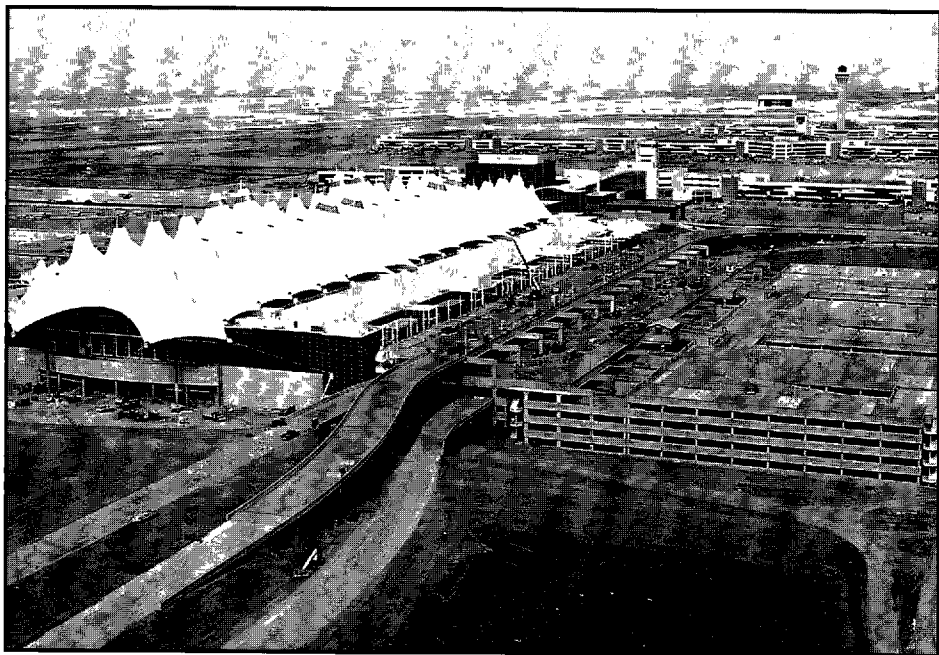


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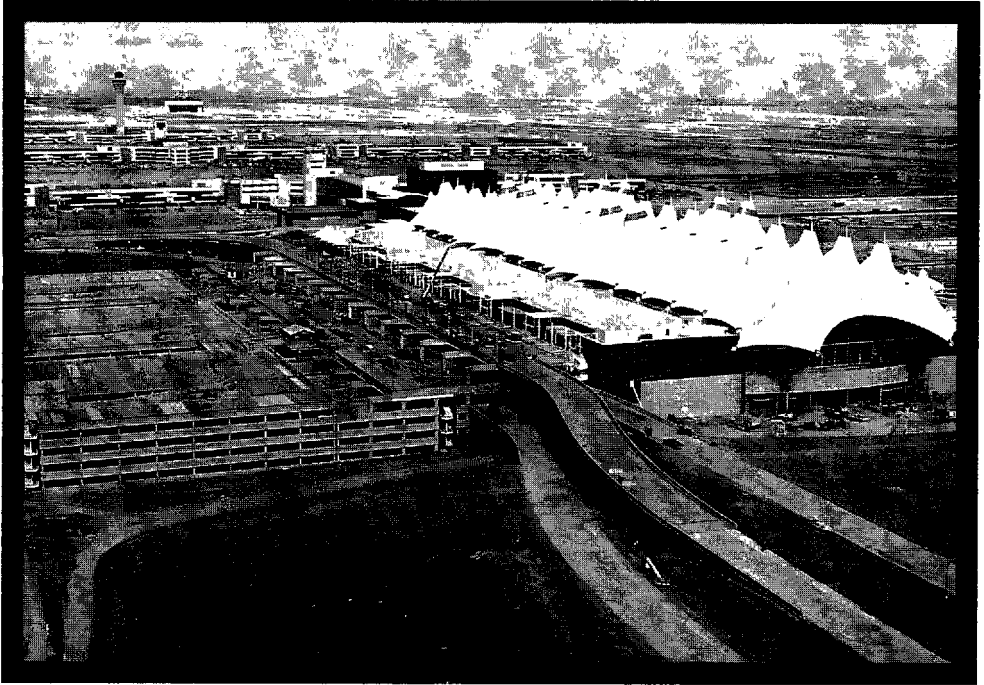


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PREFACE

In May 1978, The Canada Centre for Mineral and Energy Technology (CANMET), in association with the American Concrete Institute, the ACI Eastern Ontario and Quebec Chapter, and the Structural Division of the Canadian Society for Civil Engineering, sponsored a three-day conference in Ottawa on the use of superplasticizers in concrete. Selected papers from the symposium were published as American Concrete Institute special publication SP-62.

In 1981, CANMET in association with the above organizations, sponsored a second three-day international conference in Ottawa on the use of superplasticizers in concrete. The proceedings of the conference were published as American Concrete Institute special publication SP-68.

In October 1989, CANMET in association with the American Concrete Institute and the ACI Eastern Ontario and Quebec Chapter sponsored the third three-day international conference in Ottawa. The purpose of the third conference was to review the progress made since the meetings in 1978 and 1981; and to bring together representatives of the chemical admixtures, cement, and concrete industries to exchange information and to delineate the new areas of needed research. The scope of this conference was expanded to include chemical admixtures other than superplasticizers. The proceedings of the conference were published as American Concrete Institute special publication SP-119.

In October 1994, CANMET in association with the American Concrete Institute sponsored the fourth conference on the subject in Montreal, Canada. The objective of this conference was to bring to the attention of the concrete community the new developments in chemical admixtures since the last conference in 1989. A total of 44 papers from more than 12 countries were received and reviewed by an expert panel of ACI reviewers, and 25 were accepted for publication in the proceedings of the conference. The proceedings were published as American Concrete Institute special publication SP-148. The co-operation of the authors in accepting the reviewers' suggestions is greatly appreciated.

Particular thanks are extended to the members of the review panel for their contributions towards the publication of this volume.

The help and assistance of A. Bilodeau (Chairperson), B. Fournier, R. Chevrier (Members) of the Slide Review Panel are gratefully acknowledged. Thanks are also extended to Harry S. Wilson, Maria Venturino, and

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V.M. Malhotra, P. Eng.

Editor

Chairman, Fourth CANMET/ACI International Conference
on Superplasticizers and Other Chemical Admixtures in Concrete

October 1994

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SP 148-1

Role of Superplasticizers and Slag for Producing High Performance Concrete

by R.N. Swamy, M. Sakai, and N. Nakamura

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 m²/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 m²/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 m²/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 m²/kg compared to 323 m²/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/m³. 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/m³, 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/m³. 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 m²/kg slag fineness was obtained by the ordinary grinding process. The slags S8 and S12 of higher fineness of 786 and 1160 m²/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 m²/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/m³ 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 m²/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 m²/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 m²/kg. The elastic moduli of concretes with compressive strength in excess of 85 MPa obtained with slags of 786 and 1160 m²/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

a large size pore distribution at all ages compared with even the coarsest slag (Fig. 7 to 9). These results show that slag concrete has an inherently finer pore structure, while portland cement concrete will always have a coarser pore structure than the slag concrete.

Water Permeability

The water permeability tests reported here were carried out in accordance with what is called the "input method" reported elsewhere (11). The tests were conducted on 150 x 300-mm size cylinders which 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 cylinders were then subjected to a water pressure of 1.5 MPa for 48 hr. The depth of water penetration is then measured, and the coefficient of diffusion calculated (12).

The results of these water permeability tests in terms of the average depth of penetration and coefficient of diffusion are shown in Table 5. Fig. 12 shows typical cylindrical specimens of portland cement concrete and slag concrete of 1160 m²/kg fineness broken after the water permeability test. The depth of water penetration in the two concretes is clearly seen in this Figure.

The results of the water permeability test in Table 5 and Fig. 11 show that portland cement concrete has the highest water permeability compared to all the slag concretes. It will be seen that even the coarsest slag imparts significant improvements to water impermeability, compared to portland cement concrete. The depth of water penetration is then reduced by about 35%, whilst the diffusion coefficient is only about 45% of that of portland cement concrete. Still further improvements to the quality of concrete can be achieved when the slag fineness is increased from 453 to 786 m²/kg at the same water-binder ratio of 0.4; however, very major benefits are obtained when the slag fineness is increased further to 1160 m²/kg. At this slag fineness, the average depth of water penetration is less than 25% of that of portland cement concrete. The diffusion coefficient, on the other hand, is still further reduced. It is less than 10% of that of portland cement concrete. Quantitatively these are dramatic improvements, but when considering that water is the major transport medium for deleterious agents, the superior quality of concrete arising from the incorporation of slag in concrete can be appreciated.

