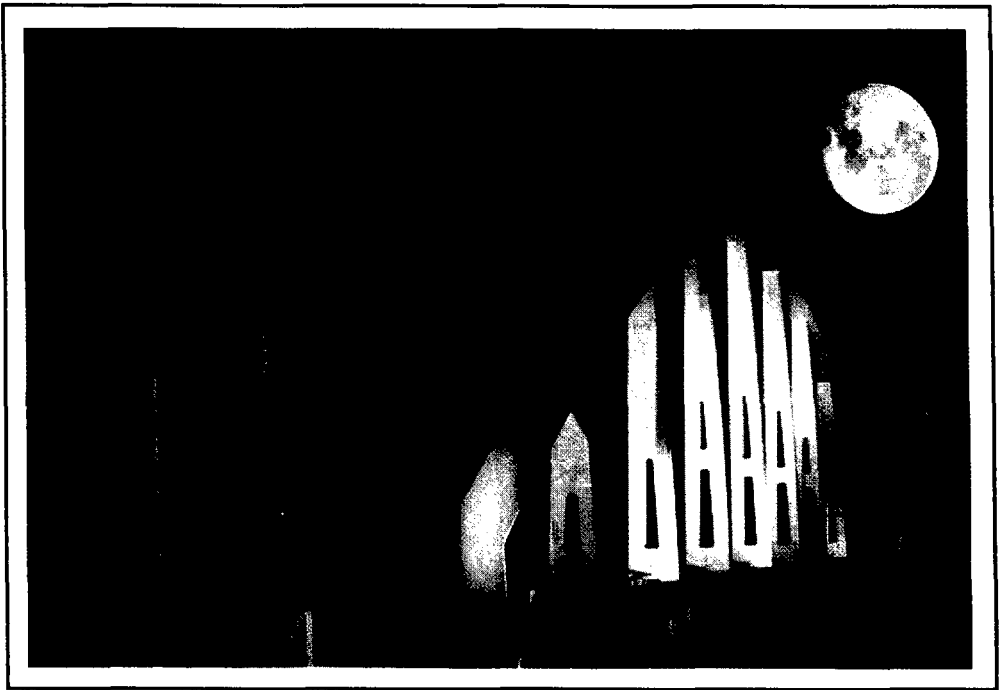


1997

**THIRD CANMET/ACI
TROISIÈME CANMET/ACI**

INTERNATIONAL • SYMPOSIUM • INTERNATIONAL



**ADVANCES IN
CONCRETE
TECHNOLOGY**

**PROGRÈS DANS LE
DOMAINE DE LA
TECHNOLOGIE DU BÉTON**

EDITOR • V.M. MALHOTRA • RÉDACTEUR EN CHEF



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Advances In Concrete Technology

**Proceedings
Third CANMET/ACI
International Conference
Auckland, New Zealand, 1997**

***Editor*
V. M. Malhotra**



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PREFACE

The Canada Centre for Mineral and Energy Technology (CANMET) of Natural Resources Canada, Ottawa, has played a significant role in Canada over 35 years in the broad area of concrete technology. In recent years, CANMET has become involved increasingly in research and development dealing with the supplementary cementing materials, high-performance normal-weight and lightweight concretes and alkali-aggregate reactions. As a part of CANMET's technology transfer program, an international symposium on Advances in Concrete Technology was sponsored jointly with the American Concrete Institute and other organizations, and held in Athens in May 1992. In June 1995, CANMET in association with the American Concrete Institute and other organizations in Canada and the U.S.A. sponsored the Second CANMET/ACI International Symposium on Advances in Concrete Technology in Las Vegas, U.S.A. For the Athens symposium, CANMET publication "Advances in Concrete Technology" constituted the proceedings of the symposium; for the Las Vegas symposium, the proceedings were published as ACI SP-154.

In August 1997, CANMET in association with the American Concrete Institute and other organizations in Canada and New Zealand, sponsored the Third CANMET/ACI International Symposium on Advances in Concrete Technology in Auckland, New Zealand. The main purpose of the symposium was to bring together representatives from industry, universities, and government agencies to present the latest information in the subject area of the symposium, and to explore new areas of needed research and development.

More than 50 papers from 15 countries were received and reviewed in accordance with the policies of the American Concrete Institute. Thirty-three of the papers were accepted for presentation and publication. In addition to the refereed papers more than 20 other papers were presented and distributed at the symposium.

Thanks are extended to the 15 members of the CANMET/ACI review panel which met in Las Vegas in January 1997 to review the papers. Without their prompt review and constructive comments, it would not have been possible to bring out the ACI special publication for distribution at the symposium in Auckland. The cooperation of the authors in accepting reviewers suggestions, and in revising their manuscripts accordingly is greatly appreciated. Particular thanks are extended to H.S. Wilson, Consultant, Ottawa, and G.D. Brearley and M. Venturino, both of CANMET, for their help in the processing of the draft manuscripts.

The help of Messrs. A. Bilodeau (Chairman), B. Fournier, and R. Chevrier (Members) of the Slide Review Panel is greatly appreciated.

Helayne Beavers, Managing Editor, ACI and her staff deserve very special mention for their assistance in getting this publication ready on time for distribution in Auckland, in view of the fact that the final revised manuscripts were delivered to ACI Headquarters only in April 1997

V.M. Malhotra, P.Eng.
Editor
Chairman, Third CANMET/ACI International Symposium
on Advances in Concrete Technology
August 1997

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CONTENTS

DESIGN FOR DURABILITY AND STRENGTH THROUGH THE USE OF FLY ASH AND SLAG IN CONCRETE
by R. N. Swamy. 1

QUALITY MANAGEMENT PLAN FOR THE CONFEDERATION BRIDGE
by W. S. Langley, R. A. Gilmour, J. Turnham, G. Forbes and T. Mostert. 73

WATER SORPTIVITY OF HEAT-CURED CONCRETE FOR BRIDGE STRUCTURES
by D. W. S. Ho, G. J. Chirgwin and S. L. Mak. 97

ROLE AND REGULATION OF THE TRANSITION ZONE IN REALIZING HIGH PERFORMANCE CONCRETE
by Hiroshi Uchikawa. 109

THE BEHAVIOR OF HIGH PERFORMANCE STRUCTURAL LIGHTWEIGHT CONCRETE AT ELEVATED TEMPERATURES
by Michael P. Gillen 131

DESIGN OF HIGH STRENGTH HIGH- PERFORMANCE CONCRETE MEMBERS
by Vijaya Rangan. 157

HIGH-PERFORMANCE CONCRETE WITH FLY ASH
by C. Müller, R. Härdtl and Peter Schießl. 173

HPC PRECAST SEWER PIPE
by D. O. Northwood, Kevin Cail and Kevin A. MacDonald. 201

EFFECTS OF HUMIC ACID TREATMENTS ON PROPERTIES OF BAMBOO FIBER REINFORCED, POLYMER-MODIFIED PASTES
by Y. Ohama and K. Demura. 209

CORROSION PROTECTION SHIELD OF STEEL BARS, DUE TO STEEL FIBERS IN CONCRETE
by Abdullah Keyvani Someh, Noboru Saeki and Takenori Notoya 227

FIBER MATRIX COMPATIBILITY CONSIDERATION IN FIBER REINFORCED CEMENTS AND CONCRETES by Collin D. Johnston	249
PERFORMANCE CHARACTERISTICS OF CONCRETE INCORPORATING A NATURAL AMORPHOUS SILICA by D. H. Chisholm	271
EFFECT OF RICE HUSK ASH BLENDING OF PORTLAND CEMENT ON COMPRESSIVE STRENGTH OF GAP-GRADED CONCRETE by D. D. Bui and P. Stroeve	297
WALL PANELS FROM AIR-ENTRAINED ASH SLAG CONCRETE by S. I. Pavlenko	309
SETTING ACCELERATOR CALCIUM NITRATE FUNDAMENTALS, PERFORMANCE AND APPLICATIONS by Harald Justnes and Erik C. Nygaard	325
DEVELOPMENT OF SUPER-WORKABLE CONCRETE WITH VISCOSITY AGENT FOR RECONSTRUCTION OF JETTY STRUCTURES DESTROYED BY THE HANSHIN GREAT EARTHQUAKE T. Fukute, H. Hamada, S.K. Sano, E.Sueoka, A. Moriwake and H. Takeuchi	339
EVALUATION OF POLYMER-MODIFIED, CEMENT-BASED MORTARS FOR REPLACING CONCRETE STRUCTURES IN COLD CLIMATES by J. Mirza, R. Lapointe and M. S. Mirza	367
A STUDY OF THE CORROSION RESISTANCE OF THERMAL SPRAYED STAINLESS STEEL COATINGS FOR REINFORCING BARS by Ping Gu, Bernard Arsenault, J. J. Beaudoin, Jean-Gabriel Legoux, Bernard Harvey and Joel Fournier	389
REINFORCEMENT CORROSION IN NEW ZEALAND CONCRETE by S. A. Freitag, S. M. Bruce and W. E. Hickman	413
AUCKLAND BASALTS AS A SOURCE OF ALKALI IN CONCRETE by Reiner Goguel and Neil B. Milestone	429
CONSTRUCTION OF JOINTS IN ROLLER COMPACTED DAM CONCRETE by Takeo Iisaka	445
MIXTURE PROPORTIONING OF ROLLER COMPACTED CONCRETE—A REVIEW by J. Marchand, R. Gagné, E. Ouellet and S. Lepage	457

USE OF DRY BOTTOM ASH AS A FINE AGGREGATE IN ROLLER COMPACTED CONCRETE
by N. Ghafoori, Y. Cai and B. Ahmadi 487

THE EFFECT OF ELECTROCHEMICAL CHLORIDE EXTRACTION TREATMENT ON THE
MICROSTRUCTURE AND MECHANICAL PROPERTIES OF CEMENTITIUS MATERIALS
by T. D. Marcotte, N. M. Ihekweba, C. M. Hansson and B. B. Hope 507

MULTIVARIATE STATISTICAL MEHTODS IN EVALUATION OF CONCRETE AND AGGREGATE
PROPERTIES
by Peter P. Hudec 531

EXTERNALLY REINFORCED CONCRETE COMPOSITES
by Peter G. Lowe 551

A NEW GENERATION OF STRUCTURAL LIGHTWEIGHT CONCRETE
by O. A. Kayyali and M. N. Haque 569

