

High-Performance Concrete

Performance and Quality of Concrete Structures

**Proceedings,
Second
CANMET/ACI
International
Conference
Gramado, RS,
Brazil, 1999**

Editors
V.M. Malhotra
P. Helene
L.R. Prudêncio, Jr.
D.C.C. Dal Molin

ACI
international®
SP-186

0662940 0544744 848 44T4450 6462990

For more details: ACI SP-186-99

High-Performance Concrete and Performance and Quality of Concrete Structures

Proceedings, Second CANMET/
ACI International Conference
Gramado, RS, Brazil, 1999

Editors

V. M. Malhotra

P. Helene

L. R. Prudêncio, Jr.

D. C. C. Dal Molin



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 November 1, 1999. All discussion approved by the Technical Activities Committee along with closing remarks by the authors will be published in the March/April 2000 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 © 1999
AMERICAN CONCRETE INSTITUTE
P.O. Box 9094
Farmington Hills, Michigan 48333-9094

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 D. Carroll

Library of Congress catalog card number: 99-62046

PREFACE

In June 1999, the Universidade Federal do Rio Grande do Sul, Universidade Federal de Santa Catarina, Escola Politecnica da Universidade de São Paulo, all of Brazil, in cooperation with the American Concrete Institute, U.S.A., and CANMET, Canada, sponsored the Second International Conference on High-Performance Concrete, and Performance and Quality of Concrete Structures in Brazil. The first conference on the subject was held in Florianopolis, Brazil, in 1996. The purpose of this second conference, which was held in Gramado, RS, Brazil, June 1-4, 1999, was to show and to disseminate technical information on emerging high-performance concrete in Brazil and other South American countries. More than 100 papers from all over the world were received, and reviewed in accordance with the policies of the American Concrete Institute and 45 were accepted for publication. To all those whose submissions could not be included in the symposium volume, the American Concrete Institute and the International Conference Organizing Committee extend their appreciation for their hard work and interest. In addition to the papers that have been published in the proceedings, a number of others were presented at the Conference.

Thanks are extended to the distinguished members of the CANMET/ACI review panel who reviewed the draft manuscripts in 1998 at the panel meeting in Brazil. Without their prompt review and constructive comments, it would not have been possible to publish the proceedings for distribution at the Conference. The cooperation of the authors in accepting reviewers' suggestions and revising their manuscripts accordingly is greatly appreciated.

The help of ACI staff for performing the administrative duties associated with this publication is greatly acknowledged.

Editors

V. M. Malhotra

P. Helene

L. R. Prudêncio, Jr.

D. C. C. Dal Molin

CANMET/ACI Second International Conference on
High-Performance Concrete, and Performance and Quality
of Concrete Structures—Gramado, RS, Brazil, 1999

International Organizing Committee

Chairmen

V. M. Malhotra, Canada
P. Helene, Brazil

Members

D. C. C. Dal Molin, Brazil
P. K. Mehta, U.S.A.
R. N. Swamy, U.K.
L. R. Prudêncio, Jr., Brazil

Local Organizing Committee

A. Masuero, Brazil
D. L. Kleim, Brazil
J. L. Campagnolo, Brazil
R. Cremonini, Brazil
M. Kulakowski, Brazil

CONTENTS

CONCRETE SULFATE ATTACK IN A SULFATE-FREE ENVIRONMENT by M. Collepardi.....	1
DESIGN AND PROPERTIES OF HIGH-VOLUME FLY ASH HIGH- PERFORMANCE CONCRETE by J. G. Cabrera and C. D. Atis.....	21
PREHYDRATED HIGH-ALUMINA CEMENT-BASED ADMIXTURE FOR COMPENSATING AUTOGENOUS SHRINKAGE IN HIGH-PERFORMANCE CONCRETE by W. L. Repette and N. P. Mailvaganam.....	39
MECHANICAL BEHAVIOR OF REPAIRED BEAMS UNDER STATIC LOADING by K. C. G. Ong W. Xu, and P. Paramasivam.....	59
CONCRETE PERFORMANCE WITH ADMIXTURES OF ELECTRICAL STEEL SLAG AND COPPER SLAG CONCERNING MECHANICAL PROPERTIES by W. Moura, A. Masuero, D. Dal Molin, and A. Vilela	81
HIGH-PERFORMANCE FIBER REINFORCED CONCRETE FOR MINE ROADWAY SUPPORT PANELS by J. Šušteršič, M. Kolenc, A. Zajc, F. Ricek, and M. Z. Pogorelnik.....	101
RHEOLOGICAL BEHAVIOR OF DRY-MIX SHOTCRETE by A. D. Figueiredo	113
CONCRETE MIX PROPORTIONING TO MEET DURABILITY CONCERNS FOR CONFEDERATION BRIDGE by W. Langley.....	129
ROLLER-COMPACTED CONCRETE INCORPORATING SUPERPLASTICIZER AND VISCOUS AGENT FOR PAVEMENTS by M. Kagaya, H. Tokuda, and Y. Inaba	149
PERFORMANCE OF POLYOLEFIN FIBER REINFORCED CONCRETE UNDER CYCLIC LOADING by V. Ramakrishnan and C. Sivakumar	161
MICROSTRUCTURE OF TWO-THOUSAND-YEAR-OLD LIGHTWEIGHT CONCRETE by R. Rivera-Villarreal and J. G. Cabrera.....	183
USE OF LOCALLY AVAILABLE AGGREGATES FOR HIGH-STRENGTH, HIGH ABRASION-RESISTANT CONCRETE IN SLOVENIA by M. Simon and J. Šelih	201

STUDY OF INFLUENCE OF RICE-HUSK FLY ASH ON COMPRESSIVE STRENGTH OF CONCRETE AT DIFFERENT AGES by G. Rodriguez de Sensale and D. C. C. Dal Molin	213
BOND INFLUENCE ON ROTATION CAPACITY OF HIGH-STRENGTH AND NORMAL STRENGTH CONCRETE BEAMS by I. A. E. M. Shehata, L. A. Ventrini, and L. C. D. Shehata	231
MICROSTRUCTURAL INVESTIGATION OF PORTLAND CEMENT MORTARS CONTAINING VARYING DOSAGES OF POLYNAPHTHALENE SULFONATE SUPERPLASTICIZER by G. Xu, J. J. Beaudoin, C. Jolicoeur, and M. Pagé	253
PHYSICO MECHANICAL PROPERTIES OF HIGH-PERFORMANCE CONCRETE by A. DiMaio, G. Giaccio, and R. Zerbino	275
GAS PERMEABILITY OF HIGH-PERFORMANCE CONCRETES—SITE AND LABORATORY TESTS by R. Torrent	291
PERFORMANCE OF FIBER REINFORCED LIGHTWEIGHT AND NORMAL-WEIGHT CONCRETE IN SIMULATED MARINE ENVIRONMENT by C. K. Ong, T. W. Bremner, T. A. Holm, and S. R. Boyd	309
COMPUTER SIMULATION OF PARTICLE PACKING IN CEMENTITIOUS SYSTEMS by M. Stroeven and P. Stroeven	327
HIGH-STRENGTH HIGH-PERFORMANCE CONCRETE USING FLY ASH AND SUPERPLASTICIZER ADMIXTURE by R. Rivera, R. Dávila, and A. Durán	341
COMPOSITE COLUMNS—STEEL PIPES WITH SQUARE AND RECTANGULAR SECTIONS AND HIGH-STRENGTH CONCRETE CORE by J. F. Fernandez and R. S. Agostini	357
CHLORIDE PENETRATION PROFILES IN MARINE ENVIRONMENTS by P. Castro, O. T. De Rincón, and E. Pazini	371
BEHAVIOR OF NORMAL AND HIGH-STRENGTH CONCRETES DURING VIBRATION by M. N. Soutos, J. H. Bungey, M. J. Brizell, and G. D. Henderson	391
FROST DURABILITY OF HIGH-PERFORMANCE CONCRETE INCORPORATING SLAG OR SILICA FUME by M. Soeda, T. Yamato, and Y. Emoto	409

INFLUENCE OF CEMENT TYPE AND CURING CONDITIONS ON INITIAL ABSORPTION OF CONCRETE by G. Camarini, J. P. Balayssac, and Ch. H. Detriché	427
BEHAVIOR OF REINFORCED HIGH-STRENGTH CONCRETE CORBELS— EXPERIMENTAL INVESTIGATION AND DESIGN MODEL by G. B. Fernandes.....	445
AXIALLY LOADED HIGH-PERFORMANCE CONCRETE COLUMNS WITH STEEL FIBERS by A. E. P. Guimarães, J. S. Giongo, and T. Takeya	463
SYNERGIC ACTION OF FLY ASH IN TERNARY MIXTURES OF HIGH- PERFORMANCE CONCRETE by G. C. Isaia	481
MECHANISMS OF ACTIONS OF DIFFERENT SUPERPLASTICIZERS FOR HIGH- PERFORMANCE CONCRETE by S. Collepardi, L. Coppola, R. Troli, and M. Collepardi.....	503
RELIABILITY UPDATING OF DETERIORATING CONCRETE FLOOR SLABS by T. J. DaSilva and P. Roca	525
DEVELOPMENT OF RESEARCH AND APPLICATION OF HIGH-PERFORMANCE CONCRETE IN BRIDGE ENGINEERING IN POLAND by W. Radomski	537
PRODUCTION AND TESTING OF SELF-LEVELLING CONCRETE by J. Ambroise, S. Rols, and J. Péra	555
HIGH-STRENGTH CONCRETE WITH LIMESTONE FILLER CEMENTS by V. Bonavetti, H. Donza, V. Rahhal, and E. F. Irassar	567
ESTIMATION OF MODULUS OF ELASTICITY IN HIGH-PERFORMANCE CONCRETE MIX AT EARLIER AND LATER AGES by R. C. A. Pinto and K. C. Hover.....	581
HIGH-STRENGTH CONCRETE DEEP BEAMS WITH WEB OPENINGS by A. P. Almeida and N. de Oliveira Pinto, Jr.....	597
ADMIXTURE COMPATIBILITY IN SPECIAL CONCRETES by N. P. Mailvaganam	615
MODELING OF SERVICEABILITY BEHAVIOR OF HIGH-PERFORMANCE FIBER REINFORCED POLYMER REINFORCED CONCRETE MEMBERS by M. A. Aiello and L. Ombres	635

MECHANICAL PROPERTIES AND DURABILITY OF HIGH-PERFORMANCE CONCRETE by R. L. Silveira, J. M. Calixto, and J. T. Fontoura.....	655
INFLUENCE OF ULTRA-FINE PARTICLE TYPE ON PROPERTIES OF VERY-HIGH-STRENGTH CONCRETE by S. Rols, M. Mbessa, J. Ambroise, and J. Pera.....	671
WATER PERMEABILITY STUDY OF HIGH-PERFORMANCE CONCRETE by J. Sebe and J. M. Calixto	687
BEHAVIOR OF HIGH-STRENGTH CONCRETE BEAM-COLUMN CONNECTIONS by R. H. Scott, S. J. Hamil, and P. S. Baglin	699
COMPARISON BETWEEN DEMAND OF SUPERPLASTICIZER ADMIXTURE AND STRENGTH DEVELOPMENT OF HIGH-PERFORMANCE CONCRETE USING SILICA FUME AND RESIDUAL RICE-HUSK ASH by S. Santos, L. R. Prüdencio, Jr, and G. P. Gava	715
APPLICATIONS OF HIGH-PERFORMANCE CONCRETE FOR ULTRA-THIN PAVEMENT OVERLAYS (WHITE-TOPPING) by J. T. Balbo.....	731
STUDIES ON HIGH-PERFORMANCE HIGH-STRENGTH CONCRETE (HPHSC) COLUMNS by B. V. Rangan.....	745
DESIGN FOR DURABLE SERVICE LIFE—LINCHPIN FOR SUSTAINABILITY IN CONCRETE CONSTRUCTION by R. N. Swamy.....	765

SP 186-1

Concrete Sulfate Attack in a Sulfate-Free Environment

by M. Collepardi

Synopsis: The present paper provides an example of the application of the holistic model to the study of one of the most complex phenomenon in the science of concrete durability, namely the deterioration caused by delayed ettringite formation (DEF) in a sulfate-free environment. By adopting the holistic approach, a new model to explain this damage is proposed. The model is based on three essential elements: late-sulfate release, microcracking, and exposure to water. Late-sulfate release from a cement with high-sulfate content (especially that with high content of clinker sulfate in less available form) can cause the delayed deposition of ettringite in pre-existing microcracks after sulfate ions diffuse through the pore solution in concrete, either intermittently, or continuously exposed to environmental water. Microcracking may be promoted by alkali-silica reaction, steam curing at high temperatures, localized high stress in prestressed concrete structures or other causes.