There is one still further implication to the data shown in Table 5. Comparing mixtures C, D and E, it can be seen that mixture D with the 786 m²/kg slag can give almost the same microstructural quality as concrete with the 1160 m²/kg slag, if instead of grinding the slag finer, a reduction in the water-binder ratio is effected. Thus concrete with slag of 786 m²/kg fineness and water-binder ratio of 0.30 can impart durability properties similar to that of concrete with 1160 m²/kg slag fineness at a higher water-binder ratio of 0.40.

A judicious combination of slag fineness and water-binder ratio can thus achieve very substantial improvements in strength, porosity and water-tightness of concrete. The data in Table 5 thus confirm that a moderate increase in slag fineness can achieve important and large improvements in durability properties. The moderate increase in costs involved can thus be fully justified by longer and durable service life and less repair costs. Indeed, it might even be possible to achieve similar outstanding durability properties with slag fineness of 453 m^2/kg and a water-binder ratio of 0.30.

One important deduction from the porosity and water permeability data is the good correspondence between the results of these tests. The total pore volume is thus a good indicator of the denseness of the concrete and its resistance to water permeability.

CONCLUSIONS

The major conclusions derived from this study are as follows.

The HRWR enabled concrete of consistent and high workability in excess of 150 mm slump to be produced, and for similar workabilities, it was possible to reduce the amount of HRWR with increase in the substitution rate of slag. The heat evolution profiles, on the other hand, showed that the HRWR also acted as a set retarder by almost doubling the time of occurrence of the peak heat evolution, for all concretes without and with slag. The bleeding rate was found to be primarily dependent on the water-binder ratio, although it did increase with increasing amounts of slag content. The major factor influencing setting times, on the other hand, was the slag content, although the water-binder ratio also had some minor influence on this property. Replacing portland cement by 50% of slag at a water-binder ratio of 0.40 reduced the peak heat evolution to about 60% of that of portland cement alone, but a combination of slag and HRWR not only maintained this reduction in peak heat evolution, but also extended the occurrence of the peak heat evolution by about the same time.

The development of compressive strength of slag concrete was almost directly dependent on the water-binder ratio and the amount of cement replacement. In general, the reduction in strength was almost inversely proportional to the amount of slag substitution, but neither the setting times nor the heat of hydration appeared to have a direct influence on or relationship to strength development. At 28 days all the concretes with slag substitution up to 50% achieved strength equal to that of portland cement concrete. At 70% replacement level, it took about 91 days for the slag concrete to achieve about the same strength as portland cement concrete. Beyond this age, all the slag concretes possessed higher elastic modulus than portland cement concrete. The

slag had also a significantly beneficial influence on the porosity of the concrete, both in terms of total pore volume and pore size distribution.

A combination of the HRWR and a finer slag than normal produced significant improvements in strength development, total pore volume and water permeability. Cylinder compressive strengths in excess of 30 MPa at 3 days and 100 MPa at 28 days were obtained with Young's elastic modulus values in excess of 40 GPa. There were also very substantial reductions in total pore volume and impermeability to water. The use of a very fine slag with a HRWR can thus produce high strength, high modulus and very low porosity.

Grinding the slag finer will involve higher costs, but the substantial improvements in the quality of the resulting concrete, and particularly in its pore structure and water tightness, can greatly offset the higher initial costs through longer and durable service life and less repair costs. However, the data also show that a judicious combination of slag fineness and water-binder ratio can achieve similar outstanding durability properties with only minimal increase in costs.

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TABLE 1 — PHYSICAL PROPERTIES AND CHEMICAL ANALYSES OF PORTLAND CEMENT AND BLAST FURNACE SLAG

Description of Test	Portland	Slag		
	cement	S4	S8	S12
<u>Physical properties</u>				
Fineness				
88 μm (passing) %	99.5	100.0	—	—
15 μm (passing) %	54.0	63.0	97.0	100.0
Average particle μm	14.0	11.7	5.1	3.1
Surface area,				
Air permeability	323	453	786	1160
(m ² /kg)				
Specific gravity	3.16	2.93	2.93	2.93
Mortar strength (MPa) *				
3 days	16.0	—	—	—
7 days	23.8	—	—	—
28 days	42.3	—	—	—
<u>Chemical analysis</u>				
%				
Ca0	63.0	41.6	41.2	41.0
Si0 ₂	21.6	33.5	33.8	33.9
Al ₂ O ₃	5.3	15.0	14.5	14.6
Mg0	2.6	6.8	6.9	6.9
Fe ₂ O ₃	3.1	Tr	Tr	Tr
S0 ₃	2.2	Tr	Tr	Tr
Na ₂ O	0.34	0.18	0.20	0.21
K ₂ O	0.44	0.18	0.20	0.21
Loss on ignition	1.2	0.0	0.1	0.1
Insoluble	0.2	0.1	0.1	0.1
Bogue Compound composition				
%				
C ₃ S	46.0			
C ₂ S	27.4			
C ₃ A	8.8			
C ₄ AF	9.4			

* Based on 40-mm cubes

TABLE 2 — DETAILS OF CONCRETE MIXTURES

NO	* W/(C+S)	Slag Fineness Blaine m ² /kg	Sub- stitution Rate S/(C+S)	+ S/A	Unit Weight kg/m ³						
					Water	OPC	Slag	Coarse Agg.	Fine Agg.	High-Range Water Reducer	
										kg/m ³	%x(C+S)
1	0.45	453	0.0	0.470	160	356	0	1007	877	4.343	0.0122
2			0.464	249		107	1015	862	3.987	0.0112	
3			0.460	178		178	1020	852	3.845	0.0108	
4			0.456	107		249	1024	842	3.845	0.0108	
5	0.40	453	0.0	0.455	160	400	0	1016	832	4.960	0.0124
6			0.449	280		120	1022	817	4.560	0.0114	
7			0.445	200		200	1026	807	4.400	0.0110	
8			0.441	120		280	1031	798	4.400	0.0110	
9	0.35	453	0.0	0.440	160	457	0	1017	784	5.758	0.0126
10			0.434	320		137	1022	769	5.301	0.0116	
11			0.430	229		229	1025	759	5.118	0.0112	
12			0.426	137		320	1029	749	5.118	0.0112	

* C : Ordinary Portland Cement
 S : Ground, Granulated Blast-Furnace Slag
 + S - sand
 A - total aggregate

TABLE 3 — PROPERTIES OF FRESH CONCRETE

Mix	W C+S	Slag replacement %	HRWR kg/m ³	Fresh Concrete		
				Slump mm	Air * %	Temperature °C
1		0	4.3	165	1.4	22.0
2	0.45	30	4.0	170	1.3	21.5
3		50	3.8	175	1.2	21.5
4		70	3.8	177	0.9	21.0
5		0	5.0	165	0.8	21.5
6	0.40	30	4.6	168	1.2	22.0
7		50	4.4	180	0.7	22.0
8		70	4.4	185	0.7	21.5
9		0	5.8	180	1.2	22.0
10	0.35	30	5.3	182	1.1	21.5
11		50	5.1	180	1.3	21.0
12		70	5.1	185	1.0	21.0

* Entrapped Air

TABLE 4 — BLEEDING RATES AND SETTING TIMES

Mix	W C+S	Slag Replacement %	Bleeding		Setting Time	
			Bleeding rate %	Vol. of bleed water cm ³ /cm ²	Initial hr min	Final hr min
1		0	1.40	0.0605	5 - 25	6 - 50
2	0.45	30	1.76	0.0760	5 - 45	7 - 20
3		50	1.49	0.0643	6 - 15	7 - 45
4		70	1.62	0.0700	6 - 20	8 - 10
5		0	0.36	0.0156	5 - 10	6 - 35
6	0.40	30	0.51	0.0220	5 - 20	6 - 55
7		50	0.56	0.0246	5 - 40	7 - 30
8		70	0.62	0.0268	5 - 45	7 - 40
9		0	0.15	0.0065	5 - 20	6 - 45
10	0.35	30	0.46	0.0199	5 - 45	7 - 25
11		50	0.48	0.0207	6 - 00	7 - 40
12		70	0.37	0.160	6 - 10	8 - 00

TABLE 5 — STRENGTH, PORE VOLUME, AND WATER PERMEABILITY OF SLAG CONCRETES

Mix	$\frac{W}{C+S}$	Slag fineness m ² /kg	Compressive Strength, MPa				Total pore vol. mm ³ /g				Water permeability	
			3d	7d	28d	91d	3d	7d	28d	91d	Penetration mm	Diff. Coeff. x10 ⁻² mm ² /s
A	0.40	None	38.6	48.9	59.5	69.3	64.9	57.4	46.7	33.5	12.3	2.27
B	0.40	453	15.2	27.7	58.7	69.5	60.4	55.9	30.7	13.0	8.1	0.99
C	0.40	786	17.9	36.4	67.8	90.6	68.5	47.6	22.8	12.0	7.1	0.76
D	0.30	786	31.3	64.2	104.2	115.8	46.1	38.0	20.0	14.5	3.5	0.18
E	0.40	1160	34.5	64.8	101.8	122.3	41.5	31.6	16.8	11.9	2.9	0.13