ASSESSING THE TIGHTNESS OF THE SURFACE LAYER OF CONCRETE
by M. Shoya, Y. Tsukinaga and S. Sugita 589

SETTING SHRINKAGE AND SETTING STRESS OF POLYMER MORTAR
by F. Omata, M. Kawakami, H. Tokushige and A. Moriyoshi 607

SULFATES IN CEMENT CLINKER AND THEIR EFFECT ON CONCRETE DURABILITY
by Jan Skalny, Vagn Johansen and F. M. Miller 625

DEICING SALT SCALING RESISTANCE OF HIGH-STRENGTH CONCRETE
by J. Stark and N. Chelouah 633

IN-SITU PERMEABILITY TESTING—A BASIS FOR SERVICE LIFE PREDICTION
by A. E. Long, P. A. M. Basheer and F. R. Montgomery 651

PERFORMANCE CHARACTERISTICS AND APPLICATIONS OF HIGH-PERFORMANCE
POLYOLEFIN FIBER REINFORCED CONCRETES
by V. Ramakrishnan 671

Design for Durability and Strength Through the Use of Fly Ash and Slag in Concrete

by R. N. Swamy

Synopsis: This paper presents a critical evaluation of the use of fly ash and ground granulated blast-furnace slag in concrete. In order to develop a rational concrete mixture incorporating these siliceous materials, their inherent characteristics are assessed, including their limitations and weaknesses. Based on the mixture proportioning methodology advocated, it is shown that fly ash and slag concretes, having the same three-day cube strength as concrete without them, can be produced. Engineering implications of using these materials such as increased bleeding and times of setting, reduced heat of hydration, low-early strength, and slow rate of gain of strength are addressed, and the need and role of a minimum period of moist curing to mobilize the chemically-bound qualities of these materials are fully emphasized. It is shown that both high-early strength and high-strength concrete can be achieved with fly ash and slag. Even with all their limitations, the durability properties of concretes with fly ash and slag are superior to those of concrete made with portland cement alone. It is shown further that extremely fine siliceous materials are only of limited use in concrete, but that a moderate increase in fineness, about thrice that of portland cement, can not only preserve and fully use the benefits of fineness on a variety of engineering properties such as bleeding, time of setting and heat evolution, but also lead to excellent chemical resistance and durability with high strength at early and later ages. It is shown that a slag fineness of about 1200 m²/kg can produce concretes of high strength and exceptional durability.

Keywords: Blast furnace slag; chlorides; concretes; durability; fly ash; high-performance concrete; high-strength concrete; microstructure; mix proportioning; porosity; pore-size distribution.

2 Swamy

ACI Fellow Professor R. Narayan Swamy is at the Structural Integrity Research Institute and the Centre for Cement and Concrete, University of Sheffield, England. His research interests are in concrete materials and concrete structures. He received the George Stephenson Gold Medal of the Institution of Civil Engineers, and the Hendry Adams Diploma of the Institution of Structural Engineers. He has also received the CANMET/ACI Awards for contributions to Durability of concrete and the Use of Supplementary Cementing Materials in Concrete. He is the Editor of the Journal Cement and Concrete Composites.

INTRODUCTION

Compared to other major construction materials such as steel, polymeric materials, and composites, concrete is the most ecologically friendly, needs the least amount of energy to produce, and can be proportioned to possess high strength and high durability. The most valuable asset of concrete is its inherent alkalinity, and in sheltered conditions and normal, non-aggressive environments, concrete can, and will give durable service life. However, although the portland cement (PC) matrix is intrinsically protective to steel, it also permits the ingress of deleterious agents, such as chlorides and sulfates, which lead to its own progressive deterioration, and the consequent destabilization of the embedded steel reinforcement.

The most direct, technically sound and economically attractive solution to the problems of reinforced concrete durability is the use of finely divided siliceous materials in concrete. It is now well-established that the incorporation of such industrial byproducts such as fly ash (FA), ground, granulated blast-furnace slag (slag) and silica fume (SF) in concrete can significantly enhance its basic properties in both the fresh and hardened states (1, 2). In particular, these materials greatly improve the durability of concrete through control of high thermal gradients, pore refinement, depletion of cement alkalis, and the capability for continued long-term hydration or pozzolanic reaction. Bearing in mind the scope for world-wide use of concrete, and the increasing demand for construction, especially in the developing world, the technical advantages of materials such as pozzolans and slag in concrete are complemented by other economic, ecological, and environmental considerations. Concrete can provide, through chemical binding, a safe haven for many of the toxic elements present in industrial wastes, and further, it is also able to provide an economic and technological solution to waste handling and disposal in a way to cause the least harm to our environment. Pozzolanic admixtures and slag thus need to be recognized not merely as partial replacements for portland cement, but as vital and essential constituents of concrete. Viewed in this way, these materials reduce substantially not only the energy consumption in the production of concrete, but also help to reduce environmental pollution through reduced emission of carbon dioxide.

However, in spite of the overwhelming technical, environmental, and economic benefits associated with the use of pozzolans and slag in concrete, there is still

considerable misinformation on their use in concrete, and an inadequate appreciation of the urgency of incorporating them in concrete, and using them as widely as possible. In addition, there is also the feeling frequently expressed by engineers that the use of these materials creates more problems than benefits to concrete construction. The aim of this paper is to remove these doubts, and show that an intelligent use of these materials can lead to their efficient utilization, and enhance the quality of construction and of the environment. The overall aim is to show that in order to achieve this, we need to take an integrated material and structural *DESIGN* strategy in using these materials (3, 4), and that we need to understand the limitations and drawbacks of these materials just as much as the technical benefits they bring, if we are to use them effectively and efficiently. The paper attempts to show how these limitations and drawbacks can be addressed in a way to enhance the properties of the composite cements in concrete, and thereby still further enhance its overall durability in aggressive environments.

MIXTURE PROPORTIONING WITH POZZOLAN AND SLAG

The integrity and durability of concrete structures is closely linked with the characteristics of the materials used, but there is no clear understanding of this inter-relationship between material characteristics and structural performance. Nevertheless, one of the great advantages of concrete is that both the choice of the constituents and the proportioning of these constituents is entirely in the hands of the engineer, and the technologist. However, there is much uncertainty, doubt and concern in the role and usefulness of fly ash and slag in concrete, and these arise primarily from two factors - the variability of these materials, particularly of fly ash, and a clear lack of understanding of the overall methodology of incorporating these materials in concrete. In the following, some of these aspects that influence concrete mixture proportioning with fly ash and slag are discussed.

Inherent Characteristics of FA and Slag

To use efficiently these materials in concrete, we need to understand the fundamental characteristics of these materials. These are

1. The ability of FA and slag to contribute to strength and durability of concrete is chemically bound within them. To extract and mobilize these qualities, and to use them in concrete, we need to understand how they affect and modify the characteristics of portland cement.
2. The hydration of slag and the pozzolanic reaction of FA are a two-stage process. These reactions lag behind that of the hydration of portland cement (5). As a consequence, their incorporation in concrete can result in low strength and slow development of strength at early ages; further, both FA and slag concretes are also therefore likely to be more susceptible to the consequences of poor or

4 Swamy

inadequate curing conditions than concrete containing portland cement alone (6, 7).

3. Because of their nature, FA and slag react more slowly with lime and water than portland cement, but they can be activated chemically. From a practical point of view, as well as for long term material stability, portland cement is the best activator for the production of concrete (8, 9). Where appropriate, the use of a fine grained pozzolan, such as silica fume, can accelerate the chemical reactivity to enhance early strength development and further pore refinement.

4. Both fly ash and slag typically reduce the water requirement to obtain a given consistency, although coarse particle size ashes, and ashes with high carbon content, such as those from older power plants, and certain slags increase the water requirement for concrete. This water-reducing effect is only partly a mechanical effect, and has little to do with the particle geometry since both the spherical particles of the FA, and the angular rough-textured particles of the slag both enhance workability (10). The water reduction associated with FA and slag is, in reality, the result of the dispersion and deflocculation of the cement particles, similar to the effect of organic water-reducing admixtures (11).

5. However, for the particle size distribution generally met with ashes and slags, and the water contents normally used in concretes, their dispersive action is not adequate to initiate early or sufficiently long-term pozzolanic action or hydration. High-range water-reducing admixtures (HRWRA) are thus integral to the requirements of both early age and long-term strength development, particularly if a very fine pozzolan, such as silica fume, is also incorporated in the concrete.

6. The combination of water-reducing properties of FA and slag, and the rheological dispersive actions of HRWRA can effectively counteract, and reduce, bleeding and segregation, and impart qualities of cohesiveness essential for pumping and finishing (8, 9). Because of the differing water demands of FA and slag, the amount of HRWRA required for given workability characteristics of concrete will be different.

7. To enhance cohesiveness and flow characteristics, and to reduce bleeding as well as to improve the paste matrix properties for use with fibre-reinforced, and other, cement composites, it is always more convenient and beneficial to use FA and slag as direct replacement of cement on a mass for mass basis. This results in more paste volume which will enhance the overall cohesiveness of the cementitious matrix.

8. In spite of the advantages of water-reduction, cement replacement on a mass for mass basis, and the use of a HRWRA, many ashes and slags, when used in concrete, may still cause some bleeding (12 - 14). The principal factor influencing

bleeding is the water-binder ratio (w/b), although both the replacement level on a mass basis, and the fineness of the ash or slag have also some influence on bleeding. A judicious combination of these three parameters can then reduce substantially, or even eliminate completely, the amount of bleeding. In practice, the addition of ash or slag to harsh mixtures of normal portland cement and sand can also reduce bleeding. Excessive bleeding also often occurs where there is a lack of fines in the fine aggregate, and the incorporation of a very fine pozzolan or grinding the ash or slag finer can substantially eliminate bleeding (13, 14).

9. Both FA and slag act in many respects as retarders of time of setting (13, 14). The major factor influencing times of setting is the level of cement replacement, although the water-binder ratio has also some minor influence (13, 14). The combination of a HRWRA with PC, FA or slag is also responsible to some extent to the increased times of setting (13, 15). The use of high levels of cement replacement may thus prolong the time during which concrete is vulnerable to plastic shrinkage cracking, and this may be undesirable in placements involving large exposed areas and deep sections. Both bleeding and times of setting can be effectively controlled through a judicious combination of w/b, cement replacement level, and ash/slag fineness or use of a fine pozzolan.

