

ACI 232.2R-18

Report on the Use of Fly Ash in Concrete

Reported by ACI Committee 232



American Concrete Institute
Always advancing



Report on the Use of Fly Ash in Concrete

Copyright by the American Concrete Institute, Farmington Hills, MI. All rights reserved. This material may not be reproduced or copied, in whole or part, in any printed, mechanical, electronic, film, or other distribution and storage media, without the written consent of ACI.

The technical committees responsible for ACI committee reports and standards strive to avoid ambiguities, omissions, and errors in these documents. In spite of these efforts, the users of ACI documents occasionally find information or requirements that may be subject to more than one interpretation or may be incomplete or incorrect. Users who have suggestions for the improvement of ACI documents are requested to contact ACI via the errata website at <http://concrete.org/Publications/DocumentErrata.aspx>. Proper use of this document includes periodically checking for errata for the most up-to-date revisions.

ACI committee documents are intended for the use of individuals who are competent to evaluate the significance and limitations of its content and recommendations and who will accept responsibility for the application of the material it contains. Individuals who use this publication in any way assume all risk and accept total responsibility for the application and use of this information.

All information in this publication is provided “as is” without warranty of any kind, either express or implied, including but not limited to, the implied warranties of merchantability, fitness for a particular purpose or non-infringement.

ACI and its members disclaim liability for damages of any kind, including any special, indirect, incidental, or consequential damages, including without limitation, lost revenues or lost profits, which may result from the use of this publication.

It is the responsibility of the user of this document to establish health and safety practices appropriate to the specific circumstances involved with its use. ACI does not make any representations with regard to health and safety issues and the use of this document. The user must determine the applicability of all regulatory limitations before applying the document and must comply with all applicable laws and regulations, including but not limited to, United States Occupational Safety and Health Administration (OSHA) health and safety standards.

Participation by governmental representatives in the work of the American Concrete Institute and in the development of Institute standards does not constitute governmental endorsement of ACI or the standards that it develops.

Order information: ACI documents are available in print, by download, through electronic subscription, or reprint and may be obtained by contacting ACI.

Most ACI standards and committee reports are gathered together in the annually revised the ACI Collection of Concrete Codes, Specifications, and Practices.

American Concrete Institute
38800 Country Club Drive
Farmington Hills, MI 48331
Phone: +1.248.848.3700
Fax: +1.248.848.3701

www.concrete.org

Report on the Use of Fly Ash in Concrete

Reported by ACI Committee 232

Karthik H. Obla, Chair
Robert E. Neal, Vice Chair

Michael D. A. Thomas, Vice Chair
Lawrence L. Sutter, Secretary

Thomas H. Adams
Gregory S. Barger
Dale P. Bentz
James C. Blankenship
Julie K. Buffenbarger
Ramon L. Carrasquillo
Barry A. Descheneaux

Jonathan E. Dongell
John M. Fox
Thomas M. Greene
Harvey H. Haynes
James K. Hicks
R. Doug Hooton
Morris Huffman

James S. Jensen
Tilghman H. Keiper
Steven H. Kosmatka
Adrian Marc Nacamuli
Bruce W. Ramme
Steve Ratchye
Michael D. Serra

Ava Shypula
Boris Y. Stein
Oscar Tavares
Paul J. Tikalsky
Thomas J. Van Dam
Craig R. Wallace
Orville R. Werner

Consulting Members

Mark A. Bury
James E. Cook

Dean M. Golden
William Halczak

G. Terry Harris Sr.
Jan R. Prusinski

Harry C. Roof
Della M. Roy

Special acknowledgements to M. U. Christiansen and K. A. MacDonald for their contributions to this report.

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.

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

CONTENTS

CHAPTER 1—INTRODUCTION, SCOPE, SOURCES, AND SUSTAINABILITY, p. 2

- 1.1—Introduction, p. 2
- 1.2—Scope, p. 3
- 1.3—Source of fly ash, p. 3
- 1.4—Fly ash and sustainability, p. 7

CHAPTER 2—DEFINITIONS, p. 9

CHAPTER 3—FLY ASH COMPOSITION, p. 9

- 3.1—General, p. 9
- 3.2—Chemical composition, p. 10
- 3.3—Crystalline constituents, p. 11
- 3.4—Glassy constituents, p. 13
- 3.5—Physical properties, p. 15
- 3.6—Chemical activity of fly ash in hydraulic cement concrete, p. 17
- 3.7—Future research needs, p. 18

ACI Committee Reports, Guides, and Commentaries are intended for guidance in planning, designing, executing, and inspecting construction. This document is intended for the use of individuals who are competent to evaluate the significance and limitations of its content and recommendations and who will accept responsibility for the application of the material it contains. The American Concrete Institute disclaims any and all responsibility for the stated principles. The Institute shall not be liable for any loss or damage arising therefrom.

