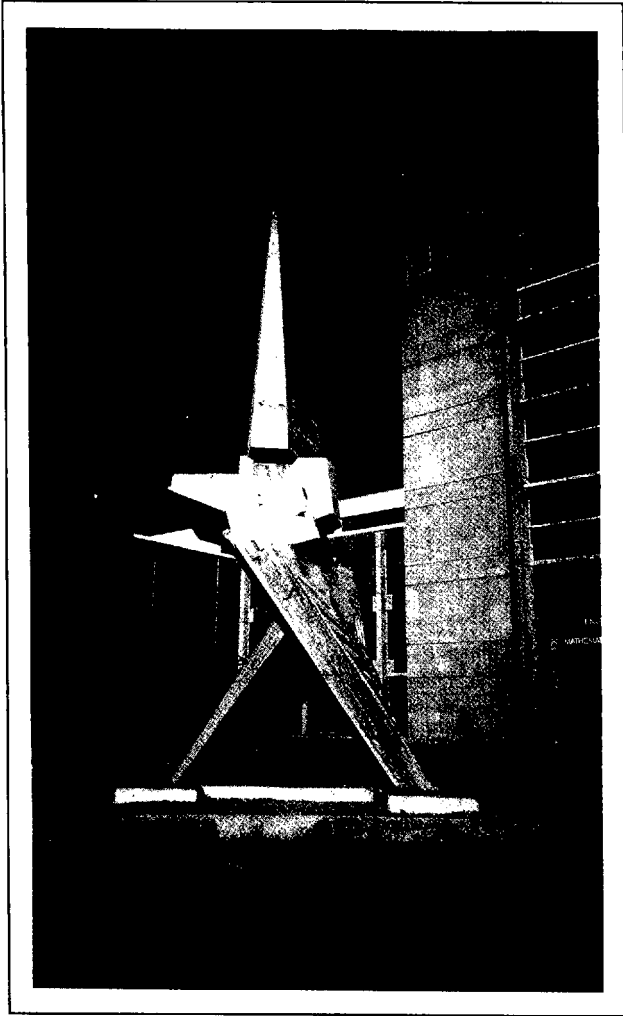

1998

**SIXTH CANMET / ACI / JCI
SIXIÈME CANMET / ACI / JCI**

INTERNATIONAL • CONFERENCE • INTERNATIONALE



**FLY ASH,
SILICA FUME,
SLAG AND NATURAL
POZZOLANS IN
CONCRETE**

**CENDRES VOLANTES,
FUMÉES DE SILICE,
LAITIERS ET POZZOLANES
NATURELLES DANS
LE BÉTON**

VOLUME 1

EDITOR • V.M. MALHOTRA • RÉDACTEUR EN CHEF



Documents

Document Sharing Hub

Fly Ash, Silica Fume, Slag & Natural Pozzolans in Concrete

Proceedings Sixth CANMET/ACI International Conference Bangkok, Thailand 1998

Editor

V. M. Malhotra Volume I SP - 178



DISCUSSION of individual papers in this symposium may be submitted in accordance with general requirements of the ACI Publication Policy to ACI headquarters at the address given below. Closing date for submission of discussion is January 1st, 1999. All discussion approved by the Technical Activities Committee along with closing remarks by the authors will be published in the May/June 1999 issue of either ACI Structural Journal or ACI Materials Journal depending on the subject emphasis of the individual paper.

The Institute is not responsible for the statements or opinions expressed in its publications. Institute publications are not able to, nor intended to, supplant individual training, responsibility, or judgment of the user, or the supplier, of the information presented.

The papers in this volume have been reviewed under Institute publication procedures by individuals expert in the subject areas of the papers.

Copyright © 1998
AMERICAN CONCRETE INSTITUTE
P.O. Box 9094
Farmington Hills, Michigan 48333

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 any electronic or mechanical device, printed or 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.

Printed in the United States of America

Editorial production: Jane Carroll

Library of Congress catalog card number: 98-85145

PREFACE

The Canadian Centre for Mineral and Energy Technology (CANMET) of Natural Resources Canada, Ottawa, has played a significant role in Canada for over 30 years in research on fly ashes, ferrous and nonferrous slags, and silica fumes, in order to conserve both resources and energy, and to reduce CO₂ emissions. In July-August 1983, CANMET, in association with the American Concrete Institute and the U.S. Corps of Engineers, sponsored a five-day international conference at Montebello, Quebec, Canada, on the Use of Fly Ash, Silica Fume, Slag and Other Mineral By-Products in Concrete. The main purpose of the conference was to bring together representatives from industries, universities, and government agencies to present the latest information on these materials, and to explore new areas of needed research. The two-volume proceedings of the conference, containing 62 papers from 15 countries, were published as ACI Special Publication SP-79.

In 1986, CANMET, in association with the American Concrete Institute, the Canadian Society for Civil Engineering, and a number of organizations in Spain, sponsored the Second International Conference on the subject of Fly Ash, Silica Fume, Slag, and Natural Pozzolans in Concrete. The conference was held April 21-25, 1986, in Madrid, Spain. The two-volume proceedings of the conference, containing 72 refereed papers from more than 20 countries, were published as ACI Special Publication SP-91.

In 1989, CANMET, in association with the American Concrete Institute, Norwegian Institute of Technology, and several other organizations in Canada and Norway, sponsored the Third International Conference on this subject. The conference was held June 18-23, 1989, in Trondheim, Norway. The two-volume proceedings of the conference, containing 83 refereed papers from more than 25 countries, were published as ACI Special Publication SP-114.

In 1992, CANMET, in association with the American Concrete Institute, the Electric Power Research Institute, U.S.A., and several other organizations in Canada and Turkey, sponsored the Fourth International Conference on this subject. The conference was held May 3-8, 1992, in Istanbul, Turkey. More than 130 papers from 32 countries were received and reviewed in accordance with the policies of the American Concrete Institute; 89 refereed papers were published as ACI Special Publication SP-132.

In 1995, CANMET, in association with the American Concrete Institute, the Electric Power Research Institute, U.S.A., Canadian Electrical Association,

Montreal, and several other organizations in Canada and the United States, sponsored the Fifth International Conference. The conference was held June 4-9, 1995, in Milwaukee, Wisconsin, U.S.A. The two-volume proceedings of the conference containing 62 refereed papers from 23 countries, were published as ACI Special Publication SP-153.

In 1998, CANMET, in association with the American Concrete Institute, the Electric Power Research Institute, U.S.A., and several other organizations in Canada and Thailand, sponsored the Sixth CANMET/ACI International Conference on Fly Ash, Silica Fume, Slag, and Natural Pozzolans in Concrete. The conference was held May 31-June 5, 1998, in Bangkok, Thailand. The two-volume proceedings of the conference, containing 59 refereed papers from 26 countries, were published as ACI Special Publication SP-178.

To all those whose submissions could not be included in the conference proceedings, the Institute and the Conference Organizing Committee extend appreciation for their interest and hard work. The refereed papers have been published in two volumes. The first volume contains papers dealing with fly ash and natural pozzolans, and the second volume consists of papers dealing with silica fume, slag, and other materials. Some papers could have been published in either volume because the material covered more than one subject.

In addition to the papers which have been published in these volumes, more than 40 other papers were presented. Most of these papers were published as supplementary papers, and the authors have been encouraged to publish them in technical journals of their choice.

Thanks are extended to the members of the Paper Review Panel which met in Honolulu, Hawaii, August 10-15, 1997, to review the papers. Without their dedicated effort it would not have been possible to publish these volumes for distribution at the conference. The cooperation of the authors in accepting reviewers' suggestions and revising their manuscripts accordingly is greatly appreciated.

The help and assistance of Mr. H.S. Wilson, Consultant, Ottawa, and Gordon D. Brearley and Maria Venturino of CANMET are gratefully acknowledged in the administrative work associated with the conference, and in processing the manuscripts for both the ACI proceedings and the supplementary volume. Thanks are also extended to A. Bilodeau (Chairman) and Messrs. B. Fournier and R. Chevrier (Members) of the Slide Review Panel for their services to ensure that slides met the CANMET/ACI criterion.

As an integral part of the conference, a special symposium was held during the conference to honor Dr. J.G. Cabrera, Professor, Department of Civil Engineering, University of Leeds, U.K. The papers presented at this symposium have been published in a separate volume.

V.M. Malhotra, Editor
Chairman, Sixth CANMET/ACI International
Conference on Fly Ash, Silica Fume, Slag
and Natural Pozzolans in Concrete
May 1998

Organizing Committee

**Sixth CANMET/ACI International Conference
on
Fly Ash, Silica Fume, Slag and
Natural Pozzolans in Concrete**

**Bangkok, Thailand
May 31-June 5, 1998**

**V. Mohan Malhotra
Chairman**

Theodore W. Bremner (Member) Wilbert (Wib) S. Langley (Member)

Henri L. Isabelle (Member) Vangi S. Ramachandran (Member)

**Harry S. Wilson
Secretary-Treasurer**

CONTENTS

PREFACE

by V.M. Malhotra iii

ROLE OF POZZOLANIC AND CEMENTITIOUS MATERIAL IN SUSTAINABLE DEVELOPMENT OF THE CONCRETE INDUSTRY

by P. Kumar Mehta 1

THE USE OF CLASSIFIED FLY ASH TO PRODUCE HIGH PERFORMANCE CONCRETE

by K.E. Hassan and J.G. Cabrera 21

SELECTIVE USE OF FLY ASH CONCRETE

by V. Sirivivatnanon and R.P. Khatri 37

INFLUENCE OF TEMPERATURE ON STRENGTH DEVELOPMENT OF FLY-ASH AND SILICA-FUME CONCRETES

by H. Saricimen, M. Maslehuddin and O.A. Eid 59

TECHNOLOGICAL COMPLEX FOR UTILIZATION OF HIGH-CALCIUM ASH AND SLAG FOR ABAKAN THERMAL POWER PLANT

by S. Pavlenko, A. Shishkanov, and Yu. Bazhenov 79

COMPARATIVE STUDY ON MORTAR CONTAINING FLY ASH FROM SOUTHEAST ASIA AND JAPAN IN RELATION TO STRENGTH AND DURABILITY

by K. Wangwichit, M. Hisada, N. Otsuki and S. Nagataki . . 91

SIGNIFICANCE OF THE TYPE OF CEMENT ON THE REACTION MECHANISMS OF POZZOLANS

by B. Meng, U. Wiens and P. Schiessl 109

A COMPARISON OF MECHANICAL PROPERTIES OF HONG KONG MEDIUM AND HIGH-STRENGTH NPC AND FLY ASH CONCRETES

by I.D. MacGregor 129

HIGHLY FLOWABLE STEEL FIBER-REINFORCED CONCRETE CONTAINING FLY ASH

by M. Kurita and T. Nomura 159

EFFECT OF STEAM CURING ON COMPRESSIVE STRENGTH OF FLY ASH CONCRETE by K. Kohno, Y. Mitsuiwa and K. Ishimaru	177
THE CHEMICAL SHRINKAGE OF POZZOLANIC REACTION PRODUCTS by H. Justnes, B. Ardoullie, E. Hendrix, E.J. Sellevold and D. Van Gemert	191
MICROSTRUCTURAL STUDY OF HYDRATION REACTIONS OF A FLY-ASH BELITE CEMENT by S. Goñi, M.P. Luxán, A. Guerrero, M.S. Hernández and A. Macías	207
A NOVEL CLINKERIZATION PROCESS FOR FLY-ASH UTILIZATION by S.A. Khadilkar, M. V. Karandikar, D. Ghosh and A.K. Chatterjee	225
FLY ASH CUSTOMIZATION FOR DEFINED PERFORMANCE CONCRETES by H.A.W. Cornelissen and J.W. van den Berg	239
INFLUENCE OF UNBURNT CARBON IN THE PERFORMANCE OF CONCRETE MIXTURES by L. Coppola, R. Trolì, P. Zaffaroni, G. Belz and M. Collepari	257
DURABILITY STUDY OF MOUNT PINATUBO EJECTA CONCRETE PAVING BLOCKS by J. G. Agron	273
OPTIMIZED SOLIDIFICATION OF MIXTURES OF MSWI FLY ASH AND BLAST FURNACE SLAG: USE OF THE STATISTICAL DESIGN OF EXPERIMENTS by S. Morel, P. Clastres, D. Mathieu and A. Pellequer	287
EFFECTS OF FLY ASH AND SILICA FUME ON HIGH PERFORMANCE CONCRETE by S. Nagataki, S. Miyazato and T. Saitoh	307
ENGINEERING PROPERTIES OF HIGH VOLUME FLY ASH CONCRETE by R. N. Swamy and H.H. Hung	331

