Role of Superplasticizers and Slag for Producing High Performance Concrete

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Synopsis: This paper presents a detailed investigation into the role and effectiveness of ground granulated blast-furnace slag and a high range water reducer (HRWR) on the quality of concrete in terms of bleeding, setting times, heat evolution, strength development and pore structure. The tests were carried out in two parts. (a) A slag of normal fineness was used, and both the replacement level and water-binder ratio were varied. It was found that both the slag and the HRWR acted as set retarders in terms of setting times and heat evolution. The water-binder ratio was the predominant factor affecting the rate of bleeding. The presence of slag, on the other hand, caused low early strength and slow strength development but had significant beneficial influence on the total pore volume and pore size distribution. (b) The fineness of slag was varied from 453 to 1160 m^2/kg and the replacement level was kept constant at 50%. It was then possible to obtain compressive strength in excess of 30 MPa at 3 days and 100 MPa at 28 days with very substantial reductions in total porosity and water permeability. The bleeding rate was also reduced and the setting times also improved. The overall conclusion of this study is that a judicious combination of HRWR and slag fineness can lead to a very effective synergic interaction to produce concretes of high strength, high modulus and very low porosity.

Keywords: Blast furnace slag; bleeding (concrete); durability; high performance concretes; permeability; porosity; setting (hardening); slags; strength; superplasticizers; water reducing agents

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INTRODUCTION

Neither the use of superplasticizers nor the incorporation of ground, granulated blast-furnace slag (GGBFS) in concrete are new to concrete technology and to the construction industry. Water-reducing agents and plasticizers and, more recently, high range water-reducers (HRWR) are, however, often largely seen as workability agents, with the emphasis on possible savings in cement and increases in compressive strength. The incorporation of GGBFS as a cement-replacement material, on the other hand, is often viewed as a means of reducing the temperature rise due to hydration, in addition to its chemical resistance, with a penalty on early age and subsequent development of strength. Both these perspectives are narrow and limited, and if one takes the broader and global view of the need for concrete structures to perform safely, satisfactorily and durably for a long time, these concepts may be argued to be not only misplaced, but unrepresentative of the potential of these concrete constituents to contribute to long-term durability, and to the conservation of resources and energy.

Whilst good workability is accepted as an essential requirement for proper placing and adequate compaction of concrete, the role of HRWRs should not be seen to be solely related to water reduction nor are HRWRs to be treated as agents of workability. GGBFS, on the other hand, has the inherent ability to contribute to strength, stiffness and durability, but this hidden potential is chemically bound and locked within the material itself, and needs to be extracted and mobilised for utilisation. A combination of slag and superplasticizer can help to bring out the unique properties of each of these components, and show that the synergic interaction between slag and superplasticizers can produce a more durable and stronger concrete than when either of these materials is used alone with portland cement. The aim of this paper is to show how this synergistic reaction between superplasticizers and portland cement-slag combination can be designed for and achieved, and thereby influence beneficially bleeding, setting time, heat of hydration, mechanical properties, and more importantly, the factors that control the durability properties of the resulting composite concrete.

SCOPE OF INVESTIGATION

This investigation was carried out in two parts. The aim of the first part was to identify the roles and effectiveness of slag and the HRWR in terms of bleeding, heat evolution, strength development and pore structure. To achieve this, tests on twelve concrete mixtures were carried out. In these tests, the fineness of the slag and the water content were kept constant; the water-binder ratio, the amount of HRWR and the cement replacement level were varied to achieve concretes of consistent workability. The second part was designed to substantially enhance the qualities of the slag concrete in terms of strength development, porosity and water permeability. This was studied by increasing the fineness of the slag but keeping the replacement level, water-binder ratio and water content constant, but proportioning the concrete mixtures to have the same high workability as in the first part.

