Lutze / vom Berg (Editors)

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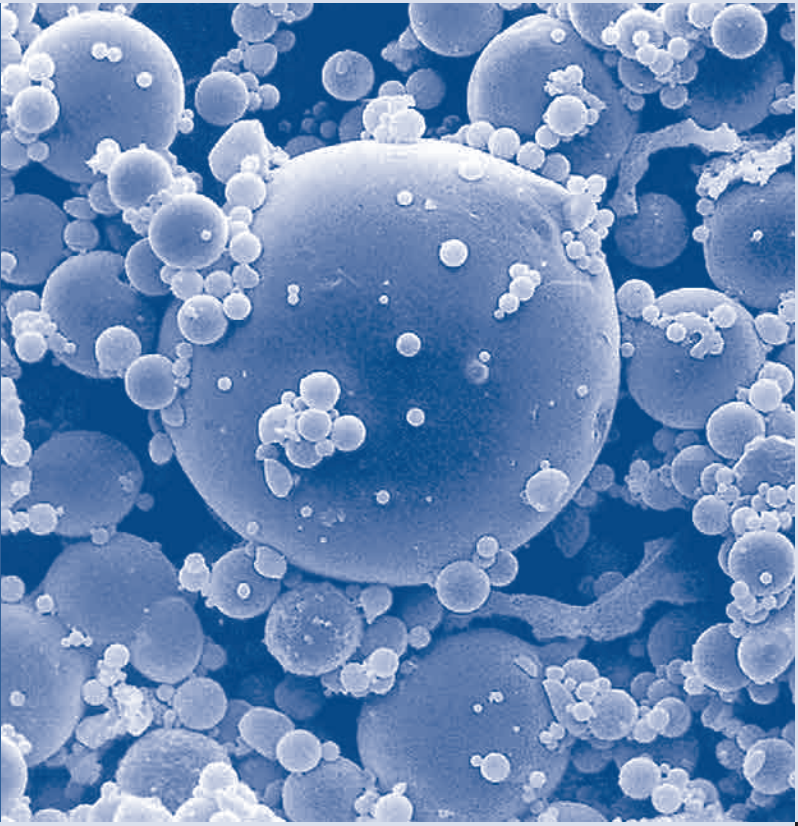
Handbook on fly ash in concrete



Principles of production and use

VERLAG BAU+TECHNIK

Lutze / vom Berg (Editors)

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Background for the translation of the “Handbook on fly ash in concrete”

The Handbook on Fly Ash in Concrete was first published in 2003 in Germany. It is serving as an information guide for concrete producers, regulators and experts in science, technology and civil engineering regarding the properties of fly ash and the benefits of the use of fly ash as concrete addition. It compiles results of research on the use of fly ash in concrete.

In addition it describes the specific regulations in Germany on the use of fly ash in concrete. The use of fly ash in concrete developed differently in the EU member states because of the differences in already existing national concrete standards and boundary conditions. By now, it was not possible to standardize the use of fly ash in concrete in detail on the European level of standardisation. Therefore different regulations based on national experience still exist in the EU member states.

In view of the fact that the handbook on fly ash for concrete is mainly related to the German approach the members of the European Coal Combustion Product Association (ECOBA) consider it useful to provide an English translation in order to make the compiled information available to the experts across Europe and to provide a contribution to future discussions on the best use of fly ash in concrete.

Essen, April 2010
ECOBA – European Coal Combustion Products Association
Hans-Joachim Feuerborn

VLB-Meldung

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Principles of production and use
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Foreword to the First Edition

As an addition and a binder component, fly ash is nowadays an indispensable material for many applications of concrete. Our current level of knowledge and experience is based on a technical development that started in Germany in the mid-1960s and has been continued worldwide with intensive and extensive research work.

The conditions existing in power stations when firing pulverized coal cause a flour-fine, pozzolanic mineral material to form from the accompanying rock in the coal. Owing to its specific characteristics, it has a positive impact on the properties of fresh and hardened concrete, and enables high-grade, durable concretes to be produced in a cost-effective manner.

The use of fly ash in concrete is also highly beneficial from an economic and ecological perspective, as the smaller quantities of cement and aggregate used enable valuable resources to be conserved, energy to be saved and pollution and carbon dioxide emissions, which are unavoidable in the production of building materials, to be reduced.