EFFECT OF CURING METHODS AND CONDITIONS ON THE PERFORMANCE OF FLY ASH CONCRETE IN DE-ICING SALT SCALING

by A. Bilodeau, M.H. Zhang, V.M. Malhotra and D.M. Golden 361

THE MICROSTRUCTURE AND CHLORIDE ION DIFFUSION CHARACTERISTICS OF CEMENTS CONTAINING METAKAOLIN AND FLY ASH

by J.G. Cabrera and S.O. Nwaubani 385

EFFECTS OF FINE AGGREGATE REPLACEMENT ON THE RHEOLOGY, COMPRESSIVE STRENGTH AND CARBONATION PROPERTIES OF FLY ASH AND MORTAR

by K.R. Hwang, T. Noguchi and F. Tomosawa 401

SLUMP LOSS: A SINGLE RULE FOR ORDINARY CONCRETE

by B. Pollet, R. Lavaud and J. Baron 411

INFLUENCE OF PALM OIL FUEL ASH ON SULFATE RESISTANCE OF MORTAR AND CONCRETE

by M. Warid Hussin and A.S.M. Abdul Awal 417

MINERALOGICAL AND CHEMICAL PROPERTIES OF MORTAR INCORPORATING COAL ASH PRODUCED BY FLUIDIZED BED COMBUSTION

by N. Shintani, T. Saitou, H. Sasaki and T. Kita 431

MECHANICAL PROPERTIES AND DURABILITY OF STRUCTURAL LIGHTWEIGHT CONCRETE INCORPORATING HIGH VOLUMES OF FLY ASH

by A. Bilodeau, V.M. Malhotra and D.M. Golden 449

SUPPLEMENTARY CEMENTING MATERIALS: THEIR ACCEPTANCE IN AUSTRALIAN SPECIFICATIONS

by D. Baweja and P. Nelson 475

DE-ICING SALT SCALING OF CONCRETE INCORPORATING DIFFERENT TYPES AND PERCENTAGES OF FLY ASHES

by M.H. Zhang, A. Bilodeau, G. Shen and V.M. Malhotra . 493

**UTILIZATION OF COAL ASH PRODUCED FROM PRESSURIZED
FLUIDIZED BED COMBUSTION POWER PLANT AS A CONCRETE
MINERAL ADMIXTURE**

by K. Fukudome, N. Shintani, T. Saitoh, T. Kita and
H. Sasaki 527

**PRACTICAL USES FOR HIGH-VOLUME FLY ASH CONCRETE
UTILIZING A LOW CALCIUM FLY ASH**

by W.S. Langley and G.H. Leaman 545

**MECHANICAL PROPERTIES AND DURABILITY OF CONCRETE
MADE WITH HIGH VOLUME FLY ASH BLENDED CEMENTS**

by N. Bouzoubaâ, M.H. Zhang, A. Bilodeau and
V.M. Malhotra 575

SP 178-1

Role of Pozzolanic and Cementitious Material in Sustainable Development of the Concrete Industry

by P. K. Mehta

Synopsis: Among the major problems facing the concrete industry at the end of the twentieth century are the enormous infrastructural needs of a rapidly urbanizing world, the premature deterioration of many concrete structures, the need to improve concrete durability in a cost-effective way, and increasing public interest in finding ecological solutions for safe disposal of millions of tons of industrial by-products that might be suitable for incorporation into cementitious materials and concrete. In this paper the author has shown that all these problems are interrelated and can be resolved by adopting a holistic approach.

Keywords: cementitious materials; cost; durability; fly ash; infrastructure; industrial by-products; slags; utilization rates.

2 Mehta

P. Kumar Mehta is Professor Emeritus in the Civil Engineering Department at the University of California at Berkeley. He is the author or coauthor of numerous papers on cementitious materials and properties of concrete including a textbook on the subject. A Fellow of the American Ceramic Society and the American Concrete Institute, he has received several awards including the ACI's Wason Medal for materials research, CANMET/ACI award for outstanding contributions to research on performance of concrete in the marine environment, and Mohan Malhotra Award for research on supplementary cementing materials. He held the Roy Carlson Distinguished Professorship in Civil Engineering at Berkeley and on his retirement he received the highest campus honor, the Berkeley Citation, for exceptional contributions to his field and to the university.

1. INTRODUCTION

In a paper, **Concrete Technology at the Crossroads**, which the author presented in 1994 at a symposium honoring Mohan Malhotra (1), the following three issues confronting the concrete industry were addressed in detail:

1. Enormous infrastructural needs of a rapidly urbanizing society in the world.
2. The need for a balance between industrial development and environmental protection.
3. The crisis in the area of concrete durability.

Since the advent of the industrial revolution, approximately four hundred years ago, not much attention has been paid to the environmental and social costs of technology. This is changing now. With the beginning of the twenty-first century in less than three years, we are entering into an era of sustainable development. This means that, in the future, it will not be possible to pursue technological goals without giving equal importance to the public interest in preserving the ecological balance on the planet earth. There is a heightened awareness now that this planet is too small to contain the wastes of our industrial civilization. In the context of this awareness, only a holistic approach in concrete technology can help us meet the material needs of an increasingly urbanized world. Therefore, one of the objectives of this paper, which is based on a presentation made last year at a symposium in honor of Professor Mario Collepardi (2), is to show how seemingly unrelated problems such as those listed above are found to be closely interconnected when examined from a holistic standpoint and therefore can be addressed with a common solution.

2. INFRASTRUCTURAL NEEDS OF THE WORLD

The twentieth century has seen unprecedented growth in human population which, during the last seventy-five years, has risen from two to six billion. By the year 2025, it is expected to increase to nine billion. Industrialization of the world occurred primarily in response to the search for sources of energy, minerals, and food as a result of population growth. Industrialization has led to urbanization. For the first time in the history of the world, more people are now living in and around cities than in rural areas. According to a U.N. report, in addition to numerous cities with a population of more than one million, there are now twenty megacities with eleven million or more inhabitants.

The infrastructure for industrial and urban areas, such as buildings, mass transit, and facilities for handling water and sewage, obviously requires large amounts of construction materials. For numerous structural applications concrete has unquestionably become the material of choice due mostly to its low cost, easy availability, versatility, and adequate engineering properties. At the same time, during the last one hundred years, portland cement has emerged as the principal hydraulic binder for concrete mixtures. The 1994 world consumption of approximately 1.3 billion tons of cement consisted mostly of portland cement because, unlike the old lime-pozzolan cements, it possesses faster setting and hardening characteristics, which are more suited to modern construction speeds. The current and the projected yearly cement consumption rates in different parts of the world up the year 2005 are shown in Table 1. Note that nearly 370 million tons out of the projected 500-million-ton total increase in cement consumption during the period 1994-2005 (i.e. 75% of the world's total) comes from Asia, and South and Central America. Due to the capital-intensive nature of the portland cement industry (U.S. \$200 per ton of annual installed capacity of cement), many poor countries will be hard pressed to find the financial resources for constructing new cement plants.

3. SUSTAINABLE INDUSTRIAL GROWTH

Limestone and clay, the basic raw materials for making portland cement, are plentiful throughout the world. The major bottlenecks in increasing the portland cement production by almost five hundred million tons annually by the year 2005 appear to lie in the high energy requirements and the high rate of CO₂ emissions. It is estimated that, with every ton of portland cement produced, one ton of CO₂ is released to the environment. Increased CO₂ loading of the earth's environment is a matter of serious concern to the intergovernmental panels on climate change. During the last one hundred years, the "greenhouse effect" has already resulted in global warming by 4° C. By the middle of the twenty-first century, CO₂ emissions from the combustion of hydrocarbon fuels and other sources, if unchecked, are expected to rise by 100%. This will have the effect of raising the average atmospheric temperature of the

4 Mehta

world to an unacceptably dangerous level. An environmental disaster would be unavoidable if China, India, and developing countries of South and Central America start consuming as much energy and materials (such as portland cement) as the West did in its march to industrialization.

As stated earlier, nearly 370 million tons, or 75% of the total projected increase in cement consumption by the year 2005, will come from the countries of Asia, and South and Central America. Because the process of industrialization in developing countries of the world cannot be stopped, we must find a way to guide it into environmentally friendly tracks. The 1992 Earth Summit in Rio de Janeiro defined **sustainable development** as economic activity that is in harmony with the earth's ecosystems. The goal of sustainable development of the cement and concrete industries is, therefore, very important, and it can be reached if we make a serious effort for **complete utilization of the cementitious and pozzolanic by-products** produced by thermal power plants and metallurgical industries, as suggested in the next paragraphs.

Manz (3) reported that, in 1989, 562 million tons of coal ash were produced, of which only 25 million tons were used for making blended portland cements or as a concrete admixture. Note that this amount represents only about 5% of the total available coal ash. The current annual production of coal ash is estimated to be around 650 million tons, of which at least 70% or 450 million tons is fly ash or fine coal ash that is generally suitable for use as a pozzolan in cementitious systems (4). Another industrial by-product which can be useful for making cement is iron blast-furnace slag. Although the world production of this slag is approximately 100 million tons/year, the use rate of the product as a cementitious material is quite low because, in many countries, only a small portion of the slag is granulated, i.e. quenched and therefore available in a cementitious form.

The author has made an interesting discovery that relatively huge volumes of disposable coal ash and iron blast-furnace slag are available in those countries which happen to require large amounts of cement. For instance, China and India together produce about 150 million tons of coal ash every year. European countries, mainly Russia, Poland, the former Czechoslovakia, Romania, Germany, Spain, and the United Kingdom produce approximately 250 million tons of coal ash per year. Also, at least 50 million tons of the total yearly production of 100 million tons of blast-furnace slag comes from China, India, and Europe. At the same time, note that nearly 440 million tons of the total projected increase in the cement consumption by the year 2005 is expected from these countries (Table 1). **It should be immediately obvious that if we can find ways to use all or most of the available coal ash and iron blast-furnace slag, either in the form of blended portland cement or as mineral admixtures in concrete, we would be able to meet the projected cement demand in the year 2005 without any increase in the present capacity of portland-cement clinker production.** A sustainable development of the cement and concrete industries, as defined above, can thus be assured. Considering the additional ecological benefits described next, it is hard to imagine a better solution to the problem.

Nearly 90% of the coal ashes and metallurgical slags produced today end up either in low-value applications such as landfills and road bases, or simply disposed off by ponding and stockpiling. Disposal in this manner is not only wasteful but also harmful to human health because it contributes to land, air, and groundwater pollution. These by-product materials generally contain toxic metals. The concrete industry provides a preferred vehicle for their disposal because most of the harmful metals can be immobilized and safely incorporated into the hydration products of cement. In fact, owing to its large size, the concrete industry is probably the ideal home for safe and economical disposal of millions of tons of by-products. Based on a study by Schiessl and Hohberg (5), Fig. 1 shows the excellent environmental compatibility of a mortar made with a cement-fly ash mixture. In a realistic leaching test (tank test), the authors reported that only 0.09 mg/kg zinc and 0.15 mg/kg chromium were leached from a cement mortar when the total amounts of the metals added to the mortar were 185 mg/kg and 53 mg/kg, respectively.