The concrete mixtures used in this study were proportioned to have low water-binder ratios and high workability with slumps in the range of 150 to 200 mm. In the first part of the study, for mixtures with the same water-binder ratio, the portland cement was replaced, mass for mass, by slag of the same fineness of 453 m^2/kg by amounts of 30%, 50% and 70% . The properties of the fresh concrete such as temperature, density, bleeding rate and setting times were determined. Heat evolution profiles from hydrating cement and slag were measured by a conduction calorimeter using cement paste. The pore structure, water permeability and the strength characteristics of the concrete were then determined. The results of these tests are compared with those of concrete without slag. In the second part of the study, slags of three different fineness, namely 453, 786 and 1160 m^2/kg, were used at a replacement level of 50%. These concrete mixtures were proportioned similar to those in the first part, and their strength development was related to porosity and water permeability. The two sets of data show that the combined use of a HRWR and slag can lead to effective synergic interaction to produce concrete of high strength, high modulus and very low porosity.

EXPERIMENTAL DETAILS

Concrete Materials

Normal portland cement, ASTM Type 1, was used for all the concretes. The physical properties and chemical analysis of the cement are shown in Table 1. The GGBFS used in the first part of the study had similar average particle size to that of portland cement but had about 40% higher surface area at 453 m^2/kg compared to 323 m^2/kg of the portland cement. Table 1 also contains the physical properties and chemical analysis of the slag. The concrete aggregates consisted of crushed sandstone with a maximum size of 20 mm with a specific gravity of 2.65, fineness modulus of 6.61 and water absorption of 0.69%. The fine aggregate was a river sand with 5 mm maximum size, 2.60 specific gravity, 2.93 fineness modulus and a water absorption of 1.20%.

The only variable in the second part of the study was the fineness of the slag. The physical properties and chemical analysis of these slags are also shown in Table 1.

Concrete Mixture Details

In the first part of the study, twelve concrete mixtures were tested with water-binder ratios of 0.45, 0.40 and 0.35. The cement replacement levels, mass for mass, were 0, 30, 50 and 70%. The aggregate contents were slightly adjusted for each mixture, with sand/total aggregate ratios varying from 0.470 to 0.426, to give dense mixtures. The mixture proportions used in the first part of the tests are shown in Table 2.

All the mixtures were proportioned to have high workability with cohesive and flowable matrices, and slumps in the range of 150 to 200 mm. The total water content for each mixture was kept at 160 kg/m^3. The high workability and control of slump was achieved by using a high range water reducer (HRWR), polyether carboxylic acid. The amount of HRWR was adjusted for the required slump, and the actual quantity used in the mixtures varied from about 3.8 to 5.8 kg/m^3, i.e. from about 1.12 to 1.22% by weight of the binder.

Test Programme

Immediately after the concrete mixing, the slump, air content, concrete temperature and density were measured. In addition, the bleeding rate and the initial and final setting times were determined according to ASTM C 232-87 and ASTM C 403-88 respectively.

The heat evolved during hydration of the portland cement and slag paste under constant temperature conditions was measured. These heat evolution profiles were determined by a conduction calorimeter using neat cement paste. The test was carried out at 20°C. Compressive strength and elastic modulus were determined from 100 x 200 mm cylinders which were cured at 20°C and 100% RH for 24 hr, demoulded, and then cured in water at 20°C. The pore structure of all the mixtures was determined from mortar samples through mercury porosimetry. The test samples were cured at 20°C in a curing room for 24 hr, demoulded and then cured in water until testing. The water permeability test was carried out on 150 x 300 mm size cylinders, which were cured in water at 20°C for 28 days followed by air curing at 20°C and 65% RH for 7 days. By applying a water pressure of 1.5 MPa for 48 hrs, the average depth of penetration and the coefficient of water diffusion were determined.

