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 m^2/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.

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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 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 alkalies, 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

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 that 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

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 emphaize 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 SiO_2 + Al_2O_3 + Fe_2O_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 dosages of air-entraining admixtures of 650 to 720 mL/m^3 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 expansioon 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 m^2/kg, and the slag was a coarsely ground slag with a specific surface of 350 m^2/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 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 alkalies 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.