4. CONCRETE DURABILITY

In most countries of the world, the heavy expenditure for repair and replacement of the infrastructure has become a matter of serious concern as too many concrete structures are found suffering from deterioration problems much earlier than their expected service life. At the same time, a growing public interest in ecology requires that the earth's natural resources are conserved as much as possible through enhancement of durability of manufactured products. Consequently, with the twenty-first century approaching, it is important that we critically examine the concrete technology of today and explore how it can be improved to make concrete a truly high-performance material of the future. Also, since many materials and methods are being promoted for enhancement of durability of concrete structures, it will be prudent to evaluate their cost effectiveness. This is because material cost will continue to be an important consideration in the construction of most structures.

It is generally known that the major causes of deterioration of reinforced concrete structures are the corrosion of reinforcing steel, exposure to cycles of freezing and thawing, alkali-silica reaction, and sulfate attack. From a review of case histories of concrete degradation, the author developed a holistic approach encompassing the major causes of concrete deterioration (1). This approach is based on field experience that, with every one of these four causes of concrete deterioration, a high degree of water saturation is a prerequisite to the mechanisms responsible for expansion and cracking of concrete. Therefore, the water-tightness of concrete, which is its first line of defense against a hostile environment, must somehow become breached before the material is seriously damaged. This shows that, compared to other properties, the soundness of concrete, i.e. the freedom from cracking, is closely related to concrete durability. It seems that modern concrete construction practice does not pay adequate attention to the two primary causes of early cracking in concrete, namely, thermal contraction

6 Mehta

and drying shrinkage. Therefore, a brief review of the fundamental principles governing the cracking of concrete from these two causes will be helpful here.

When a freshly placed and hardened concrete is exposed to ambient temperature and humidity, it experiences both thermal and drying shrinkage strains. The type and magnitude of the shrinkage strains will depend on the temperature and the humidity of the environment, the size of the concrete element, the temperature of the concrete, the characteristics of the concrete-making materials, and the mixture proportions. Under the restraining conditions in hardened concrete, a shrinkage strain would result in an elastic tensile stress which, as a first approximation, may be assumed as equal to the product of the strain and the elastic modulus of the material. The concrete would crack when the induced tensile stress exceeds its tensile strength. However, due to the viscoelastic or creep behavior, some of the stress is relaxed, and it is therefore the residual stress which determines whether or not cracking would occur. **This interplay between the tensile stress generated by restrained shrinkage and the stress relief due to creep, as illustrated in Fig. 2, is at the heart of early cracking and microcracking in concrete structures that would later destroy its watertightness.** It is clear from the illustration of fundamental principles in Fig. 2 that the risk of cracking in concrete due to restrained shrinkage can be reduced by one or more of the following factors: a high tensile strength, a low shrinkage strain, a low elastic modulus, and a high creep strain (6).

Driven by the high speed of construction, concrete mixtures today tend to contain a high content of normal or high-early strength portland cement. Obviously, as shown in Fig. 3, the extensibility or crack resistance of such concretes would be low due to increase in the drying shrinkage, thermal shrinkage, and elastic modulus on the one hand, and a reduction in the creep coefficient on the other hand. This is the reason that high-early-strength concrete mixtures are more vulnerable to cracking than moderate or low-strength concrete mixtures. Traditionally, structural cracking is controlled by the use of sufficient steel reinforcement but, as explained below, substitution of a few wide cracks with numerous invisible and unmeasurable microcracks is not a good solution for concrete durability problems.

The preceding theoretical considerations are confirmed by field experience. In 1995 the U.S. National Highway Cooperative Research Program conducted a survey of recently built concrete bridge decks. Noting that more than 100,000 bridge decks showed transverse cracks even before the structure was one month old, Rogalla et al. (7) drew the following conclusions:

1. A combination of thermal shrinkage and drying shrinkage caused most of the cracks, not traffic loads or vibration during the hardening of the concrete.
2. Generally, decks are made of high-strength concrete. These concretes have a high elastic modulus at an early age. Therefore, they develop high stresses for a given temperature change or amount of drying

shrinkage, and most important, the concrete creeps little to relieve these stresses.

3. High-strength concretes typically contain more cement. Therefore, they shrink more and produce higher temperatures during early hydration. Modern cements are apt to cause cracking because they are finer and contain higher sulfate and alkali contents.

In conclusion, according to the holistic approach to concrete deterioration, a well constituted and properly consolidated and cured concrete will remain essentially watertight as long as the pores and cracks present in the interior do not form an interconnected network of pathways leading to the surface. Structural loads as well as weathering effects such as exposure to cycles of heating-cooling and wetting-drying facilitate the propagation of microcracks that normally pre-exist in the transition zone between the cement mortar and coarse aggregate in concrete. This happens during the first stage of the structure-environment interaction. Once the watertightness of concrete has been lost, it can become saturated and harmful ions also can move into the interior. This marks the beginning of the second stage of the structure-environment interaction during which the deterioration of concrete takes place through successive cycles of expansion, cracking, loss of mass, and increase in permeability.

Gerwick (8) has given a list of preventive and mitigating measures which are commonly adopted for minimizing the degradation of concrete due to corrosion of reinforcing steel, with representative values of their cost appended in parentheses (given as a percentage of the first cost of the concrete structure). A part of this list is reproduced below. These costs are valid for Western countries, and as of 1994, can be used for comparison purposes:

1. Use of fly ash or slag as a partial replacement for cement (0%).
2. Pre-cooling of the concrete mixture (3%).
3. Use of silica fume and a superplasticizer (5%).
4. Increase cover by 15 mm (4%).
5. Use of a corrosion-inhibiting admixture (8%).
6. Epoxy-coating of reinforcing steel (8%).
7. External concrete coatings (20%).
8. Cathodic protection (30%).

Obviously, where thermal cracking and durability are of primary interest, **the most cost-effective solution** is Option 1, i.e. the replacement of part of the portland cement in the concrete mixture with fly ash or slag, while meeting the setting and hardening requirements of the job under given ambient conditions. Options 2, 3, or 4 may be necessary for special structures. The last four options, namely, the use of a corrosion-inhibiting admixture, epoxy-coated steel reinforcement, external coatings for concrete, and cathodic protection are much more expensive and a relatively small extension in service life from the use of these expensive options is expected once the first line of defense, i.e. watertightness, is breached. **Experience in the field of human health shows**

8 Mehta

that preventive measures are always more cost-effective than the remedial measures needed after the body has become afflicted with disease.

For building durable highway structures, it seems that many transportation departments in the U.S. are already showing a preference for Option 1. According to Keck and Riggs (9), since the construction of the Sunshine Skyway Bridge in 1986, the use of fly ash in bridge concrete, including prestressed concrete elements exposed to a moderately aggressive environment, has been made mandatory by the Florida Department of Transportation. A minimum cement replacement rate of 18% is specified. Also permitted are Type IP cement containing 15 to 40% pozzolan, and Type IS cement containing 50 to 70% granulated blast-furnace slag. In mass concrete replacement of up to 50% cement by fly ash is permitted. A nearly linear relationship between the rate of cement replacement by fly ash and the 7-day heat of hydration is the reason behind the use of fly ash in hot weather and mass concreting. Further, according to Keck and Riggs (9), epoxy-coated reinforcing steel was used on many projects but did not perform as well as expected in chloride exposure, for instance, the Seven Mile Bridge in Key West, Florida. Extensive evaluation of chloride permeability was done by the Florida Department of Transportation in arriving at the standard specification, making the use of fly ash mandatory in concrete exposed to aggressive environment.

Alkali-silica reaction (ASR) has been a problem in North Carolina, and the use of fly ash in concrete is mandatory if the alkalis in cement exceed 0.4% (9). At one time, fly ash usage during cold weather was prohibited, but due to the ASR problem year-round use is now permitted. ASR has also been a problem in Virginia, and concrete is required to either contain cement with alkali less than 0.4% or Class F fly ash. To address the problem of corrosion of reinforcing steel, an upper limit of 2,000 coulombs in the rapid chloride permeability test is considered; this level of permeability can be achieved economically with pozzolans such as Class F fly ash. Similarly, the South Carolina Department of Transportation requires 83 kg/m³ fly ash in concrete to reduce permeability and reinforcement corrosion.

Among researchers in the area of concrete durability, there is now an increasing appreciation for a holistic or integrated approach. In his elegant review of alkali-aggregate attack in concrete, Swamy (10) stated, "to attack and cause damage, **all three members of the triad must be present, namely: sufficient alkali in the concrete, critical amount of the reactive aggregate, and sufficient moisture.**" The economic and ecological implications of this conclusion should be apparent. For example, why should it be necessary to reject high-alkali raw materials for cement making, or reactive aggregates for making concrete mixtures, if proper steps are taken so that the concrete structure remains dry during its service life? As discussed earlier, the use of fly ash or other pozzolanic materials is one of the most cost-effective steps to achieve this end.

Similarly, in his excellent review of a highly controversial topic in concrete technology today, namely, the damage caused by the DEF phenomenon

(delayed ettringite formation), Collepardi (11), using the holistic approach, has concluded that **a high risk of damage due to the DEF would occur only if all three of the following conditions are present together: late sulfate release, microcracks in concrete, and exposure to water (Fig. 4).** Again, the economic and ecological implications of this conclusion are profound. For example, for production of portland cement clinker, rather than stopping the use of secondary fuels such as old automobile tires and petroleum coke, which usually have a high sulfur content, a preferable solution is to reduce the chance of cracking and subsequent water penetration into the structure. Again, the incorporation of pozzolanic or cementitious materials into concrete mixtures can reduce the permeability and improve the crack resistance, thus resulting in enhanced durability to both internal and external sulfate attack.

5. OVERCOMING THE OBSTACLES PREVENTING HIGH USE RATES OF POZZOLANIC AND CEMENTITIOUS BY-PRODUCTS IN CONCRETE

To achieve sustainable industrial development in the future and to dramatically accelerate the rate of use of pozzolanic and cementitious by-products in the concrete industry by the year 2005, it will be necessary to identify and remove the barriers preventing their large-scale use. This task should be given a high priority not only by the developing countries of Asia, Eastern Europe, and South America, but also by the developed countries because the success or failure of this mission has global ecological implications. Discussed below are some of the well known arguments that have been advanced in the past against the use of fly ash and granulated blast-furnace slag in concrete.

5.1 Variable Chemical Composition

The chemical composition of a fly ash or slag from an industrial facility is controlled by the raw materials used and the processing conditions. These vary not only from one plant to another but also within the same plant. Large variations in the chemical composition of fly ashes and slags are, therefore, natural. However, it is generally accepted now that the pozzolanic and cementitious properties of materials are governed less by the chemistry, and more by the mineralogical or phase composition and particle size (3).

Again, industrial fly ashes and slags happen to differ widely in both the phase composition and particle size which, of course, influence their reactivity. A particular application may require a relatively reactive material; others may not require high reactivity. Thus, instead of an outright rejection of by-product materials on account of differences in reactivity, an integrated approach to safe and economical disposal of these materials would require innovative match-making to find suitable homes within the concrete construction industry for every type of fly ash and slag produced. Bhanumathi Das and Kalidas (12) at the Institute of Solid Waste Research and Ecological Balance, Visakhapatnam, southern India, have developed the technology to make fly ash-lime-gypsum or fly ash-portland cement bricks and blocks. By disregarding the standard chemical

10 Mehta

and physical requirements for use of fly ash in the cement and concrete industries, the authors found that tailor-made blends of even nonstandard fly ashes with lime and gypsum or with portland cement produced adequate strength on normal curing. With one hundred small units in operation and hundreds more on the way, it is obvious that this type of entrepreneurship is vital for making a dent in the fly ash disposal problem while conserving energy and top soil, which are the base materials used in the manufacture of fired-clay bricks.

Sometimes the reactivity of a fly ash or slag may have to be altered. Fine grinding and thermal curing are two well known methods of accelerating the pozzolanic and cementitious reactions. On the other hand, with highly reactive materials it may be necessary to retard the reactivity before use. This can be achieved by partial prehydration. For instance, for the construction of a roller-compacted concrete dam in Greece, a very reactive high-calcium fly ash with 42% total CaO (15% free CaO, and some C_3A and calcium sulfate) is being used after grinding and prehydration (13).