TEST RESULTS AND DISCUSSION

Properties of Fresh Concrete

The properties of the fresh concrete immediately after casting are given in Table 3. The slump results show that the designed workability was obtained for all the mixtures. The actual slump varied from 165 to 185 mm giving concretes of excellent flow characteristics. The effect of the incorporation of GGBFS in concrete in enhancing their flow properties can be assessed from the amount of HRWR added to these mixtures. For similar workabilities, it was possible to reduce the amount of HRWR with increase in the substitution rate of the slag for cement. In general, with the highest replacement level of 70%, about 10% less HRWR was used compared to that for normal portland concrete.

The air content of the fresh concrete varied from 0.7% to 1.4%. In general, the entrapped air decreased with the amount of cement replacement. The temperature of the fresh concrete immediately after mixing remained relatively constant, at 21-22°C, with the slag concrete mixtures registering more or less the same temperature as the concrete without slag. The density of the fresh concrete also varied little between the different mixtures, ranging from 2390 to 2430 kg/m^3. The incorporation of slag had thus little effect either on the temperature (immediately after casting) or the density of the fresh concrete compared to concrete without slag.

Rate of Bleeding

The rate of bleeding of all the mixtures was determined according to ASTM C 232-87. The bleeding rate (%) and the volume of bleeding water are shown in Table 4, and typical variations of bleeding with time are shown in Fig. 1 and 2. In general, the bleeding rate is seen to increase with an increase in the substitution rate of slag for cement, although there appears to be no consistent pattern between the amount of bleeding and the level of cement replacement. However, the results taken altogether show that there is a progressive reduction in bleeding as the water-binder ratio is decreased. The major reductions in bleeding occur when the water-binder ratio is decreased from 0.45 to 0.40, and still substantial reduced bleeding rates can be obtained when the water-binder ratio is decreased still further to 0.35.

The bleeding test shows that the water-binder ratio is the principal factor affecting bleeding, but that the replacement level has also an important influence on the rate of bleeding. Tests reported elsewhere (1) also show that the slag fineness is also a parameter affecting this property, so that a judicious combination of these three factors can ensure a very highly workable mixture with the minimum of bleeding.

Setting Times

The initial and final setting times of all the mixtures were determined according to ASTM C 403-88. The results of these tests are included in Table 4 and typical variation of the penetration resistance with time is shown in Fig. 3 for cement pastes with water-binder ratio of 0.40.

These results show that although the water-binder ratio has some minor influence on the setting times, the major factor influencing this property is the amount of cement replacement. Both the initial and final setting times increase as the level of cement replacement increases. In general terms, at a replacement level of 70%, both the initial and final setting times are increased by about 1 hr to 1½ hr. In the setting time tests, the mortar temperature was almost equal to the concrete temperature taken soon after mixing. The temperature in all cases was almost equal to 20°C.

The increased setting times with the incorporation of slag confirm that the cement-slag hydration is a two-stage process (2-5) and that the presence of slag acts in some respects as a set retarder. The combination of the HRWR with the slag is also responsible to some extent to the increased setting times. The carboxylic acid ether HRWR used in these tests is designed to obtain high slumps easily, particularly with low water-binder ratios, and it is also designed to control the slump loss. The setting time with the HRWR therefore tends to lag behind that without the admixture as confirmed by the heat of hydration tests shown later in this paper.

The use of high slag replacements may thus appear to prolong the time during which the concrete is vulnerable to plastic shrinkage. This may particularly be undesirable in deep section concrete members where the slag concrete may bleed longer than comparable cement concrete. In practice, this does not appear to be the case because of the cohesive and dense nature of the concrete mixtures, and the relatively short increases in the setting times achieved by the controlled use of the HRWR. In situations where the environment is such as to likely enhance the adverse effects of bleeding and increased setting times, other precautions need to be taken irrespective of whether the concrete is made without or with slag.

Heat of Hydration

The heat evolved during the hydration of the cement-slag combination was measured by conduction calorimetry. The tests were carried out at 20°C on neat cement pastes without and with the HRWR and with cement-slag mixtures. Fig. 4 shows typical heat evolution profiles for mixtures with water-binder ratio of 0.40 and cement replacement of 50%.