10. The relation between FA and slag concrete strength and w/b is far more sensitive to changes in water content than that with PC concrete. In general, FA and slag concretes, like PC concrete, largely follow Abrams' Law. However, the relative differences in strength between PC concrete and FA or slag concrete decrease as the w/b decreases (16). Further, for a given increase in w/b, the compressive strength is reduced relatively more at early ages than at later ages for both PC and FA/slag concretes (2, 17-20). If contribution to strength of FA and slag is therefore to be maximised, then the w/b needs to be as low as practicable, or desirable.

11. Durability considerations also lead to the same most important single parameter for FA/slag concrete mixture proportioning - the w/b. The major factor contributing to the superior resistance of FA and or slag concrete to chemical attack, and particularly to sulphate resistance, is the pore refinement resulting from the pozzolanic action of the fly ash, and the hydration of the slag (21). Similarly, the most important factor that influences the penetration of carbonation into concrete is also the w/b, and the most effective way of limiting carbonation depends on the control of this parameter.

12. With siliceous by-products that contribute to strength through pozzolanic or hydraulic reactivity, there is considerable evidence to show that early-age strength development is governed more by the reactivity of PC than that of the pozzolan or slag, whereas long-term strength development depends more on the reactivity of the pozzolan or slag (8, 9, 22, 23). A minimum cement content, a low

6 Swamy

but *adequate* w/b, and an HRWRA are therefore necessary to achieve high early-age strength development.

Ingredients of Mixture Proportioning

Curing is not generally considered as part of concrete mixture proportioning, but with siliceous materials that depend on their reactivity to contribute to strength and stability, curing has to be considered as an essential part, and an integral component, of concrete mixture proportioning. Thus the three important criteria for mixture proportioning of concrete containing FA and/or slag have to be

- low w/b
- early, and longer, moist curing
- workability through HRWRA.

The simplest approach to mixture proportioning FA and slag concrete is the direct partial replacement of portland cement by mass, and modification of the mixture constituents to suit the strength and workability requirements of a given application (8, 9, 24-26). The advantages of this procedure are:

- i. direct replacement by mass of PC with FA or slag increases the paste content of the mixture, and thus, enhances the cohesiveness and flow characteristics of the resulting concrete
- ii. workability can be adjusted to suit the application while enabling the use of a low w/b, essential for durability
- iii. the role and effectiveness of the fly ash and slag can be readily assessed and modified

The level of replacement of PC is obviously dictated by considerations of strength and durability, as well as the particular requirements of a given application. The level of replacement is also related to the minimum PC content, since the chemical reactivities of PC and FA or slag are inextricably linked. Aggressive environments and structural requirements i.e. considerations of durability and structural strength, will ultimately decide the precise combination of PC and FA or slag. This is discussed later in the paper.

In the following, the various points discussed above are illustrated with examples of FA and slag concrete mixture proportioning, and the properties of the resulting concrete obtained. Obviously, it is not possible to discuss in a single paper every structural property of FA and slag concrete, but sufficient range of details is presented to emphasize the wide-ranging technical benefits that could be derived by judiciously incorporating FA and slag in concrete. Only low calcium FA, with a

minimum of 75% of $\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3$ content, corresponding to ASTM class F, is discussed here.

FLY ASH CONCRETE

25-30% Replacement Level

A replacement level of 25-30% is now generally considered acceptable for a variety of civil and structural engineering applications. Table 1 summarizes the data reported on class F British fly ashes obtained from 18 power stations over a period of two years (18). In the fly ashes used in this study, over two-thirds of the ashes were outside the limits of the British specifications, and the 45- μm sieve residue, in particular, varied from 15 to 30% for a large number of the ashes, with one exceptional value of about 43%. The mixtures were proportioned for a 30% cement replacement by mass, and a 28-day cube strength of 30 MPa. The water content was adjusted for a slump of 75 mm, and both plasticized and non-plasticized mixtures were produced. The data in Table 1 emphasize the effects of several parameters such as w/b, HRWRA, and the type of ash on early and long-term strength development. In a way, these results also emphasize how ashes outside normal specifications can also be utilized in practice to give good quality concrete (27).

Replacement at 50 Percent Level

This mixture proportioning technique can be readily extended to a cement-replacement level of 50%, and Tables 2 and 3 show the mixture proportions, rate of strength development, and the effect of curing regime on strength development. All these mixtures (except the non-structural 20 MPa concrete mixture) conform to the mixture proportioning criteria discussed earlier - i.e. low w/b, and high workability through the use of HRWRA, for example, to obtain one-day strengths of about 10 to 20 MPa, and 28 day strengths of 40 to 60 MPa. Table 3 also shows that high-strength concrete can be developed through cement replacements up to 50% level, provided care is taken in mixture proportioning, and adequate and sufficiently early and longer curing is carried out, to enable the concrete to develop strength and a microstructure for low permeability.

Replacement at 50 to 60 Percent Level

The development of high volume fly ash concrete (HVFAC), pioneered by the extensive research of Malhotra and his group (28, 29), is a natural progression in the use of FA in concrete from that described earlier. Typically, the PC content in HVFAC is kept at about 150 kg/m^3 , the w/b at about 0.30, and FA content between 56 and 60 percent by weight of the total cementitious material. The presence of the high percentage of fly ash in the concrete mixture necessitates the use of high dosages of HRWRA for slumps of 150 to 200 mm, and equally high

8 Swamy

dosages of air-entraining admixtures of 650 to 720 mL/m³ to entrain 5 to 6 per cent air. The final times of set are also retarded by about 3h compared to the control. Extensive test data show that regardless of the type of FA and brand of ASTM Type I cement used, air-entrained HVFAC performs well as regards workability, bleeding, times of setting, temperature rise and mechanical properties. They also possess excellent durability characteristics in freezing and thawing cycling, resistance to chloride-ion penetration and resistance to sulfate attack. They have low water permeability, and reduce substantially potential expansion due to alkali-aggregate reaction (28, 29).

Low early-age strength, and slow development of strength are inevitable consequences of the presence of such large amounts of FA in the concrete mixture. One-day cylinder compressive strengths with ASTM Type I cement thus vary from 5 to 9 MPa, depending on the cement-fly ash combination, with strengths of 60 MPa at one year. Using ASTM Type III, high-early strength cement, the one-day cylinder strengths can be enhanced to values of the order of 15 MPa, with 3-day, 28-day and one-year strengths of about 25, 45 and 60 MPa. Table 4 gives typical mixture proportions for this type of concrete, and the strength development with age.

HVFAC, made with ASTM Type I or Type III cement, thus possesses many characteristics typical of high performance concrete, and can give excellent serviceability in applications such as mat foundations, thick structural elements and hydraulic structures.

SLAG CONCRETE

The basic principles of mixture proportioning described earlier can be extended to slag concrete to produce both high-early strength and long-term high strength. Tables 5 and 6 show details of several PC-slag mixtures, and the development of compressive strength with age up to 28 days. The PC used in this study was a low-alkali content ASTM Type I cement with a specific surface of 380 m²/kg, and the slag was a coarsely ground slag with a specific surface of 350 m²/kg. The w/b of the PC-slag concrete mixtures ranged from 0.40 to 0.46, with a slump of 160 - 200 mm, and the HRWRA content was constant at 1.8% by mass of PC and slag. The results confirm that concrete containing a relatively coarse slag can be utilized to give consistent 28 day cube strength of 50 to 55 MPa. The table also highlights the relative significance on strength of the proportions of PC, and slag particularly at early ages - as the PC content is reduced, the one day strength is progressively reduced, and to obtain the required 28-day strength consistently, the total cementitious content (compared to the PC control concrete) needs to be increased by about 10% for 50% cement replacement, and by about 20% for the 65% cement replacement. With such an approach, PC-slag concretes, like fly ash concretes, can be proportioned to give compressive strengths, comparable to that of PC concrete, from 3 days onwards. These results confirm that an engineering approach to

concrete mixture proportioning, rather than a blind direct replacement approach without other relevant considerations, can help the engineer to develop slag-concrete mixtures with adequate strength at early and later ages.

STRENGTH DEVELOPMENT

In engineering applications, early-age strength, and particularly, the early-age rate of gain of strength are important considerations in design, because of the implications on increased formwork pressure and times of setting. One of the inherent characteristics of FA and slag is that, because of their pozzolanic and cementitious nature, early-age strength and early-age strength development will be slow. Nevertheless, much of this slow strength development can be overcome by judicious mixture proportioning as shown in Tables 3 and 6. This strength development of fly ash and slag concretes shown in Tables 3 and 6 is further evaluated in Tables 7 and 8 for FA and slag concretes respectively in order to assess their structural implications. Table 7 shows that, with proper mixture proportioning, fly ash concretes can have strength development similar to that of PC concrete from about three days onwards. With slag, at 1 day, the hydration of slag concrete is slow. One day strength at 50% replacement is about 10 to 20% of its 28-day strength, compared to about 10 percent or less for the 65 percent replacement. At 3 days, however, slag concrete at both replacement levels developed about 45 percent of its 28-day strength, compared to about 55 percent for the PC concrete. At 7 days, both slag concretes developed 65 to 75 percent of their 28-day strength, compared to about 80 percent for the PC concrete. The results in Tables 7 and 8 thus clearly show that, by careful mixture proportioning, incorporating a HRWRA, keeping the water content low, and making other modifications to the mixture, it is possible to ensure comparable strength development for fly ash and slag concretes at 3 days and beyond - for fly ash, at a replacement level of 50 percent, and for slag, at replacement levels of 50 and 65 percent. Later in this paper, it is shown how these strength values can still be further enhanced through additional modifications to the mixture proportioning.

SIGNIFICANCE OF MOIST CURING

Influence on Strength

It has been pointed out earlier that another characteristic of FA and slag, because of their respective pozzolanic and cementitious nature, is their sensitivity to lack of moist curing. Pozzolanic and cementitious reactivity demand water, and similarly, their continuation at early and later ages at an acceptably rapid rate also requires early and more prolonged moist curing than PC concrete. This section attempts to highlight the role of water curing in such situations.