In short, it is not the variability from one source of supply to another which seems to be a major obstacle in the way of accelerating the use of fly ash and slag in concrete. A real bottleneck is the lack of consumer confidence in the uniformity of quality within a single source. This also is not an unsurmountable obstacle. For years the cement and concrete industries have practiced the art of blending large amounts of materials of different compositions in order to obtain end-products with acceptable uniform quality. Given the willpower and proper incentives, the producers and potential consumers of these by-products can work together to overcome this problem. The increased handling cost will be easily justified if the producers of these by-products are heavily penalized for their hazardous disposal practices.

5.2 Nomenclature, Specifications and Codes

The terms, mineral admixtures and supplementary cementing materials have been generally used for fly ash and other siliceous by-products, such as silica fume, rice-husk ash, and ground granulated blast-furnace slag. These terms imply a second-class status relative to portland cement, and therefore are denigrating. In fact, the terminology or nomenclature has probably played some role in preventing the general acceptance of these by-product materials by the construction industry.

Now that their importance is well established in sustainable development of the cement and concrete industries, and in the enhancement of durability of portland-cement concrete, with little or no increase in cost, it is strongly recommended that pozzolanic and cementitious by-products are addressed by the term, **complementary cementing materials**. These materials need portland cement for their activation; and portland cement-based products need them for improvement of their durability and ecological profile. In the industrial world, it will be hard to find similar or better examples of complementarity or marriage between two components, where each component makes an equally important contribution for the good of the whole system.

For historical reasons, standards for portland cements, slags, pozzolans, and blended portland cements in most countries of the world are "prescriptive" in the sense that they tend to specify maximum or minimum limits on certain chemical constituents. Although performance-based specifications are being introduced in some countries, most engineers lack the confidence to use them. This is one of the most serious bottlenecks to large-scale use of pozzolanic and cementitious by-products in concrete. From a detailed examination of the current world standards on pozzolanic and cementitious materials (4), it appears that many prescriptive requirements in the individual standards are no longer necessary and therefore may be deleted in favor of a few that are considered adequate for the purposes of assuring uniformity in quality. It is then possible to develop a simple, performance-oriented, single standard covering all pozzolanic and cementitious materials. In fact, the Canadian Standard CSA-A23.5 has already taken this approach.

Another bottleneck to large-scale and innovative uses of by-product complementary cementing materials in the cement and concrete industries is the fact that codes of recommended practice and standard specifications restrict the maximum permissible amounts that can be incorporated into blended cements or concrete. For example, the Indian Standard Specification limits fly ash in blended portland-fly ash cement to a maximum of 25% by mass. Such restrictions no longer make any sense in the context of CANMET investigations (14) by Malhotra and his colleagues that, with the addition of a superplasticizer, approximately 60% cement can be replaced by fly ash. The resulting concrete mixtures have shown excellent strength and durability characteristics.

Obviously, the replacement of prescriptive requirements in standard specifications with performance-based ones will accelerate the rates of use of fly ash and slags in cement and concrete. This will also help the development of ternary and quaternary cementitious systems containing two or more complementary cementing materials blended with portland cement. Blended portland cements containing silica fume and fly ash or slag are already being developed (15). Rice husk ash, another highly active pozzolanic material, is an excellent substitute for silica fume (16). Asian countries, for example China, India, Indonesia, Japan, the Philippines and Thailand, with a potential availability of over 10 million tons of rice husk ash every year, offer exciting possibilities for the production of blended portland cements containing rice husk ash and fly ash or slag.

5.3 Effect on Properties of Concrete

The water-reducing properties of fly ash and ground granulated iron blast-furnace slag are well established. Therefore, it is generally observed that their use has a positive influence on the rheological properties of fresh concrete, such as pumpability. In hardened concrete the effect of incorporation of complementary cementing materials on two interrelated properties, namely, durability and strength, needs a more detailed examination.

12 Mehta

It is a misconception that the durability of reinforced concrete containing fly ash or slag exposed to sea water or de-icing chemicals would be less than that of concrete without these constituents. Overwhelming evidence both from theoretical considerations as well as from field experience shows that pozzolanic and cementitious materials, when of proper quality and when used in correct proportion followed by proper curing of concrete, have a very positive influence on concrete properties. Use of pozzolanic materials results in concrete with reduced permeability and reduced expansive stresses, and therefore reduced tendency for cracking. Concrete receives additional protection from corrosion and other expansive phenomena, including the alkali-silica reaction and sulfate attack, when complementary cementing materials are properly used.

Regarding the effect of fly ash or slag on the compressive and tensile strengths of concrete, whereas the ultimate strengths are generally improved, the setting and hardening rates at early ages are significantly slower, especially with less reactive materials and under cold weather conditions. A higher rate of strength development similar to plain portland cement concrete may be achieved by the application of one or more of the following methods: (i) heat curing, (ii) partial replacement of the fine aggregate rather than portland cement, (iii) finer grinding of the fly ash or slag, (iv) reduction of water-cement ratio with the help of a superplasticizer, and (v) partial replacement of a less reactive slag or fly ash with a more reactive pozzolan (such as silica fume or rice-husk ash) or with very finely ground slag. However, as discussed below, structures made with slow-hardening concrete generally show a better long-term performance than those containing fast-hardening concrete which, unfortunately, has become the common practice in modern concrete construction.

From a review of performance of concrete during the period 1930-1980, it was concluded by the author (17) that many problems with premature deterioration of concrete structures were attributable to the acceleration of construction speeds, increase in the water content of concrete mixtures, and production of portland cements with high early strengths and, consequently, low cement content in concrete. In response to concern for durability, especially under aggressive environmental conditions, the pendulum may have swung toward the increasing use of concrete mixtures containing high cement content and very low water-cement ratio. As explained earlier, these concretes are characterized by low creep and high elastic modulus even at early ages and, therefore, are quite susceptible to cracking induced by thermal and drying stresses. Crack widths, of course, can be controlled by the use of reinforcing steel. However, this does not help the impermeability or watertightness of concrete because it is the unseen and unmeasurable microcracks which eventually would enlarge with time and become interconnected. Note that the high creep associated with the slow rate of setting and hardening of portland-fly ash or portland-slag cements (Fig. 3) will have a beneficial effect on both thermal contraction and drying shrinkage cracking.

In conclusion, if durability is of primary interest, then the slow rate of setting and hardening associated with the incorporation of fly ash or slag in concrete is an advantage, not a disadvantage. Any economic disadvantage as a

result of delay in the removal of formwork would be easily offset by the lower life-cycle cost of the structure, and by the ecological impact associated with enhancement of the durability of concrete as well as the safe and cost-effective disposal of large amounts of hazardous industrial wastes.

6. EXAMPLES OF HIGH-VOLUME FLY ASH APPLICATIONS

Due to its large size, the construction industry is the primary focus of attention throughout the world in efforts to accelerate the rates of use of fly ashes and slags. The concrete industry, in particular, appears to be the ideal home for safe and most beneficial disposal of millions of tons of these hazardous by-products. These by-products actually serve as **complementary cementing materials** with portland-cement concrete because without them the concrete would not be as energy-efficient, ecologically friendly, and durable. Although examples of high-volume fly ash alone are given below, it is understood that, in general, similar or even larger portions of granulated blast-furnace slag can be substituted for fly ash.

For use in general construction, it is helpful to divide fly ashes into two categories, namely those meeting any of the physical-chemical or performance standards for fly ash as a pozzolan, and others that do not meet the standards. A fly ash complying with a standard specification is permitted for use as a complementary cementing material in concrete or as a component of blended portland-fly ash cements. In such applications, the current construction practice generally restricts the proportion of fly ash to 20% by mass of the total cementitious material. As stated earlier, studies by Malhotra (14) with superplasticized concrete mixtures have shown that, when the water/cementitious is limited to 0.3 or less, up to 60% cement can be replaced with a Class F or Class C fly ash (ASTM C 618) to obtain excellent strength and durability characteristics. For instance, a test mixture containing 150 kg/m³ ASTM Type I cement, 200 kg/m³ ASTM Class F fly ash, 102 kg/m³ water, 1220 kg/m³ coarse aggregate, 810 kg/m³ fine aggregate, and 7 L/m³ superplasticizer gave 8 MPa, 55 MPa, and 80 MPa compressive strengths at 1, 28, and 182 days, respectively. This innovative, high-volume application of fly ash unquestionably signals the best value-added use of the material in the construction industry.

If complete use of all coal ash is our goal, then we must also identify the segments of the construction industry which can profit from the use of nonstandard fly ash and pulverized bottom ash. A coal ash may not meet certain minimum chemical or physical requirements prescribed by a standard specification, but it may still be useful on account of its fine particle size. Examples of these applications are cited next.

Roller-Compacted Concrete Dams: Since the 1980's, roller-compacted concrete (RCC) has been accepted worldwide as the most rapid and economical method for construction of medium-height dams. According to Dunstan (13), until the end of 1992, 96 RCC dams had been built in seventeen different

14 Mehta

countries and 82 of the RCC mixtures contained a pozzolan. The high-paste-content RCC mixtures typically contain 250 kg/m^3 cementitious material of which 70-80% is a pozzolan. Fly ash has been used as a pozzolan in 90% of the 82 RCC mixtures. The Upper Stillwater Dam in the U.S. contains 1.24 million m^3 of concrete with 79 kg/m^3 portland cement and 173 kg/m^3 fly ash. In all, over 200,000 metric tons of low-calcium fly ashes from six different power plants were used. Imagine the volume of pozzolanic materials needed for the Zungeru Dam in Japan which contains 5 million m^3 RCC, and the 217-m high Longton Dam in China that will contain 7.5 million m^3 RCC. Further, according to Dunstan (13), even nonstandard fly ash is being successfully used as a component of RCC mixtures. For instance, the RCC mixture for the construction of 95-m high Platanovryssi Dam in Greece contains 35 kg/m^3 portland cement and 250 kg/m^3 of treated (pulverized and hydrated) fly ash which has an unusually high calcium content (42% total CaO). The fly ash is generated from thermal power stations using lignite as fuel.

Concrete Pavements for Highways: According to Golden (18), approximately 70% of the low-volume highways and local access roads in the U.S. require upgrading. Considering the cost savings resulting from the replacement of cement with high volumes of fly ash, EPRI (Electric Power Research Institute) funded several demonstration projects. In North Dakota, during the summers of 1988 and 1989, 20,000 m^2 of a 200-cm thick concrete pavement was constructed with "pozzocrete," which is a 0.43 w/c, air-entrained concrete mixture containing 100 kg/m^3 portland cement and 220 kg/m^3 high-calcium fly ash. Demonstration projects in Kansas have successfully used both low-calcium and high-calcium fly ashes in concrete pavement mixtures (10-20% fly ash by mass of concrete). An innovative feature of this project was the use of the crushed concrete from the old pavement as a source of coarse aggregate in the concrete mixture for the new pavement.

Base-Courses and Embankments: High-volume fly ash and bottom ash applications in highway construction may include soil stabilization, pavement base-courses, embankments, and road shoulders. According to Golden (18), in 1989, 350,000 tons of fly ash were used for the construction of a highway embankment in Pennsylvania. In Georgia, cement-treated fly ash mixtures have been used as base-courses in highway test sections. In Michigan, high-carbon fly ash is being used at the rate of 300,000 tons per year for the construction of base-courses and road shoulders.

Controlled Low-Strength Material (CLSM): CLSM is regarded as an ideal backfill material for use on street cut/repair and infrastructure rehabilitation projects. To allow for future excavation, most current CLSM applications require an unconfined compressive strength of 2 MPa or less. The upper strength limit of CLSM, 1,200 psi (8 MPa), is for those applications whose future excavation is not expected, such as structural fills under buildings. Self-compacting, flowable backfills require less labor and, therefore, often result in lower in-place cost compared to a compacted-soil backfill.