The results of the conduction calorimetry shown in Fig. 4 emphasize the role of both the HRWR and slag on the heat evolved during hydration. The presence of a HRWR, capable of reducing slump loss with time, has extended the peak time of heat evolution by a factor of almost two, from about 9.2 hr to about 17.2 hr. Replacing portland cement by 50% of slag at a water-binder ratio of 0.40 is seen, on the other hand, to reduce the peak heat evolution to about 60% of that of portland cement alone and this peak occurs at about the same time as that for portland cement. The incorporation of a HRWR, in addition to slag, on the other hand, again delays, as for portland cement, the occurrence of the peak heat evolution by about the same period. It is thus clear that both slag and the HRWR act as retarders so far as both setting times and heat evolution are concerned.

The heat of hydration is a major factor influencing the long-term durability of concrete. Early-age thermal cracking, arising from undesirable thermal gradients, is not easy to heal, and takes a long time to disappear. The results of the study reported here show that incorporating slag and a HRWR can not only reduce the heat evolved but can also extend the time of its evolution which will allow proper placement and compaction of the concrete in reinforcement congested sections and in hot, dry environments to be carried out.

PROPERTIES OF HARDENED CONCRETE

Compressive Strength and Elastic Modulus

Many studies have shown that the hydration of slag in combination with portland cement is a two-stage process (2-5), and because slag hydration tends to lag behind that of the portland cement component's hydration, there will always be a penalty on early age and subsequent development of strength and elastic modulus of slag concrete (5-9). The data presented in Table 4 and Fig. 4 provide basic confirmation of this phenomenon in terms of both setting times and time of peak heat evolution. Conventional mixture proportioning methods of incorporating slag in concrete are therefore likely to show a slower rate of strength development than the corresponding portland cement concrete. However, modifying the mixture proportions to compensate this can achieve high early strength as shown elsewhere (5). The test data reported here are, however, based on direct replacement of cement by slag, mass for mass, with no mixture modifications to counteract the slower development of early strength.

The early development of compressive strength and Young's modulus measured on 100 x 200-mm cylinders for the mixture proportions given in Table 2 is shown in Fig. 5 and 6. The compressive strength results of Fig. 5. show that at 3 and 7 days the slag concrete had lower compressive strength than the portland cement concrete for all substitution levels and water-binder ratios. The reduction in strength is almost inversely proportional to the amount of slag substitution. At 28 days all the mixtures with a substitution rate of slag up to 50% were able to achieve strength equal to that of the portland cement concrete, and this compressive strength varied from 50 to 70 MPa. At 70% replacement level, however, it took about 91 days for the slag concrete to achieve about the same compressive strength as portland cement concrete. At this age, all the slag concretes showed higher strength than the portland cement concrete, and this varied from 60 to 85 MPa.

Fig. 6 shows the variation of Young's modulus with compressive strength. At 28 days, this value varied from 27.0 to 34.0 GPa, and only two concretes with 70% slag at water-binder ratios of 0.45 and 0.40 showed lower modulus than the corresponding portland cement concrete. At 91 days, all the slag concretes showed higher elastic modulus than the portland cement concrete, and this ranged from 35 to 38 GPa.

Pore Structure

The influence of slag on the pore structure of the mixtures with water-binder ratios of 0.40 was determined by mercury intrusion porosimetry. Typical data on the cumulative pore volume and pore size distribution on portland cement mixtures and portland cement with 50% slag mixtures are shown in Fig. 7 to 9. These figures clearly show that the presence of slag has a significantly beneficial influence on the porosity of the resulting concrete, both in terms of total pore volume and the distribution of pore sizes. These are substantial advantages which positively contribute to enhanced durability and superior serviceability life compared to normal portland cement concrete: however, the fact remains that this superior pore structure is obtained at the expense of lower and slower early-age strength up to about 28 days at all cement replacement levels.