The development of compressive strength for fly ash concrete at 50 per cent replacement levels, and for slag concrete at 50 and 65 percent replacement levels

10 Swamy

under three different curing regimes is shown in Tables 3 and 9 respectively. The data in these tables emphasize the need for early curing, and the incorporation of a minimum period of water curing as an integral part of mixture proportioning of fly ash and slag concretes. In the absence of any initial water curing, both FA and slag concretes are unable to achieve their target 28-day strength. This should not come as a surprise, since both fly ash and slag can contribute to the development of hydration and microstructure only in the presence of water. These data thus portray the significance of pozzolanic and cementitious reactivity to concretes with FA and slag. This reactivity is chemically locked in the material. In slag, for example, this is chemically bound within its glassy structure. The glassy structure can be disturbed, but the reactivity can only be released in the presence of water, and alkalis and sulfates released by the PC reaction. Thus, what these data in Tables 3 and 9 emphasize is that such release of reactivity can continue to occur only when adequate moisture is available, and that, the presence of fly ash or slag does not automatically ensure the continuation of the reactivity, which is the key to their contribution to strength and a tight microstructure. The data in Tables 3 and 9 related to compressive strength development with no water curing and continuous exposure to a drying environment soon after demolding dramatically highlight this need for early water curing, and to ensure its availability in the early stages of the formation of the structure of the concrete. Table 9 shows that both mixtures M4 with 50 percent slag replacement level and mixture M7 with 65 percent replacement level, failed to reach their target strengths of 50 MPa at 28 days, although at the lower replacement level of 50 percent, mixture M4 reached almost 90 percent of its target strength. What is equally important to realize in structural design is that mixture M4, with 50 percent replacement, took 90 days to reach the target strength, and showed a modest improvement at 180 days, whereas mixture M7, with 65 percent replacement, failed to reach the target strength even at 180 days. The data in Table 3 for fly ash concrete tell a similar story.

The long-term adverse effects of continuous exposure to a drying environment with no initial water curing, and the benefits of a well-planned curing period when pozzolans or slag are incorporated in concrete are typically highlighted in Table 10 for slag concretes with 50 and 65 percent replacement levels. The data in this Table are related to the strength development shown in Table 9, and reveal why water curing is needed to release the chemical reactivity locked in pozzolanic and cementitious admixtures. The apparent retrogression of strength with time and with continued exposure to air drying, particularly at high replacement levels, is a factor to be recognized in mixture proportioning with fly ash and slag, even though much of this loss of strength can be reversed by extended initial water curing. Indeed, the results of 7-day water curing in Table 10 show that even this period of initial water curing is really inadequate for both 50 and 65 percent slag replacement levels. On the other hand, the data in Table 10 also point out that a concrete well protected from drying can bring immense benefits to the long term stability of the material.

The data in Tables 3, 9 and 10 reveal, in a clear engineering way, the usefulness of fly ash and slag, and their ability to make concrete stronger and more durable - and the need to realize that there is only one way to mobilize and exploit this property - which is so essential to, and which alone can, make concrete construction remain serviceable for a long time.

Comparison with PC Concrete

Although concretes made with FA and slag should be considered in their own right, it is inevitable that comparisons will be made with concrete made from PC alone. To put these data in a proper perspective, some typical strength development data of a PC concrete design for 60 MPa cube strength at 28 days are presented in Table 11, and these can be compared with the strength development data of FA and slag concrete given in Tables 12 and 13 which are derived from their strength development shown in Tables 3 and 6. The benefits of incorporating a pozzolan such as FA can be readily seen in Table 12; the benefits of using a cementitious material such as slag, are, also superior to that of the concrete based on PC alone as shown in Table 13. These data again confirm that FA and slag concretes can bring tangible benefits in terms of strength compared to PC concrete alone. Later in this paper, these benefits are related to those in terms of durability arising from FA and slag.

Influence on Pore Structure

The more fundamental effect of water curing is on the development of the pore structure of the concrete. Lack of any water curing, and lack of adequate water curing can very significantly affect pore refinement, which is a fundamental characteristic of fly ash and slag concrete. The effects of continuous water curing, limited initial water curing, and no water curing are highlighted in Figs. 1 and 2. Pore structure is directly related to durability, and it can be readily seen how lack of a sufficiently long water curing period in concrete with mineral admixtures can in the long term, lead to the denial of pore refinement, and to loss of durability. Lack of adequate water curing also affects PC concrete, as discussed later, but here it is emphasized how the real benefit of FA and slag, in terms of pore refinement, can be lost if the necessary precautions to prevent moisture loss and to continue hydraulic activity are not taken.

Influence on Shrinkage and Expansion

Early age water curing has also a beneficial effect on drying shrinkage, particularly at early ages, as shown typically in Figs. 3 and 4 for slag concretes with 50 and 65 percent replacement levels respectively. High shrinkage strains at early ages, on the other hand, can have a significant effect on shrinkage cracking, particularly if the concrete has also a slow development of flexural strength, and they can also have an adverse influence on prestress losses. The results shown in Figs. 3 and 4 also

12 Swamy

emphasize the need for water curing to be carried out for an adequate period of time, if high shrinkage strains are to be avoided both early and in the long term.

The swelling strains, also shown in Figs 3 and 4 again emphasize, how the level of replacement is also a critical parameter in determining the period of curing. Concretes with 65 percent slag replacement show expansion more than twice that of the concrete with 50 percent replacement. PC concrete, when exposed to a continuous moist regime, expands by about 20 to 25 percent of its drying shrinkage. The data in Figs. 3 and 4 show that at 65 percent replacement level, the slag concrete shows swelling strains at about 60 percent of the shrinkage at 6 months, compared to about 25 percent of the 6 month shrinkage for the 50 percent replacement level. FA concrete, at 50 percent replacement level, also shows high swelling strains, some 40 to 55 percent of its shrinkage as shown in Fig. 5. These large swelling strains at high replacement levels of FA and slag concretes are indicative of the ability of, and the need, for these concretes to absorb large amounts of water to enable the reactions due to the slow pozzolanic or cementitious activity to continue for a long time. They also emphasize the need for more prolonged water curing for concretes with high cement replacement levels of FA and slag, if their full potential for continued pozzolanic and cementitious activity is to be achieved and exploited.

BLEEDING RATES AND TIMES OF SETTING

As pointed out earlier, bleeding is characteristic of most concrete made using fly ashes and slags, and they also act as retarders of time of setting. Bleeding is influenced by three major factors in fly ash and slag concretes - the w/b, the level of replacement on a mass basis, and the fineness of the ash or slag. Tests reported by Carette and Malhotra (12), and Malhotra (30) on fly ash and slag concretes confirm this. Typical data for slag concretes identifying the role of w/b and replacement level on bleeding rates is shown in Table 14 - these data relate to slag concretes containing PC with a surface area of 323 m²/kg and slag, with a surface area of 453 m²/kg. Most slags have a specific surface area slightly higher than comparable PC, and the results in Table 14 show that a judicious combination of w/b, and replacement level can substantially reduce bleeding rates.

Fly ash and slag also act as retarders of time of setting (12, 13, 30). The principal factor influencing times of setting is the level of cement replacement as shown in Table 14 for slag concretes containing various levels of replacement; the w/b has a much less significant influence on time of setting, again as shown in Table 14. The data in Table 14 confirm that major reductions in bleeding can be achieved by reducing the w/b ratio from 0.45 to 0.40, and at the w/b of 0.40, the initial and final setting times are increased only by about 30 min and 1 hour respectively at slag replacement levels of 50 percent and 65 percent. A judicious combination of w/b and cement replacement level is thus necessary if the benefits of fly ash and slag are to be optimized in practice in terms of bleeding and retardation of times of setting.

Experience in concrete technology shows that the addition of fly ash or slag to harsh mixtures of PC concrete or PC concrete containing inadequate amount of fines in the fine aggregate can also reduce bleeding. Similar effects can also be obtained by the addition of a very fine pozzolan. Alternatively, grinding the slag can be beneficial in more than one respect. It can not only reduce bleeding, but can also bring substantial benefits in terms of strength and durability properties (which are shown later). Table 15 shows the bleeding rates and setting times of slag concretes with a w/b of 0.40, and three different slag fineness, namely, 453 m²/kg, 786 m²/kg and 1160 m²/kg respectively at a replacement level of 50 percent. These data show that increased slag fineness can almost completely eliminate bleeding with only moderate increases in initial time of setting of 25 to 45 min and final times of setting of 10 to 35 min. The increased fineness helps to reduce the increasing time of setting normally associated with fly ash and slag, and further, it brings in much more useful benefits of strength and durability (as shown later), than what can be achieved by a very fine pozzolan. Grinding fly ash may appear to be not so practical for obvious reasons, but intergrinding with PC can be widely and beneficially done to produce portland-pozzolan blended cements. Grinding slag, on the other hand, is an established process in the production of slag. Grinding slag finer may appear to increase the initial cost of the material; however using an air elutriator in the grinding process can reduce this cost, but the long-term overall benefits to the concrete, in terms of both strength development and durability far outweigh the moderate increases in initial cost, or the use of a very fine pozzolan such as silica fume.

Bleeding is not merely a physical phenomenon affecting the strength, abrasion resistance and diffusion characteristics of the surface concrete. A poorly proportioned concrete creating bleeding in the inner parts of the concrete can create weak matrix-aggregate interfaces, which in the long run, can affect adversely the permeability properties of concrete. Bleeding, and a lot of bleeding, can in fact be good, provided delayed revibration is practised. A more detailed discussion of this aspect has to be done elsewhere, but a recognition of the engineering implications of bleeding are vital to the long-term durable service life of concrete structures.

RESISTANCE TO THERMAL CRACKING

It is not often realized, nor recognized, that excessive development of heat due to hydration, particularly at the early ages of concrete maturing, can affect the long-term durability of concrete. The effects of strain differentials, and the associated internal microcracking arising from thermal stress gradients, are slow to heal, and it is important to ensure at the construction stage that heat evolution is fully controlled to enable the concrete to develop a dense, homogeneous, and crack-free microstructure. The problem is exacerbated even in moderately large structures, particularly when high cement contents are used, or when the construction activity

14 Swamy

takes place in high-temperature environments. It is here that the incorporation of fly ash or slag in concrete can provide an invisible and unseen beneficial property, far more significant in relation to the durability of the material than improvements in strength.