Fly-Ash, Silica Fume and Slag 15

Large volumes of a nonstandard fly ash, as a substitute for fine aggregate, may be used in making a CLSM slurry. To address Boston's heavy traffic congestion problems, the new Central Artery Tunnel project provides a good example of a CLSM application. According to Sullivan (19), in the cut and cover method of tunnel construction for this project, the space between the tunnel boxes and support walls in the excavated trenches is filled with CLSM. The 0.4 MPa (28-day) CLSM is composed of 23 kg cement, 970 kg of a high-carbon fly ash, and 330 kg water. CLSM slurries containing cement-treated fly ashes typically contain 5%, 10%, and 15% cement by mass of total cementing material (cement plus fly ash) for strength levels of 0.7 MPa, 1.4 MPa, and 2.1 MPa, respectively. According to Goldbaum et al. (20), since 1990 the Colorado Department of Transportation has used CLSM for backfilling around pipes and box culverts under existing substandard bridges to convert them to on-grade roadways. Typical mixture proportions for CLSM used in a Colorado project are as follows: 60 kg/m³ cement, 240 kg/m³ fly ash, 1,440 kg/m³ fine aggregate, and 300 kg/m³ water.

7. CONCLUDING REMARKS

The twentieth century will be remembered for significant advancements in the science and technology of materials. These advancements are based on the knowledge that the properties of materials can be engineered if we can understand and control their microstructure. Although concrete is a product of simple technology, it possesses a complex microstructure which is sensitive not only to the quality of component materials and mix proportions, but also to the processing methods used in construction practice. As we draw closer to the end of this century, it is apparent that this knowledge base has helped us in the development of very high-strength cement-based products using special admixtures and special processing techniques. In recent construction, with structures exposed to aggressive environments, advantage has been taken of the low permeability that is normally associated with high-strength concrete mixtures. Therefore, sophisticated concrete structures in many large projects have been constructed with high-strength concrete mixtures. However, high costs of materials and processing have prevented the application of this technology to ordinary structural concrete.

With the dawn of the twenty-first century, we are entering an era of sustainable development. The concrete industry will be called upon to serve the two pressing needs of human society, namely, protection of the environment and meeting the infrastructural requirement for increasing industrialization and urbanization of the world. Also due to its large size, the concrete industry is unquestionably the ideal home for the economic and safe disposal of millions of tons of industrial by-products such as fly ash and slag. Due to their highly pozzolanic and cementitious properties, fly ashes and slag can be used in large amounts as complementary cementing materials in concrete. In fact, superplasticized concrete mixtures containing 60 to 70% fly ash or slag by mass of the total cementitious material have shown high strength and durability at

16 Mehta

relatively early ages. This development has removed one of the strong objections to the high-volume application of fly ash and slag. It is obvious that large-scale cement replacement in concrete with these industrial by-products will be highly advantageous from the standpoint of cost economy, energy efficiency, durability, and overall ecological profile of concrete. **In the industrial world it will be hard to find better examples of excellent complementarity or marriage between two components of a system, one of which happens to be an industrial waste. Therefore, in the future, the use of by-product complementary cementing materials ought to be made mandatory.**

In conclusion, if the twenty-first century world is governed by the environmental agenda, then the future of cement and concrete industries would very much depend on our ability to interlink the growth of these industries with the goal of sustainable development on the planet earth. As presented in this paper, a holistic approach can help us achieve the goals of rising demand for concrete, enhancement of concrete durability with little or no increase in cost, and ecological disposal of large quantities of waste products from the thermal power and metallurgical industries.

8. REFERENCES

1. Mehta, P.K., "Concrete technology at the crossroads—problems and opportunities," American Concrete Institute, SP-144, Editor: P.K. Mehta, pp. 1-30, 1994.
2. Mehta, P.K., "Bringing the concrete industry into a new era of sustainable development," Proc. Mario Collepari Symposium, Rome, Italy, Editor: P.K. Mehta, Oct. 1997.
3. Manz, O.E., "Worldwide production of coal ash and utilization in concrete and other products," Proc. 10th International Ash Utilization Symp., Orlando, Florida, 1993.
4. Malhotra, V.M., and Mehta, P.K., *Pozzolanic and Cementitious Materials*, Gordon and Breach Publishers, Philadelphia, 191 pages, 1996.
5. Schiessl, P., and Hohberg, I., "Environmental compatibility of cement-based building materials," Proc. Mario Collepari Symp. on Concrete Science and Technology Today, Rome, Italy; Editor: P.K. Mehta, Oct. 1997.
6. Mehta, P.K., and Monteiro, P.J.M., *Concrete: Microstructure, Properties, and Materials*, McGraw-Hill College Division, 548 pages, 1996.
7. Rogalla, E.A., Krauss, P.D., and McDonald, D.B., "Reducing transverse cracking in new concrete bridge decks," *Concrete Construction*, V. 40, pp. 735-738, 1995.

8. Gerwick, B.C., "Economic aspects of durability—how much added expense can be justified," Proc. P.K. Mehta Symp. on Durability of Concrete, Editors: K.H. Khayat and P.C. Aitcin, 1994.
9. Keck, R.H., and Riggs, E.H., "Specifying fly ash for durable concrete," *Concrete International*, V. 19, No. 4, pp. 35-38, 1997.
10. Swamy, R.N., "Alkali-aggregate reaction—the bogeyman of concrete," American Concrete Institute, SP-144, Editor: P.K. Mehta, pp. 105-140, 1994.
11. Collepardi, M., "A holistic approach to concrete damage induced by delayed ettringite formation," Proc. Mario Collepardi Symp. on Concrete Science and Technology Today, Rome, Italy; Editor: P.K. Mehta, Oct. 1997.
12. Bhanumathidas, N., and Kalidas, N., "Imperatives on mass scale fly ash utilization in India," *Cement Industry*, pp. 133-134, 1995.
13. Dunstan, M.R.H., "Future trends in roller-compacted concrete dam construction," American Concrete Institute, SP-144, Editor: P.K. Mehta, pp. 307-324, 1994.
14. Malhotra, V.M., "CANMET investigation dealing with high volume fly ash concrete," *Advances in Concrete Technology*, Natural Resources, Ottawa, Canada, Editor: V.M. Malhotra, pp. 445-482, 1994.
15. Uchikawa, H., and Okamura, T., "Binary and ternary component blended cements," *Mineral Admixtures in Concrete*, pp. 1-83, Editors: S. Sarkar and S. N. Ghosh, 1993.
16. Mehta, P.K., and Folliard, K., "Rice-husk ash — a unique supplementary cementing material: durability aspects," American Concrete Institute, SP-154, Editor: V.M. Malhotra, pp. 531-542, 1995.
17. Mehta, P.K., "Durability of concrete—fifty years of progress?," American Concrete Institute, SP-126, Editor: V.M. Malhotra, pp. 1-31, 1991.
18. Golden, D.M., "U.S. power industry's activities to expand coal ash utilization," *Proc. International Workshop on Utilization of Fly Ash*, Seoul, Korea, 1997.
19. Sullivan, R.M., "Boston Harbor Tunnel Project utilizes CLSM," *Concrete International*, V. 19, No. 5, pp. 40-43, 1997.
20. Goldbaum, J.E., Hook, W., and Clem, D.A., "Modification of bridges with CLSM," *ibid.*, pp. 44-47, 1997.

18 Mehta

TABLE 1—PROJECTION OF REGIONAL CEMENT CONSUMPTION, million tons*

Area	Year		
	1994	2000	2005
Europe, including countries of former Soviet Union	313	393	432
Asia	680	853	1000
Middle East	65	79	82
Africa	63	71	77
North America	90	92	92
South and Central America	92	118	142
Miscellaneous	7	9	10
Total	1310	1625	1835

*Adapted from: *World Cement*, V. 27, No. 5, May 1996.

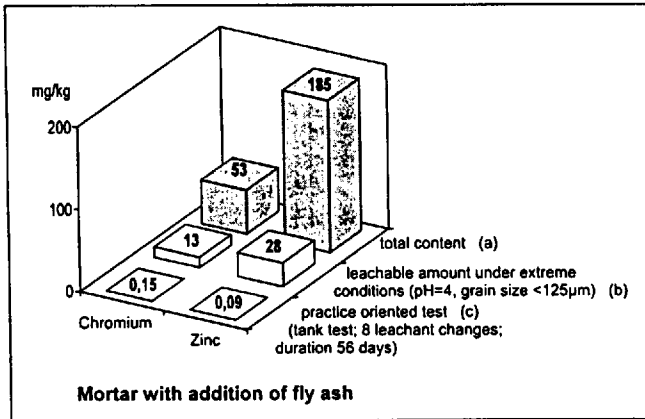


Fig. 1—Immobilization of heavy metals in a mortar containing fly ash (Ref. 5)

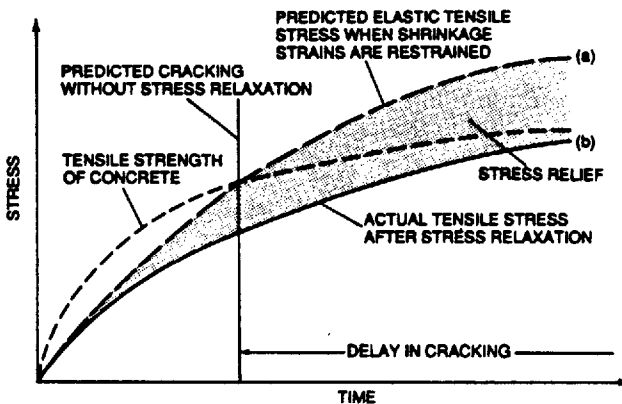


Fig. 2—Influence of shrinkage and creep on concrete cracking (Ref. 6)

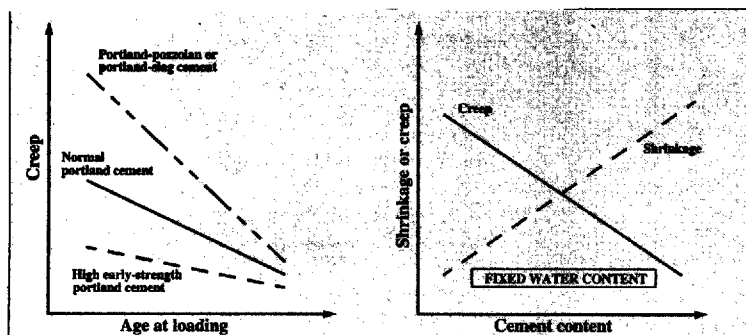


Fig. 3—Influence of cement type and content on shrinkage or creep (Ref. 6)

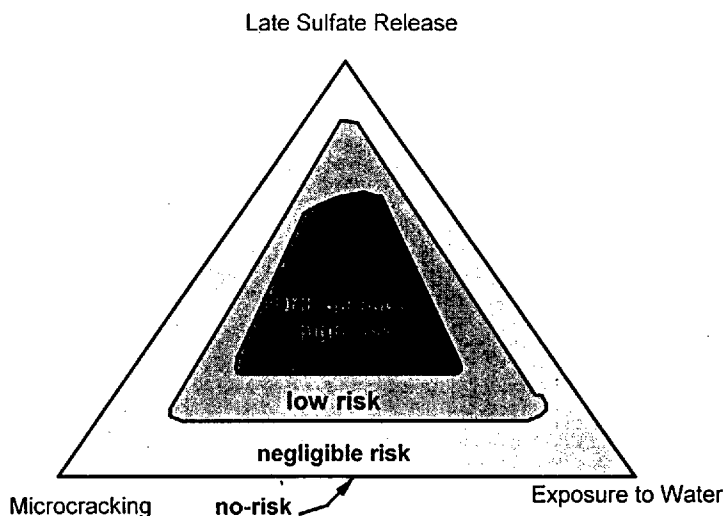


Fig. 4—A holistic model showing DEF-damage as a function of late sulfate release, microcracking, and exposure to water (Ref. 11)

SP 178-2

The Use of Classified Fly Ash to Produce High Performance Concrete

by K.E. Hassan and J.G. Cabrera

Synopsis: Waste materials may be upgraded to specification standards and occasionally to premium materials for use in the preparation of composites or for use in their own. The treatment for upgrading is a matter of cost and of the potential environmental problems that the treatment can create. The investigation presented in this paper shows an example of the improvements of fly ash properties achieved by a simple physical process, that is, air cyclone separation. This process gives a very fine ash with adequate pozzolanic activity and is suitable for producing high performance concrete with excellent durability particularly when exposed to aggressive environments.