Theoretically, the DEF-induced damage occurrence can be reduced or prevented by controlling at least one of the above three parameters. In practice, the best way of reducing the DEF-induced damage risk is either to avoid cements with high clinker sulfate that are responsible for the late-sulfate release, or to adopt lower and more homogeneous stress distribution derived from the prestressing process in precast elements, such as concrete ties.

Keywords: delayed ettringite formation; durability; microcracking; prestressed concrete elements; sulfate attack

2 Collepardi

Mario Collepardi is Professor of Materials Science and Technology in the Ancona University, Italy. He is author or co-author of numerous papers on concrete technology and cement chemistry. He is also the recipient of awards for his contributions to the fundamental knowledge of superplasticizers and their use in concrete.

INTRODUCTION

Sulfate attack is related to the expansive character of the ettringite formation by reaction of internal (concrete) or external (from the environment) sulfate with the hydrated calcium aluminate of the hardened-cement matrix.

Not necessarily the ettringite formation produces a damaging effect. When it occurs *homogeneously* and *immediately* (within hours or days) in a mixture or in a deformable concrete - *early ettringite formation (EEF)* - the related expansion does not cause any significant localized disruptive action (Table 1). This happens when ground gypsum reacts with anhydrous calcium aluminates within some hours (set regulation) or when a calcium aluminate sulfate (C_4A_3S) hydrates within few days producing a relatively small, homogeneous, harmless and rather useful stress (expansive cements for shrinkage compensating concretes).

On the other hand, when ettringite forms *heterogeneously* and *later* (after months or years) - *delayed ettringite formation (DEF)* - the localized related expansion in a rigid hardened concrete produces cracking, spalling, and strength loss. Therefore only *DEF* - and not *EEF* - is associated with a damaging sulfate attack (Table 1).

There are two different types of *DEF*-related damage depending on the sulfate source (Table 2): external or internal sulfate attack. External sulfate attack (*ESA*) occurs when *environmental sulfate* (from water or soil) penetrates concrete structures. Internal sulfate attack (*ISA*) occurs in a sulfate-free environment for the *late sulfate release* from either gypsum-contaminated aggregates or sulfur-rich clinker phase (1). According to the terminology currently used, the term "*DEF*" is related to the internal sulfate attack only. However, more correctly **delayed** ettringite formation would mean that ettringite forms **later** regardless of the sulfate source.

HOLISTIC AND REDUCTIONIST APPROACHES

The holistic approach considers **concrete construction in its entirety with environmental and structural loading in service**, rather than concrete as material of laboratory curiosity. Mehta (2) adopted the holistic approach to explain the behavior of concrete structures in the field in contrast to what happens to laboratory specimens and in particular he studied the role played by microcracks in determining the concrete deterioration process.

Brittleness, combined with poor tensile strength, is responsible for microcracking in concrete structures subjected to thermal and drying shrinkage, as well as to static and cycling dynamic loading in service. According to Mehta (2) microcracks, promoted by weathering effects and loading in service, represent preferential paths for the penetration of aggressive environmental agents such as air, humidity, sulfate and chloride ions. Therefore, pre-existing discontinuous microcracks act as precursors in the corrosion of the reinforcement and in the deterioration of the cement matrix itself as well as that of the reactive aggregates, if any. Once any of these processes is initiated (all having an expansive-disruptive nature), microcracks grow to become macrocracks. After an initial period of a few years or more, the degradation process - in the form of cracking, spalling and loss of mass - increases very rapidly.

The holistic approach has been used by Mehta (2) to re-examine the four principal causes of concrete deterioration: external sulfate attack, alkali-silica reaction, corrosion of reinforcing steel, and freezing-thawing cycles. In the present paper, based on a previous work of the author (1), the holistic model is used to address the internal sulfate attack. According to the terminology currently used, in the present paper the term "*DEF*" is used to indicate the ettringite-related deterioration of concrete in a **sulfate-free environment**.

Different researchers have adopted a reductionist approach, instead of a holistic one, to explain concrete distress induced by *DEF*. Each has reached a different conclusion by relating the concrete distress with a specific predominating mechanism. Among these, the following hypothesis can be mentioned as the most important:

- (i) ***DEF* promoted by high temperature steam curing:** In normal portland cement pastes ettringite, that forms during the plastic stage of fresh concrete, is destroyed by steam curing at 65-100°C; then ettringite forms again at later ages in concrete structures stored in water either intermittently or permanently and causes disruptive expansion of the hardened concrete in service. According to Heinz *et al.* (3,4), *DEF* expansion in concrete is due to the transformation of metastable monosulfate into ettringite when steam-cured concrete is exposed to normal temperature moist-curing at later ages. According to Lawrence (5), the correlation between expansion and sulfate content of the cement points out the importance of ettringite in the expansion mechanism of steam-cured mortar prisms; however, the expansive hydration of MgO may increase the sensitivity of cements to heat cure. On the other hand, Fu *et al.* (6-8) argued that, although steam curing of concrete at high temperatures is a key element, the *DEF* mechanism process is different from that based on thermal decomposition of ettringite: at temperatures above 65°C, calcium silicate hydrate (*C-S-H*) would adsorb very quickly sulfate from gypsum, so that this would not be available to react with the aluminate phase and produce normal ettringite; later sulfate ions, slowly released from the *C-S-H* phase, would diffuse through pore solution and feed the nucleation

4 Collepardi

of ettringite crystals in the tip-zone of the pre-existing microcracks. In the case of *DEF* associated with steam curing the specific mechanism is highly controversial. On the one hand, Scrivener and Taylor (9) and others (10, 11) think that the *DEF* effect in steam-cured concretes is related to a uniform and homogeneous paste expansion that occurs in the post steam-curing exposure. Accordingly to Johansen *et al.* (10) the uniform paste expansion results in rim cracks around aggregates; subsequently ettringite deposition would fill the rim cracks, but this is considered to be benign since ettringite deposition is considered to play no role in the expansion and cracking of concrete. On the other hand, Diamond (12) and others (6-8) think that the expansion and cracking induced by *DEF* are related to the crystal pressure exerted by the growing ettringite crystals on their surroundings. In particular, on the basis of free-energy considerations, it was shown (7) that ettringite crystal nuclei should first form in the tip-zone of the pre-existing microcracks; after nucleation, the growth of these ettringite crystals would be responsible for the opening of the microcracks.

- (ii) ***DEF* promoted by alkali-silica reaction (ASR) or other microcrack-causing mechanisms:** *ASR* is the primary cause of deterioration in the form of cracks and microcracks, whereas ettringite, that is found in the cracks in moist-curing conditions at later ages, is considered to have formed as a consequence of the pre-existing cracks rather than being the cause of it (13,14). Thaulow *et al.* (15) found mixtures of alkali-silica gel and ettringite in steam-cured prestressed concrete railroad ties. However, Diamond and Ong (16) found that, in the presence of siliceous reactive aggregates, initial expansion and cracking were caused by the *ASR*, but after about one month no more *ASR* gel formed and the subsequent further expansion was caused by deposition of ettringite. Steam curing at high temperatures is suspected to aggravate reactivity of silica and silicates with alkali (17,18). Therefore, according to Taylor (17), limestone aggregates would be preferable to siliceous aggregate in manufacturing *DEF*-free steam-cured concrete. Additional conditions that are considered essential to the *DEF*-damage process include: microcracking promoted by thermal stresses in steam-cured precast concrete (18,19), or freezing-and-thawing in service (3,4), or dynamic loading and fatigue stress (13). The use of ASTM Type III portland cement (20) or relatively high contents of SO_3 ($> 3.6\%$), MgO ($> 1.6\%$) and equivalent Na_2O ($> 0.8\%$) in portland cements (21) are factors that would aggravate expansion of steam-cured concrete.
- (iii) ***DEF* promoted by large amounts of sulfate in clinker and/or high cement sulfate content:** Portland cement contains a mixture of sulfur compounds from the cement clinker and from added calcium sulfate (e.g. gypsum, $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) which acts as set regulator. The sulfates from different sulfur sources have different water-solubility kinetics: sulfate from the gypsum dissolves sufficiently fast to participate in the regulation of the setting of the cement, whereas sulfate from the clinker phase is usually unavailable for the setting

regulation. Therefore, cements with the same *total* sulfate content, but with different proportions of sulfate from the clinker phase and that from the gypsum source, may perform in different ways.

In many present-day clinker kilns there are poly-functional burning systems which are capable of using either gaseous or liquid hydrocarbons, as well as solid small-particle coals, depending on the cheapest source of available fuels. The sulfur content of these different fuels can change and cause unwitting variations from one day to another of sulfate incorporated in the clinker phase. Moreover, the clinker sulfate content may increase with the use of high-sulfur organic residues, such as tires that are burned in cement kilns to destroy environmentally harmful products in a safe and cost-effective way.

According to Hime (22), present-day cements produced in kilns that burn sulfur-rich fuels or waste materials, can incorporate large amounts of sulfates, up to 3% by clinker mass. When high sulfate levels are not balanced by a high alkali content, the excessive SO_3 may occur as CaSO_4 or react with calcium aluminates or even occur as interstitial impurity in the alite and belite phases. According to Hime, all these forms of sulfate in the clinker phase are slowly soluble in the mixing water and, therefore, can lead to **late-sulfate release** which is essential for the delayed ettringite formation (*DEF*)-related damage. According to this recent perspective, based on field occurrence, *DEF* is not restricted to overheated steam-cured concretes, since precast Friday ties*, cured at the factory temperature, present the same distress incidence as the steam-cured products (23). Moreover, there is evidence from the field that cast-in-place concrete structures (12,22,23) may show evidence of the same *DEF*-induced damage occurrence as that of steam-cured precast concrete products. According to this hypothesis, *DEF* by itself causes microcracks radiating from localized areas of ettringite development, expansion of the cement matrix relative to coarse aggregates, and macrocracks due to the internal expansion relative to the exterior surface region (23). On the other hand, Miller and Tang (24) found that North American and European present-day clinkers may contain sulfate levels from a few hundredths of a percent to about 2.5%. However, they did not find CaSO_4 in the clinker phase and concluded that, under ambient curing conditions, the sulfur-containing phases of the present-day commercial clinkers are unlikely to cause expansive stress and cracking induced by internal sulfate attack.