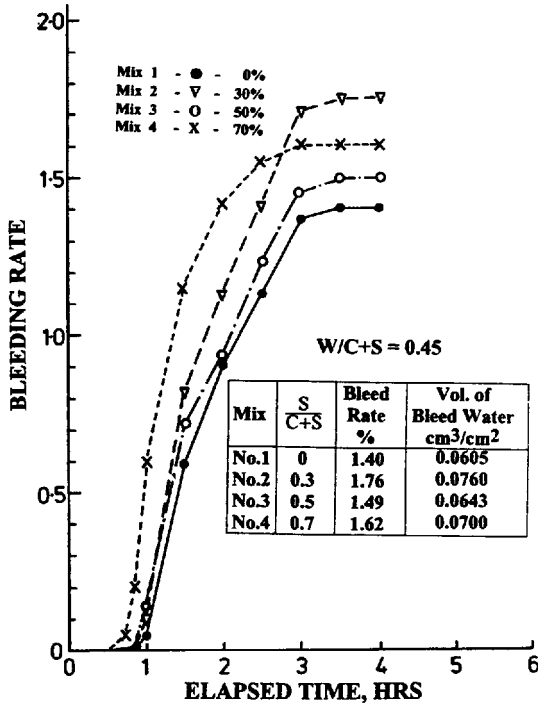


Fig. 1—Bleeding rate for mixtures with water-binder ratio of 0.45

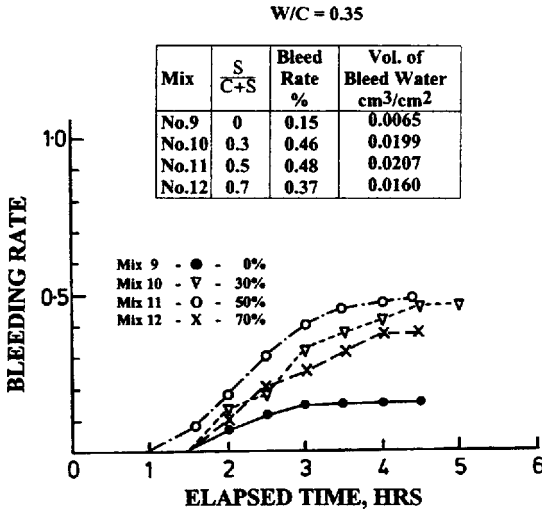


Fig. 2—Effect of slag replacement level on bleeding rate for water-binder ratio of 0.35

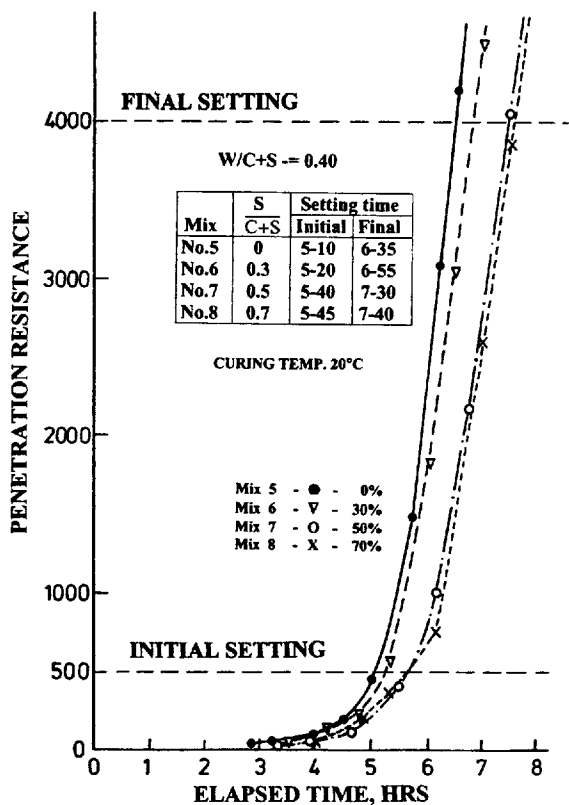


Fig. 3—Initial and final setting times for slag concretes with water-binder ratio of 0.40

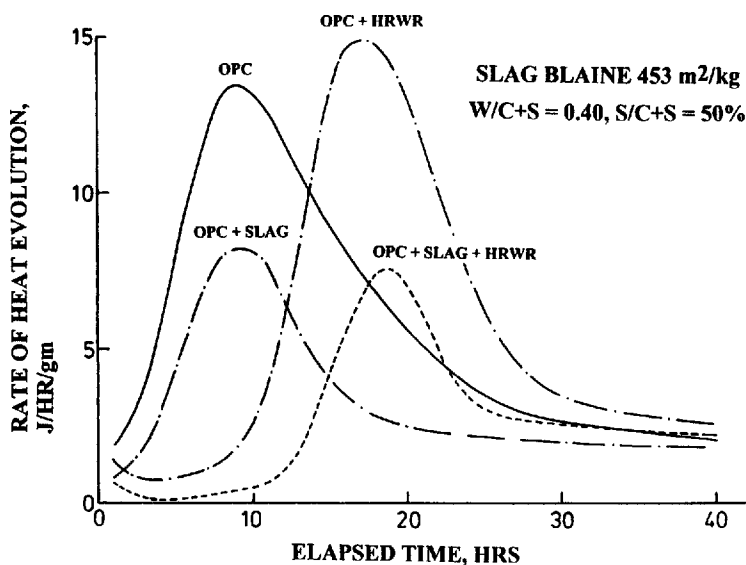
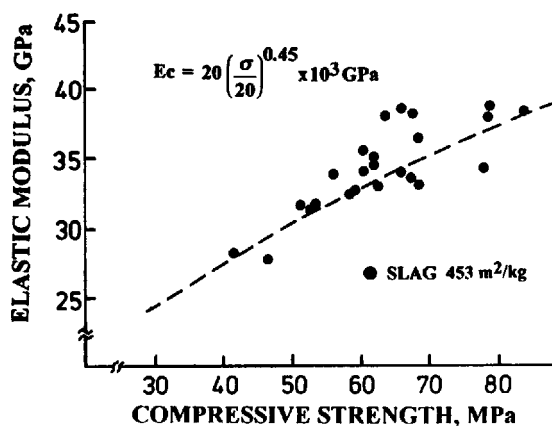
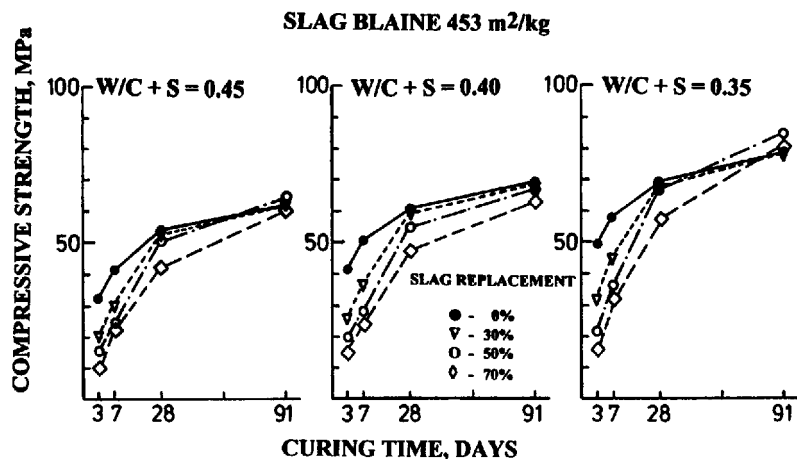