The paper presents data on the properties of the fine fly ash including lime reactivity, composition, size distribution and shape. The investigation was carried out using two fly ashes obtained by the process of air separation using a prototype small air cyclone separator and an air mini-splitter. The properties of these ashes were compared to the properties of the original raw ash and with the properties of a fly ash processed industrially by the conventional mechanical separation process, which produces a fly ash conforming to the appropriate British specifications for use in the production of structural concrete.

In this test programme, high performance concrete made with 0.3 fly ash and 0.7 ordinary Portland cement (by weight) as binder was assessed by measuring strength, porosity, and permeability. These properties were used to evaluate the performance of concrete and potential long term durability.

Keywords: concretes; durability; fly ash; high performance concrete; permeability; porosity; strength.

22 Hassan and Cabrera

ACI member J G Cabrera is Professor of Civil Engineering Materials at the University of Leeds. He has carried out extensive research on the performance, properties and durability of concrete. He is also responsible for the development of a number of test methods and equipment for the assessment of concrete performance. He has written extensively on the subject of pozzolanic additions to concrete and performance of civil engineering materials.

Dr K E Hassan is a Post-doctoral Research Fellow within the Civil Engineering Materials Unit in the School of Civil Engineering at the University of Leeds. His Ph.D. research dealt with the influence of surface treatments on the durability performance of concrete. Dr. Hassan is also a ACI member and working mainly in the areas of concrete repair and protection, transport properties of concrete and also the durability of fly ash concrete.

INTRODUCTION

The production of high performance concrete depends on careful mixture proportioning and requires the use of mineral admixtures and chemical surface active agents (1). Mineral admixtures are normally natural or artificial pozzolans. The most commonly available man-made pozzolans are fly ash, micro-silica and metakaolin. Their main function when used as part replacement of normal Portland cement in concrete is to improve the consistency of the concrete by reducing bleeding thereby improving the microstructure of the aggregate paste interface and by providing the amorphous silica and alumina which reacts with the lime and contributes to the reduction of the capillary pores (1,2).

The effectiveness of the pozzolan depends of its intrinsic properties. Because this paper is concerned with the use of fly ash, the comments made will be restricted to this material. Fly ash (fa) in the UK is classed as ASTM F type, i.e., it is a by product of burning pulverised bituminous or subbituminous coal and therefore it contains very low amount of calcium oxide. Its most important properties are fineness and pozzolanic reactivity. Fly ash used as part replacement of normal Portland cement for the production of structural concrete has to conform with the specifications given in the British Standard 3892 (3) or the European standard EN 450 (4). Although very few of the as produced fa in the UK may conform to the requirements of the BS or CEN most ashes require treatment which mainly consist in reducing the coarse part of the ash and reducing the organic carbon remaining in it. This process is carried out industrially by mainly mechanical sieving and it requires a large input of energy. Attempts to reduce the energy input have been made by the use of systems based on elutriation.

This paper presents the results of the evaluation of the properties of an ash which was subjected to a process of elutriation by using an air cyclone separator in one case and an air mini-splitter on the other. The object was to improve the potential properties of the fa for use in structural concrete. The first part of the paper presents the properties of the treated ashes and compares them with the properties of the raw original ash and with a commercially processed ash which is considered one of the best ashes in the UK.

The ashes were then used to produce a high performance concrete and the properties measured to evaluate its potential performance are compressive strength, porosity and permeability.

CONCRETE MATERIALS AND MIXTURE PROPORTIONING

Fly ashes The investigation involved the assessment of the properties of a fly ash (fa) which was subjected to a simple physical process of air separation, using a prototype small air cyclone separator (fa labelled cms) and an air mini-splitter (fa labelled staffs). The ash was obtained from Drax Power Station in the UK. The properties of the processed ashes are compared with the properties of the original raw ash and with the properties of a commercially processed conventional fly ash (wb), obtained from West Burton Power Station, UK. This ash was selected for being in the fineness range of the two processed ashes. It complies with the requirements of BS 3892 (3) for use in structural concrete.

Cement Normal Portland cement (npc) conforming to the requirements of BS 12 (5) was used throughout the programme of the study.

Aggregate Quartzitic sand and gravel used as aggregates. The sand was medium grading conforming to zone M of BS 882 (6) and the gravel had a nominal maximum size of 14 mm, also conforming to BS 882 (6).

Mixture proportioning The proportioning of the npc control concrete was that of the "Leeds control mixture" which is based on the concept of optimisation of particle packing and thus minimum porosity. This mixture has been used extensively for the last two decades and therefore provides an adequate control mixture for studying the effect of different binders and minimises the variability arising from the repeatability and reproducibility of the measurements due to different mixtures. The composition of the npc control mixture in terms of cement, sand, gravel was 1: 2.33: 3.5 (by weight), with a npc content of 325 kg/m³. The fly ash concrete mixtures were made by substituting 30% (by weight) of npc with fly ash, and adjusting the water content to achieve approximately the same workability as that of the control

24 Hassan and Cabrera

mixture. The workability of the different concrete mixtures was controlled using the slump test in accordance with BS 1881: Part 102 (7). Table 1 shows the mixture proportions and the water/binder ratio of the control and fa mixtures.

CHARACTERISATION OF FLY ASHES

The characterisation of the raw and processed fly ashes was made by measuring the properties listed in Table 2. These include: particle size distribution, particle shape, specific gravity, surface area, fineness, and lime reactivity. Table 2 presents a summary of the various characterising properties.

Specific gravity The measurement of specific gravity was carried out using a Helium Pycnometer (8). The results in Table 2 confirm that ashes staffs, cms and Drax are from the same source and that the value of specific gravity of these fly ashes is slightly lower than that of the wb ash which has a slightly higher Fe_2O_3 content.

Particle size distribution A laser particle-size analyser was used to determine the particle size distribution of the ashes. The results in Table 2 show that the air separation process was most effective for increasing the fineness of the staffs and cms ashes. These ashes compared well with the commercially processed wb ash, but most importantly showed a very large improvement when compared with the original Drax ash. In fact the raw original ash does not comply either with the current BS (3) or with the European CEN (4). The British Standard (3) requires that a fa for use in structural concrete should have less than 12% (by weight) of fa retained in a sieve of 45 μm diameter and the CEN (4) requires that not more than 40% (by weight) should be retained in a sieve of 45 μm diameter and that its variation should be not more than 8%. It can be seen that in terms of particle size the air separation was highly effective.

Surface area The improvement in surface area was considerable, this is of course the result of eliminating the coarser particles by the air separation procedure. The surface area either measured or calculated increased by more than 40% bringing the ashes to the class of very fine and comparable to the finest ash produced by physical commercial sieving methods.

Fly-Ash, Silica Fume and Slag 25

Shape factor Particle shape is probably the most important physical property of an ash. Predominantly particles of spherical shape improve the flow properties of concrete and allow a reduction of water/binder ratio thereby improving the properties of concrete. The particle shape was measured in this study using the method proposed by Cabrera and Hopkins (9), where the measured surface area is plotted versus the calculated one in a Cartesian co-ordinate system. The parametric space of the plot is divided into 6 regions, region 1 corresponds to the spherical shape and 6 to the completely irregular shape. Table 2 shows that all the processed ashes have a shape factor of 1, which corresponds to ashes predominantly spherical, but the raw ash has a particle shape which varies between factor 2 and 3

Lime reactivity Various methods have been proposed in the literature (10) to assess the reactivity of fly ash. Indirect methods include for example the measurement of compressive strength of npc/fa and npc mixtures and expresses the reactivity as a percentage of the ratio of npc/fa strength over npc strength. However, indirect methods do not reflect the actual pozzolanic reactivity of a material.

Thermogravimetry analysis is used in this investigation, as a direct method, to assess the amount of lime consumed at different curing times in a wet mixture of 50% Ca(OH)_2 and 50% fa exposed to 60°C in a 100% RH environment.

The mechanism of the Ca(OH)_2 - fa reaction is mainly diffusion controlled. The equation which represents best the laboratory data are the Ginstling and Brounshtein equation (11). This equation is:

$$kt = 1 - \frac{2x}{3} - (1-x)^{2/3} \quad (1)$$

where:

- x = fraction of lime which has reacted
- t = time of the reaction, days
- k = constant proportional to the rate constant

The rate of the fa - Ca(OH)_2 reaction is relatively very rapid from 0 to 1 day and thereafter slows down noticeably. For this reason the reactivity of fa is characterised by two values of the rate constants, i.e. from 0 to 1 day and from 1 day to 90 days. The results are shown in Table 3.

These results indicate that the wb fa is the most reactive in the short term, in fact cms is 10% less reactive and staffs is 30% less reactive than wb. However, in the long term cms fa gives a value of reaction which is 10% higher than that of wb while the staffs fa is 20% less reactive than the wb ash.

The values obtained for the three ashes tested lie within the upper range of values which have been measured for most of the fly ashes available in the UK.

26 Hassan and Cabrera

Table 4 gives values of the reaction constants measured for other pozzolans (11,12). It can be seen that the fly ashes of this study exhibit short term k values which are higher than the values for natural pozzolans, of the same order as the k value of metakaolin but lower than the values found for micro-silica.

PROPERTIES OF FLY ASH CONCRETE

The properties of fresh and hardened concrete made with the fly ashes which were discussed in the previous section, are presented in the following sections.

Fresh concrete properties The water/binder ratio of the npc and fly ash concrete mixtures were adjusted to give mixtures of equal workability. Table 1 gives the slump values of the different mixtures and highlights the beneficial effect of using fly ash in reducing the water content without impairing the workability of the concrete. This is attributed to the shape of the particles which enhances the rheology of the fresh concrete. The effect of the different fly ashes was found to be similar, as they all reduce the water content by 11% of the water of the npc control mixture. This value is within the range proposed by other researchers (13,14) who concluded that each 10% by weight of ash in a blend of (npc+fa) results in a reduction of water content of 3 to 4%.

Hardened concrete properties The properties of hardened concrete which were measured to assess the performance of npc and npc/fa concretes include compressive strength, porosity and oxygen permeability.

The compressive strength was measured on 100 mm concrete cubes in accordance with BS 1881: Part 116 (15). Cores of 50 mm diameter and 40 mm length were used for the measurements of porosity and oxygen permeability. The cores were drilled out from the cast face of the concrete slabs (400x250x40 mm). All test specimens were cured at 20°C and 100% RH.

Compressive strength The compressive strength test was measured at the ages of 1,3,28 and 90 days. The numerical values of the compressive strength are given in Table 5, and the graphical presentation of the compressive strength-age relationship is given in Fig 1.

From the results of compressive strength, the following observations can be made:

- At one day the compressive strength of the cms and wb ash-concretes are of equal magnitude to that of the npc concrete mixture. The staffs-concrete mixture exhibits noticeably lower strength.
- By the age of 28 days the processed fa concretes have reached more than 50 MPa. wb, cms and the npc mixtures are statistically equal but the

Fly-Ash, Silica Fume and Slag 27

staffs mixture is still the mixture exhibiting the lowest compressive strength value.

- At the age of 90 days staffs and npc mixtures are approximately of equal compressive strength but mixtures cms and wb are stronger. The compressive strength of these mixtures is 20% higher than the compressive strength of the npc mixture.
- The compressive strength of the unprocessed Drax fa mixture is lower than the strength of all other mixtures. This result is as expected and it serves to illustrate the advantages of the air separation process.
- In terms of compressive strength the small air cyclone separated fa (cms) performed noticeably better than the mini-splitter separated fa (staffs).

Porosity The porosity of concrete is one of the parameters used to control the performance of concrete and in particular its durability when exposed to aggressive environments. The measurements of total porosity were carried out using the vacuum saturation apparatus (16). Fig 2 shows the porosity versus age curves for all the concrete mixtures studied in this investigation, while the numerical values of porosity are given in Table 6.