In this book, the authors have combined the latest discoveries from the field of research with practical experience of the use and effects of fly ash in concrete for the user. We hope that this book delivers all the necessary information and provides interesting suggestions for the targeted use of fly ash in concrete, thus promoting the use of this valuable raw material.

Dortmund and Essen, December 2003

Dietmar Lutze
Dr. Wolfgang vom Berg

Foreword to the Second Edition

After five years, the results of new research into the effect of fly ash in concrete and the properties of fly ash concrete, and their implementation in the rapidly changing regulations on the production of concrete have inspired the authors to extensively revise and update the Handbook on Fly Ash in Concrete. The situation as regards standards relating to this field as of August 2008 has also been incorporated. The authors hope that this Second Edition will prove to be a helpful, practical resource for the production of concrete with fly ash in compliance with the applicable standards.

Dortmund and Aachen, August 2008

Dietmar Lutze
Dr. Wolfgang vom Berg

Content

1 Basic Principles

1.1 Definition

According to DIN EN 450-1 “Fly ash for concrete” [N 6], fly ash is a fine powder of mainly spherical, glassy particles derived from burning of pulverized coal. It has pozzolanic properties and consists essentially of SiO_2 and Al_2O_3, the content of reactive SiO_2 being at least 25 mass %. Fly ash is obtained by electrostatic or mechanical precipitation of dust-like particles from the flue gases of furnaces fired with pulverised coal, with or without co-combustion materials.

With the exception of one lignite fly ash approved by the building authorities, all types of fly ash used as a concrete addition in Germany have a low reactive lime content and a high reactive SiO_2 content. They are known as siliceous or silicon-rich fly ash and may also come from lignite-fired power plants.

To date, calcareous fly ash (reactive CaO > 10 mass %) has not been provided for use as a concrete addition in Germany (aside from the aforementioned exception). However, according to DIN EN 197-1 [N 3], calcareous fly ash may be used as a main constituent in the production of fly ash cement CEM II/A-W or CEM II/B-W. As cements of this type are not produced as yet in Germany, and the use of calcareous fly ash as a concrete addition is also not generally permitted at the present time, this type of fly ash will not be discussed here.

In this book, fly ash should be understood to mean siliceous fly ash in accordance with DIN EN 450-1. This type of fly ash is generally obtained by firing hard coal and is therefore frequently referred to in the literature as hard coal fly ash.

However, fly ash conforming to DIN EN 450-1 can also be produced by processing in suitable production plants. The processed fly ash may consist of fly ash from different sources complying with the above definition. If one or more of the initial fly ashes is produced in power plants with co-combustion of secondary fuels, the processed fly ash is considered to be fly ash obtained via co-combustion, for which specific verification is required.

1.2 Historical development

As early as the 1930s, efforts were made to find a use in the building materials industry for the increasing amounts of fly ash produced when firing coal in large power plants in Europe and America. One proposal was to use it as a substitute for cement as an addition in autoclaved aerated concrete and concrete blocks. In the U.S.A., fly ash was used to replace 35 % of the Portland cement in about 3 million m^3 of concrete during construction of the Hungry Horse Dam in Montana in 1948. In Germany, only fly ash from hard coal power stations was initially used, due to the fact that it was available at the quality required and had the desired degree of uniformity.

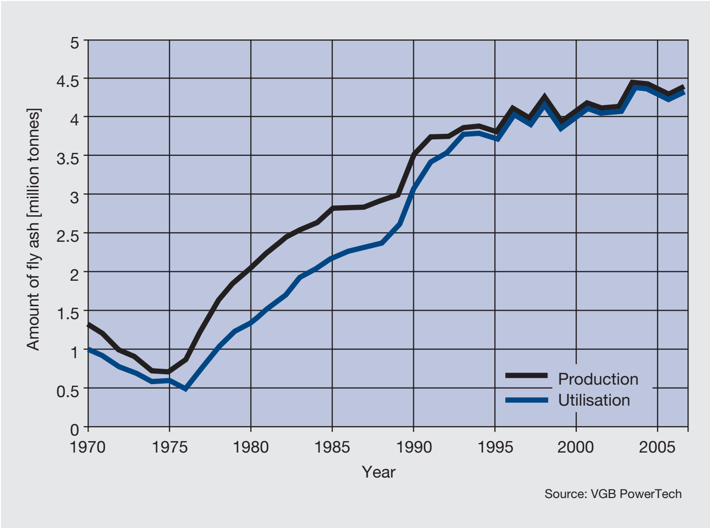

Fig. 1.2-1:
Development in the production and utilisation of fly ash from hard coal power plants in Germany

In Germany, fly ash began to be used in significant amounts in the 1960s and, owing to the increasing amounts being produced, became an economic and ecological necessity from the mid-1970s onwards (Fig. 1.2-1). Since the mid-1990s, almost 100 % of the fly ash generated in hard-coal-fired power plants has been used in the production of building materials, of which 75 % has been used to make all types of concrete.