Fig. 4—Effect of HRWR and slag on heat evolution



EFFECT OF SLAG FINENESS ON POROSITY

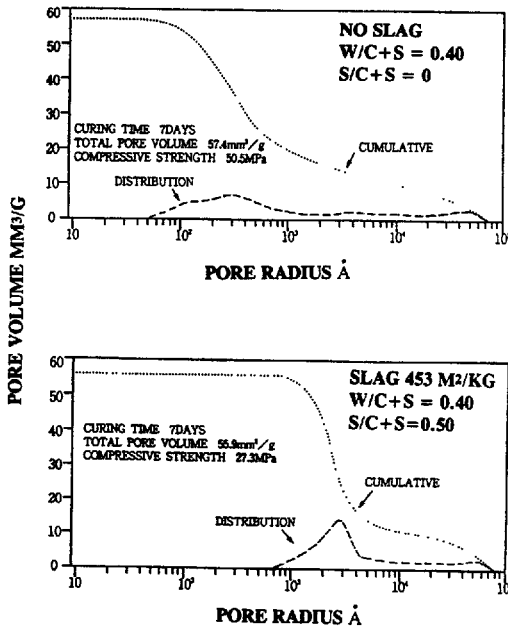


Fig. 7—Pore structure of portland cement and slag concretes: 7 days

EFFECT OF SLAG FINENESS ON POROSITY

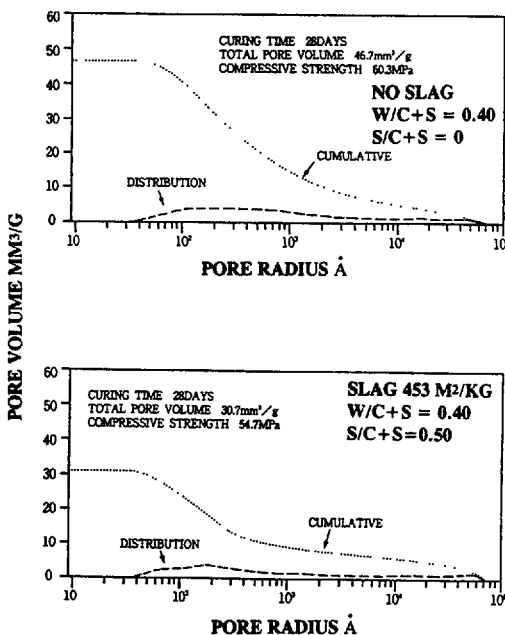


Fig. 8—Pore volume of portland cement and slag concretes: 28 days

EFFECT OF SLAG FINENESS ON POROSITY

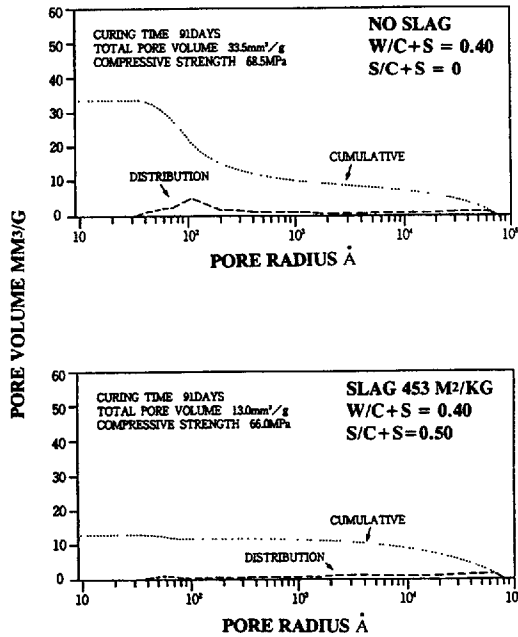


Fig. 9—Effect of slag pore volume: 91 days

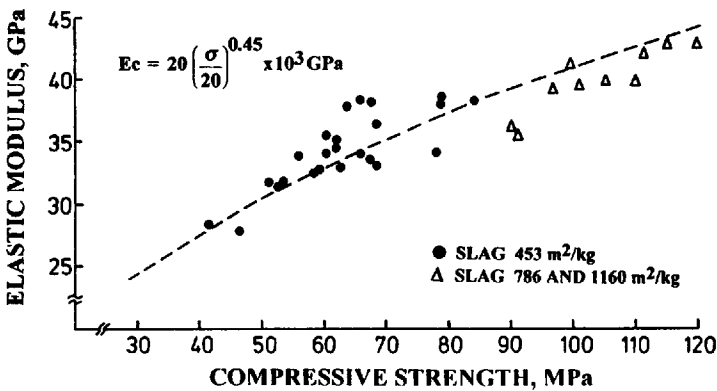


Fig. 10—Variation of Young's modulus with cylinder compressive strength for all slag concretes

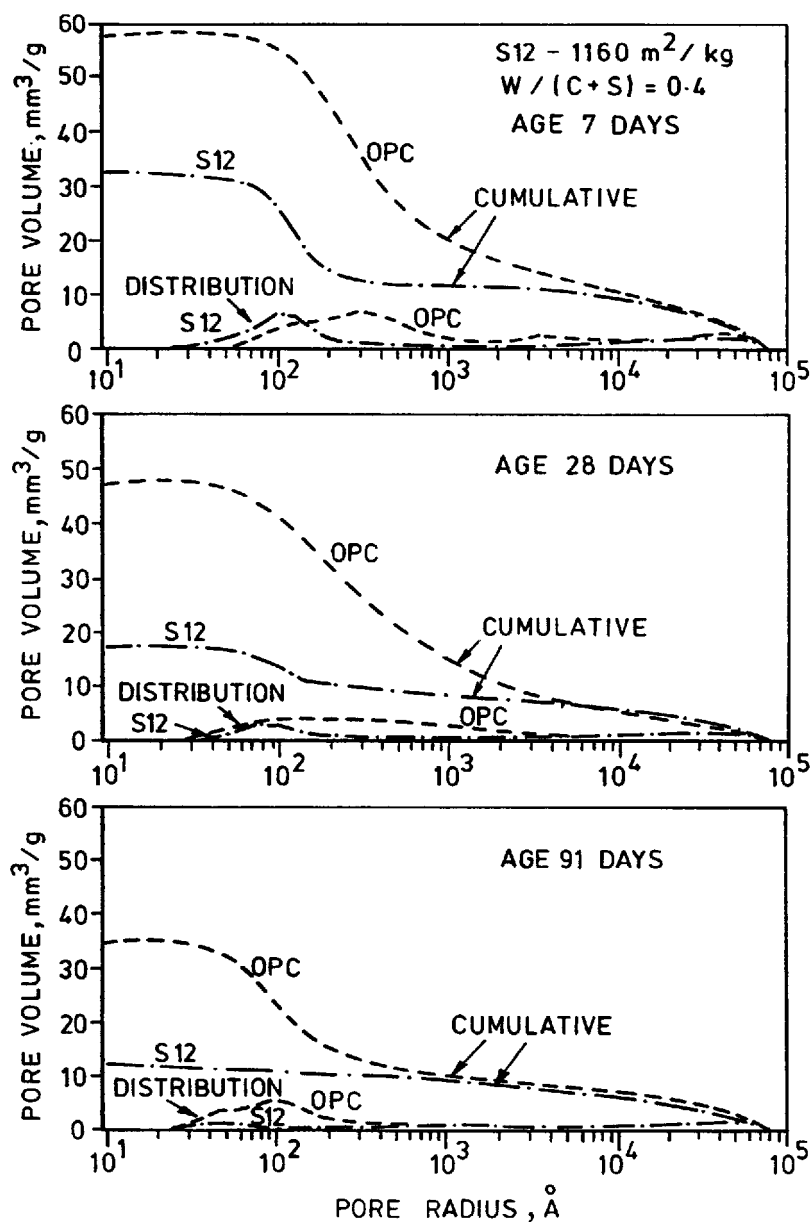


Fig. 11—Pore structure of portland cement concrete and slag concrete with very fine slag