Each of the above hypothesis - from (i) to (iii) - can be partly correct; however, they cannot solely explain all the available data from the field on the *DEF*-induced damage of concrete structures. For instance, it may be true that many *DEF*-induced concretes were subjected to steam curing at high temperatures, but there are also apparently proven cases of *DEF*-related deterioration in the absence of steam curing. On the other hand, it may be true

* Friday ties are manufactured on Friday and cured at room temperature because by Monday they would attain adequate strength to allow for cutting the prestressing strands.

6 Colleparidi

that *ASR* acts as the precursor of some *DEF*-related damages, but there are also *DEF*-distress cases in the absence of *ASR*. Finally, it may be true that present-day cements incorporate large amounts of slowly soluble sulfate in the clinker, but not all present-day concrete structures are subjected to *DEF*-induced damage. It is opinion of the author that, due to the reductionist approach, each researcher or research-team over-emphasized their own results and under estimated or rejected others. Moreover, each of the above hypotheses cannot give a satisfactory answer to the following questions:

1. Why are some specific concrete products (e.g., prestressed concrete **railway ties**) **more vulnerable to DEF-induced distress** than other precast or cast-in-place concrete structures?
2. Why is **DEF-induced damage so erratic** in the sense that, everything apparently being the same, it occurs only under some specific circumstances and not others?

FIELD EXPERIENCE OF DEF-RELATED DAMAGE

An attempt will be made in the present paper to integrate all the above mentioned information, as well as results from the field experience of this author, with the available knowledge on concrete science and technology.

The results from field experience directly available to the author include two different types of concrete structures: a) prestressed precast concrete ties and b) cast-in-place concrete structures.

For each of the above concrete structures, *DEF*-related damage cases were found with ettringite appearing, as a gel-like mass under the optical microscope, in the cracks of the damaged structures. By use of a scanning electron microscope and an X-ray elemental analyzer the gel was identified as fibrous consisting of calcium, sulfur, and aluminum. It was definitely confirmed by X-ray diffraction analysis indicating that the product was primarily ettringite.

- a) **Concrete ties.** For the *DEF*-damaged concrete ties almost all the results published by Mielenz *et al.* (23) were confirmed, and in particular field observations revealed that:
- The *DEF*-induced damage incidence was identical whether concrete ties were steam cured or not.
 - Unused stock-piled ties underwent the same distress-incidence as the ties in service subjected to vibrational distress caused by the passage of high-speed trains.
 - Ties not exposed to rain (such as those in railroad tunnels or un-used ties below and in the middle of outdoor storage stacks) did not deteriorate.
- In addition to these results, field experience showed the important role played by the **microcracks produced during the prestressing process** in determining

the *DEF*-induced damage. Microcracks (i.e. cracks invisible to the naked eye) were detected by using an optical microscope, specially adapted for field experience. The appearance of microcracks (10-100 μm in thickness) on the surface of concrete ties was monitored either immediately after cutting the prestressing strands or later on in stock-piled products and those in service. In all the concrete ties of a plant, where there were complains for the *DEF*-induced damage, **microcracks were detected immediately after cutting the prestressing strands**. They initially appeared as microcracks parallel to the prestressing wires and later as irregular cracking.

Field observations of microcracks of un-used concrete ties revealed that their presence was related with the specific type of manufacturing process, and in particular with the local stress level induced in the concrete by the sudden cutting of the prestressing strands. Two typical processes are adopted for manufacturing prestressed concrete ties. In one of these - named *long-line method* (Fig. 1) and widely used all over the world - the same set of prestressing strands is used for 15 to 20 lined up concrete ties. Each concrete batch is in general placed in a row of 6 or 8 parallel ties. When the concrete attains adequate compressive strength, the prestressing strands are cut. At this time **excessive local stress can occur in the concrete area close to one end of the tie**, especially in the eight ties located at the two extreme parallel rows.

In the other process - named *anchored steel-plate method* (Fig. 2) - each concrete tie is individually prestressed using reinforcing wires anchored to steel plates by special cold-worked heads. The anchored steel plates, embedded in the concrete mixture at the ends of each tie, transfer the prestressed force from the wires to the concrete when this reaches adequate compressive strength. This process consumes more time and also workmanship, and therefore prestressed concrete ties processed according to this method are more expensive. However, as a matter of fact, in concrete ties manufactured with this process microcracks do not appear or occur to less extent at the time of prestressing, and the frequency occurrence of the *DEF*-induced damage seems to be lower than in concrete ties manufactured with the *long-line method*.

Not all the microcracked concrete ties subsequently evidenced macrocracks and deposition of ettringite into the cracks. The frequency of occurrence of the *DEF*-related distress was found to be high only in the presence of other two events accompanying the initial microcracking. These events are:

- relatively high cement sulfate level that sometimes surpassed the limit of 4%, in terms of SO_3 content, according to the European Norm EN 197/1;
- intermittent exposure to rain water, aggravated by alternate drying caused by sunny conditions.

8 Collepardi

The role played by the micro-climate (Fig. 3) was studied by examining unused, two-year old, stock-piled concrete ties, all microcracked as evidenced by the field optical microscope. Those exposed to the alternate actions of rain and sun (on the sides and specially at the tops of outdoor storage stacks) were severely macrocracked and *DEF*-damaged; those exposed to rain but in a permanent shadow condition evidenced a less severe distress; concrete ties permanently protected from both rain and sun exposure (below and in the middle of stacks) remained only microcracked without any further crack growth and apparent *DEF*-related damage.

- b) **Cast-in-place concrete structures.** Many pedestals for electric power-line installations deteriorated very severely over a period of 2-3 years after being cast in place in 1993 (Fig. 4). Since they were located in an area (near Ancona, Italy) where siliceous reactive aggregate are frequently found, an *ASR*-damage was initially diagnosed. However, due to the unusual and severe macrocracking not always accompanied by the typical gel appearance of the *ASR* product, some cored samples were analyzed and massive local deposits of ettringite in the cracks were detected by XRD. No significant sulfate content ($<0.01\%$) was detected in the environmental ground surrounding the pedestals as well as in the coarse aggregate extracted from the concrete. The latter, on the other hand, was found to be a slowly reactive siliceous aggregate when tested according to the ASTM C 289 procedure. On the basis of the SO_3 content in the concrete, the known nominal portland cement content, and the concrete specific gravity, the SO_3 level for the cement used was assumed to be as high as 4.4%. The unusually high SO_3 level of the cement was related with the clinker sulfate as high as 2% according to the available information for the cement used at that time in the area. Most of the clinker sulfate is not available for early cement hydration reactions because of its lower (25) and /or slower (22) water solubility, especially when the alkali content in the clinker phase is relatively low (26,27). Therefore, the amount of total SO_3 in the cement (from the clinker source and the gypsum used for setting regulation) increases by increasing the clinker sulfate and sometimes surpasses the EN limit (4%). The required amount of gypsum *available* for the setting regulation, besides the *unavailable* sulfate from the clinker phase, can become relatively high in high-strength portland cement with high fineness and high C_3A content.

NEW PROPOSED MECHANISM FOR DEF-RELATED DAMAGE

The following factors are considered to be essential for the *DEF*-related damage: microcracks promoted by the manufacturing process itself (e.g. prestressing in railway ties) or *ASR* or other causes including those related to steam curing;

- exposure to wetting-drying cycles;

- late sulfate release from the cement clinker or other sources;
- migration of reactant ions (SO_4^{2-} , Al^{+3} , Ca^{+2}) through the pore aqueous solution of concrete exposed to water or saturated air;
- deposition of ettringite inside the existing microcracks, and subsequent crack opening by ettringite swelling or crystal growth.

The holistic approach for the *DEF*-induced damage is based on the occurrence of three essential events. The three events are:

- **Microcracking**
- **Exposure to water or saturated air**
- **Late-sulfate release**

Each event, in turn, can be determined by one or more possible causes which will be considered in detail further on. First, a synthetic representation of the holistic approach for the *DEF*-related damage will be examined through the help of Fig. 5 where each event corresponds to a circle. The area in the middle of the triangle corresponds to situations of serious risk for *DEF*-related deterioration since all the three needed elements of the system are present: **late sulfate release** caused by cement with high sulfate content (especially that with high content of clinker sulfate in less available form) can feed the delayed deposition of ettringite in the **pre-existing microcracks** after diffusing through the pore solution in concrete **exposed to environmental water**. In the absence either intermittently or continuously of one of these elements, *DEF* cannot occur and this explains the erratic character of this phenomenon.

Each of the three needed elements of the system can be related to numerous causes. For instance, concrete microcracking can be promoted by one or more of the following causes:

- Curing at high temperatures ($> 65^\circ\text{C}$), excessive heating/cooling rate or too short preliminary curing at room temperature
- *ASR* with microcracks around aggregate particles
- Weathering effects cycles including wetting/drying and heating/cooling changes
- Dynamic loads in service
- Plastic shrinkage in poorly cured slab structures
- Freezing/thawing cycles
- Excessively high porosity in aggregate particles
- Weak transition zone at the interface aggregate- or steel-cement matrix
- Localized high stress in prestressed structures.

Everything else being the same, steam-curing at high temperatures causes additional microcracking with respect to room temperature curing, and therefore there is a higher frequency of occurrence of *DEF*-induced damage in precast steam-cured concretes when cements with high sulfate content in the clinker phase are used. This also explains why in many laboratory studies (3-5, 7) only overheated steam cured specimens were subjected to *DEF*-related damage in contrast to what occurred in the corresponding concrete specimens cured at room temperature.

The last cause of microcracking in the above list - that is localized high stress induced by the prestressing process itself - can occur in all the precast concrete ties, particularly in those manufactured by the *long-line method*. This provides a clear justification of why with this type of structure there is a higher frequency of occurrence of *DEF*-related damage than in any other concrete element. However, since this deterioration did not occur in concrete ties manufactured in the late 1970s by using the same method as that presently employed (24), an additional event must be identified to explain why the distress to some of these ties began to occur in the late 1980s. This additional event seems to be the late sulfate release, which, in turn, is attributable to a number of possible causes:

- High cement sulfate content is related to the clinker sulfate increase with the use of high-sulfur fuel or organic residues - such as tires - burned in cement kilns to destroy environmentally harmful products in a safe and cost-effective way (22).
- Other sources of slowly soluble sulfate from artificial lightweight aggregates or gypsum-contaminated natural aggregates, and shrinkage-compensating cements based on sulfo-aluminate products.
- Slowly released sulfate ions from that adsorbed on the *C-S-H* phase in high temperature ($> 65^{\circ}\text{C}$) steam-cured concretes (6).
Thermal decomposition of ettringite at high temperature in steam-cured concrete (3,4).

Only the first cause of late sulfate release in the above list can justify why there was an increase in the *DEF*-related distress-incidence, from the 1970s to the 1980s, particularly in concrete structures - such as ties - more prone to microcracking for the manufacturing process itself. On the other hand, in present-day manufactured concrete ties the *DEF*-induced damage seems to be an exceptional and discontinuous phenomenon rather than a general and continuous occurrence, although many ties per each process-day are microcracked. This erratic occurrence of the *DEF*-induced damage can be related either to intermittent use of sulfur-rich organic residues in the clinker kiln or to change in the sulfur content of ordinary fuels. In many present-day clinker kilns there are poly-functional burning systems that are capable of using either gaseous or liquid hydrocarbons, as well as solid small-particle coals, depending on the cheapest source of available fuels. The sulfur content of these different fuels can change and cause unwitting variations from one day to another of sulfate incorporated in the clinker phase.

Chemical interactions - causing a decrease in the pH of the pore solution phase - can favor normal formation of ettringite from environmental sulfate attack (28). Therefore, one cannot exclude that carbonation as well as *ASR* can interact with the *DEF* process, creating more favorable conditions for ettringite deposition in the existing microcracks. In particular, since *ASR* consumes alkalies and OH^- from pore solution (16), this process can reduce the pH and presumably the ettringite deposit in the aqueous phase of pores and microcracks.