It took more than 10 years, by convincing potential users, developing the necessary logistic infrastructure and opening up the market for the product fly ash, to reach today's successful outcome. One of the initial problems which had to be dealt with was the fact that the use of fly ash was not regulated in the sector of building construction relevant to the building inspectorate and was not included in constructional regulations. This applied to all applications of fly ash, but in particular to its use in concrete, which already represented a significant market at that time. A crucial breakthrough was made in this regard on 29 June 1970, when the German State of North Rhine-Westphalia, as the highest building authority, granted H. Keller, a company which sold and distributed by-products from German coal-fired power plants, a technical approval for "EFA-Füller RM" fly ash from the Rheinstahl power plant in Marl as a binder for use in combination with cement. This decision was crucial from a cost perspective, as the approval allowed some of the cement required for concrete to be replaced by fly ash, and the recognition given to fly ash as a binder component attracted the interest of concrete manufacturers. Unfortunately, it was not long before this positive development was brought to a halt when the German states assigned some of their responsibilities for building inspection to the Institute of Building Technology. This Institute was founded in 1969 and, to begin with, no longer allowed fly ash to be counted in the total binder content as a binder for use in combination with cement. Fly ash had been granted 31 marks of approval by 1979, but the industry had to wait until 1983 for new regulations allowing fly ash to be counted as part of the binder content. However, these new regulations were far more restrictive than the building inspectorate approval given in 1970. By 1995, a total of 85 marks of approval had been granted on the basis of the “Guidelines for Granting Marks of Approval for Hard Coal Fly Ash”, developed in 1980 by the Institute of Building Technology and the subsequent (1990) “Guidelines for Granting Approval for Inorganic Concrete Additions (Approval Directive)” [R 1].

It was necessary to perform extensive research to establish the current value of the “countability factor” of k = 0.4 in the approvals. Fly ash became a standard building material when DIN EN 450 [N 5] was introduced by the building inspectorate in 1996. Building inspectorate approvals are now granted only for fly ashes not covered by the standard, such as fly ash produced by firing hard lignite and lignite as well as fly ash produced by the co-combustion of sewage sludge or petroleum coke.

As a result of new technological developments in the power industry and knowledge gained from the application of DIN EN 450, fly ash from co-combustion power plants and processed fly ashes were also incorporated into the successor standards DIN EN 450-1 and DIN EN 450-2, which were adopted by the building inspectorate in 2006.

The use of standard fly ash in concrete has been regulated by the application guidelines “Use of Fly Ash Complying with DIN EN 450 in Concrete Construction” [R 3] issued by the DAfStb (German Committee for Reinforced Concrete) in 1996 and adopted by the building inspectorate. The contents of these application guidelines were later incorporated into DIN 1045-2, which has been a mandatory requirement since 1.1.2007. Since then, the range of potential applications has been broadened on the basis of new research results and has been incorporated into DIN 1045-2 by way of the Amendments A1 and A2. Amendments A1 and A2, as well as Amendment A3 to DIN 1045-2, which was only published as a draft standard and essentially contained the preliminary standards of the DIN V 20000 series in DIN 1045-2, were incorporated into a consolidated version of DIN 1045-2, 2008-08 edition [N 13].

1.3 Raw materials, production and quality control of fly ash

1.3.1 Raw materials

In 2006, approximately 50 million tonnes of hard coal were used in power plants across Germany to generate electricity and heat. Increasing quantities of hard coal imported from Eastern Europe and overseas were fired in addition to hard coal from Germany.