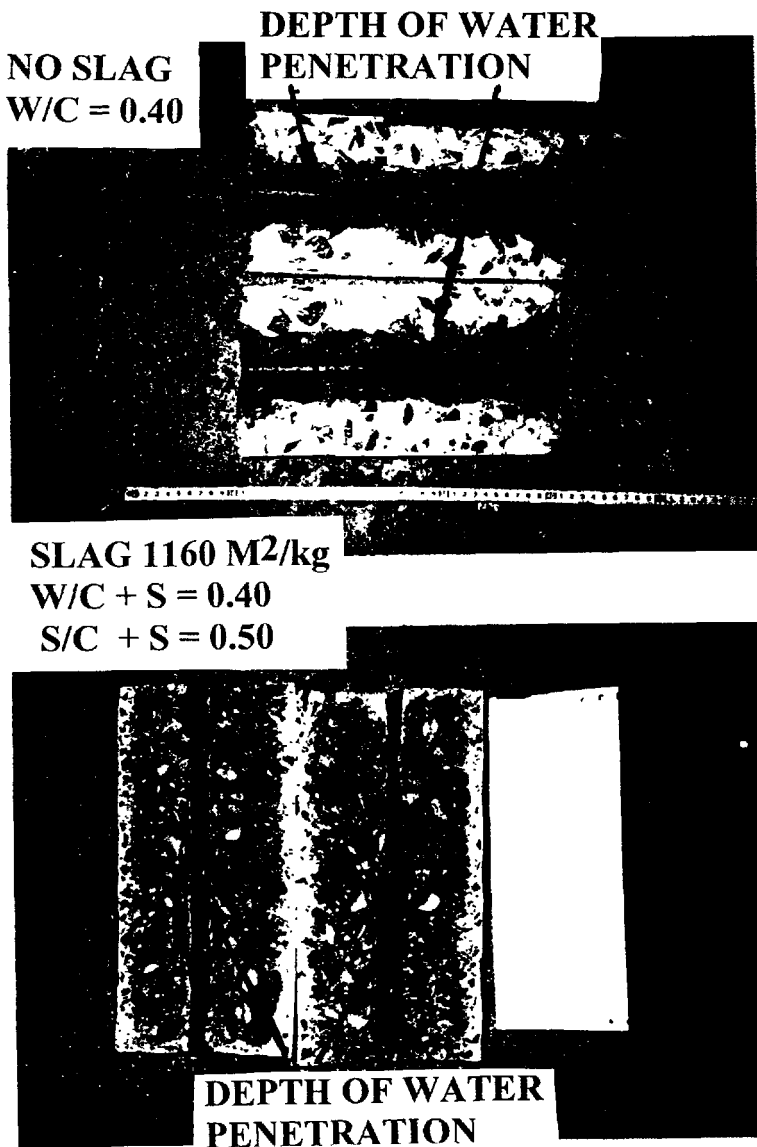


Fig. 12—Typical broken cylindrical specimens showing effectiveness of slag in reducing water permeability

SP 148-2

Application of a New Superplasticizer for Ultra High-Strength Concrete

by K. Mitsui, T. Yonezawa,
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Synopsis. The key to casting high-strength concrete with compressive strength of more than 100 MPa into complicated reinforced structures are to give the concrete high fluidity as well as to improve strength. The authors developed an acrylic copolymer-based new superplasticizer that can improve fluidity of concrete with water to binder ratio of around 0.20.

This paper gives the results of a series of studies conducted to determine the properties of fresh and hardened high-strength concrete using the newly developed superplasticizer. The effect of the new superplasticizer was examined with varying water to binder ratio, type of cement, and temperature compared with conventional superplasticizers. The new superplasticizer needed much less dosage than conventional superplasticizers to attain a certain slump (250 mm) for a water to binder ratio of around 0.20 and it significantly reduced the viscosity of concrete. Sufficient workability was kept for 2 hours without much delay in setting time while conventional superplasticizers showed large slump loss and excessive delay in setting time. The results of strength development, drying shrinkage and freezing and thawing resistance did not show any harmful effect.

Field studies were conducted on application of the high-strength concrete to a prestressed concrete bridge with design strength of 100 MPa using the new superplasticizer. Workability and strength development of concrete were tested and resulted in sufficient quality.

Keywords: Bridges (structures); coarse aggregates; compressive strength; drying shrinkage; flowability; fly ash; freeze thaw durability; high strength concretes; mix proportioning; setting (hardening); silica fume; slump; superplasticizers; temperature; workability

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INTRODUCTION

The development of concrete technology in recent years has led to considerable increases in the strength of concrete. As a result, high-rise buildings and long-span bridges have been constructed with concrete, and high-strength concrete has become essential for such huge structures. Further increases in the strength of concrete are now required in order to construct structures of even greater scales economically. Commercialization of ultra high-strength concrete exceeding 100 MPa is anticipated.

It is necessary to limit the water-to-binder ratio to a level as low as 0.20, in order to produce ultra high-strength concrete with a design strength exceeding 100 MPa. This produces viscous concrete and a loss of fluidity hampering the in-situ placement of such concrete.

The authors developed a new acrylic superplasticizer that greatly improves the fluidity of concrete with a water-to-binder ratio in an extremely low range, and retains sufficient fluidity for a longer time, when compared with conventional superplasticizers.

This paper reports on the results of experiments to compare the properties of ultra high-strength concrete in fresh and hardened states containing the newly developed superplasticizer with those of ultra high-strength concrete containing conventional superplasticizers. It also reports on the experimental study and actual application of this superplasticizer to a prestressed concrete bridge with a design strength of 100 MPa.

OUTLINE OF LABORATORY EXPERIMENT

Comparisons were made between the new superplasticizer and conventional superplasticizers, with regard to dosages, slump and viscosity losses over time, setting time, and compressive strength development.

Materials used

New superplasticizer. The newly developed superplasticizer (herein referred to as SSP) comprises an acrylic graft copolymer with graft chains and polyethylene glycol chains, with an adequate mole ratio of carboxylic groups and sulfonic groups ($-\text{COOH}/-\text{SO}^3 = 80/20$) in the molecule

Other chemical admixtures: A conventional polycarboxylic superplasticizer (SP) and a conventional naphthalene superplasticizer (NSF) were used for comparison with the SSP.

Cements: Two types of Portland cement were used, i.e. normal Portland cement (N) and Portland fly ash cement (FB).

Aggregates: River sand with a specific gravity of 2.61, water absorption of 1.16%, and fineness modulus of 2.81 was used as the fine aggregate. Crushed limestone with a maximum size of 20 mm, a specific gravity of 2.70, water absorption of 0.38%, and fineness modulus of 6.42 was used as the coarse aggregate.

Silica fume: Undensified silica fume as presented in Table 1 was used to replace 10% of the cement by weight.

Mixture proportions

The mixture proportions of the concrete are presented in Table 2. The concrete were proportioned to have the same volume of cementitious paste content (cement + silica fume + water). The flow, which was determined as the average diameter of the concrete after spreading at slump test, was measured to determine the workability of concrete. The dosages of the superplasticizers were established to provide a flow of 550 ± 50 mm. The air content was $2.0 \pm 1.0\%$.

Experimental procedure

Mix mortar for 1 minute in a pan-type mixer. Add coarse aggregate and mix for 2 minutes. Measure the slump, flow, air content, and viscosity of the concrete at 30, 60, 90, and 120 minutes after mixing. Measure setting time in accordance with ASTM C403. Test the compressive strengths using cylindrical specimens 100 mm in diameter and 200 mm in length. Measure the drying shrinkage using beam specimens 100 x 100 x 400 mm in size at a temperature of 20 °C and relative humidity of 60%. Test the freezing and thawing resistance in accordance with ASTM C666 procedure A.

Measurement of viscosity of concrete

Because high-strength concrete with a very low water-to-binder ratio has considerably high viscosity, the workability of the concrete should be evaluated not only by slump tests, but also in terms of the viscosity of the concrete (1).

The viscosity of concrete was measured by an L-shaped flow tester, a handy viscometer proposed by the authors (2). The shape of this tester is shown in Fig. 1. Concrete is filled in the vertical part of this meter. When the gate is opened, the concrete is allowed to flow into the horizontal part. Sensors are attached to the horizontal part at distances of 50 and 100 mm from the gate. The time the concrete takes to pass through this distance of 50 mm (T) is recorded. The average flow velocity of the concrete over the distance, $L_v = 50/T$ (mm/sec), is referred to as L-flow velocity. It represents the plastic viscosity of the fresh concrete. When the concrete has stopped, the lateral flow (L_f) and vertical slump (L_s) are measured. L_s and L_f correspond to slump and flow values in conventional slump testing.

It is known that the flow properties of high-slump concrete are approximated to those of Bingham liquid (3), for which the constitutive equation is

$$\tau - \tau_y = \mu \dot{\gamma} \quad (1)$$

where τ : shear stress, τ_y : shear yield stress, μ : plastic viscosity, $\dot{\gamma}$: shear strain rate

Concrete with the same slump is expected to have the same shear yield stress. When such concrete flows through the L-flow meter, shear stress histories during deformation will not differ very much. The L-flow velocity is a parameter that represents shear strain rates. Thus, it is expected, for concrete with the same slump, that the inverse of the L-flow velocity is a parameter expressing the plastic viscosity of the concrete.

RESULTS AND DISCUSSIONS

Properties of fresh concrete

Dosages of superplasticizers

Fig. 2 shows the relationship between the dosages of the superplasticizers and the water-to-binder ratios with the types of cement, when the target flow is 550 mm. The dosage of each superplasticizer is converted and expressed as the solid content.

The superplasticizers demand to obtain the required flow increased as the water-to-binder ratio decreased in all cases, but the tendencies varied with the type of superplasticizers. When the water-to-binder ratio was 0.30, the demand for SSP was similar to that for SP, and slightly smaller than that of NSF. As the water-to-binder ratio decreased down to 0.20, however, the demand for NSF increased, up to more

than 3 times the demand for SSP, which was less than 1%. As for SP, a dosage of more than 5% did not lead to the required flow. Thus the superplasticizers showed marked differences in their performance. In other words, when compared with conventional superplasticizers, the effects of SSP on the fluidity of concrete becomes more evident as the water-to-binder ratio decreases, and SSP imparts sufficient workability to the concrete with a smaller dosage.