The other potential causes of late sulfate release - related with the sulfate contamination of aggregates, or the adsorption of sulfate on the *C-S-H* phase at high temperatures or thermal decomposition of ettringite in steam-cured concrete - can occur, but cannot explain why there was a significant change in the *DEF*-induced damage-incidence during the last decade or so. Neither they can explain why microcracked concrete ties showed *DEF*-related distress regardless of the use of steam curing.

The third element - that is intermittent or continuous exposure to air or humid air - seems to be the one on which all the researchers agree. There is data from the field that show that the microcracked ties, with the same cement source causing *DEF*-related damage in concrete structures, do not show such a type of deterioration when they are protected from the contact with water. This field experience includes:

- Concrete ties in railroad tunnels (24)
- Stock-piled concrete ties below the outdoor storage stacks (24)
- Concrete ties in service when protected by hydrophobic treatment (13).

RECOMMENDATIONS TO PREVENT DEF-INDUCED DAMAGE

On the basis of the proposed holistic model, *DEF*-related deterioration of concrete can be avoided provided that one or two of the above mentioned essential elements are precluded. The most easy preclusion apparently would relate to water exposure. However, in practice, permanent protection of concrete structures from exposure to water is very expensive by using the present-day available impermeable coatings or hydrophobizing products. This technique, may be considered for use with concrete structures in service showing initial *DEF*-related damage in order to reduce or block the deterioration process.

Therefore, the other two essential elements for the *DEF*-induced concrete damage should be taken into account first. One of these - microcracking - can be significantly reduced to harmless levels by adopting adequate measurements during the design and the execution phases. For instance, precast concrete ties with lower and more homogeneous stress distribution, deriving from the prestressing method itself, should be taken into careful consideration by the design engineers. Steam-curing process with lower thermal gradients, from

controlled heating and cooling rates, can also reduce microcracking, and consequently mitigate the *DEF*-induced deterioration risk. Use of sound aggregates to prevent *ASR*-related cracking is a mandatory requirement regardless of the *DEF*-related deterioration. However, pozzolanic materials can advantageously be used to avoid or to reduce the risk of microcracking promoted by alkali-reactive aggregates when unwittingly used.

The most important challenge in preventing the *DEF*-induced deterioration of concrete structures is related to cement manufacture. First, cement producers should take into careful consideration the fact that clinker with lower sulfate content can significantly reduce the risk of *DEF*-induced damage in concrete structures. Moreover, there is evidence from the field that the risk of *DEF*-related damage significantly increases by using high-strength (high C_3S and C_3A) portland cements, whereas concrete mixtures with portland-pozzolan and portland-slag cements are much less prone to the *DEF* risk in steam-cured concretes (4,21,30). The behavior seems to be related with the lower amount of gypsum required for setting-time regulation and/or the lower amount of clinker sulfate content in blended cements. Pozzolan materials, including silica fume at a dosage level as low as 10% by cement mass (29), can be additionally advantageous also in reducing the risk of *DEF*-induced damage through the pore-size refinement effect with consequent reduced diffusion rate of ions, in particular of sulfate ions, through the pore solution.

CONCLUSIONS

Concrete damage induced by delayed ettringite formation is one of the most complex problems in the science of concrete durability. A holistic model was adopted to study this problem. According to this model three elements are essential for the occurrence of the *DEF*-related damage: microcracking, late-sulfate release, and exposure to water.

Each of these elements, in turn, is influenced by a number of causes. In this perspective *ASR* and steam-curing are two of the possible causes of microcracking. Therefore, *DEF*-related distress could occur even in the absence of *ASR* and steam-curing.

Theoretically *DEF*-induced damage can be prevented by eliminating one of the three elements from the system. From a practical point of view, two approaches are possible. First, portland cements with high clinker sulfate content - those responsible for the late sulfate release - should be avoided and portland-pozzolan or pozzolan-slag cements should be preferred. Second, microcracking should be reduced, particularly with precast concrete ties, by adopting lower and more homogeneous stress distribution from the prestressing process itself.

REFERENCES

1. Collepardi, M., "A Holistic Approach to Concrete Damage Induced by Delayed Ettringite Formation" Proceedings of the "Mario Collepardi Symposium on Advances in Concrete Science and Technology", pp. 373-396, Editor P.K. Mehta, CANMET/ACI 1997.
2. Mehta, P.K., "Concrete Technology at the Crossroads - Problems and Opportunities", Mohan Malhotra Symposium, pp. 1-30, Editor P.K. Mehta, ACI SP-144, 1994.
3. Heinz, D. and Ludwig, U., "Mechanism of Secondary Ettringite Formation in Mortars and Concretes Subjected to Heat Treatment" in Concrete Durability, Katharine and Bryant Mather International Conference, Editor J.M. Scanlon, ACI SP-100, pp. 2059-2071, 1987.
4. Heinz, D., Ludwig, U. and Rüdiger, I., "Delayed Ettringite Formation in Heat Treated Concretes", Concrete Precasting Plant and Technology, Vol. 11, pp. 56-60, 1989.
5. Lawrence, C.D., "Mortar Expansions Due to Delayed Ettringite Formation. Effects of Curing Period and Temperature", Cement and Concrete Research, Vol. 25, pp. 903-914, 1995.
6. Fu, Y. and Beaudoin, J.J., "Mechanism of Delayed Ettringite Formation in Portland Cement System", ACI Materials Journal, pp. 327-333, 1996.
7. Fu, Y., Xie, P., Gu, P. and Beaudoin, J.J., "Significance of Pre-existing Cracks on Nucleation of Secondary Ettringite in Steam Cured Cement Paste", Cement and Concrete Research, Vol. 24, pp. 1015-1024, 1994.
8. Fu, Y., Gu, P., Xie, P. and Beaudoin, J.J., "A Kinetic Study of Delayed Ettringite Formation in Hydrated Portland Cement Past", Cement and Concrete Research, Vol. 25, pp. 63-70, 1995.
9. Scrivener, K.L. and Taylor, H.F.W., "Delayed Ettringite Formation: a Microstructural and Microanalytical Study", Advances in Cement Research, Vol. 5, pp. 139-145, 1993.
10. Johansen, V., Thaulow, N., Jakobsen, U.H. and Palbøl, N., "Heat Cured Induced Expansion", Proceedings of the 3rd Beijing International Symposium on Cement and Concrete, pp. 144-156, 1993.
11. Lewis, M.C., Scrivener, K.L. and Kelham, S., "Heat Curing and Delayed Ettringite Formation, Materials Research Soc. Proc. 370, Editor S. Diamond et al., Materials Research Society, Pittsburgh, pp. 67-76, 1995.
12. Diamond, S. "Delayed Ettringite Formation-Process and Problems", Cement and Concrete Composites, Vol. 18, pp. 205-215, 1996.

14 Collepardi

13. Shayan, A., "Behaviour of Precast Prestressed Concrete Railway Sleepers Affected by AAR", in *Real World Concrete*, R. N. Swamy Symposium, Editor G. Singh, pp. 35-56, 1995.
14. Oberholster, R.E., Maree, H. and Brand J.H.B., "Cracked Prestressed Concrete Railway Sleepers: Alkali-Silica Reaction or Delayed Ettringite Formation", 9th International Conference in Alkali-Aggregate Reaction in Concrete, Vol. 2, pp. 739-749, The Concrete Society, Wexham, Slough, U.K., 1992.
15. Thaulow, N., Hjorth Jacobsen, U. and Clark, B., "Composition of Alkali-Silica Gel and Ettringite in Concrete Railroad Ties: SEM-EDX and X-Ray Diffraction Analysis", *Cement and Concrete Research*, Vol. 26, pp. 309-318.
16. Diamond, S. and Ong, S., "Combined Effects of Alkali Silica Reaction and Secondary Ettringite Deposition in Steam Cured Mortars", in *Cement Technology Symposium*, Editors E.M. Gartner and H. Uchikawa, *Ceramic Transactions*, Vol. 40, pp. 79-90, 1993.
17. Taylor, H.F.W., "Delayed Ettringite Formation", *Advances in Cement and Concrete*, pp. 122-131, Editor M.W. Grutzeck and S.L. Sarkar, ASCE, New York, 1994.
18. Tepponen, P. and Eriksson, B.E., "Damages in Concrete Railway Sleepers in Finland", *Nordic Concrete Research*, Vol. 6, pp. 109-209, 1987.
19. Sylla, H.M., "Reactions in Hardened Cement Paste through Heat Treatment", *Beton* Vol. 38, pp. 449-545, 1988.
20. Fu, Y. and Beaudoin, J.J., "Microcracking as Precursor to Delayed Ettringite Formation in Cement Systems", *Cement and Concrete Research*, Vol. 26, pp. 1493-1498, 1996.
21. Lawrence, C.D., "Laboratory Studies of Concrete Expansion Arising from Delayed Ettringite Formation", BCA Publication C/16, 147 pp., British Cement Association, Crowthorne, Berres. U.K., 1993.
22. Hime, W.G., "Clinker Sulfate: A Cause for Distress and a Need for Specification", *Concrete in The Service of Mankind, Concrete for Environment, Enhancement and Protection*, pp. 387-395, Editors: R.K. Dhir and T.D. Dyer, E. & F.N. Spon, 1996.
23. Mielenz, R.C., Marusin, S.L., Hime, W.G. and Jugovic, Z.T., "Investigation of Prestressed Concrete Railway Tie Distress", *Concrete International*, pp. 62-68, December 1995.
24. Miller, F.M. and Tang, F.J., "The Distribution of Sulfur in Present-Day Clinkers of Variable Sulfur Content", *Cement and Concrete Research*, Vol. 26, pp. 1821-1829, 1996.
25. Taylor, H.F.W., *Cement Chemistry*, Academic Press, London, 1990.
26. Odler, I. and Zhang, H., "Investigation on High SO₃ Portland Cement Clinkers", *World Cement*, pp. 73-77, February 1996.

27. Jøns, E., "Measuring the Sensibility of Sulphate in Cement", World Cement, pp. 65-68, June 1996.
28. Brown, P.W., "An Evaluation of the Sulfate Resistance of Cements in a Controlled Environment", Cement and Concrete Research, 11, pp. 719-727, 1981.
29. Ghorab, H.Y., Heinz, D., Ludwig, V. and Meskendahl, T., "On the Stability of Calcium Aluminate Sulphate Hydrates in Pure Systems and in Cements", VII International Congress on Chemistry of Cements, Vol. IV, pp. 496-503, Paris, (France), 1980.

TABLE 1—EARLY AND DELAYED ETTRINGITE FORMATION.