All the fa concrete mixtures showed lower porosity values than the npc control concrete at all ages (1-90 days). At early age (1-3 days), the initial reduction in porosity between the fa and npc mixtures is attributed to the lower W/C of the fa concretes. However, the reduction in porosity increases with concrete age due to the formation of additional hydration products resulting from the reaction between the fa and calcium hydroxide generated by the npc hydration, and to the improved aggregate - paste interface morphology which arises from the consistency of the mortar and its reduction of bleeding. These characteristics are improved by the fa.

The lowest values of porosity are given by the wb and cms mixtures. The staffs mixture is slightly more porous than wb and cms mixtures, but as shown in Fig 2 far less porous than the npc mixture. The porosity of the Drax fa mixture is far higher than that of the other ash mixtures and the npc mixture, confirming the fact that the process of air separation is of greater benefit to the properties of fa concrete

Oxygen permeability The permeability of concrete gives the best indication of its performance when exposed to aggressive environments. The oxygen permeability measurements were carried out using the Leeds permeameter following the method described in reference (17). The procedure consists briefly of measuring the flow of oxygen applied to the dried specimen at a pressure of 315 N/m^2 for a period which varies from 15 minutes to several hours, depending on the pore structure and the degree of saturation of the specimen. The intrinsic permeability is calculated using a modified D'Arcy

28 Hassan and Cabrera

equation to take into account the average pressure within the specimen. The values of intrinsic permeability measured at ages of 1 to 90 days for the npc and fa concrete mixtures are given in Table 7 and Fig 3.

The results of intrinsic permeability show almost the same values for all the mixtures at 1 day of age. The fa concrete mixtures exhibited lower permeability than the npc mixture at ages greater than 1 day. At 90 days age, all the fa concretes, with the exception of the Drax mixture, showed lower permeability values than the npc concrete by almost 1 order of magnitude.

When oxygen permeability is analysed in conjunction with porosity and compressive strength, a model of concrete performance can be formulated (18). This will be discussed in the following section.

DISCUSSION

The values of compressive strength ensure that a concrete mixture is adequate to satisfy the structural requirements of design, however, the performance and durability of concrete have to be assessed by parameters related to the ability of the concrete to resist penetration of harmful substances. In this context the total pore volume and permeability are the two parameters which are accepted as predictors of durability. When relating these parameters to each other and to concrete strength a better picture of performance can be obtained

As with any other material, concrete can be better discussed by the relation which exist between strength and porosity. This type of relation gives an insight of the likely distribution of pores whose sum is the total porosity.

For the case of this study, Fig 4 shows that the relation between compressive strength (f_{cu}) and the total porosity (P) is a logarithmic decay function of the form:

$$\ln f_{cu} = A - B(P) \quad (2)$$

where:

f_{cu} = compressive strength (MPa)

P = porosity (%)

A, B = constants related to the pore volume characteristics.

The most important aspect brought by Fig 4 is that mixtures of the same strength may exhibit very different porosities. From analysis of the permeability results it is clear that the pore size distribution of the different concretes is different as reflected by the large differences in intrinsic permeability values. Therefore mixtures whose strength - porosity function shows large porosity values for the same strength are more permeable even though they may have the same compressive strength.

In the context of this research cms and staffs concrete mixtures exhibited similar performance to that of the wb mixture, while the Drax concrete mixture showed far higher porosity than all other mixtures including the npc mixture.

The total pore volume or porosity is statistically related to permeability as shown in Fig 5. This is not always the case since it is the capillary pores which have the greatest influence on permeability. As it can be seen in Fig 5 the values of Drax mixture do not fit the statistical relationship calculated for the all other values. The numerical expression is:

$$K_o = 3 \times 10^{-21} e^{0.88(P)} \quad r^2 = 0.90 \quad (3)$$

where:

K_o = oxygen permeability (m^2)

P = porosity (%)

Taking all the results into consideration it can be said that the concretes made with the processed fly ashes can be considered to be high performance mixtures since their permeabilities measured after drying reach values which are comparable to those specified for the production of high performance concrete in the Jubilee Line Extension Project, London-UK (19), although their compressive strengths lie probably at the boundary of what is considered to be high strength - high performance concrete

It should be also stated that the mixtures were made without any water reducing admixture. Its use would bring the water/binder ratio to values below 0.33 without impairing the workability of the mixtures and will reduce the total pore volume and permeability to far lower values. This was not done since the main purpose of this work was to assess the effectiveness of the air separation process to compare the fa properties and the properties of concrete made with them.

CONCLUSIONS

The most important aspects related to this study are:

1. The air cyclone separation process was the most effective for improving the fineness and lime reactivity of a coarse fly ash.
2. Concrete made with processed fly ash gave results which were superior to the results obtained using only normal Portland cement. The strength of the cms and wb ashes at early age was equal to that of the npc but at 90 days the strength of these ash mixtures was nearly 20% higher than the strength of the npc mixture.

30 Hassan and Cabrera

3. The porosity and permeability of the processed ash concrete mixtures were lower than that of the npc mixture. At 3 days and more the permeability of the fa concrete mixtures was nearly one order of magnitude lower than that of npc.
4. The raw unprocessed Drax fly ash mixture showed poor performance. It was more porous and more permeable than the npc mixture.
5. The overall performance of concrete mixtures made with the processed ashes allow them to be classified as high performance concrete.

REFERENCES

1. Mehta, P.K., "Durability of high strength concrete", Paul Klieger Symposium on Performance of Concrete, ACI-SP-122, pp. 19-27, 1990.
2. Cabrera, J.G., "The use of pulverised fuel ash to produce durable concrete", Improvement of concrete durability, ICE, pp. 29-59, 1986.
3. British Standard Institution, BS 3892: Part 1, "Pulverised-fuel ash: specification for pulverised-fuel ash as a cementitious component for use with Portland cement", BSI, London, 1992.
4. European Norm. 450/1995, "Fly ash for concrete/ definitions, requirements and quality control", EN 450, 1995.
5. British Standard Institution, BS 12, "Specification for Portland cements", BSI, London, 1991.
6. British Standard Institution, BS 882: Part 2, "Coarse and fine aggregate from natural sources for concrete", BSI, London, 1983.
7. British Standard Institution, BS 1881: Part 102, "Method of determination of slump", BSI, London, 1983.
8. Micromeritics, AccuPyc 1330 Pycnometer operator's manual
9. Cabrera, J.G. and Hopkins, C.J., "The shape factor: a parameter to assess the effect of pulverised fuel ash on the flow properties of cement pastes and concrete", Int. Symposium on cement and concrete science, pp. 1-14, 1984.
10. Wesche, K. Ed., "Fly ash in concrete", Properties and performance, Rilem Report 7, pp. 17-19, Spon-UK, 1991

Fly-Ash, Silica Fume and Slag 31

11. Ramezaniapour, A. and Cabrera, J.G., "The measurement of lime reactivity of natural and artificial pozzolans", Second Int. Seminar on Cement and Building Materials, Vol. 4, pp. 1x81-88, New Delhi-India, 1989
12. Cabrera, J.G., "Evaluation of the properties of recovered fly ash from Aberthaw and assessment of their potential to produce structural concrete", Report to National Power PLC, 1994.
13. Hassan, K.E., Cabrera, J.G., and Bajracharya, Y.M., "The influence of fly ash content and curing temperature on the properties of high performance concrete", Proc. of the 5th Int. Conf. on Deterioration and Repair of Reinforced Concrete in the Arabian Gulf, Bahrain, Oct. 1997.
14. Brown, J H, "The strength and workability of concrete with fly ash substitution", Proc. of the International Symposium on the use of fly ash in concrete, Ed J G Cabrera and A R Cusens, Vol. 2, pp. 151-159, Leeds, UK, 1982.
15. British Standard Institution, BS 1881: Part 116, "Methods for determination of compressive strength of concrete cubes", BSI, London, 1983.
16. Hassan, K E, "The influence of surface treatments on the durability performance of concrete", Ph.D. thesis, University of Leeds, UK, 1993.
17. Cabrera, J.G., and Hassan, K.E., "Controlling the quality of concrete by measuring its permeability", Proc. of the 13th Int. Conf. on Building Materials, Vol. 3, pp.3-005 to 3-017. Weimar-Germany, September 1997.
18. Cabrera, J.G., Cusens, A.R., and Lynsdale, C.J., "Porosity and permeability as indicators of concrete performance", IABSE Symposium on Durability of Structures, Vol. 57/1, pp. 249-254, Lisbon, 1989.
19. Jubilee Line Extension Project, "Specifications for concrete durability", London Underground Limited, London, 1993.

TABLE 1—PROPORTIONS OF THE CONCRETE MIXTURES (KG/M³)

Mixture	binder content		Water	sand-gravel	w/binder ratio	slump (mm)
	npc	fa				
npc	325	-	178.75	757.3-1137.5	0.55	60
staffs	227.5	97.5	159.25	757.3-1137.5	0.49	55
cms	227.5	97.5	159.25	757.3-1137.5	0.49	50
wb	227.5	97.5	159.25	757.3-1137.5	0.49	55

TABLE 2—CHARACTERIZING PROPERTIES OF THE FLY ASHES

Property	Fly ashes			
	staffs	cms	wb	Drax*
Specific gravity	2.305	2.312	2.396	2.29±0.07
Measured surface area (m ² /g)	0.314	0.324	0.391	0.220±0.07
Calculated surface area (m ² /g)	0.391	0.458	0.348	0.250±0.10
Average particle diameter from specific surface (μm)	8.3	8.0	6.4	12.73±3.07
Median particle diameter from particle size distribution (μm)	6.2	7.1	5.5	11.23±3.18
Particle > 45 μm diameter	0.0	0.0	0.0	27.0±9.29
Particle < 10 μm diameter	82.4	91.6	94.3	30.0±6.74
Particle < 2 μm diameter	23.4	14.4	31.3	6.70±2.5
Shape factor**	1	1	1	2 to 3

* mean value for raw unprocessed fa

** The shape factor defines the shape of the fly ash particles
i.e. 1 = spherical and 6 = irregular

TABLE 3—DIFFUSION REACTION EQUATIONS AND LIME ACTIVITY OF THE FLY ASHES

Fly ash	G-B equation and lime activity rate constant (0-1) day	G-B equation and lime activity rate constant (1-90) day
staffs	$F(x) = -1.33 + 17.38t$ $r^2=0.94$ $k = 17.38 \times 10^{-4}$	$F(x) = 86.28 + 1.30t$ $r^2=0.78$ $k = 1.30 \times 10^{-4}$
cms	$F(x) = -1.31 + 22.18t$ $r^2=0.88$ $k = 22.18 \times 10^{-4}$	$F(x) = 98.83 + 1.75t$ $r^2=0.72$ $k = 1.75 \times 10^{-4}$
wb	$F(x) = -1.55 + 24.37t$ $r^2=0.92$ $k = 24.37 \times 10^{-4}$	$F(x) = 90.60 + 1.58t$ $r^2=0.80$ $k = 1.58 \times 10^{-4}$

TABLE 4—LIME ACTIVITY OF VARIOUS POZZOLANS (11,12)

Pozzolan	Lime reactivity ($k \times 10^{-4}$)
Natural trass	1.60
Heated trass	3.64
Kaolin	2.40
Metakaolin	25.00
fa (average)	20.00
Micro-silica	27 to 97

TABLE 5—COMPRESSIVE STRENGTH (MPa) OF THE DIFFERENT CONCRETE MIXTURES

Age (days)	npc	staffs	cms	wb	Drax*
1	15.6	12.4	15.4	16.1	9.8
3	37.1	30.6	34.4	35.1	23.9
28	56.1	50.7	55.4	58.2	44.1
90	61.3	63.9	72.6	73.0	54.7

* values of unprocessed fa

TABLE 6—POROSITY VALUES MEASURED BY VACUUM SATURATION (%)

Age (days)	npc	staffs	cms	wb	Drax*
1	12.25	11.59	11.59	11.65	N/A.
3	11.48	10.89	10.70	10.34	15.26
28	9.90	8.78	7.91	8.16	13.49
90	9.73	8.34	7.89	7.92	13.04