CONCRETES WITH SLAG OF VARYING FINENESS

It is obvious that the maximum technical, practical and economic advantages of utilizing slag concrete can be realised if one could combine the superior pore structure with high-early strength and rapid strength development comparable at least to that of portland cement concrete. Because of the inherent nature of the portland cement and slag hydration processes, it is also clear that low and slow development of strength will always be part of slag concretes, unless some slag activation techniques are used. On the other hand, the results presented above show that the combination of HRWR and slag possesses intrinsic capabilities to produce high-early strength, high strength at later ages and excellent durability. One method of overcoming some of the limitations recognized in the first part of this study then appears to be to grind the slag finer, and use the finer slag.

It is recognised that higher costs will be incurred in grinding the slag finer, but these cost disadvantages can be greatly offset by the substantial improvements in the quality of the resulting concrete and particularly in its pore structure and water tightness, as shown later. In the tests reported here the slag S4 with 453 m^2/kg slag fineness was obtained by the ordinary grinding process. The slags S8 and S12 of higher fineness of 786 and 1160 m^2/kg respectively were obtained by classifying the S4 slag with an air classifier.

In the following sections, the strength development, pore structure and water permeability of concretes containing these finer slags and the same HRWR used previously are presented. In these tests three degrees of slag fineness, namely, 453, 786 and 1160 m^2/kg were used; the slag replacement level was kept at 50% by mass, and the water-binder ratio at 0.40 and 0.30. Only typical data are shown here to emphasize how the use of fine slag and a HRWR can lead to concrete of high strength and excellent durability.

DEVELOPMENT OF STRENGTH AND ELASTIC MODULUS

Table 5 presents data on cylinder (100 x 200-mm) compressive strength development with age for portland cement concretes without and with 50% slag replacement. These concretes were proportioned in a way similar to that shown in Table 2; the water content was kept at 160 kg/m^3 and sufficient HRWR was used to give slumps of 170 to 190 mm. Although not reported here to save space, both the bleeding rate and the setting times also improved as the fineness of slag was increased. The strength results show that slags of 786 and 1160 m^2/kg fineness gave strengths comparable to portland cement concrete at 3 days and that these concretes gave strengths at 91 days in excess of about 60% to 70% compared to that of portland cement concrete. The strength data show that with slag fineness of 786 and 1160 m^2/kg, cylinder compressive strengths in excess of 30 MPa at 3 days and 100 MPa at 28 days can be obtained.

Fig. 10 shows the variation of Young's modulus with cylinder compressive strength for all slag concretes tested in this study with slag finenesses of 453 to 1160 m^{2}kg. The elastic moduli of concretes with compressive strength in excess of 85 MPa obtained with slags of 786 and 1160 m^2/kg fineness are identified separately in Fig. 10. These results show that slag concretes can develop elastic moduli comparable to that of portland cement concrete. For the very high cylinder strengths of 110 to 120 MPa, the elastic modulus was in excess of 40 GPa.

Porosity

The total pore volume of portland cement concrete and of slag concretes of varying slag finenesses is shown in Table 5. Fig. 11 shows a comparison of the cumulative pore volume and pore size distribution of portland cement paste with that of cement-slag combination with the highest slag fineness. These data show dramatic improvements in the refinement of pores and reduction in pore volume of slag concretes compared to that of portland cement concrete. Two significant factors stand out. Whilst the period of wet curing has a strong influence on the resulting pore structure, the data in Table 5 show that while the total pore volume for portland cement concrete is reduced by about 50% after 91 days curing, compared to that at 3 days, that of concrete even with the coarsest slag fineness of 453 m/kg at the same age of 91 days is only about 1/5 of its total pore volume at 3 days. As the slag fineness is increased, further significant reductions in total pore volume compared to that of portland cement concrete are also obtained. These are major improvements in the quality of slag concrete which will have a direct impact on its long-term durability.

Secondly, typical data as shown in Fig. 11, portray how the pore structure becomes finer as the slag fineness becomes higher. With all slag finenesses, the pore size is almost uniformly small, whilst the portland cement concrete shows