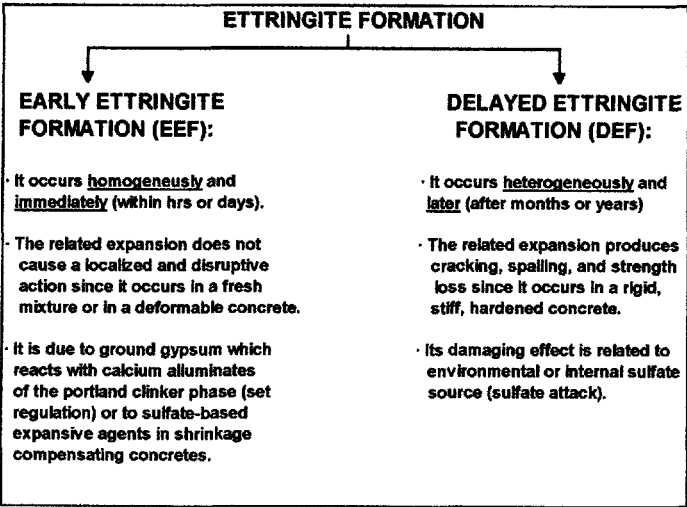
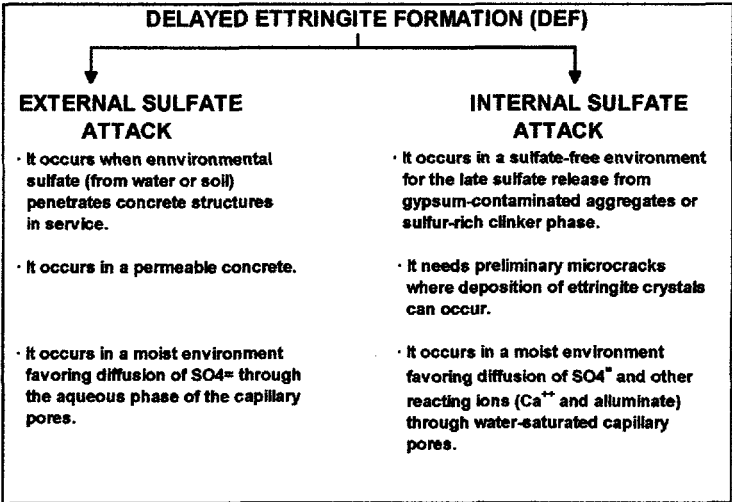


TABLE 2—DELAYED ETTRINGITE FORMATION BY EXTERNAL AND INTERNAL SULFATE ATTACK.



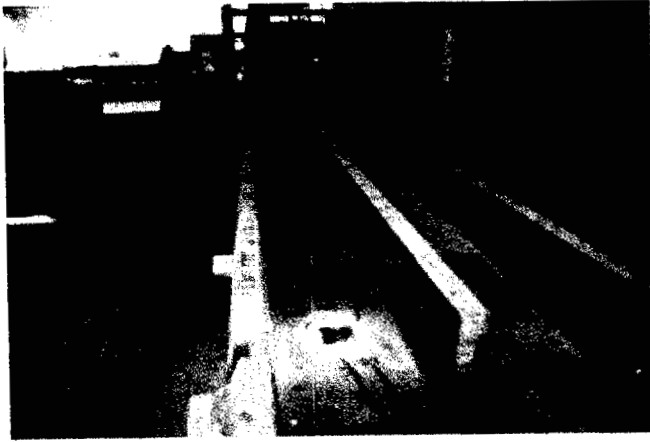


Fig. 1—Parallel formworks of concrete ties in the long line method.

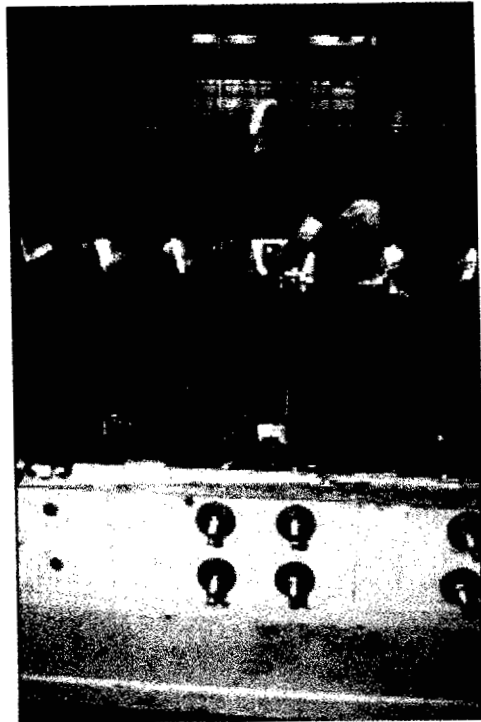


Fig. 2—Formwork of concrete tie in the anchored steel plate method.

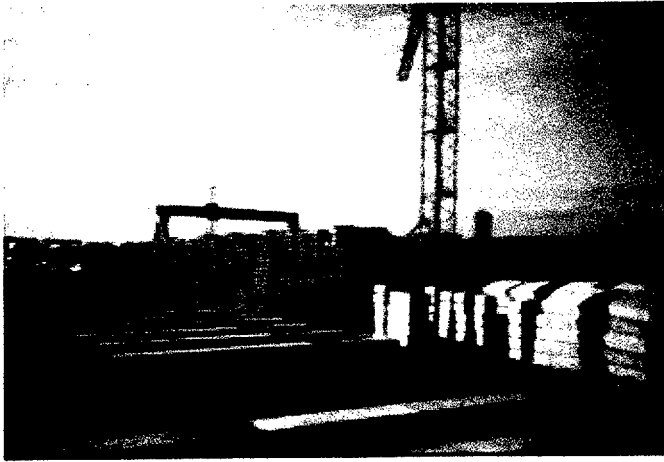


Fig. 3—Unused stockpiled concrete ties exposed to different micro-environment (sun and shadow, dry and rain).



Fig. 4—Cracking in cast-in-situ concrete pedestal for electric power line.

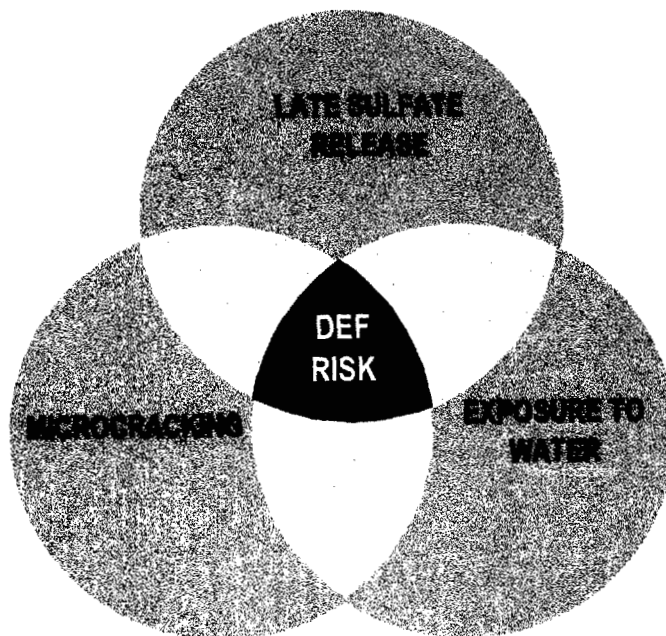


Fig. 5—Holistic model showing delayed ettringite formation damage as a function of late sulfate release, microcracking, and exposure to water.

SP 186-2

Design and Properties of High-Volume Fly Ash High-Performance Concrete

by J. G. Cabrera and C. D. Atis

Synopsis:

The paper discusses a new method for the determination of the optimum W/C + FA for maximum compaction of no slump concrete made with high volumes of fly ash. It explores the effect of fly ash fineness and particularly, carbon content on the compressive strength of the mixtures made with 50% and 70% replacement of normal portland cement with fly ash. By using an appropriate surfactant the no slump concrete mixtures are rendered workable and suitable for structural applications. The strength attained at 28 days is 60 MPa or more, and therefore these mixtures are considered to yield high-strength concrete. The performance of the high-volume fly ash concrete is assessed in terms of abrasion and fatigue resistance that are the most appropriate performance indicators for concrete that will be used for the construction of pavements.

Keywords: abrasion; fatigue-resistance; fly ash; high-performance; high-strength concrete; workability

ACI Member J G Cabrera is Professor of Civil Engineering Materials and Head of the Civil Engineering Materials Unit (CEMU) at the University of Leeds. He has carried out extensive research on the performance, properties and durability of concrete and on the use of waste and low-grade materials for the production of composites. He is also responsible for the development of a number of test methods and equipment for the assessment of concrete performance. He was awarded the first ISCOWA gold medal for his *"outstanding contribution to the development of technologies for using waste materials in construction"*. In 1997 he received the CANMET-ACI award for his contribution to the design of concrete for durability.

C D Atis read for a PhD at CEMU. His topic was the use of fly ash on high performance concrete, he is now lecturer in engineering materials at Gukurova Universitesi, Muhendislik Mimarlik Fakultesi in Turkey.

INTRODUCTION

High-volume fly ash concrete contains a reduced amount of hydraulic cement (normally ordinary portland cement) and a large quantity of fly ash. Improved engineering and performance properties are obtained by minimising the W/C + FA. Water reduction leads to a mixture, which has no measurable workability when tested using the methods applied to ordinary concrete mixtures. To achieve workability it is necessary to use a surfactant, normally a superplasticiser. The dosage used is related to the W/C + FA and the fines content. It is generally a higher dose than that used for ordinary superplasticised concrete.

Because the amount of hydraulic cement in high-volume fly ash concrete is relatively low, i.e. 70–120 kg/m³ and because these mixtures when used without a superplasticiser are placed with the same equipment and techniques used for "roller compacted concrete", high-volume fly ash has been often confused with "roller compacted concrete", which is used extensively for the construction of gravity dams. This material contains a very low quantity of cementitious material, between 70 and 150 kg/m³. Roller compacted concrete has a closer resemblance to a granular soil than a concrete mixture; the effectiveness of a surfactant is practically minimal due to the low quantity of the cementitious phase. In high volume fly ash concrete the cementitious component, i.e. the hydraulic cement plus the fly ash is relatively high, from 300 to 450 kg/m³, thus the use of a superplasticiser is effective in making this type of mixture workable. High-volume fly ash concrete has nevertheless been used extensively instead of roller compacted concrete for the construction of gravity dams using the same equipment and technology developed for roller compacted concrete (1,2).

To achieve relatively high strength and high performance, it is necessary to reduce the W/C + FA to a realistic minimum value, without impairing the compactability (relative workability) of the mixture so that it can be placed and rolled; however, if the requirement is to use this type of mixture instead of normal workable concrete, it is necessary to add a surfactant, which will effectively convert the mixture into a

workable material where its workability can be measured with the same tests as those used for ordinary concrete mixtures.

High-volume fly ash concrete has a number of potential advantages for its application to the construction of concrete pavements providing it can be placed with the same methods as ordinary concrete and to the same narrow surface tolerance levels specified for concrete pavement slabs. This cannot be achieved with a high-volume fly ash concrete that is not workable even if it is compactable, however, making a high-volume fly ash concrete (HVFAC) workable using a superplasticiser makes this type of concrete a very attractive material both in terms of cost and environmental considerations. The properties and performance of HVFAC are highly dependant on the W/C + FA as it is the effectiveness of the surfactant, thus the amount of water that is critical for the production of HVFAC.

In this study therefore, a new method to assess the optimum W/C + FA of HVFAC is discussed, and the results of using two different fly ashes at two normal portland cement replacement levels are presented. The results are discussed in terms of compressive strength, abrasion and fatigue resistance that are properties considered to be the most important for the long term performance of concrete pavements.

THE VIBRATING SLUMP TEST

The objective of this method is to measure the minimum amount of water to be added to a HVFAC mixture by measuring the maximum value of compactability that can be achieved with a quantity of water that is then considered the "optimum water content" for maximum compactability. The handling and placing of a mixture at its optimum water content is normally done using the same equipment used for compacting wet soils. HVFAC behaves more like a wet soil than conventional concrete.

Cabrera and Lee (3) have described the method in detail elsewhere, here the authors give only a summary of the method and a brief discussion of other available methods used in practice.

Available test methods

There are two tests that are commonly used to control the water content of HVFAC or roller compacted concrete, these are the Cannon test (4) and the Compactability Index (5). The repeatability of the Cannon test is poor, unless the operator is fully trained and has experience, the test is qualitative in nature and consists of determining the amount of water that will result in a mixture which, when vibrated in the V-B apparatus for 25 seconds produces a "clean" rim of cement paste around the periphery of the V-B cylinder. Since small variations in the W/C + FA can, and indeed do, cause large variations of strength and performance it is clear that the amount of water is critical and should not be judged by mere observation.