To illustrate the effects of siliceous materials such as fly ash and slag on heat of hydration, heat evolution profiles obtained from conduction calorimetry tests carried out at 20°C are presented here. Since FA or slag should never be used without a HRWR, particularly when high volumes of FA or slag are used, the data shown here relate to (i) PC, (ii) PC with a HRWR, (iii) PC + slag and finally (iv) PC + slag + HRWR. The PC used in these tests had a Blaine specific surface of 323 m²/kg, and was used with a w/b of 0.40 and a slag replacement level of 50 percent. The slag had a specific surface of 453 m²/kg, and the HRWRA used was polyether carboxylic acid with ability to control slump loss. The HRWRA was used in sufficient quantities to give a slump of 160 - 200 mm.

The data shown in Figs. 6 and 7 emphasize the role of the HRWRA and slag on the heat evolved during hydration. HRWRAs, capable of reducing slump loss with time, generally exercise a retardation effect: in the case shown in Fig. 6, the peak time of heat evolution has been extended by a factor of almost two, from about 9.2 hr to about 17.2 hr. Replacing PC by 50 percent slag at a w/b of 0.40, on the other hand, has reduced the peak heat evolution to about 60 percent of that of PC alone, and this peak occurs at about the same time as that for PC. The incorporation of the HRWRA, in addition to slag, also delays the occurrence of the peak heat evolution by about the same period when the HRWRA is used alone. What the data in Figs. 6 and 7 emphasize is that with a careful selection of HRWRA, level of cement replacement and w/b, the retardation of time of setting properties of the slag, as well as the heat evolution during the early stages of hydration, can be effectively and positively controlled.

As pointed out earlier, there are distinct benefits to be derived, particularly from the bleeding point of view, by incorporating fly ash, slag, or a more finely divided pozzolan in concrete. A finely ground slag, on the other hand, can also bring other technical benefits, as shown later, but a too finely divided material may have adverse effects on the heat evolution. Figure 8 shows the effect of slag fineness on peak heat evolution, and the time at which this peak heat evolution occurs. These results show that grinding slag to a reasonable degree of fineness of 2 to 3 times that of normal PC causes little adverse effects in terms of heat evolution; on the contrary, in spite of the increased fineness, not only a substantial reduction in heat evolution can be achieved, but also some of the retardation effects of slag on strength development can also be overcome.

An extremely fine pozzolan, such as SF, may have undue adverse effects on the heat of hydration. A moderately fine material, such as slag, on the other hand, can preserve the benefits of fineness on a variety of engineering properties such as

bleeding, setting times, heat evolution, strength, and durability without unwanted side effects.

USE OF COMBINATIONS OF POZZOLANS AND SLAG

The data presented earlier in this paper show that, from an engineering point of view, the use of fly ash and slag in structural concrete may have two possible disadvantages, under certain circumstances. These relate to their low early strength and the slower rate of gain of strength, particularly at early ages. The data on strength development, and times of setting presented earlier confirm this - that the PC-fly ash pozzolanic activity and PC-slag hydration are a two-stage process, and that these combinations inherently lead to slower rate of gain of strength at early ages. It is therefore obvious that the incorporation of a pozzolanic activity or a hydration activator, especially in the form of a fine pozzolan, could lead to significant benefits in terms of strength development and durability properties. Further, since early strength development depends primarily on PC content, a minimum PC content is also essential for early strength and engineering properties. These concepts can be used to develop a high-early-strength concrete with excellent durability properties. Since space will not permit a full discussion of all aspects of this approach to mixture proportioning, only the strength development aspects are discussed here.

In the following data, the total cementitious material content was kept constant at 350 kg/m^3 , and the w/b at 0.45. The PC content was specified at a minimum of 250 kg/m^3 , and a highly reactive pozzolan, SF in this case, was incorporated at a nominal amount of 20 kg/m^3 . Tables 16 and 17 summarize the cube strength development of a set of these concretes at early ages and later ages up to 260 days respectively. Table 16 shows that 1-day cube strengths of about 16 to 24 MPa can be achieved by this concept, with 7-day strengths ranging from 40 to 50 MPa. At 28 days, all the concretes with FA or slag registered cube strengths of 60 to 70 MPa compared to 53 to 58 MPa for PC concrete (Table 17). These data show 260-day strengths of 65 to 90 MPa, the concretes with FA or slag outperforming PC concrete even when no water curing was made available. It is emphasized here, however, that no concrete should be used in construction without water curing; these data are presented here simply to show how the inherent internal reactivity locked in pozzolans and slags could be extracted and utilized to advantage in concrete construction.

MINERAL ADMIXTURES WITH LIGHTWEIGHT AGGREGATES

Structural lightweight-aggregate concretes (LWAC) offer many technical and economic benefits for several practical applications through their ability for enhanced strength and durability without increased mass. The range of applications for structural LWAC is no less than for normal-weight aggregate concretes, from infrastructure construction to offshore applications, but they have the added

16 Swamy

advantage of providing an economic and technological solution to waste handling and waste disposal in a way to cause the least harm to our ecological system. Considerable reservations exist, however, in their use, partly because of a misplaced instinctive and irrational feeling that a lightweight concrete has to be less strong and durable, and is only suitable for secondary structural elements. Structural lightweight aggregates with combinations of pozzolans and slags can offer as much strength and durability properties as normal-weight aggregate as shown below (31 - 33).

In the data presented here, the concrete mixtures were proportioned to have a one-day cube strength of 20 to 30 MPa, and a 28-day cube strength of about 50 MPa utilizing a total cementitious material content of 350 kg/m^3 , and a constant free w/b of 0.40 (Table 18). A minimum PC content of 250 to 300 kg/m^3 was specified to ensure the one-day strengths of 20 to 30 MPa together with high durability. The coarse aggregate was a lightweight aggregate made from sintered fly ash. Natural sand was used as fine aggregate.

The cube compressive strength results are shown in Fig. 9. These results show that a combination of a minimum PC content with a highly reactive pozzolan can compensate for the loss of early age strength associated with FA and slag (as shown in Tables 2 and 5), the degree of compensation depending upon the type of pozzolan or cementitious admixture, and the level of replacement. Figure 9 shows that one-day cube strengths of 25 to 27 MPa was obtained with FA and slag, whereas the FA/slag/SF combination with a PC content of 250 kg/m^3 achieved about 17 MPa. The three-day strength for the FA and slag mixtures was about 35-40 MPa, and about 60 MPa at 28 days. The FA/slag/SF mixture gave slightly lower strength up to about 28 days, but was able to achieve about 50 MPa at 28 days. These results show how a judicious combination of a highly reactive pozzolan with FA or slag can achieve high strength at all ages even with a lightweight aggregate. Some durability test data associated with these concrete mixtures are presented later to show that FA and slag contribute not only to strength but also to durability.

HIGH-STRENGTH CONCRETE

Engineers and concrete technologists appear to be interested with very high strength concrete, far in excess of 80 - 100 MPa, although the range of applications for such high strengths is limited. It is also often assumed that a high strength concrete will automatically ensure high durability, although there is no rational basis to entertain such an expectation. On the other hand, it seems logical, and an eminently engineering approach, to design for high strength through durability rather than to hope for high durability through high strength. These concepts are exemplified below.

The data presented so far show that for high-early strength, and for high rate of gain of strength at early ages, two basic conditions need to be met, namely, a

minimum PC content, and a highly reactive pozzolan to accelerate the reactivity of the PC, FA, and slag. For many of the reasons discussed earlier, the PC content also needs to be kept as low as practicable, and the FA and slag content maximized to enhance durability. A highly reactive pozzolan is always helpful and desirable to compensate the slow strength development of FA and slag, but in construction practice, there are also distinctive advantages to be gained by keeping the number of different cementitious materials as few as possible. A combination of high early strength, high strength, and high durability can be achieved by a judicious and careful choice of the mineral admixture.

Slag is unique in this respect. It is slowly reactive, but it is a hydraulic cement, and not a pozzolan. A very fine pozzolan, such as SF, can be highly reactive, but then, with such a very high degree of fineness, there are problems and concerns associated with huge losses of workability, shrinkage cracking, and the presence of large amounts of unreacted silica, all of which may have a cumulative adverse effect, if not carefully considered and dealt with. In practice, therefore, the amount of such very fine pozzolans that can and should be incorporated in concrete with confidence has to be thoughtfully planned. Further, much of the SF added to concrete may remain unreacted, and act as an expensive filler, particularly if the SF is added in powder or compacted form. All these point out to the fact that such very high degrees of fineness, of a pozzolan, or indeed, of PC or mineral byproduct, are really unnecessary for concrete, and impossible to be utilized in practice.

A possible approach would then seem to be to grind FA or slag finer, say to about two or three times smaller than their normal particle size, which then can be utilized and mobilized to contribute to both durability and strength. Because of their pozzolanic and cementitious nature, a fine FA or slag can combine the effects of a pozzolanic or cementitious material, accelerated reactivity, and substantial contribution to both strength and durability. Some of these aspects are illustrated below with the example of slag with a smaller than normal particle size. As pointed out earlier, grinding slag finer may appear at first sight to be more expensive, but in practice, the technical benefits usually will far outweigh the increase in initial costs.

In the tests reported here, three slag finenesses, namely, 453 m²/kg (S4), 786 m²/kg (S8), and 1160 m²/kg (S12) were used. The normal slag S4 was obtained by the ordinary grinding process. The two finer grades of slag, S8 at 786 m²/kg and S12 at 1160 m²/kg were then obtained using an air elutriator. The approximate particle size distribution of the slags, in comparison with PC, is given in Table 19. The effect of this variation in slag fineness on bleeding and times of setting is shown in Table 15, and it can be seen that with the finest slag S12, bleeding can be eliminated with only minor increases in times of setting. The effect of this fineness on heat of hydration is shown in Fig. 8, and again, the benefits of slag in terms of

18 Swamy

reduced heat of hydration, and overcoming part of its inherent retardation effect can be readily seen.

To evaluate the role of the fineness of slag, a number of concrete mixtures at three w/b, and 50 percent replacement level, were made. These mixtures incorporated a HRWRA, and were proportioned to have slumps of 160 to 200mm. The cylinder compressive strength results under water curing conditions are shown in Fig. 10. These results show that a prudent selection of w/b, and slag fineness can give high strengths in the range of 80-120 MPa. Thus, with a w/b of 0.4 and a slag fineness of 1136 m²/kg, 3-day strengths of 30 MPa and 28-day strength of 100 MPa can be readily achieved. The results shown in Fig. 10 also emphasize the relative but interactive roles of PC, slag fineness and w/b on strength development at a given replacement level. The options for strength and durability (as shown later) at the disposal of the engineer and concrete technologist are thus unlimited, but the choice is not easy.