Reference to this document shall not be made in contract documents. If items found in this document are desired by the Architect/Engineer to be a part of the contract documents, they shall be restated in mandatory language for incorporation by the Architect/Engineer.

ACI 232.2R-18 supersedes ACI 232.2R-03 and was adopted and published April 2018.

Copyright © 2018, American Concrete Institute.

All rights reserved including rights of reproduction and use in any form or by any means, including the making of copies by any photo process, or by electronic or mechanical device, printed, written, or oral, or recording for sound or visual reproduction or for use in any knowledge or retrieval system or device, unless permission in writing is obtained from the copyright proprietors.

CHAPTER 4—EFFECTS OF FLY ASH ON CONCRETE, p. 18

- 4.1—Effects on properties of fresh concrete, p. 18
- 4.2—Effects on properties of hardened concrete, p. 20

CHAPTER 5—CONCRETE MIXTURE PROPORTIONING, p. 26

- 5.1—General, p. 26
- 5.2—Considerations in mixture proportioning, p. 27

CHAPTER 6—FLY ASH SPECIFICATIONS, TEST METHODS, AND QUALITY ASSURANCE/QUALITY CONTROL, p. 27

- 6.1—Introduction, p. 27
- 6.2—Chemical requirements, p. 28
- 6.3—Physical requirements, p. 29
- 6.4—General specification provisions, p. 30
- 6.5—Methods of sampling and testing, p. 30
- 6.6—Source quality control, p. 30
- 6.7—Startup, oil, and stack additives, p. 31
- 6.8—Rapid quality control tests, p. 32

CHAPTER 7—FLY ASH IN CONCRETE CONSTRUCTION, p. 32

- 7.1—Ready mixed concrete, p. 32
- 7.2—Concrete pavement, p. 32
- 7.3—Mass concrete, p. 33
- 7.4—Roller-compacted concrete, p. 33
- 7.5—Self-consolidating concrete, p. 33
- 7.6—High-volume fly ash concrete, p. 34
- 7.7—High-performance concrete, p. 34
- 7.8—Long-life structures, p. 34
- 7.9—Bulk handling and storage, p. 35
- 7.10—Batching, p. 36

CHAPTER 8—FLY ASH IN CONCRETE PRODUCTS, p. 36

- 8.1—Concrete masonry units, p. 36
- 8.2—Concrete pipe, p. 37
- 8.3—Precast/prestressed concrete products, p. 37
- 8.4—No-slump extruded hollow core slabs, p. 38
- 8.5—Concrete tile, p. 38
- 8.6—Miscellaneous concrete products, p. 38

CHAPTER 9—OTHER USES OF FLY ASH, p. 38

- 9.1—Grouts and mortar, p. 38
- 9.2—Controlled low-strength material, p. 39
- 9.3—Soil cement, p. 39
- 9.4—Plastering, p. 39
- 9.5—Cellular concrete, p. 39
- 9.6—Shotcrete, p. 39
- 9.7—Waste management, p. 40
- 9.8—Cements, p. 40

CHAPTER 10—REFERENCES, p. 40

- Authored documents, p. 41

APPENDIX A—RAPID QUALITY CONTROL TESTS, p. 54

- A.1—Loss on ignition, p. 54
- A.2—Carbon analysis, p. 54
- A.3—Particle size, p. 54
- A.4—Color, p. 55
- A.5—Density (specific gravity), p. 55
- A.6—Fly ash adsorption, p. 55
- A.7—Organic material, p. 55
- A.8—CaO content, p. 55
- A.9—Presence of hydrocarbons (startup oil), p. 55
- A.10—Presence of ammonia (precipitator additive), p. 55
- A.11—Calorimetry, p. 55

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

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 States: 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 incorporated 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.

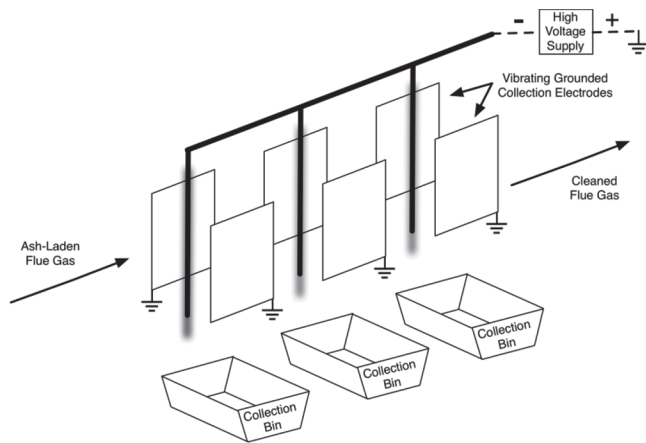


Fig. 1.3.1—Typical gas flow pattern through electrostatic precipitator.