The Compactability Index is obtained using a test which essentially consists of compacting a cylinder filled loosely with concrete, and compacting it by applying 100

blows of a hammer which has the same design as the hammer used for the compaction of soils described in the appropriate British Standard (6). The Compactability Index is expressed as a ratio of the height of compacted concrete over the height of the loose concrete (height of mould) multiplied by 100. The optimum amount of water as determined by this test is the water content for which the Compactability Index attains a maximum value. The test is cumbersome and requires much energy on the part of the operator, it has been used by Australian investigators, but it has not been used in Europe or USA.

The vibrating slump test

This test and methodology was developed by Cabrera and Lee (3) and was the result of a large programme on the design and evaluation of HVFAC using different fly ashes and at different replacement levels. The test uses essentially available equipment slightly modified. It is described in the following paragraphs.

- a) A standard slump cone whose foot-pieces are perforated so that the cone can be firmly secured on the base plate by means of wing nuts;
- b) A metal base plate with rubber gasket, over which the cone is firmly held. The base plate is secured on a V-B standard vibrating table, also by means of wing nuts. The apparatus is shown in Figure 1(a), Figure 1(b) and Figure 1(c).

The detailed procedure for carrying out the test is given in Appendix 1. Very briefly, it consists of vibrating the cone filled with concrete for 20 seconds and measuring the drop of the concrete surface. The drop of the concrete surface is expressed in millimetres and this is the "Cabrera Slump Value" (CSV). Figure 2 shows a schematic measurement of CSV. The measurement of CSV is repeated for at least five W/C + FA. The results of CSV versus W/C + FA plotted in Cartesian co-ordinates give a maximum value of CSV, which is the optimum for maximum compactability. The repeatability of the results is $\pm 5\%$ of the mean value for a wide range of mixtures including silica fume, slag and metakaolin concretes.

MATERIALS USED IN THE INVESTIGATION

Cement

The cement used was normal portland cement. It conforms to the current specifications as described in BS 12 (7). Its mineralogy and physical properties are given in Table 1.

Fly Ash

Two fly ashes obtained from electricity generating power stations in England, Drax Power Station and Aberthaw Power Station, were used in the investigation. The chemical composition and physical properties are given in Table 2. The ashes are low calcium fly ashes classified as Class F (8). As Table 2 shows the ashes are different in

terms of LOI and fineness. Drax ash complies with the requirements of BS 3892: Part 1 (9), however, Aberthaw fly ash does not comply with BS 3892: Part 1, or Part 2 (10). It also fails in terms of LOI with regards to the European Standard EN 450 (11).

The Aberthaw fly ash was specially selected so that the effect of LOI could be studied in HVFAC. High carbon content is believed to interfere with the hydration reactions as well as reducing the workability and increasing the water demand when used in normal concrete to replacement levels of not more than 30% of the hydraulic cement content.

Mineral Aggregates

The sand and gravel used in this study were obtained from deposits in North Nottinghamshire, England. The sand complied with the requirements of BS 812. Its particle size analysis shows that it falls within zone M of the Standard. The absorption value measured in the laboratory was 0.1% and its relative density (saturated surface dry) was 2.65.

The gravel was 10 mm maximum nominal size. It has a water absorption value of 0.6% and its relative density (saturated surface dry) was 2.63.

Superplasticiser

The superplasticiser used was a commercial material, Sikament 10, which is a high range water reducing material suitable for fly ash concrete. It is a low alkali water soluble polymer, formaldehyde-free. Its relative density is 1.11 and its chloride content is less than 0.2% w/w.

CONCRETE MIXTURE COMPOSITION

The control mix used in this study was designed using the method based on minimum porosity. The proportions of the control normal Portland cement (NPC) mixture were: 1:1.5:3 NPC, sand and gravel respectively. The quantity of NPC was 400 kg/m^3 and the W/C was 0.50. The HVFAC was made using two NPC replacement levels 50% and 70% by weight. The mixtures were made with and without a superplasticiser.

The first step in the determination of water content for the HVFAC was to find the optimum water content for maximum compactability using the vibrating slump test. The results of this test are shown in Figure 3. The optimum W/C + FA obtained from Figure 3 were then used to produce the HVFAC mixtures. Some of these mixtures were made workable by the use of the superplasticiser. Table 3 presents the composition of the mixtures produced and tested.

The use of the superplasticiser was very effective. The mixtures containing it were practically flowable. The values of CSV and Flow Table measurements are given in Table 4.

The mixtures were very stable, they did not bleed, their entrapped air content varied from 1.5 to 2.9 percent, the setting time was of the same order of magnitude of that found in ordinary concrete. The quantity of the superplasticiser added to the mixture was critical, small variations resulted either in a concrete with no measurable workability or a flowing concrete. The mixtures were cast and demoulded after 24 hours in the laboratory and placed at 20°C and 100% RH until the time required for testing. Although the programme included a study on the effect of relative humidity on the properties of HVFAC, this is reported elsewhere (13).

STRENGTH OF HIGH-VOLUME FLY ASH CONCRETE

The strength of concrete is the most important property with regards to structural stability. The tendency in modern construction is to use high-strength concrete that sometimes is confused with high-performance concrete. High-performance concrete does not need to be a concrete exhibiting high strength and a high-strength concrete may not be a high-performance concrete. Although there is no agreement on the value of strength which divides ordinary concrete from high-strength concrete, in the UK it is accepted that a concrete with a compressive strength (cube 100 mm side) of 60 MPa at 28 days of age is considered to be high-strength concrete.

The results of the compressive strength obtained in this study testing cubes according to the procedures laid down in BS 1881: Part 108, 116 (14) are presented in Figure 4 and Figure 5.

Figure 4 shows that at one day of age, mixture M8 attained similar compressive strength to the corresponding control mixture, M0. However, the strength of mixture M4 at one day was greater than the strength of the control mixture, M0. Mixtures M1, M2 and M3 made with Drax fly ash and mixtures M5, M6 and M7 made with Aberthaw fly ash, had considerably lower strength than the control mix M0 at one day of age. Nevertheless, they gained enough strength to be de-moulded and placed in the appropriate curing environment.

At 28 days, the compressive strength of the mixtures containing 50% Drax fly ash were higher than the control mixture. The mixtures containing 70% Drax fly ash were lower than the compressive strength of the control mixture. However, at one year of age the compressive strength of the mixtures containing Drax fly ash was higher than the strength of the control mixture.

Mixtures made with Aberthaw fly ash attained reasonable strengths at 28 days, from 20 MPa up to 50 MPa (see Figure 5). Mixture M8 exhibited the same strength as the control mixture at 28 days, mixtures M5, M6 and M7 however, showed lower strengths than the control mixture, while mixtures M5 and M6 attained lower strength than that of the control mixture.

Comparison of Compressive Strength results with Findings of other Investigators

Various investigators particularly Malhotra (15), EPRI (16), Swamy (17), Mukherjee et al (18) and Naik (19) have carried out extensive work on the properties of HVFAC. It is interesting to compare their compressive strength results with the findings of this study. Table 5 shows the results of some of these investigators for mixtures that are approximately equivalent.

The results of compressive strength obtained in this study indicate clearly that the mixtures prepared and tested can be classified as high-strength concrete mixtures. Whether these are also high-performance will depend on the manner in which they will be used in construction and on the environments to which they will be exposed.

As indicated in the objectives of this paper, the HVFAC mixtures were designed for possible use in the construction of concrete pavements. The most important performance properties of a concrete for use in pavements are abrasion resistance and fatigue resistance. It is also necessary to control shrinkage but this can be achieved by the correct spacing of joints and therefore is not considered here.

ABRASION CHARACTERISTICS OF HIGH VOLUME FLY ASH CONCRETE

Pavement concrete surfaces are subjected to wear by scraping or by the sliding action of vehicles. The friction between road surface and vehicle tyre creates wearing and abrasion of the surface of the concrete. For safety reasons it is necessary to maintain roughness on the surface of a pavement so that the friction between vehicle tyre and concrete surface ensures that sliding does not occur.

Abrasion resistance has been measured by a number of methods selected in such a manner as to simulate the actual abrading situation. ACI Committee 201 (20) has reviewed the methods in use.

The major problem when using abrasion values is the fact that there are no guidelines on the values that should be used for assessing if a concrete will perform adequately, that means that abrasion values do not provide quantitative performance values, so that the results can only be used on a comparative basis.

The results obtained in this study confirm other findings in that abrasion is closely related to the compressive strength of concrete. The test that was used to obtain results in this study was the method described in BS 812 (21) which is normally used for the assessment of abrasion characteristics of aggregates.

The statistical relationship between abrasion and compressive strength obtained in this work shows that the function that describes better the relationship is a hyperbolic function of the following form:

$$A = 4.002 + 86.754/CS$$

Where:

A = Abrasion value (%)

CS = Compressive strength (MPa)

This equation is shown graphically in Figure 6.

FATIGUE RESISTANCE OF HIGH VOLUME FLY ASH CONCRETE

The literature on fatigue resistance of fly ash concrete is very sparse notwithstanding the fact that fatigue behaviour of concrete is an important issue for the design of structures subjected to repetitive loading like bridges and pavements. When pavements are constructed with un-reinforced concrete slabs the issue of fatigue performance becomes critical.

In this study the fatigue test configuration adopted was the “three point test” using a machine that could produce up to 50 Hz. The specimen configuration was a beam of 500 mm length with a 100 x 100 mm section. Two specimens were tested for each stress level.

The “failure point” or fatigue failure adopted was that used by Bjorklund (22). The failure point is determined from the relation between strain and number of cycles. In this relationship, at the start of the test the strain increases rapidly, then grows steadily and finally increases drastically. This change in rate of strain increase is arbitrarily considered the failure point.

The fatigue versus number of load repetitions is shown in Figure 7. These results only include the mixtures made with Drax fly ash. Aberthaw ash was not used for the fatigue study. It can be seen that the control mixture M0 has relatively low fatigue resistance in comparison to the mixtures containing fly ash. There is no great difference between mixtures containing 50 or 70% fly ash neither between mixtures made with or without the superplasticiser. The important fact to highlight here is that HVFAC mixtures perform better than NPC concrete containing the same amount of the binder.

CONCLUSIONS

From the limited investigations performed, the following conclusions can be drawn:

1. The compactability of no slump HVFAC can be effectively controlled using the vibrating slump test. This test allows the determination of the “optimum W/C+FA” for maximum compaction.
2. A no slump mixture at its optimum W/C+FA can be efficiently converted in a workable mix or even a flowing mixture using a surfactant. The resultant mixture could then be used for structural applications.
3. The compressive strength of HVFAC with or without the superplasticiser places these mixtures in the class of high-strength concrete.
4. The abrasion resistance of HVFAC is shown to be related to the compressive strength by a hyperbolic statistical function.
5. The fatigue resistance of the HVFAC gave clearly better performance results than the control NPC mixture. This has great significance for the use of HVFAC in concrete pavements.