The effect of three curing regimes, namely, continuous water curing, 1 day in mold followed by air curing (20°C, 60% RH) and 1 day in mold + 6 days in water + air curing at 20°C and 60% RH for 21 days are shown in Figs. 11 and 12. These data confirm, in general, the trend of strength development shown in Tables 3, and 9 to 13, when the concrete is inadequately cured or subjected to prolonged air drying. Fabricating concrete without any water curing should obviously be never practised, but with proper selection of fineness, w/b, replacement level and adequate curing, slag concretes can be proportioned to give compressive strengths of 30 to 50 MPa at 1 day and 70 to 100 MPa at 28 days. When these strength attainments are combined with the enhanced durability properties of the resulting composite concrete, the overall and over-riding benefits of incorporating a fine slag in concrete can be fully appreciated.

The presence of slag does not reduce the Young's modulus of elasticity of the concrete as shown in Fig. 13 for both normal as well as fine slag. For compressive strengths of 60 to 85 MPa, and, for concretes containing up to 70% replacement with slag of 453 m²/kg fineness, the elastic modulus is shown to vary from 35 to 38 GPa, compared to 34 to 36 GPa for PC concretes with compressive strengths of 60 to 75 MPa. For compressive strengths in excess of 100 MPa, Fig. 13 shows elastic moduli in excess of 40 GPa. These results confirm that structural properties need not be sacrificed when FA or slag is incorporated in concrete, but that an engineering approach to concrete material selection is essential to appreciate the limitations as well as the potentialities of these materials, and the techniques to be employed to overcome the weaknesses.

DURABILITY PROPERTIES

There are considerable published data on the role of FA and slag on the durability properties of concrete incorporating them. Some of the data appear to be

contradictory, whilst others seem to indicate the benefits to be minimal. Here some consistent and co-ordinated data obtained over a period of several years are presented to show the tangible benefits to durability that can be achieved with the use of FA and slag.

Resistance to Chloride Penetration

Chloride ions are now universally recognized to be the major cause of premature corrosion of reinforcing steel in reinforced concrete. Chloride ions can only be transported into concrete or diffuse through it in the liquid phase with water, and the mechanism of their intrusion is the result of a time-dependent phenomenon combining physical processes and chemical interactions. The paths that provide chloride intrusion depend on the pore structure of concrete. There is, however, no direct relationship between porosity and permeability, in general terms, and the only proof of resistance to chloride ion penetration is laboratory test data which are based on chlorides actually intruding into concrete.

In the data presented here, reinforced concrete slabs 1000 x 500 x 150 mm, simulating structural elements such as pavements and bridge decks, were subjected to cyclic ponding with 4% sodium chloride solution on the cast face for 7 days followed by drying at ambient conditions for 3 days. The concrete mixtures used in the slabs contained a constant total cementitious material content of 350 kg/m³ and a constant, but high w/b of 0.60, quite deliberately, to highlight the role of pozzolans and slag in concrete. FA and slag were used as cement replacement materials, mass for mass, FA at 30% and slag at 65%, without the use of a water-reducer or HRWRA. With slag, additional tests were also carried out at 0.75 w/b. The PC used in these tests had a fineness of 345 m²/kg; the FA satisfied the BS specifications, while the slag had a fineness of 417 m²/kg. To understand the role of a very fine pozzolan such as SF, slabs with SF at 10% cement replacement level were also tested.

Figure 14 summarizes the chloride concentrations at different depths from the slab surface after 50 cycles of exposure. These data prove that FA and slag positively reduce the penetration of chlorides into concrete, compared to concrete with PC alone. The results also identify the adverse effects of bleeding on diffusion properties, and that pozzolans such as FA, which are more prone to bleeding can affect chloride permeability of the top surface layers of the concrete. These results also emphasize the need to recognize that mechanical properties such as bleeding, can affect long-term durability and that, it is worthwhile to ensure, at the concrete mixture proportioning stage, that bleeding is as low as practical.

From Fig. 14, slag is seen to be slightly superior to FA in its ability to resist chloride penetration. This is confirmed by the data in Fig. 15, which shows that even at a w/b of 0.75, slag concrete is far superior to PC concrete in controlling chloride ion penetration. Of course, it is recognised that w/b of 0.60 and 0.75 are

20 Swamy

not recommended for use in severe chloride exposure conditions, but what the test data in Figs. 14 and 15 confirm is that FA and slag are extremely effective in controlling chloride ion intrusion into concrete. Such resistance can only come from pore refinement, and the data in these figures confirm this pore refinement produced by FA and slag.

The results in Fig. 14 also emphasize the role of a very fine and highly reactive pozzolan such as SF. Such extremely fine pozzolans, with a degree of fineness many times over that of PC, should be seen not as tools for high strength but as hydration or pozzolanic reaction activators and contributing to very high pore refinement through their pozzolanic activity. As pointed out earlier, very high degrees of fineness will inevitably carry other concomitant problems, and the benefits of such high fineness cannot always be mobilized and realized in practice. A cost-effective utilization of such fine pozzolans is to use them in small quantities for durability, as shown in Fig. 14, or for high early strength as shown in Tables 16 to 18, and Fig. 9. A realistic engineering appreciation of SF can lead to its wider use for the benefit of concrete construction.

Resistance to Expansion due to Alkali-Silica Reactivity

Mineral admixtures are known to be effective in controlling the expansion associated with alkali-silica reactivity (ASR) (34 - 37). The precise mechanisms of how this control is achieved is not totally clear, but pore refinement and reduced permeability of the concretes containing pozzolans and slag as evidenced by the data in Figs. 14 and 15, and later in this paper, play a very significant part in controlling these expansive reactions. Partial replacement of PC by FA or slag also usually reduces the total alkali content of the concrete, and the pozzolanic and cementitious reactions contribute to the depletion of hydroxyl ions, further formation of C-S-H products and a lower $\text{CaO}_2/\text{SiO}_2$ ratio. There is also some argument as to the possibility of the alkali content of the FA and slag to contribute to expansion, but there is incontrovertible proof that, all pozzolans and slags, when of proper quality and used correctly and in the required amount, have a very positive role in controlling effectively and substantially the expansive strains, cracking, loss of strength, loss of elastic modulus, and structural distortions arising from ASR (35, 36 - 38). It is also equally important to realize and to appreciate that FA and slag cannot, and do not, remove these deleterious effects completely (37, 38 - 40), but that they do suppress expansion and its structural deformations very substantially.

Table 20 summarizes the ability of one typical FA in controlling expansive reactions, and in restoring the strength and elastic modulus of concrete affected by ASR. It can be readily seen that the level of cement replacement is an important parameter, and that when replaced at the required level, FA can reduce expansion significantly, and that it can preserve the original strength of the concrete, and a large part of its original elastic modulus, even for expansions in excess of 6000 μs

(millionths). Although the expansive strains are not completely eliminated, and there is about 10% reduction in the original elastic modulus of the concrete, what the data in Table 20 emphasize is that concrete can be proportioned, and structures can be designed to be protected against the degradation in engineering properties induced by ASR.

The effectiveness of FA in controlling expansion, and the resulting structural deformations in reinforced concrete beams, such as tensile steel strain and crack width, is shown in Table 21. These data again reaffirm that FA is able to control expansive concrete strains and steel strains very substantially; on the other hand, its presence has eliminated all cracking, and restores the denseness of the concrete, as evidenced by the pulse velocity, to its original value. Fly ash, thus, has an important role in combating structural damage due to ASR. Similar results are also available with slag, and all these data show how their innate qualities can be mobilized to counteract deterioration induced by concrete constituents.

Pore Refinement

Enhancement of the quality of the internal microstructure and pore refinement are the most direct results of incorporating fly ash and slag in concrete. The data on resistance to chloride ion penetration given in Figs 14 and 15, and the results of resistance to ASR expansion and its detrimental effects on structural performance shown in Tables 20 and 21 are, in effect, indirect evidence of the superior quality of the microstructure imparted by FA and slag. The most direct evidence of pore refinement, however, is given by mercury intrusion porosimetry tests, and this is illustrated here in relation to structural lightweight aggregate concrete described in Table 18 and Fig. 9. These concretes were made with lightweight aggregates derived from sintered fly ash, and contained FA or/and slag together with a small amount of the highly reactive pozzolan, SF. The pore volume and porosity of these concretes, as determined by mercury-intrusion porosimetry from mortar samples extracted from these concretes at the age of 180 days are shown in Table 22. These results show that, under continued water curing, all the concretes with FA or slag have reduced the total intrusion volume and total porosity more than the control concrete made of PC alone. Slag concrete is seen to give good performance, better than FA, and this is confirmed again by similar data at the same age, when the concretes were subjected to prolonged drying after 7 days wet curing. These data also seem to indicate that FA is much more sensitive to air drying than slag, and this also applies to concretes containing combinations of FA, slag, and SF. It can be seen that this susceptibility of FA to air drying and bleeding is also confirmed by the chloride-penetration data given in Fig. 14, but in spite of this, the overall benefit of FA and slag in enhancing durability of concrete, far better than PC concrete, remains unquestionable.

The pore size distribution at 180 days age, related to the pore volume data shown in Table 22 for the concretes described in Table 18 and Fig. 9, is illustrated in Figs.

22 Swamy

16 and 17 for concretes subjected to continuous water curing and long-term air drying respectively. The data in these two figures again confirm the pore refinement effect of FA and slag compared to that of normal PC matrix, even when the matrix is exposed to prolonged air drying. There is a significant shift in pore size distribution displayed in these figures caused by the presence of FA and slag - there is a decrease in large pore volume, and an increase in fine pore volume - a process which has a favorable and decisive influence on the permeability of the concretes. It is this pore refinement that gives concretes with pozzolans and slags the ability to resist and control the rate of deterioration of aggressive atmospheric agencies such as chlorides, sulfates, and CO_2 , and enhance the durability of concrete.

What is impressive about the data given in Table 22 and Figs. 16 and 17 is that provided there is adequate water curing, which is essential to any concrete, fly ash or slag will enhance the quality of the pore structure of the concrete, which is the key to durable performance in aggressive environments.