Viscosity of concrete

Fig. 3 shows the relationship between the L-flow velocity and the water-to-binder ratio. As explained above, concrete with a higher L-flow velocity has lower viscosity. Both in the case of N and FB cement, lower L-flow velocity, and thus higher viscosity were observed as the water-to-binder ratio decreased and the strength of concrete increased. Concrete with FB cement showed higher L-flow velocity than with N cement. When the water-to-binder ratio was 0.30, the L-flow velocity of concrete with either one of the superplasticizers was practically the same. However, the differences in L-flow velocity by the types of superplasticizers increased as the water-to-binder ratio decreased. When the water-to-binder ratio was 0.20, the L-flow velocity of concrete containing NSF was approximately half and concrete containing SP was less than 1/10, of that of concrete containing SSP. It appears that SSP substantially reduces the viscosity, and improves the placeability, when compared with conventional superplasticizers. The effect of conventional superplasticizers on fluidizing concrete results from the electronic repulsion between cement particles to the molecules of the superplasticizer adsorbed on the surface of the cement (4). In spite of low dosage, the reason for the excellent fluidizing effect of SSP with a low water to binder ratio is considered to be due to the synergistic effect of the electrostatic repulsion and stabilization of the adsorbed protective layer due to the steric hindrance of the graft chains (5).

Fig. 4 shows the relationship between the dosage, the L-flow velocity, and the mixing temperature. In the range of a concrete temperature between 10 and 30 °C, the demand of SSP and NSF to obtain the required flow does not vary with temperature. However, SSP showed higher L-flow-velocity as temperature rose, while NSF showed no difference with temperature. In other words, as the temperature rises, the NSF's effect of improving the fluidity remains unchanged, whereas SSP's effect increases.

Loss of fluidity over time after mixing

Fig. 5 shows the relationship between the loss of flow and L-flow velocity and the temperature. In the case of 10 and 20°C, the flow of concrete containing SSP remained practically the same for 2 hours after mixing. The L-flow velocity also showed little loss, indicating good fluidity retention effects even with a very low water-to-binder ratio. Concrete containing NSF showed slightly larger loss in flow than in the case of SSP, but the loss of L-flow velocity was much greater than in the case of SSP. It indicates that, in high-strength concrete, the viscosity of concrete would increase over time after mixing while the flow would not show significant loss, and it varies with type of superplasticizer. The slump loss is considered to be caused by the physical agglomeration of particles (6). The steric hindrance of SSP's graft

chains is considered to be effective in preventing this physical agglomeration especially with very low water to binder ratio.

Setting time

The results of the setting time tests are tabulated in Table 3. Because concrete containing a lower water-to-binder ratio requires a higher dosage of superplasticizer, the setting time tends to be delayed. With a water-to-binder ratio of 0.25, the dosages of the superplasticizers, especially SP, were so high that proper setting was considerably delayed. Concrete containing SP did not set even at 7 days after mixing. Setting of concrete containing NSF also tended to be delayed substantially. On the other hand, the setting time of concrete containing SSP with a water-to-binder ratio of 0.20 was faster than that of concrete containing NSF with a water-to-binder ratio of 0.30. Thus the concrete incorporating SSP did not show such excessive set-retarding effects as found in conventional superplasticizers, even with a very low water-to-binder ratio.

Properties of hardened concrete

Compressive strength

Fig. 6 shows the results of compression tests at 7, 28, and 91 days. With water-to-binder ratios of 0.30 and 0.20, no appreciable difference was observed between the effects of the superplasticizers on the strength development. With a water-to-binder ratio of 0.20, however, the concrete containing SP showed unsatisfactory setting characteristics due to an overdose. It had not set at 7 days, and the strengths at later ages were substantially low. Though the concrete containing NSF attained a similar strength at 91 days as that containing SSP, the strengths at 7 and 28 days were lower than that containing SSP strengths. This may be due to the marked delay caused by the high dosage of NSF, similar to the case of the concrete incorporating SP.

Drying shrinkage

Fig. 7 shows the results of drying shrinkage tests. The drying shrinkage of the concrete containing SSP tended to be slightly lower than that of concrete containing NSF. The concrete containing either SSP or NSF showed smaller drying shrinkage with water-to-binder ratios of 0.25 and 0.20 than with water-to-binder ratio of 0.30.

Freezing and thawing resistance

Fig. 8 shows the results of freezing and thawing resistance tests. Because the air content was set to as low as 2.0% in this investigation, great losses in the relative dynamic modulus of elasticity were observed in spite of the low water-to-binder ratio of 0.25 and 0.20. However, the concrete containing the SSP indicated higher durability than that containing NSF. The concrete containing the SSP with a water-to-binder ratio of 0.20 showed no loss in the relative dynamic modulus of elasticity up to 300 cycles of freezing and thawing, in spite of the air content being as low as 2.0%. It is possible to improve freezing and thawing resistance without entraining air in such high strength concrete.

APPLICATION OF SSP FOR A 100 MPa HIGH-STRENGTH CONCRETE BRIDGE

Based on the results of the laboratory tests, the newly developed superplasticizer was applied to a cast-in-place ultra high-strength prestressed concrete bridge with a design strength of 100 MPa. The concrete was of the highest strength ever cast in situ for structures in Japan. The structure is a bridge connecting two buildings. As shown in Fig. 9, the ratio of the beam depth to the span is as small as 1/40. Therefore the design strength was set at 100 MPa, so as to ensure the strength and rigidity required for the structure. The concrete was proportioned as presented in Table 4, so as to satisfy the requirements established from the results of the laboratory tests, i.e. $W/(C+SF) = 0.20$, slump = 250 mm, flow = 550 mm and air content = 2.0%.

The concrete was produced in batches of 1.5 m³ with a pan-type mixer at a ready-mixed concrete plant. Silica fume was charged into the mixer by a special device, which was developed by the authors, (as shown in Fig. 10). This device is designed to automatically store, convey, batch, and charge undensified silica fume, which has stronger effects of increasing the fluidity and strength of concrete than densified silica fume (7). The mixing time was set at 70 sec, which is 1.5 times the time for normal concrete with W/C around 0.55

MOCK-UP TEST

Before the actual application, a construction test was conducted using a full-scale model, in order to study the quality and placeability of the fresh concrete, as well as the surface texture and strength development of the hardened concrete. The model was made to have identical cross-sections and bar arrangement as the bridge, but was 1/10 in length. The filling capability of the concrete was investigated by using transparent forms. The concrete was deposited with a bucket, and was consolidated with an internal vibrator.

Properties of fresh concrete

Table 5 presents the results of the tests on fresh concrete. Though the concrete arrived at the site 100 minutes after mixing, changes in the qualities of fresh concrete were marginal. The required qualities such as slump = 250 mm, flow = 550 mm and air content = 2.0%, were retained at the time of placing.

Compressive strength development

Fig. 11 shows the results of compressive strength tests on the control specimens and on cores drilled from the model. The control specimens were cured in water at 20 °C, seal-cured on site, or seal-cured to be synchronized with the thermal history monitored at the center of the model. Both water-cured and field-cured specimens indicated 110 MPa at 28 day, exceeding the design strength. At 91 days, the water-cured and field-cured specimens had compressive strength of 140 MPa and 121 MPa, respectively. The drilled cores and the specimens synchronized with the thermal

history of the model also reached strength of 115 MPa at 28 days. Thus it was confirmed that concrete with sufficient strength of the structure was obtainable.

Thermal history of the model

Fig. 12 shows the thermal history of the model monitored with thermocouples embedded in the center and near the surface of the model. The temperature of the concrete at the time of placing was 18.4 °C, and no delay in setting was observed. The temperature began to rise 11 hours after placing, due to the heat of hydration, and the temperature in the center reached a maximum of 55 °C 31 hours after mixing. It has been pointed out that, in high-strength concrete, high volume cement content causes high temperature rises within structures, resulting in lower strength development in drilled cores than field-cured specimens. Here the temperature rise was curbed, because the new superplasticizer enabled the unit water content to be limited to 135 kg/m³, and the use of fly ash and silica fume enabled the cement content to be limited to 470 kg/m³.

Filling of concrete

Fig. 13 shows the vertical distribution of compressive strength and coarse aggregate content tested by cores drilled vertically across the center of the model. The vertical variations of the strength and aggregate content were small, and no segregation or defective filling was observed. Adequate filling of the concrete was confirmed by inspection of the transparent forms and by the appearance of the concrete after removal of the forms.