REFERENCES

1. **CABRERA J G, DIAS CASCON G AND POLANCO J.** *Permeability and Strength of High Volume Fly Ash Concrete for Dam Construction.* Diseno y Construcción de Presas, Vol 34, no. 6 pp 86-93, 1992.
2. **POLANCO J.** *Propiedades y Durabilidad de Concreto con Alto Volumen de Cenizas Volantes.* Doctoral Thesis (Unpublished). University of Cantabria, Spain, 1989.
3. **CABRERA J G AND LEE R E.** *A new method for the measurement of workability of high pulverised fuel ash concrete.* Proc. of 7th Int Ash Utilisation Symposium, Vol. 1, pp 347-60, 1985.
4. **TENNESSEE VALLEY AUTHORITY.** General Construction Specification G-48. *Roller compacted concrete.* Appendix B - Procedure for measuring consistency of no slump concrete. Knoxville, Tennessee, USA, 1975.
5. **AUSTRALIAN STANDARDS.** As-1012, Part 3. *Methods for the determination of properties related to the consistency of concrete.* Standard Ass. from Australia, NSW, 1983.
6. **BRITISH STANDARD BS 1377, PART 4, 1990.** *Methods of tests for soils for Civil Engineering Purposes, Compaction Related tests.* BSI London 1990.
7. **BRITISH STANDARD BS 12, 1996.** Specification for Portland Cement, BSI, London 1996.
8. **AMERICAN SOCIETY FOR TESTING AND MATERIALS ASTM C618-98.** *Standard Specification for Fly Ash and Raw Calcined Natural Pozzolan for use as a Mineral Admixture in Concrete.* Annual Book of ASTM Standards, 1998.
9. **BRITISH STANDARD BS 3892, PART 1, 1992.** *Specification for Pulverised-Fuel Ash for Use with Portland Cement.* BSI London, 1992.
10. **BRITISH STANDARD BS 3892, PART 2, 1984.** *Specification for Pulverised-Fuel Ash for Use in Grouts and Miscellaneous Uses in Concrete.* BSI London 1984.
11. **EUROPEAN STANDARDS EN 450, 1994.** *Fly Ash for Concrete - Definitions, Requirements and Quality Control.* EN Brussels, 1994.
12. **CABRERA J G AND HOPKINS J C.** *The influence of pulverised fuel ash on the workability of concrete.* Proceedings of the Second International Conference on Ash Technology and Marketing ,pp 393-398, CEBG, 1984.

13. **ATIS C D.** *Design and Properties of High-Volume Fly Ash Concrete for Pavements.* Unpublished Thesis, University of Leeds, 1997.
14. **BRITISH STANDARD BS 1881, PART 108 1983.** *Method for Making Test Cubes from Fresh Concrete.* BS London 1983 and Part 116 1983. *Method for the Determination of Compressive Strength.* BSI London 1983.
15. **MALHOTRA V M.** *Superplasticised fly ash concrete for structural applications.* Concrete International, Vol. 15, no. 4, pp23 -28, 1993.
16. **ELECTRICAL POWER RESEARCH INSTITUTE.** *Investigation of High-Volume Fly Ash Concrete Systems.* EPRI TR-103151, Project 3176-06, Final Report, 1993.
17. **SWAMY R N AND MAHMUD H B.** *Mix proportions and strength characteristics of concrete containing 50 percent low-calcium fly ash.* Proc. of ACI/Canmet Second International Conference on Fly Ash, Silica fume, Slag and Natural Pozzolans in Concrete, Editor V M Malhotra, SP-91, pp 413-433, 1986.
18. **MKHERJEE P K, LOUGHBOROUGH M T AND MALHOTRA V M.** *Development of high-strength concrete incorporating a large percentage of fly ash and superplasticisers.* ASTM Jour. Cement, Concrete and Aggregates, Vol. 4, pp 81-86, 1982.
19. **NAIK T R, RAMME B W AND TEWS J H.** *Pavement construction with high volume class C and class F fly ash concrete.* ACI Materials Journal, Vol 92, no.2 pp 200-210, 1995.
20. **ACI MANUAL OF CONCRETE PRACTICE, PART I.** *Guide to Durable Concrete.* ACI Committee 201, 2R-1982, Chapter 3: Abrasion Resistance, 1996.
21. **BRITISH STANDARD BS 812 PART 113, 1993.** *Method for Determination of Aggregate Abrasion Value.* BSI, London 1993.
22. **BJORKLUND N A.** *Permanent deformation and resistance to fatigue of resurfaced pavements.* A laboratory investigation performed on beams taken across the wheel path and resurfaced in the laboratory. Proceedings of the AAPT Vol 54, pp 551-568, 1985.

APPENDIX

Detailed Test Procedure:

- i) The modified slump cone is placed on its own base seated over a rubber gasket, to prevent bleeding of water at the joint.
- ii) The apparatus is then clamped to the Vebe consistometer vibrating table as shown in Figure 1.
- iii) The concrete mix to be tested is placed into the modified slump cone following the same procedure as that one indicated for the normal slump test in BS 1881 (1970).
- iv) The concrete in the cone is levelled off and is vibrated for twenty seconds.
- v) The depth of concrete from the top of the cone is measured in millimetres. This is the Cabrera Slump value.
- vi) The concrete is removed from the apparatus and is returned to the mixer.
- vii) Additional water is added to the concrete material to increase the water cementitious ratio.
- viii) Steps i-vii are then repeated for a minimum of five water-cementitious ratios.
- ix) The relation between the Cabrera Slump and the water/cementitious ratio is obtained by plotting the values resulting from steps v and vii in a graph and joining the points with a smooth curve. The optimum value of water/cementitious ratio is the one which corresponds to the maximum Cabrera Slump value.

TABLE 1—MINERALOGY AND PHYSICAL PROPERTIES OF NORMAL PORTLAND CEMENT USED IN THE INVESTIGATION.

Compound	Oxide Composition	Percentage
Tricalcium Silicate	3 CaO SiO ₂	51.1
Dicalcium Silicate	2 CaO SiO ₂	20.5
Tricalcium Aluminate	3 CaO Al ₂ O ₃	7.8
Tetracalcium Alumino-Ferrite	4 CaO Al ₂ O ₃ Fe ₂ O ₃	9.3
Property	Value	
Relative Density	3.15	
Specific Surface (cm ² /g)	3500	

TABLE 2—CHEMICAL COMPOSITION AND PROPERTIES OF FLY ASHES USED IN THE STUDY.

Chemical Oxide Composition (%)	Drax Fly Ash	Aberthaw Fly Ash
SiO ₂	50.20	44.90
Al ₂ O ₃	28.59	25.20
Fe ₂ O ₃	13.17	7.50
CaO	2.55	2.40
MgO	1.28	1.20
SO ₃	0.57	0.28
K ₂ O	2.39	2.90
Na ₂ O	0.98	1.00
Loss on Ignition (LOI)	2.85	15.60
Physical Properties		
Relative Density	2.40	2.28
Fineness (% retained in 45 micron)	8.50	22.50
Measured Specific Surface (cm ² /g)	3060	2870
Calculated Specific Surface (cm ² /g)	4120	4250
Shape Factor (reference 12)	1	3

34 Cabrera and Atis

TABLE 3—COMPOSITION AND NOMENCLATURE OF MIXTURES PRODUCED AND TESTED (QUANTITIES IN KG/M³).

Mix	Npc	Fly Ash		Gravel	Sand	Water	Superplasticiser
		Drax	Aberthaw				
M0	400	-	-	1200	600	200	-
M1	120	280	-	1200	600	112	5.6
M2	120	280	-	1200	600	116	-
M3	200	200	-	1200	600	132	5.6
M4	200	200	-	1200	600	120	-
M5	120	-	280	1200	600	172	5.6
M6	120	-	280	1200	600	160	-
M7	200	-	200	1200	600	172	5.6
M8	200	-	200	1200	600	156	-

TABLE 4—VALUES OF CABRERA SLUMP VALUE (CSV) AND FLOW TABLE MEASUREMENTS.

Mix	Slump (mm)	Flow Table (mm)	CSV (mm)
M0	Collapse	550	-
M1	Collapse	550	-
M2	0	-	65
M3	Collapse	600	-
M4	0	-	75
M5	Collapse	560	-
M6	0	-	70
M7	Collapse	570	-
M8	0	-	65

TABLE 5—COMPARISON OF RESULTS OF COMPRESSIVE STRENGTH FOR MIXES CONTAINING BETWEEN 40 AND 70 PERCENT FLY ASH AND $W/C + FA$ BETWEEN 0.28 AND 0.33 MPa.

Age (days)	Ref. 15 Mix 7	Ref. 16 Ep1	Ref. 17	Present results		
				M1	M3	M7
3	16.7	18.8	21.8	17.8	32.8	19.1
7	23.9	28.8	43.3	24.8	40.8	24.4
28	41.6	38.7	63.3	43.1	63.5	41.2
91	53.1	52.0	70.5	63.4	81.6	59.3
C+FA (kg/m ³)	437*	456*	470	400	400	400

* Air entrained mixtures corrected by 25% (5% per each 1% of entrained air)



Fig.1—Vibrating slump apparatus; (a) base plate with gasket and cone; (b) cone mounted in base plate; and (3) cone and plate secured in V-B vibrating table.

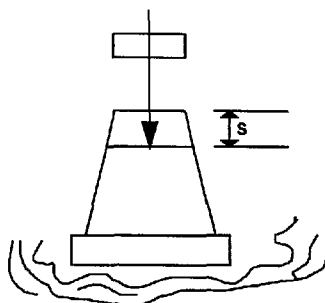


Fig. 2—Schematic representation of measurement of CSV value.

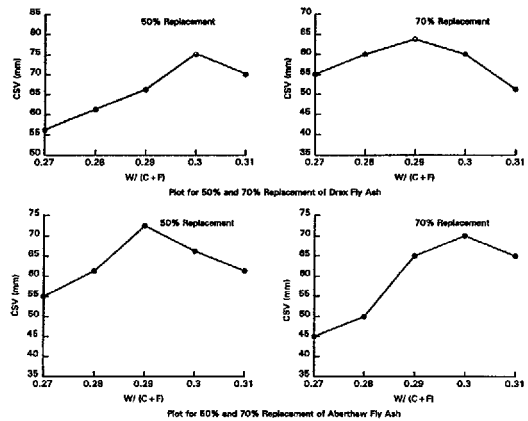


Fig. 3—Relation between CSV and $W/C + FA$ for two replacements and two fly ashes used.

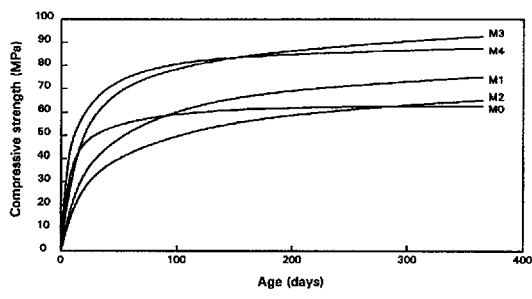


Fig. 4—Compressive strength age relationship for hvfac made with Drax fly ash and cured at 20 deg C and 100 percent RH.

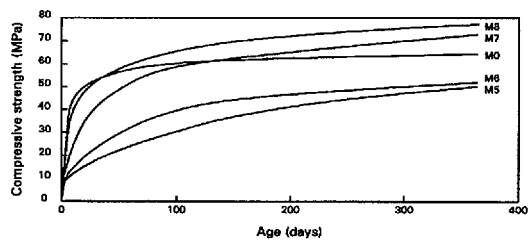


Fig. 5—Compressive strength age relationship for hvfac made with Aberthaw fly ash and cured at 20 deg C and 100 percent RH.

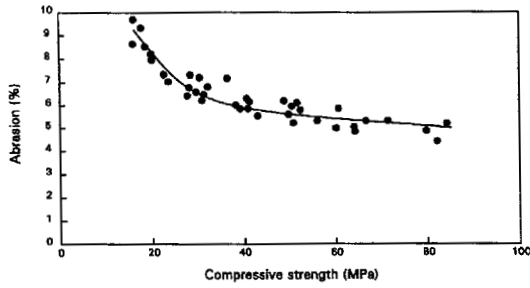


Fig. 6—Abrasion versus compressive strength for all hvfac mixes tested.