Pore refinement is thus inherent in materials such as FA and slag, whether they are pozzolanic or cementitious, and whether they are used alone or in combination with others. This is further illustrated here by the role of slag fineness in the refinement of pore structure as revealed by mercury-intrusion porosimetry tests, and these are quantified in Table 23. The slags used in these tests are the same as those shown in Table 19, and Table 15 and Figs. 10 to 12: the slags were used in three degrees of fineness, $453 \text{ m}^2/\text{kg}$, $786 \text{ m}^2/\text{kg}$, and $1160 \text{ m}^2/\text{kg}$, at a replacement level of 50 percent by mass.

The results in Table 23 demonstrate the influence of various parameters on pore refinement, and also show the interrelationship between strength and total pore volume. Several important effects of slag stand out.

- i. Substantial reduction in total pore volume occurs even with the coarsest slag. At 28 days, the pore volume of PC concrete is about 70% of that at 3 days while the presence of slag at $453 \text{ m}^2/\text{kg}$ fineness has reduced this to about 50% of that at 3 days.
- ii. With continued water curing, i.e. in favorable humid environments, continued pozzolanic activity enhances the pore refinement. At 91 days, the total pore volume of slag concrete is less than 20% of that at 3 days, whereas with PC concrete, this is only of the order of 50 percent.
- iii. Increases in fineness, from $453 \text{ m}^2/\text{kg}$ to $786 \text{ m}^2/\text{kg}$ at a w/b of 0.40, make only small improvements in the reduction in total pore volume. A reduction in w/b at the same degree of fineness, on the other hand, results in a further reduction in total pore volume, particularly at early ages.

iv. A further increase in the degree of fineness, of the order of three, from 453 m²/kg to 1160 m²/kg, is required to effect major reductions in total pore volume at all ages, and the benefits arising from such increases in fineness can be significant as shown further later. At this fineness, slag concrete will have about one-half of the total pore volume of PC concrete at early ages and, about one-third at 28 days and beyond.

What the results shown in Table 23 emphasize is that the nature of the two materials, i.e. PC and PC + FA or slag, is quite different - their continued rate of pozzolanic reaction or hydration, and the effect on pore structure are totally different. It can be readily seen that a humid environment imparts far more benefits to concrete with a FA or slag than to PC concrete. The enhancement of impermeability achieved by an adequately increased fineness, as shown in Table 23, is perhaps the strongest support for the argument that the manufacture or production of cementitious materials should be governed more by considerations of durability than by considerations of strength.

Permeability of Concrete

There is considerable test evidence to conclude that there can be no direct relationship, in general terms, between permeability, pore structure and durability. Indeed, one cannot expect a single or unique relationship, since several factors influence pore structure, as for example, shown by, or reflected in, the data in the Tables 20 to 23 and Figs. 14 and 15. Permeability values of concrete, on the other hand, are very much influenced by the pre-conditioning of test sample, prior to the test, and durability is very much governed by climatic changes of temperature and humidity as well as the micro-climate to which the structural element is exposed. It therefore stands to reason that unique or single relationships relating pore structure to permeability, or the general concept of durability, cannot be expected to have validity over all exposure conditions. This argument is reinforced by the fact that the over-riding factor influencing durability has to be cracking - cracking due to imposed loads aiding and abetting internal microcracking developing from (i) fabrication processes such as bleeding, plastic shrinkage, or heat of hydration, (ii) environmental conditions such as moisture and thermal movements, and (iii) internal deterioration processes such as freezing and thawing and expansive forces.

Nevertheless, permeability tests are valid and offer guidance as to the ability of concrete to withstand aggressive environments, and indeed, for a given type of concrete, there may exist broad relationships between pore structure, permeability, and durability. Irrespective of the presence or absence of such relationships, the property of permeability is recognized as one of the most critical parameters in determining the durability of concrete in aggressive environments. In the following, both air (i.e. oxygen) and water permeability are discussed in relation to the pore structure of concrete with fly ash or slag.

24 Swamy

appears to be a synergistic interaction between w/b and fineness of slag in their influence on durability.

The resistance to water penetration is only slightly changed when the slag fineness is increased from 453 m²/kg to 786 m²/kg at the w/b of 0.40, but dramatic increases to resistance to water penetration are achieved both when the fineness is further increased to 1160 m²/kg, or when the w/b is decreased to 0.30 from 0.40 at a slag fineness of 786 m²/kg. These data seem to imply that both fineness and w/b have a synergistic effect on durability, although there are clear indications that fineness has an edge on w/b in terms of their influence on durability. The data in Table 23 clearly show that a slag fineness of 1160 m²/kg at a w/b of 0.4 imparts far superior microstructural and durability properties to concrete than fineness at 786 m²/kg at a w/b of 0.30. There are, in addition, practical considerations and technical arguments for the use of a w/b of 0.40 in practice than a ratio of 0.30, although the latter may appear, at first sight, to give a better quality concrete than that with w/b = 0.40.

PROTECTION OF CONCRETE AT EARLY AGES

One cannot afford to conclude a paper of this nature without reference a particularly significant single factor related to the contribution of FA and slag to strength and durability, i.e. curing. The data given in Tables 20 to 23, and Figs. 14 to 18 confirm that pore refinement is inherent in concretes containing FA or slag or their combinations, and that this is the most outstanding property imparted by FA or slag to PC concrete. These results emphasize two important aspects of pore refinement. Firstly, pore refinement is influenced by many factors, such as the type of cement replacement material used, the level of cement replacement, the w/b, and the degree of fineness in relation to that of PC. Secondly, the development of a dense microstructure and pore refinement is a time-dependent process, and the degree of refinement is a function of the duration, from the day of casting, of exposure to a humid environment which alone facilitates the continuation of cementitious and pozzolanic reactions. Figure 19 graphically demonstrates this prime dependence of pore structure on water curing, which alone can lead to a high degree of impermeability, and Figs. 1 and 2 dramatically emphasize how this lack of water curing can significantly and adversely affect this development of a very fine pore structure. All these data confirm that water curing has to be an integral part of the design and fabrication processes of concretes containing fly ash or slag, if the chemically bound reactivity of pozzolans or slag is to be released and mobilized.

Figures 1, 2 and 15 emphasize the need for a sufficiently long curing period to develop this very low permeability and negligible ionic diffusivity of concrete. Since in practice, water curing is almost never effectively carried out, even for a short period of time, protection of the concrete and prevention of its drying, particularly at early ages, becomes a paramount necessity, especially when the

Oxygen Permeability

The oxygen permeability of the concretes, described in Tables 18 and 22, and in Figs. 9, 16 and 17 are shown in Fig. 18. This test was carried out on 50-mm dia x 35-mm high samples, cored out of parts of the prisms after the flexural test. The samples were then dried in an oven at 105°C for about 24 hours. The permeability data in Fig. 18 generally follow the same trend as the pore volume data in Table 22 and the pore refinement data in Figs. 16 and 17. The concretes with FA or slag are seen to possess reduced permeability even at 7 days, and at 28 days, the values of permeability for concretes with FA or slag are only about one-half of that of the control PC concrete, irrespective of the nature of curing. Obviously with continued ageing and air drying, the permeability values will change, but it is unlikely that the trend will be totally reversed to make fly ash and slag concretes worse than PC concrete.

Water Permeability

Permeability to water is probably more critical to concrete than permeability to gas, because the former is not only a measure of its resistance to steel corrosion (like gas permeability), but it also represents a measure of its resistance to water-borne aggressive agents such as chlorides, sulfates, and chemical reactions such as alkali-silica reactivity. In the tests reported here, cylindrical specimens 150 x 300 mm were initially cured in water at 20°C for 28 days, followed by air curing at 20°C and 60% RH for 7 days. The test specimens were then subjected to a water pressure of 1.5 MPa for 48 hours, and the depth of water penetration determined. Three test specimens were used for each measurement. The diffusion coefficient can then be calculated from the equation

$$\beta_1^2 = a D_m^2 / 4(t e^2)$$

where β_1^2 = Diffusion coefficient in mm²/sec

D_m = Average depth of penetration, in mm

t = Time during which pressure is applied, in secs

a = Coefficient related to t , 175.7

e = Coefficient related to pressure, 1.301

The results of these tests are also presented in Table 23. It is readily seen that PC concrete has the highest water penetration, and also, the highest diffusion coefficient. All the slag concretes have lower depths of water penetration, and a much lower diffusivity to water. The results of water permeability tests in Table 23 generally follow a similar trend to total pore volume given in the same Table; but much more importantly, the influences of the combinations of w/b and slag fineness on total pore volume and water tightness are very similar. In other words, there

26 Swamy

concrete is exposed to aggressive agents in hot, humid environments favorable to the penetration of chlorides and sulfates. Field research shows that, in salt-laden environments, chlorides can penetrate concrete within a short period of time of exposure (41), and if such exposure occurs before the material has had a chance to develop adequate refinement of its pore structure, then the durability of that concrete with time will certainly be in danger. In aggressive environments, and in rapidly drying ambient conditions, the protection of concrete through appropriate coatings or membranes becomes a necessity. Without such protection, concrete can not develop its full potential for a high degree of impermeability to ionic diffusion.

CONCLUDING REMARKS

The overall objective of this paper is to show that FA and slag can impart significant benefits to the quality and durability of concrete which are far superior to what can be achieved when PC alone is used as the binder matrix in concrete. Blind incorporation of these materials is, however, unlikely to unravel their ability to contribute to durability, and through durability, to long-term serviceability of cement-based materials and concrete structures. Indeed, such an approach will be unable to tap the technical and economic advantages that these materials can bring to the construction industry, and may, sometimes, lead to the misuse of such materials.

The paper discusses the inherent and fundamental characteristics of FA and slag, and shows that the ability to contribute to durability and strength is chemically bound in them. A clear understanding of these qualities is essential to develop the mixture proportioning criteria that will optimize their incorporation in concrete. It is then shown that, on this basis, fly ash and slag concrete mixtures can be proportioned to develop 3-day strengths equivalent to those of PC concrete without any cement replacement materials.

Attention is drawn to the fact that, by their very pozzolanic and cementitious nature, early age strength and the rate of gain of strength of FA and slag concretes will necessarily be low. This apparent drawback is further aggravated by the need for an adequate period of moist curing, as the lack of it will affect not only strength development but also the refinement of the pore structure, and engineering properties, such as shrinkage. Extensive data are presented to show how these disabilities can be overcome by an engineering approach, and how, even with continued air drying, FA and slag can impart superior qualities to concrete than when PC is used alone.