* values of unprocessed fa

TABLE 7—OXYGEN PERMEABILITY VALUES OF THE CONCRETE MIXTURES (M^2)

Age (days)	npc	staffs	cms	wb	Drax*
1	1.41×10^{-16}	1.25×10^{-16}	1.49×10^{-16}	1.37×10^{-16}	N/A.
3	3.44×10^{-17}	2.03×10^{-17}	2.12×10^{-17}	2.05×10^{-17}	4.30×10^{-17}
28	1.45×10^{-17}	6.47×10^{-18}	5.58×10^{-18}	5.54×10^{-18}	2.10×10^{-17}
90	1.11×10^{-17}	3.14×10^{-18}	2.45×10^{-18}	2.77×10^{-18}	1.40×10^{-17}

* values of unprocessed fa

Fig. 1—Compressive strength of the different concrete mixtures

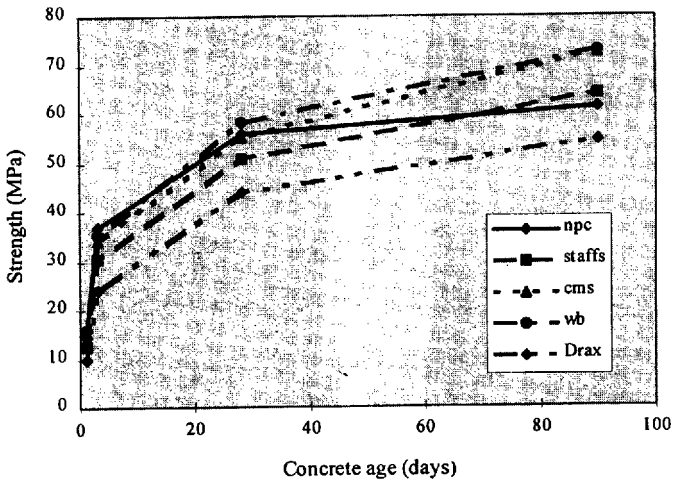


Fig. 2—Reduction of porosity of the npc and fa concrete mixtures

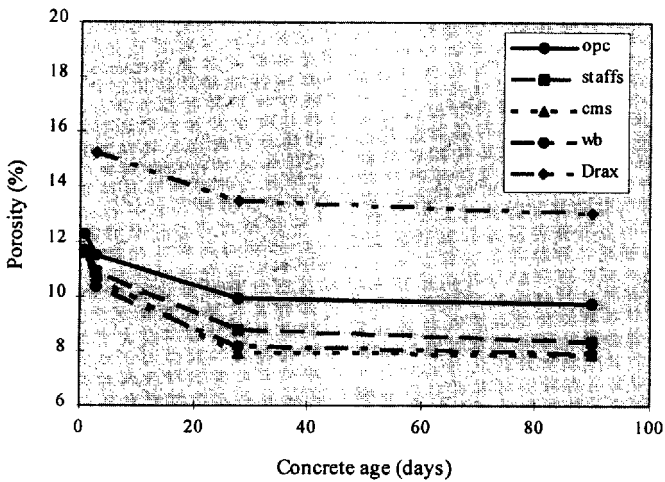


Fig. 3—Intrinsic permeability-age relations for the mixtures studied

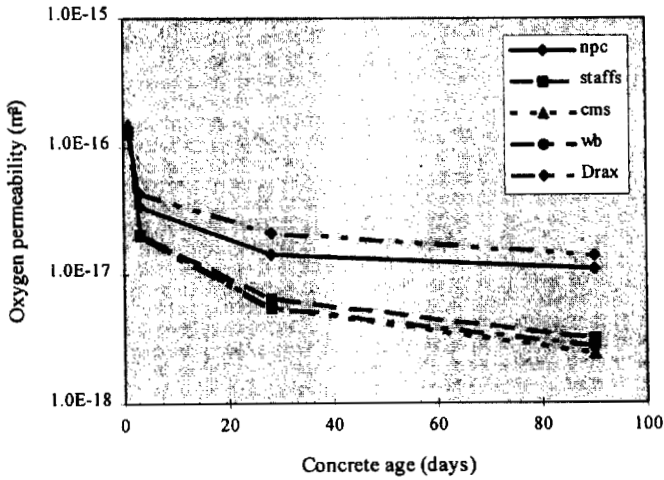
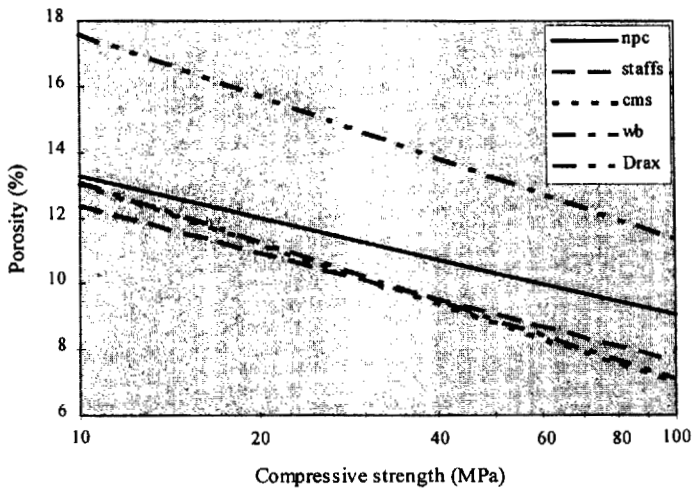


Fig. 4—Strength versus porosity relationship



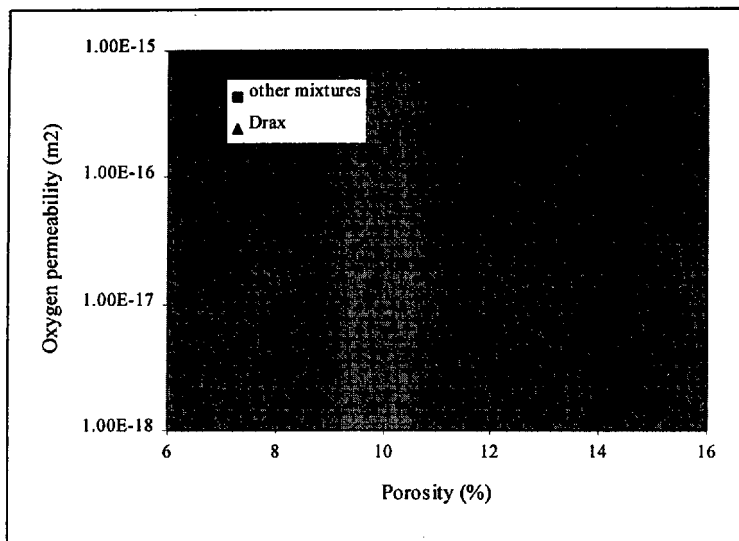


Fig. 5—Relation between the oxygen permeability and the porosity of the concrete mixtures studied

SP 178-3

Selective Use of Fly Ash Concrete

by V. Sirivivatnanon and R.P. Khatri

Synopsis : Structural grade fly ash (FA) concrete and concrete with high volume of fly ash (HVFA) are well accepted and utilized in the Australian construction industry. These are concretes with fly ash (ASTM C 618 type F) making up between 10 and 50 % by weight of the total cementitious material. This paper is intended to demonstrate the importance of the selection of the appropriate amount of FA content for a range of applications. The durability performance of the FA concretes was compared with portland cement concretes of equivalent 28-day compressive strength, in terms of the resistance to carbonation, chloride penetration and sulfate attack. Some mixture design data for both FA and HVFA concretes and their mechanical properties are given. The likely optimum fly ash percentages for a range of applications are highlighted with respect to their properties and construction demands. It was found that a lower fly ash dosage would be more suitable for above-ground structures where a carbonation-related deterioration mechanism applied. However, for structures in aggressive sulfate ground condition or in marine environments, HVFA concrete was found to be much more suitable. Available field performance data have confirmed laboratory evaluated performance.

Keywords : carbonation; chlorides; durability; fly ash; marine environments; sulfates.

38 Sirivivatnanon and Khatri

Vute Sirivivatnanon is a Principal Research Scientist and Project Leader of the CSIRO Sydney based *Concrete Technology* research team. The team conducts advanced research in binder formulation and high performance concrete. The team has successfully collaborated with industry in the development of a marine concrete used in the sea-wall of the *Sydney Parallel Runway*, and high volume fly ash (HVFA) concretes used in parts of the *Melbourne Casino* project. He also provides consultancy in concrete mixture formulations and evaluations, specifications, quality improvement and quality control (QC) in Australia and South-East Asia.

Radhe Khatri is a Scientist with CSIRO Building, Construction and Engineering, Australia. He is working on the role of permeability in the durability of concrete. He is also working on improving resistance of concrete to chloride and sulfate environments by incorporating mineral additives in the binder. He obtained his PhD in Engineering Mechanics from The Pennsylvania State University, USA, and worked in The Research Institute of King Fahd University of Petroleum and Minerals in Saudi Arabia.

INTRODUCTION

For structural grade concretes the use of fly ash (FA) in Australia is quite common. It has been claimed that 90% of the concretes produced in Sydney contains FA. In most of the concretes, the binder (cementitious material) is either a binary blend of ordinary portland cement (OPC) and FA or a ternary blend of OPC, FA and silica fume (SF) or ground granulated blast furnace slag (S). In some concretes, a quaternary blend is also used which contains OPC, FA, SF and S. This paper mainly focuses on concretes prepared from binary blends of OPC and FA.

The typical amount of FA in a concrete mix varies from 60 to 100 kg/m³. This represents about 20% or less by weight of the total binder. High volume fly ash (HVFA) concrete refers to structural concrete with an FA proportion substantially higher than conventional FA concretes. In Australia, an FA content of about 40 to 50 wt.% (percentage by weight) of the total binder is classified as an HVFA concrete.

In this study, fresh concrete properties and mechanical properties of concretes prepared with a range of fly ash proportions were studied. Mechanical properties and volume stability properties of FA concretes were also compared to those of OPC concretes. Also durability properties of OPC concretes were compared to similar 28-day strength

FA concretes. Their resistance to carbonation, chloride penetration and sulfate attack was evaluated.

Based on the fresh concrete, mechanical and durability properties of FA concretes, the optimum amount of FA in a concrete for a range of applications was recommended. It is expected that for different construction methods or for structures exposed to different environments, the likely optimum FA content could be different. For example, if the early strength is important for rapid construction or early formwork removal, then the FA content should be chosen to provide early strength. On the other hand, if the workability is important in a congested steel then the appropriate FA content should be selected to give improved workability. Similarly the type of environment a concrete structure is exposed to could also dictate the proportion of FA. For example, concrete structures exposed to high sulfate environments should have FA content optimum for sulfate resistance. Also concrete structures such as wharfs or jetties should have FA content which gives them best chloride resistance. Thus, depending upon the construction methods and the requirements of the resistance to the exposure environments, the proportion of FA content should be carefully selected. The aim of this study is to enable the selection of appropriate FA concrete for a specific application.

FRESH CONCRETE PROPERTIES

Table 1 gives the chemical composition of the OPC and FA. The fly ash meets the specification of Australian Standard 3582.1-1991 (equivalent of ASTM C 618-97).

FA concretes were found to generally contain higher total binder (OPC+FA) than the equivalent OPC concretes. Increasing the FA content causes fresh concrete to become more cohesive as observed after a slump and flow test. For similar slumps, FA concretes were found to have marginally lower flow values.

Table 2 shows the setting time of various concretes. It can be seen that FA concretes with an FA content 40-50 wt.% of the binder have longer setting times than OPC concretes. The increase was about 20 to 40% when the concretes had 40 wt.% of the binder as FA. However, the increase in setting times was about 50 to 100% when the concretes had 50 wt.% of the binder as FA. Increasing the FA content causes an increase in setting times. Thus it is expected that FA concretes (FA content of 20 to 40 wt.% of total binder) will have setting times between those of OPC and HVFA concretes. Thus FA concretes with FA content up to 40 wt.%