ACTUAL CONSTRUCTION

As in the mock-up experiment, concrete in the actual construction was deposited with buckets. Because of no accumulation of bleeding water, the surface of the concrete was kept moist by being sprayed with water from immediately after placing through the final setting, so as to avoid plastic shrinkage cracks due to rapid drying.

Properties of fresh concrete

Fig. 14 shows the results of the tests on the fresh concrete immediately after mixing and upon arrival at the site. Though it took 2.5 hours to haul the concrete, changes in the quality over time were marginal, and all testing lots satisfied the quality requirements. This is because the atmospheric temperature was 14 °C, at which the new superplasticizer's fluidity-retaining effects are fully exerted.

Compressive strength development

Fig. 15 shows the results of the compressive strength tests. The strength of the water-cured specimens was 127 MPa at 28 days and 134 MPa at 91 days. The strength of the specimens seal-cured on site was 62 MPa at 5 days, when prestressing was applied, and 110 MPa at 91 days. The synchronized specimens had a strength of 112 MPa. Thus the concrete attained required the design strength.

Fig. 16 shows the appearance of the bridge after the completion. The concrete filled every corner of the forms without any cold joint or honeycomb, and was in accordance with the quality control requirements.

CONCLUSIONS

The newly developed acrylic graft copolymer-based superplasticizer greatly improves the fluidity of ultra high-strength concrete with an extremely low water-to-binder ratio. This enabled an ultra high-strength concrete with a design strength of 100 MPa to be placed on site.

1 The newly developed acrylic graft copolymer-based superplasticizer reduces the viscosity of concrete with a lower dosage than conventional carboxylate superplasticizers and naphthalene superplasticizers. The viscosity-reducing effect of the new superplasticizer, when compared with conventional superplasticizers, becomes more evident as the water-to-binder ratio decreases.

2 The new superplasticizer maintains fluidity of even an ultra high-strength concrete with a water-to-binder ratio of 0.20 for 2 hours without appreciable losses in the flow and viscosity. Also, concrete containing this superplasticizer develops sufficient strength without excessive retardation in setting, and has the same or better durability than concrete containing conventional superplasticizers.

3 An ultra high-strength concrete made using the new superplasticizer with a design strength of 100 MPa was applied to a prestressed concrete bridge, and was confirmed to have good placeability on site and adequate strength development.

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TABLE 1 — PHYSICAL PROPERTIES AND CHEMICAL COMPOSITION OF THE SILICA FUME

Specific gravity	Bulk density (kg/m ³)	Surface area (m ² /g)	SiO ₂ (%)	Carbon (%)	Moisture (%)	Loss on Ignition (%)
2.35	325	14.1	93.8	0.78	0.40	2.76

TABLE 2 — MIXTURE PROPORTIONS USING FLY ASH CEMENT

Mixture No.	Cement	Water/Binder	Air (%)	Unit Weight (kg/m ³)			
				Water	Binder		Fine Aggregate
					Cement	Silica Fume	
1	Fly-Ash	0.30	2.0	165	495	55	688
2		0.25		149	536	60	
3		0.20		130	585	65	
4	Normal	0.30	2.0	170	510	57	688
5		0.25		154	555	62	
6		0.20		135	608	68	

TABLE 3 — TIME OF SETTING

W/(C+SF)	Super-plasticizer	Setting Time(hour)	
	Type	Initial	Final
0.30	SSP	7.17	8.50
0.25		7.75	9.17
0.20		8.58	10.33
0.30	SP	7.75	9.50
0.25		9.00	10.17
0.20		*	*
0.30	NSF	9.42	10.58
0.25		9.83	11.17
0.20		11.08	12.17

*:not reached in 3 days

TABLE 4 — MIXTURE PROPORTION OF 100 MPa HIGH STRENGTH CONCRETE

W/(C+SF)	Unit Weight (kg/m ³)					
	Water	Cement	Silica Fume	Fine Aggregate	Coarse Aggregate	Super-plasticizer
0.20	135	574	101	748	836	13.5

Cement: Fly ash cement, Superplasticizer: SSP

TABLE 5 — PROPERTIES OF FRESH CONCRETE ON MOCK-UP TEST FOR THE BRIDGE CONSTRUCTION

Testing Point	Time after mixing (min.)	slump (mm)	flow (mm)	Air content (%)	Concrete Temperature (°C)	L-flow Velocity (mm/sec)
plant	0	260	605	2.1	18.0	96
site	100	250	540	2.3	18.4	56

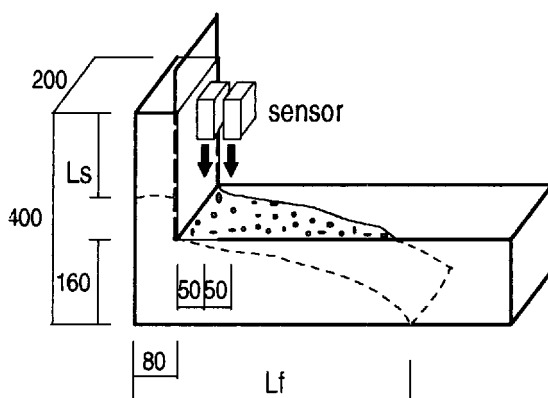


Fig. 1—L-flow meter

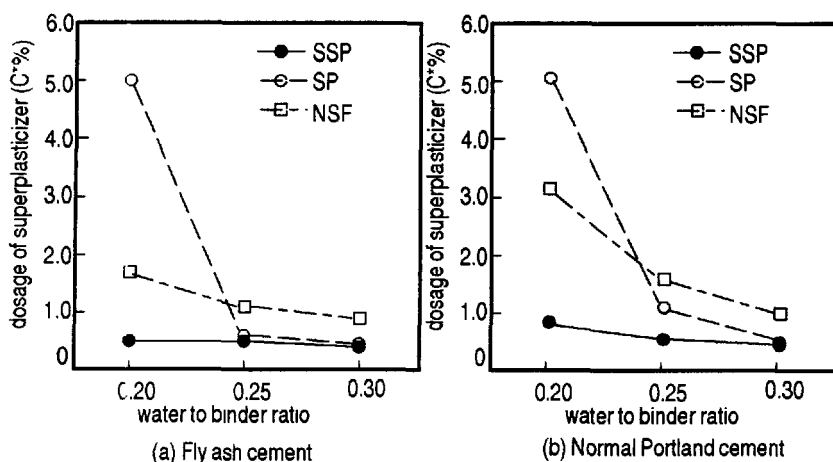


Fig. 2—Relationship between $W/(C + SF)$ and dosage of superplasticizer

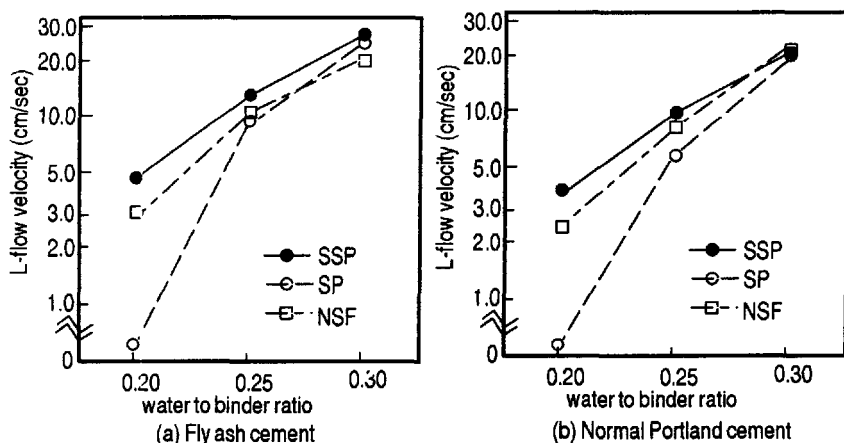


Fig. 3—Relationship between $W/(C + SF)$ and L-flow velocity

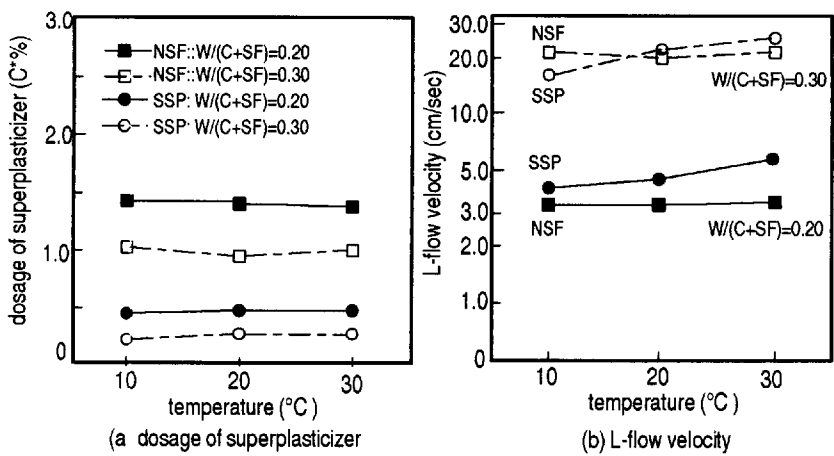


Fig. 4—Effect of temperature on dosage of superplasticizer and L-flow velocity (fly ash cement)