The paper identifies the factors that influence bleeding and times of setting, and shows how FA and slag concretes can be proportioned to reduce and control bleeding rates and times of setting. The benefits of increased resistance to thermal cracking imparted by FA and slag are discussed, and it is shown the incorporation

of FA and slag can bring significant benefits in this respect, superior to that of PC alone, and to the durability of the material.

Data are presented to show that the incorporation of a small quantity of a fine pozzolan can significantly enhance the contributions of FA and slag to strength and durability. An extremely fine pozzolan, several orders of magnitude finer than PC, is, in reality, unproductive in concretes, and can only be of limited use, and may even lead to undesirable side effects. An increase in fineness of two to three times that of normal PC, on the other hand, of the slag itself, for example, can preserve the benefits of material fineness on a variety of engineering properties such as bleeding, time of setting, heat evolution, high strength and excellent durability. A judicious combination of slag fineness, w/b and replacement level can produce a very high performance concrete with very high strength.

The durability properties of FA and slag concretes are discussed. Extensive data are presented to show their improved resistance to chloride penetration, and to expansion and other structural deformations arising from ASR, pore refinement, gas permeability and water permeability. It is shown that FA and slag, when properly incorporated in the proper amounts, can produce a high quality and highly impermeable concrete that can lead to durable service life even in very aggressive environments. The need to protect the concrete, particularly at early ages, and to enable the concrete to achieve and develop its microstructure refinement, which is the key to durable performance, cannot, however, be overemphasized. Availability of moisture for a sufficiently long period, immediately after fabrication, is fundamental to the use of FA and slag, and one can only ignore this basic requirement at the sacrifice of all those qualities that improve concrete constructions.

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28 Swamy

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TABLE 1—DEVELOPMENT OF COMPRESSIVE STRENGTH (CUBES) WITH CLASS F FLY ASHES (18)

Cube strength (MPa)*						
Mix	W/(C +F)	3 days	7 days	28 days	84 days	1 year†
Plasticized mixtures						
Group A	0.43-0.46	23-27	31-35	43-49	55-61	46-48
Group B	0.42-0.46	20-20	28-38	41-52	52-67	45-49
Non-plasticized mixtures						
Group B	0.44-0.51	18-26	25-35	37-49	44-63	32-42‡

*100 mm cubes: design strength 30 MPa at 28 days, slump 75 mm; water-cured 20°C for 3 to 28 days.
†Site curing
‡Tested at 182 days

TABLE 2—MIXTURE PROPORTIONS FOR CONCRETE WITH 50% CEMENT REPLACEMENT

Constituent	Dry mass per m ³ (kg)		
	20 MPa*	40 MPa	60 MPa
Cement	133	174	233
Fly ash	133	174	233
Fine aggregate	760	720	660
Coarse aggregate	1120	1093	1035
Water	163	148	145
HRWRA	1.7	1.8	1.8
%(cement + PFA)			

*Target strength

TABLE 3—DEVELOPMENT OF CUBE COMPRESSIVE STRENGTH WITH FA - 50% CEMENT REPLACEMENT

Mix No.	Age (days)	W/(C + PFA)	Compressive Strength MPa		
			Moist	Lab,	7 days moist + lab
20	1	0.61	4.4	-	-
40		0.43	11.8	-	-
60		0.32	21.8	-	-
20	7	0.61	13.0	14.1	-
40		0.43	31.3	31.3	-
60		0.32	43.3	42.2	-
20	28	0.61	23.7	19.9	25.2
40		0.43	46.6	38.7	48.6
60		0.32	63.3	53.2	64.9
20	150	0.61	41.8	24.9	26.5
40		0.43	65.4	46.1	51.2
60		0.32	85.5	65.3	76.0
20	270	0.61	46.8	22.7	28.1
40		0.43	70.0	48.3	56.4
60		0.32	88.8	60.5	78.7
20	365	0.61	49.5	23.5	27.1
40		0.43	75.6	47.3	52.2
60		0.32	92.5	61.9	77.0

34 Swamy

TABLE 4—HVFAc MIXTURE PROPORTIONS (29)

Mixture No.	Batch	W/(C+FA)*	Water, kg/m ³	Cement kg/m ³	Fly Ash,		Coarse Agg., kg/m ³	Fine Agg., kg/m ³	AEA,** mL/m ³	HRWRA L/m ³
					Source	kg/m ³				
1	A	0.32	119	155	FA1	214	1192	642	640	6.8
	B	0.32	119	155	FA1	214	1192	642	575	6.3
2	A	0.32	118	154	FA2	214	1202	647	185	4.1
	B	0.32	117	154	FA2	213	1195	643	185	4.1
3	A	0.32	117	153	FA3	212	1189	639	185	3.6
	B	0.32	119	155	FA3	214	1202	647	180	3.7
4	A	0.45	170	380	-	0	1041	694	90	2.5
	B	0.45	171	384	-	0	1054	702	85	2.5

*Water-to-(Cement + Fly Ash) Ratio

**Air-Entraining Admixture



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TABLE 5—MIXTURE PROPORTIONS FOR SLAG CONCRETE WITH 50% AND 65% REPLACEMENT LEVELS

Mixture	M1	M2	M3	M4	M5	M6	M7	M8
Replacement, Percent	0	50	50	50	65	65	65	65
OPC, kg/m ³	360	205	200	200	154	150.5	147	147
Slag, kg/m ³	0	205	200	200	286	279.5	273	273
OPC + slag, kg/m ³	360	410	400	400	440	430	420	420
Gravel, kg/m ³	1011	1011	1011	1011	1078	1011	1011	1011
Total aggregate, kg/m ³	1711	1711	1711	1711	1728	1711	1711	1711
Aggregate-cement ratio	4.75	4.17	4.28	4.28	3.93	3.98	4.07	4.07
Sand/total aggregate	41	41	41	41	41	41	41	41
Water/(cement & slag) ratio	0.55	0.40	0.45	0.43	0.46	0.40	0.40	0.40
HRWRA, % by weight of (cement & slag)	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80
Slump, mm	55	>160	>160	>160	>160	>160	>160	>160

TABLE 6—STRENGTH DEVELOPMENT OF SLAG CONCRETE

Age, days	Compressive strength, MPa							
	17.40	11.70	6.03	9.00	4.80	5.40	4.90	4.40
1								
3	26.10	25.80	21.50	25.40	-	25.00	24.00	24.70
7	38.50	40.50	36.80	38.50	35.10	40.50	36.80	37.10
28	47.50	55.70	53.70	56.70	47.90	57.50	55.90	55.70
Mix	M1	M2	M3	M4	M5	M6	M7	M8

TABLE 7—RATE OF GAIN OF STRENGTH FOR FA CONCRETE WITH 50% CEMENT REPLACEMENT

Concrete Strength MPa	Strength as percentage of 28-day strength		
	1 day	3 days	7 days
20	22	44	64
40	22	48	71
60	32	56	71

TABLE 8—RATE OF STRENGTH GAIN FOR SLAG CONCRETE AT 50% AND 65%
REPLACEMENT LEVELS

Age, days	Strength development as percentage of 28 days								t levels
	37	21	11	16	10	9	9	8	
1									
3	55	46	40	45	-	44	43	44	
7	81	73	69	68	73	70	66	67	
28	100	100	100	100	100	100	100	100	
Mix	M1	M2	M3	M4	M5	M6	M7	M8	

TABLE 9—STRENGTH DEVELOPMENT OF SLAG CONCRETE AS A FUNCTION OF CURING REGIME

Mixture	Age, days	Compressive strength, MPa		
		Fog, F	Lab, L	7F + L
M4	1	9.83	7.20	6.00
M7	1	4.40	4.10	4.30
M4	3	27.90	28.90	28.20
M7	3	23.90	19.00	23.73
M4	7	38.20	39.00	41.00
M7	7	36.60	27.40	37.60
M4	28	57.70	46.80	58.80
M7	28	54.60	34.20	57.00
M4	90	72.00	54.90	69.00
M7	90	66.90	38.20	59.40
M4	180	72.10	57.10	73.30
M7	180	68.70	36.47	57.63

*Mix M4: 50 MPa with a 50% slag replacement; W/C + S = 0.43

†Mix M7: 50 MPa with 65% slag replacement; W/C + S = 0.40

TABLE 10—INFLUENCE OF INITIAL WATER CURING ON STRENGTH DEVELOPMENT OF SLAG CONCRETE

Mixture	Age, days	Compressive strength Ratio		
		L/F	7F + L/F	7F + L/L
M4	1	0.73	0.61	0.83
	3	1.03	1.01	0.98
	7	0.98	1.07	1.05
	28	0.81	1.01	1.25
	90	0.72	0.96	1.26
	180	0.79	1.02	1.28
M7	1	0.93	0.98	1.05
	3	0.83	0.99	1.25
	7	0.75	1.03	1.37
	28	0.63	1.04	1.67
	90	0.57	0.89	1.55
	180	0.53	0.83	1.58

*F = fog curing; L = Lab curing; 7F + L = 7 days for fog curing + drying in internal environment.

TABLE 11—STRENGTH DEVELOPMENT OF PC CONCRETE

Required strength MPa	Age, days	Compressive strength, MPa		Percentage of 28 days strength	
		Fog	Dry	Fog	Dry
60	7	49.5	38.7	81	88
60	28	61.0	44.0	100	100
60	90	69.2	46.0	113	105
60	360	71.9	44.0	118	100

42 Swamy

TABLE 12—RATE OF STRENGTH DEVELOPMENT WITH CURING REGIME FOR FA
CONCRETE AT 50% REPLACEMENT LEVEL

Percentage of 28-day strength										
Strength 20 MPa			Strength 40 MPa			Strength 60 MPa				
Age days	Fog	Dry	7F + D	Fog	Dry	7F + D	Fog	Dry	7F + D	7F + D
1	19	-	-	25	-	-	34	-	-	-
7	55	71	-	67	80	-	68	79	-	-
28	100	100	100	100	100	100	100	100	100	100
150	176	125	104	140	119	105	135	123	117	117
270	197	114	110	150	125	116	140	113	121	121
365	209	118	106	162	122	107	146	116	118	118