Hard coal, a fossil fuel, is an organic sediment formed at its site of deposition from the remains of plants and animals which have been converted into coal by geological processes. The deposits of hard coal in the earth were generally formed during the Carboniferous Period between 285 and 360 million years ago. Hard coal is composed of an organic component, carbon, which has a high calorific value, and between 5 mass % and 35 mass % of associated mineral matter that cannot be removed by processing, namely the ash. The various grades of coal are determined by carbon content, volatile constituents, sulfur content, and content of associated mineral matter. Only certain selected grades of coal are suitable for use as steam coal in a coal-fired power plant.

After hard coal has been mined, the majority of the accompanying rock is separated from it as refuse by flotation and other methods during the coal processing procedure. To obtain particular, defined properties, coals of different origins are often mixed, occasionally in special mixing facilities at the power plant.

Biomass and/or secondary fuels derived from waste are nowadays also co-combusted in some power plant boilers with the standard coal fuel for economic and ecological reasons [1-1]. In Germany, these secondary fuels currently generally take the form of petroleum coke from oil refining and sewage sludge from municipal sewage treatment works. In some other European countries, other secondary fuels processed for use in power plants as well as biomass are also co-combusted with coal. The amount of co-combustion material used in each case is limited by the provisions of the standard, which ensure that the concrete technology and environmental properties of the fly ash are not adversely affected.

1.3.2 Production

Coal is transported by heavy goods vehicle, rail or ship from the mine or an international port to power plants. It is then stockpiled or directly conveyed to the coal bunkers of the power plant, as required. The coal is subsequently ground in coal mills (generally vertical roller mills). The fineness of the pulverised coal is determined by screening, ensuring that 80 mass % of the coal particles have a particle size of < 90 µm. The pulverised coal is conveyed along with the combustion air to the burners, and passes through them to the combustion chamber, where the organic constituents in the coal are burnt within seconds with the release of heat. Some of the non-combustible mineral constituents agglomerate to form coarser particles and, depending on the furnace system used, fall to the bottom of the boiler as in liquid or lump form. For example, glassy slag-tap boiler slag is formed in wet bottom boilers (furnace temperature 1,500 to 1,700 °C) and bottom ash is formed in dry bottom boilers (1,100 °C to 1,300 °C).

The fine mineral particles found in the flue gas are also largely melted. They are entrained by the flue gas and, when they cool, solidify to form glassy, amorphous ash particles having a predominantly spherical shape (Fig. 1.3-1).

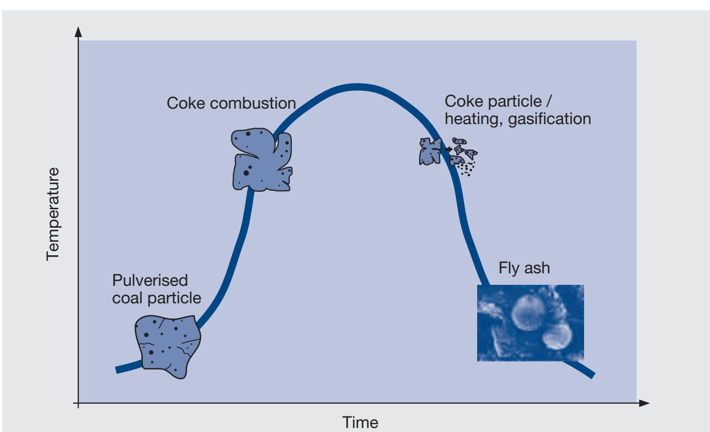

Fig. 1.3-1:
From coal particle to fly ash

These ash particles are separated from the flue gas by electrostatic separation in multi-stage electrostatic precipitators and are obtained as fly ash. The fly ash is conveyed pneumatically or mechanically from the electrostatic precipitator and collected in a silo.

According to DIN EN 450-2 [N 7], it is possible to process fly ash in suitable production facilities to optimise its properties. Suitable methods for this purpose include, for example, classification, selection, sieving, drying, blending, grinding and carbon reduction. Processing fly ash by classification, selection or sieving processes serves primarily to increase the fineness and to improve the particle shape and granulometric composition, thus reducing the water demand. It is necessary for the fly ash used for processing to be inspected and for it to comply with DIN EN 450-1 [N 6], with the exception of the requirements on loss on ignition, fineness and variations in fineness.