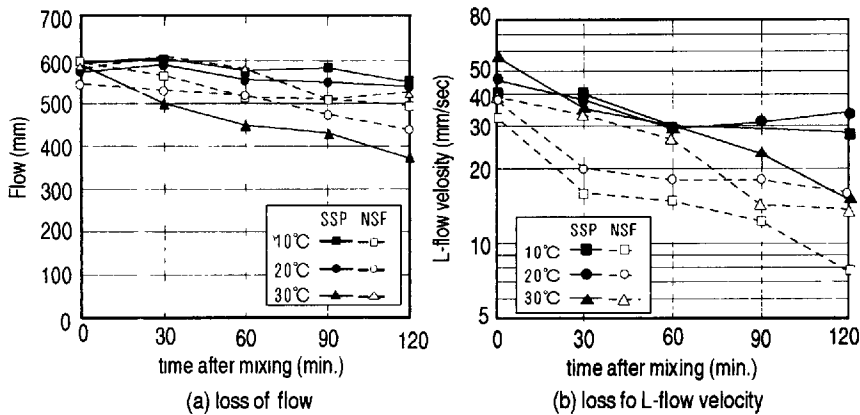


Fig. 5—Loss of fluidity of concrete with time after mixing (fly ash cement, W/(C + SF) = 0.20)

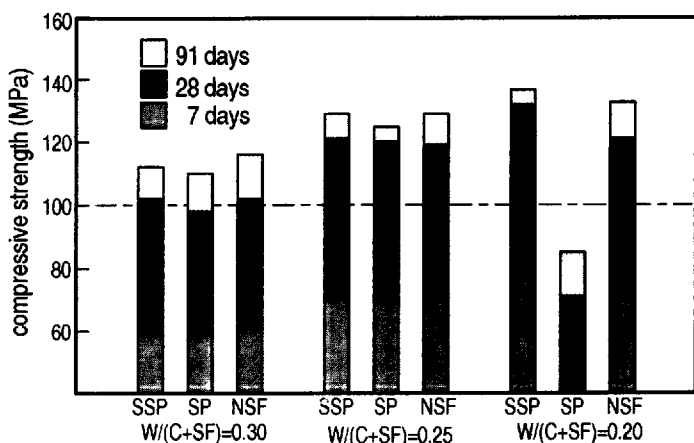


Fig. 6—Compressive strength development (fly ash cement)

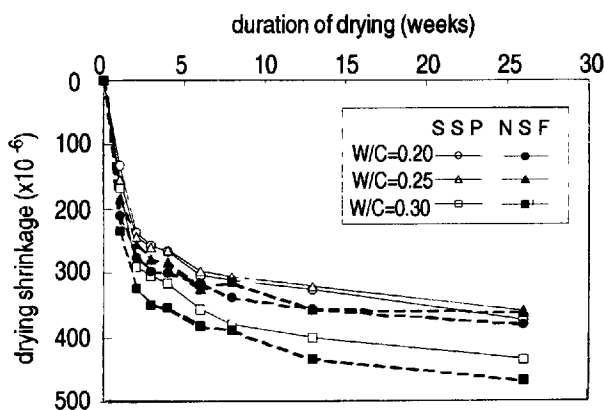


Fig. 7—Relationship between drying shrinkage and age (fly ash cement)

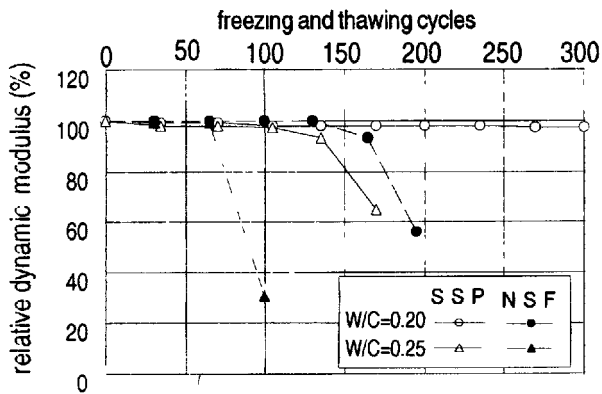


Fig. 8—Freezing and thawing resistance (fly ash cement)

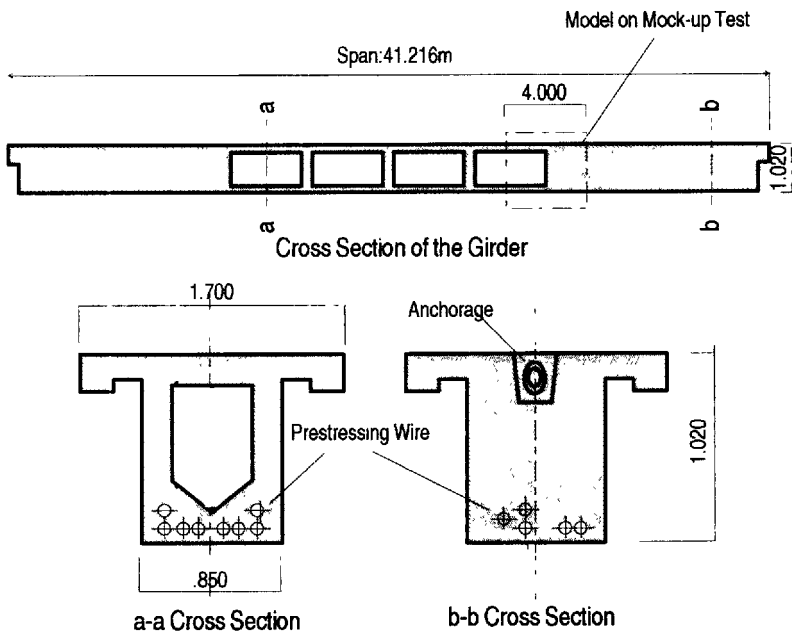


Fig. 9—Girders and cross-sections of the prestressed concrete bridge

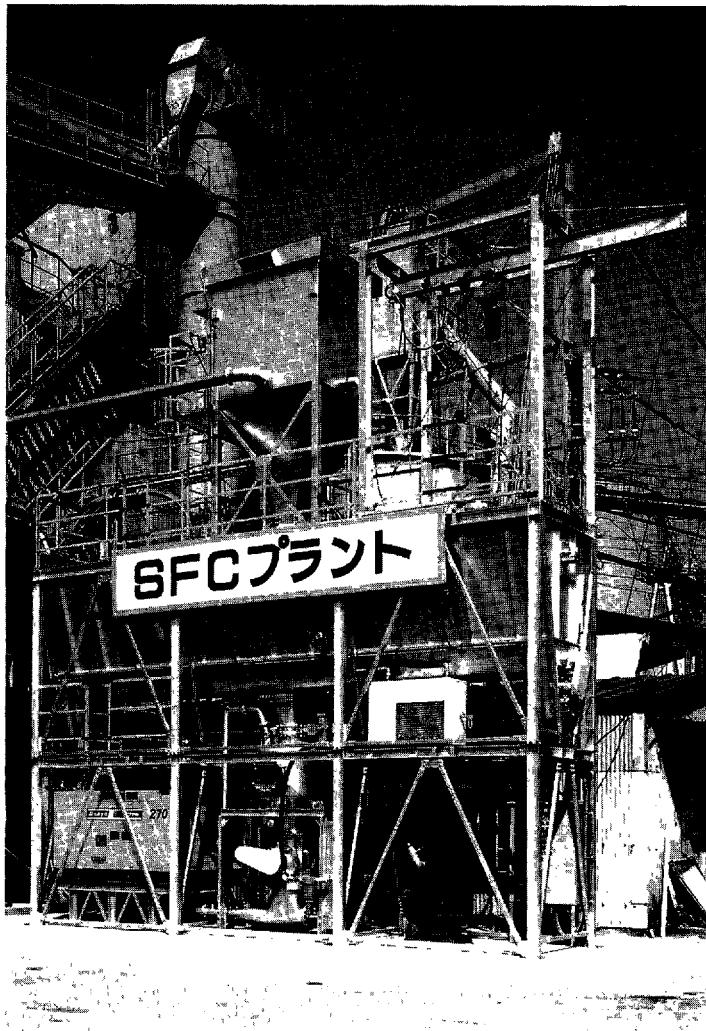


Fig. 10—A special device for using silica fume and ready-mixed concrete plant