources, typically subbituminous and lignite. Enhanced economics and improved technologies, both material- and mechanical-based, have led to a greater use of fly ash throughout the ready mixed concrete industry. Extensive research has led to a better understanding of the chemical reactions involved when fly ash is incorportated in concrete.

Fly ash is used in concrete for many reasons (refer to Chapter 4), including improvements in workability of fresh concrete, reduction in temperature rise during initial hydration, improved resistance to sulfates, reduced expansion due to alkali-silica reaction, and contributions to the durability and strength of hardened concrete. In the 1990s and 2000s, some power plants made changes to co-fire coal with biomass and to improve air quality by using scrubbers to reduce sulfur oxide emissions (SO_x), catalytic reduction equipment to reduce nitrous oxide emissions (NO_x), and various systems to reduce mercury emissions. These additional systems have the potential to alter the composition of the fly ash by incorporating such compounds as ammonia, sulfate, sulfite, alkalis, and carbon residues. These changes should be considered when selecting fly ash sources, as additional quality control parameters may be required for acceptance.

1.2—Scope

The scope of this report is to describe the use and characterization of fly ash, its properties, and its impacts on concrete properties. Guidance is provided concerning specifications, quality assurance, and quality control of fly ash itself, as well as that of concrete and related products produced using fly ash.

1.3—Source of fly ash

Due to the increased global use of pulverized coal as fuel for electric power generation, particularly in China and India, fly ash is available in many areas of the world. Approximately 53.4 million tons (48.4 million metric tons) of fly ash are produced annually in the United States (American Coal Ash Association 2015). An estimated 27 percent of that total is used in the production of cement, concrete, and manufactured concrete products.

1.3.1 *Production and processing*—The ash content of coals by mass may vary from 4 to 5 percent for subbituminous and anthracite coals, to as high as 35 to 40 percent for some lignites. The combustion process, which creates temperatures of approximately 2900°F (1600°C), liquefies the incombustible minerals. Rapid cooling of these liquefied minerals upon leaving the firebox causes them to form spherical particles with a predominantly glassy structure. Many variables can affect the characteristics of these particles. Among these are coal composition, grinding mill efficiency, the combustion environment (for example, temperature and oxygen supply), boiler/burner configuration, mineral additions, processing conditions, and the rate of particle cooling.

Modern coal-fired power plants that burn coal from a uniform source produce very consistent fly ash. Fly ash particles originating from the same plant and coal source will vary in size, chemical composition, mineralogical composition, and density. Particle sizes may run from less than 1 μm to more than 200 μm, and density of individual particles may vary from less than 62.4 lb/ft^3 (1 g/cm^3) for hollow spheres to more than 187 lb/ft^3 (3 g/cm^3) for fly ash with a preponderance of solid spheres. The true density of bulk fly ash produced by a single coal-burning plant will typically not vary dramatically.

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