1.3.3 Monitoring and certification

Until 1995, it was necessary to obtain a technical approval from the German Institute of Building Technology (DIBt) to be able to use fly ash as an addition in concrete in accordance with DIN 1045 [N 12]. These technical approvals, which had to be granted individually for each fly ash from a particular power plant or power plant unit, contained material-specific requirements, the rules for use of fly ash in concrete in accordance with DIN 1045 and the regulations for the product control required. The European standard EN 450 “Fly ash for concrete”, published in September 1994, was published as DIN EN 450 [N 5] together with the test standards DIN EN 451-1 [N 8] and DIN EN 451-2 [N 9] in January 1995 and, after a transition period, replaced the technical approvals required before that point.

In 2005, DIN EN 450-1 [N 6] and DIN EN 450-2 [N 7] were published as successor standards to DIN EN 450:1995 and were adopted by the building inspectorate in 2006 by incorporation into the Building Code, Section B. DIN EN 450-2 superseded conformity evaluation standard DIN 18990 [N 29]. In DIN EN 450-2, as in DIN 18990, conformity of fly ash is demonstrated in accordance with system 1+ on the basis of factory production control performed by the manufacturer using a works’ quality manual, as well as on the basis of audit testing by a recognised body which assesses and evaluates the results of the internal tests and also carries out audit testing itself. Only six of the more than 150 European building materials standards require demonstration of conformity in accordance with system 1+, which consists of continuous factory production control by the manufacturer and testing by a recognised body. This demonstrates how high the standards of quality for fly ash as a concrete addition are in comparison with other building materials. A certificate of conformity which confirms the compliance of the fly ash with the requirements of the material standard DIN EN 450-1 and which is issued by a recognised certification body is granted as a result of this quality control process. The certificate of conformity and the associated conformity mark (CE mark) on the delivery note indicates that the fly ash may be used as a concrete addition in compliance with DIN EN 206-1 / DIN 1045-2.

When co-combustion materials are used, substances which affect the environment may be incorporated in the fly ash and released due to the leaching processes when this fly ash is used in concrete. According to DIN 1045-2 [N 13], only fly ash which does not have any harmful environmental effects, in particular with respect to soil and water, may be used in concrete. This must be established by obtaining general technical approval. In addition to the CE mark, all fly ashes also receive an Ü mark to demonstrate their compatibility with the environment. Depending on the type of co-combustion material used, tests are as specified in the German Institute of Building Technology's reference document "Evaluation of impact of building materials on soil and groundwater" have to be performed as part of the approval procedure [M 1].

Either the power plant or, if the fly ash is processed, the production plant counts as the production site.

1.4 Material properties of fly ash

1.4.1 Mineral and chemical composition

The types of mineral present in the coal and the accompanying rock are determining factors of the chemical composition and the mineral phase constitution of the fly ash. The minerals which are the most common and occur most widely in coal include clay minerals, iron sulfides and carbonates. These types of minerals may account for up to 95 % of all the minerals contained in the coal. Other minerals generally found in coal include quartz and various iron oxides and hydroxides. This mineral phase constitution of hard coal is comparable to the raw materials used for earthenware (clay slate, etc.).

When pulverised coal particles are burnt in the flames of the coal burner, the minerals accompanying the coal are heated to temperatures > 1,300 °C, causing conversion processes to take place, such as dewatering, de-carbonation, oxidation and sintering. The majority of the mineral material melts and then solidifies in a glassy, amorphous form during the following cooling process in the stream of flue gas. The resulting glass content of the fly ash lies between 60 mass % and 85 mass %. The main crystalline phases likely to be found in this glass matrix are mullite (as the recrystallisation product of the alumino-silicate melt), quartz and iron oxide (Table 1.4-1).

The mineral phase constitution described produces a chemical composition which is characterised by its three main components: SiO_2 (silica), Al_2O_3 (alumina) und Fe_2O_3 (iron oxide). In contrast to most of the fly ash produced in lignite power plants, fly ash obtained from firing hard coal is low in lime and sulfates and is rich in silicon (see Table 1.4-2). Trace elements such as lead, nickel and arsenic are only present in low concentrations. The sum of these elements, together with zinc and manganese, accounts for less than 1 mass %. As expected, organic trace substances such as polycyclic aromatic hydro-

Mineral phases	Content [mass %]
Glass	60 … 83
Mullite	4 … 25
Quartz	4 … 18
Haematite	0,5 … 2
Magnetite	1 … 7
Quick coke	0.5 … 5

Table 1.4-1: Mineral phases in siliceous fly ash