Collection of these particles from the furnace exhaust gases is routinely accomplished by electrostatic or mechanical precipitators or by bag houses. A typical gas flow pattern through an electrostatic precipitator is shown in Fig. 1.3.1.

As fly ash particles are collected in a bag house or mechanical precipitator, they segregate in sequential precipitator hoppers according to their size and density; the larger and heavier particles tend to accumulate closer to the fly-ash-laden gas inlet, whereas the smaller and lighter particles tend to collect farther from the inlet. In electrostatic precipitators, however, the particle size and density trends in sequential hoppers are disrupted due to the influence of the charged collection grids. The fineness, density, and carbon content of fly ash can vary significantly from hopper to hopper in both mechanical and electrostatic precipitators. Hoppers can be selectively emptied and transported to a main silo. Blending occurs as a natural result of pneumatic material handling operations.

1.3.2 Impact of environmental regulations—Nitrous oxide emissions are considered to contribute to the production of ozone levels; along with SO_x , both are considered to contribute to acid rain. Additionally, air regulations are being implemented that further limit fine particulate and mercury emissions.

It has been suggested that some approaches to pollution reduction in coal combustion may modify the cementitious or pozzolanic properties of fly ash. Changes in fly ash glass content and mineralization, combined with changes in particle size distribution and particle morphology, can affect fly ash reactivity. The impact on reactivity can vary from significant to inconsequential, depending on the specific fuel and combustion modification system employed. Post-combustion technologies for reducing NO_x emissions and mercury emissions may also impact fly ash quality. The processes are summarized in the following sections.

1.3.2.1 SO_x reduction technologies—To reduce SO_x emissions, the power-generating industry has adopted a two-pronged approach. The first is a shift toward fuel sources that are lower in sulfur content, and the second is to apply technologies such as flue gas desulfurization (FGD). With regard to low-sulfur coal sources, some coal-fired power

plants have shifted from the use of eastern and central U.S. coal sources in favor of western coal sources, primarily those from the Powder River Basin (Energy Information Administration 2015). Due to low natural gas prices, the increased supply of natural gas due to fracking technology, and the need to reduce CO_2 emissions from power generation, the U.S. is expected to decrease its reliance on coal in future years. In 2013 (Energy Information Administration 2015), U.S. coal production fell below one billion short tons in the United States—3.1 percent lower than 2012—with production from the Western Region representing 53.8 percent of the U.S. total.

FGD methods have been in place for many years as a result of limits placed on SO_x emissions as part of the Clean Air Act (CAA). In general, SO_x is removed from flue gases by a variety of methods that include wet scrubbing using a slurry of sorbent such as limestone or lime, spray-dry scrubbing using similar sorbents, or dry sorbent injection systems (Nolan 2000). Normally, the by-product is a material that is currently unusable for portland cement concrete. However, some FGD materials have been used as a calcium sulfate source for the cement and wallboard industries. The presence of FGD materials in fly ash is detected by testing SO_3 levels.

Other approaches include the increased use of fluidized bed combustors, which result in lower SO_x production but also result in production of fluidized bed combustor ash that currently is not marketed for use in portland cement concrete production. Reducing the excess air in the combustion process also controls formation of SO_x ; however, limits on excess air could lead to increases in unburned fuel, which increases the loss on ignition (LOI) value or, theoretically, could result in incomplete oxidation of mineral species. Effects stemming from the latter concern have not been reported in the literature reviewed.

1.3.2.2 NO_x reduction technologies—The control of NO_x emissions is addressed primarily through the use of low- NO_x burners and a variety of downstream treatment technologies including the use of over-fire air, selective catalytic reduction (SCR), and selective noncatalytic reduction (SNCR).

NO_x forms during the combustion of coal as a result of two primary mechanisms. Thermal NO_x results from the oxidation of nitrogen in air while fuel NO_x results from oxidation of nitrogen in coal. The first source, thermal NO_x , increases exponentially with temperature and is controlled by moderating flame temperature and oxygen concentration at the burner (LaRue et al. 2001). Limiting the oxygen available during the early stages of the combustion process controls fuel NO_x . Technologies that reduce oxygen availability at the flame will effectively reduce NO_x , but as a by-product of this process change, there tends to be an increased amount of unburned fuel that can be found in the flue gases as either carbon monoxide (CO) or as carbon particulate. Even with the addition of over-fire air, higher unburned fuel amounts occur with the same total amount of combustion air (LaRue et al. 2001).

The basic principle of SCR is the reduction of NO_x to N_2 and H_2O by the reaction of NO_x and ammonia (NH_3) within a catalyst bed. SCR catalysts are manufactured using ceramic