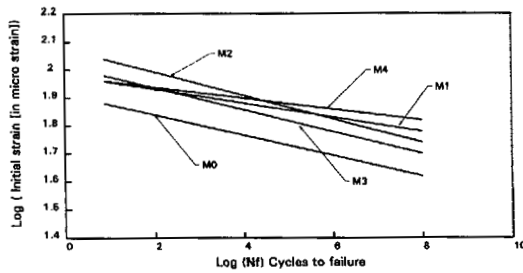


Fig. 7—Fatigue functions obtained for the mixes made with Drax fly ash.

SP 186-3

Prehydrated High-Alumina Cement-Based Admixture for Compensating Autogenous Shrinkage in High-Performance Concrete

by W. L. Repette and N. P. Mailvaganam

Synopsis: One of the limitations of high-performance concrete is its susceptibility to autogenous shrinkage, which can considerably compromise its durability and mechanical strength despite diligent cure during the hardening stage. Although calcium-sulfoaluminate admixture (CSA) and shrinkage-reducing admixture (SRA) can play a role in reducing autogenous shrinkage, rapid set and low effectiveness have been associated with their use in concrete with low water content. Recently, an innovative type of CSA admixture based on pre-hydrated high alumina cement (H-HAC) has been developed, but its potential in reducing autogenous shrinkage has not yet been evaluated. In this paper, the effects of H-HAC expansive admixture in decreasing the shrinkage during the early hardening and hardening stages are described. It was hoped that the expansion generated from hydration of the expansive components would offset the volume reduction due to autogenous shrinkage. The influences of particle size distribution, dosage and type of H-HAC hydrates in determining expansion are evaluated and discussed. Microstructural and chemical aspects are studied through XRD and SEM techniques. Tests on the evaluation of the H-HAC admixture to offset autogenous shrinkage are described and preliminary results are presented. The results show that in specific dosage and particle size distribution, H-HAC is a suitable admixture for compensating shrinkage, although autogenous shrinkage in high-performance concrete has not been prevented by the use of this admixture.

Keywords: admixture; autogenous shrinkage; expansive admixture; high-alumina cement; high-performance concretes

Wellington L. Repette, Ph.D., is a Researcher in the Concrete and Corrosion Group of the National Research Council Canada's Institute for Research in Construction. His research focuses on evaluation of deterioration and development of advanced materials for the repair and protection of existing and new concrete structures.

Noel P. Mailvaganam is a Principal Research Officer in the Concrete and Corrosion Group of the National Research Council Canada's Institute for Research in Construction. He has published numerous papers in peer-reviewed journals and conferences and has edited and co-authored 3 books on Admixtures and Repair.

INTRODUCTION

Shrinkage in cementitious materials occurs in three basic modes: plastic, drying and autogenous. Plastic shrinkage occurs before final-set due to the rapid evaporation of bleed water from the exposed surface of the concrete, resulting in map-like surface cracking. Drying shrinkage takes place after the cement undergoes final-set and occurs due to reduction of volume caused by evaporation of water from the pores of concrete. Autogenous shrinkage is defined as the change in volume under constant temperature and without loss of moisture from the concrete to the environment (1). Studies on the mechanism of autogenous shrinkage reveal that capillary depletion (meniscus effects) caused by the reduction of the relative humidity in the pores as the hydration of the cement takes place, is the most important factor responsible for the volume reduction (2,3).

High-performance concrete (4) is characterized by its low water-cement ratio ($W/C < 0.4$); this is considered to be the main reason for its improved durability in relation to normal concrete. High-performance concrete is less susceptible to plastic and drying shrinkage due to its low water content. If adequate curing is provided, cracks due to these modes of shrinkage are less likely to occur. However, the lower water contents intensify the autogenous shrinkage to the extent that it cannot be ignored, as is often the case for normal concrete (5). Indeed, autogenous shrinkage is possibly one of the most important causes for cracking in high-performance concrete (6).

Proper curing and appropriate timing for form-removal are often regarded as adequate procedures for offsetting drying shrinkage of normal strength concrete (< 50 MPa) not exposed to elevated temperatures, low relative humidity and high winds. Although the mechanism that triggers both autogenous and drying shrinkage is the reduction of the relative humidity in the cement pores, curing is not as effective in reducing autogenous shrinkage. This is attributed to the difficulty for the curing water to penetrate the concrete's bulk, making curing only

effective in the outer layer of the concrete which is in direct contact with the water. Therefore, reduction of the autogenous shrinkage due to curing is more effective for thin concrete elements than for thicker ones. Expansion-producing calcium-sulfoaluminate (CSA) based admixtures and shrinkage-reducing admixtures (SRA) have been used in a number of applications to offset volume changes from shrinkage and settlement of normal concrete. SRAs, most having glycols as their active ingredient, act by lowering the surface tension of the pore water in the hardening concrete, diminishing the tension due to menisci formation generated in the pore by the adsorbed water layer during the lowering of the relative humidity (7). CSAs compensate shrinkage by promoting the controlled formation of ettringite within the cement paste. Ettringite generates expansion that balances the volumetric changes due to shrinkage.

Quantitative estimation of the shrinkage compensation promoted by formation of ettringite is an extremely difficult task. Mathematical models for estimation of autogenous shrinkage are being developed, but regardless of the advances recently achieved (2,3,8,9), for most applications the autogenous shrinkage cannot be quantitatively predicted. The mechanisms governing the formation of ettringite are also still not clear and several hypotheses have been advanced. The "swelling theory" proposed by Mehta (10) and the "crystal growth theory" by Cohen (11), generally are the most accepted. However, none of these theories allow for a precise quantitative estimation of the amount of chemical elements involved in the reactions (especially in cementitious medium) or the kinetics and quantities of ettringite formed. Even more complex is the quantitative estimation of the expansion eventually produced by formation of ettringite, since aspects of the ettringite formation must be considered in conjunction with physical-mechanical characteristics of the materials, both at macro (concrete and paste) and microscopic (capillary pores) scales (12). The lack of information imposes a situation where the potential of the admixture is best evaluated by experimental work. Nevertheless, based on the available information, it is possible to speculate about basic requirements that could increase the effectiveness of an expansion-producing admixture (e.g., CSA) in offsetting autogenous shrinkage in concrete:

- the formation of ettringite must not cause a significant lowering of the relative humidity in the pores; otherwise the potential expansion promoted by its formation would be offset by an increase of the autogenous deformation;
- the expansive admixture must provide efficient shrinkage compensation during the first days of hydration, since autogenous deformation is more intense at the early ages (close to $\frac{3}{4}$ of the total shrinkage before 7 days);
- the admixture must not cause excessive formation of ettringite at very early stages of the hydration process, since it can induce rapid-set or drastic loss of workability of the concrete. The formation of ettringite before the final-set is not effective in compensating for shrinkage, as the expansion is easily dissipated due to high creep of the concrete at very early ages; and,
- no decrease in mechanical or physical properties must result from the use of the expansive admixture.

Commercially available CSAs often include mixtures of $C_3A_3\bar{S}$ and gypsum, and mixtures of Type 10 (ASTM Type I) cement, high alumina cement - HAC, gypsum ($CaSO_4 \cdot 2H_2O$) and lime (CaO). Detailed descriptions of these admixtures are published elsewhere (13,14). Although CSA and SRA admixtures can play a role in reducing autogenous shrinkage, rapid-set, strength reduction and low effectiveness have been associated with their use (15). Recently, a new CSA has been developed, namely pre-hydrated high alumina cement based admixture (H-HAC) (16,17), and has been rigorously investigated at Institute for Research in Construction of the National Research Council Canada for its reproducibility of desired expansion values and implementation into field practice. The advantages in relation to the other CSAs (17-19) are the abilities of H-HAC to provide normal set and effective expansion for compensation of drying shrinkage in normal concrete, without altering its mechanical and physical properties. Thus, the H-HAC characteristics complied with most of the above qualitative requirements and therefore showed promise for providing compensation for autogenous shrinkage in concrete. Furthermore, the previous research (16-19) did not fully investigate the effects of different processes of production of the H-HAC admixture or the influence of its particle size on the rate and extent of promotion of expansion. Optimization of these factors could even improve the potential for compensating autogenous shrinkage in concrete.

This paper reports the results of an investigation which had the following objectives: manufacture of a specific H-HAC admixture defined by a given composition and particle size range; and evaluation of this admixture with respect to autogenous shrinkage compensation. This study is part of an ongoing investigation at Institute for Research in Construction's laboratories on H-HAC and its effectiveness for compensation of drying and autogenous shrinkage. The characteristics of the expansive admixtures obtained from mixtures of pre-hydrated high alumina cement, gypsum, and lime are described and the expansion obtained is evaluated. The primary role played by the characteristics of the compounds formed during the pre-hydration of the HAC and its particle size in the extent and timing of expansion is discussed. A potentially suitable H-HAC admixture for compensating autogenous shrinkage was determined based on mortar tests. The admixture was tested for compensation of autogenous shrinkage in high-performance concrete for evaluation of its effects on volumetric changes, compressive strength, and slump.

DEVELOPMENT AND EVALUATION OF A H-HAC ADMIXTURE

Background

H-HAC based admixture is a blend of pre-hydrated HAC, gypsum and hydrated lime. In relation to HAC (unhydrated) based admixture, the innovation consists in the pre-hydration of the HAC, prior to grinding, drying and mixing with defined amounts of gypsum and hydrated lime. By pre-hydrating the HAC, the admixture's alumina-bearing component is no longer CA, but its hydrated products. These products present lower solubility than that of the CA and therefore, most of the ettringite formation takes place after the cement's initial setting time and after a certain tensile strength has been achieved by the concrete. This aspect is what makes the H-HAC based admixture more effective in compensating shrinkage than the currently available used materials. For normal concrete and unlike the anhydrous HAC, H-HAC does not significantly affect the cement's setting time and rapid-set does not occur. Particle type (characteristics of the HAC hydrates), size, composition, mixture proportion, and presence of moisture determine the rate and extent of expansion.

Experimental

Two different processes of hydration of HAC were used in the H-HAC characterization experiments. The effect of the different processes of hydration as well as that of its particle size distribution on the expansion of 100% RH cured mortars specimens was determined.

Preparation of the H-HAC--The H-HAC based admixture was prepared with a HAC supplied by Lafarge Inc., having the following oxide composition (given by the supplier, % by mass): $\text{SiO}_2 = 19.8$; $\text{CaO} = 39.8$; $\text{Al}_2\text{O}_3 = 41.2$; $\text{Fe}_2\text{O}_3 = 11.3$; $\text{MgO} = 0.6$; $\text{Na}_2\text{O} + \text{K}_2\text{O} = 0.1$.

Hydration processes employed are referred to us as the "cake process" and "slurry process". For the cake process individual slabs of 35 cm length, 30 cm width and 4 cm high were cast with a HAC paste with W/C of 0.5. Immediately after casting, the slab was covered with a plastic sheet and placed in the humidity room at 21°C and 100% RH. The hydration reactions caused the temperature of the paste to rise to more than 70°C approximately 6 hours after the casting; remaining above this value for at least 12 hours. For the slurry process, the HAC and the water, both at temperature of 5 °C, were mixed with a W/C of 7.5 and stirred for 24 hours in a mechanical mixer placed in a cold-room at 5°C. The continuous stirring was employed to avoid settlement of the hydrating cement. After about 6 hours, the temperature of the slurry rose to 7 °C, staying at this level