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STRENGTH AND FREEZE-THAW CHARACTERISTICS OF CONCRETE INCORPORATING GRANULATED BLAST FURNACE SLAG

V.M. MALHOTRA

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STRENGTH AND FREEZE-THAW CHARACTERISTICS OF CONCRETE INCORPORATING GRANULATED BLAST FURNACE SLAG

by

V.M. Malhotra*

SUMMARY

Portland cement is a highly energy intensive material requiring 6570 MJ per tonne of product representing 42% of the total plant production cost. Attempts are thus being made to find materials which are less energy intensive to partially replace cement in concrete. Considerable potential has been shown by slag, the non metallic product normally discarded when making pig iron in the blast furnace. This report gives results of laboratory investigations to determine the strength and freeze-thaw durability characteristics of concrete incorporating granulated iron blast furnace slag.

A series of thirty-two 0.062-m^3 mixes was made with water to cement plus slag ratios ranging from 0.30 to 0.65, and the percentage of slag used as a partial replacement for normal portland cement ranged from 25 to 65% by weight. All mixes were air entrained and some incorporated a superplasticizer in addition to an air-entraining agent. A number of 100 x 200-mm cylinders were cast for testing in compression and splitting tension at ages up to one year. Test prisms, 90 x 100 x 405 mm, were also cast to determine flexural strength and freeze-thaw durability.

Test data showed that the dosage required for the agent to entrain a given amount of air increased markedly with increased slag content whereas there were indications that the percentage of the superplasticizer needed to obtain a slump of 200 mm was lower for concrete incorporating slag than for control concrete.

Visual examination of the fresh concrete and slump test determinations did not show any increased workability of concrete incorporating slag; on the contrary, there was evidence of higher water demand for concrete mixes having a lower water to cement plus slag ratio.

Regardless of the water to cement plus slag ratio there was generally a wide gap between the strength of control concrete and that incorporating slag, with the former being greater. The dif-

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ference in strength narrows between 7 and 91 days depending on the water to cement plus slag ratio; beyond 91 days, the difference widens again. The above strength development pattern is more marked for concrete with water to cement plus slag ratios of 0.30 and 0.38.

The flexural strength of concrete with water to cement plus slag ratios of 0.46 and 0.56 is comparable to or greater than the corresponding strength of control concrete. The reverse is true for concrete with a water to cement plus slag ratio of 0.38 for both air entrained, and air entrained and superplasticized concretes; at 65% slag replacement, there is a drop in strength in the order of 20% compared with the control concrete. The 14-day flexural strength of concrete ranged from 4.2 to 6.0 MPa for a water to cement plus slag ratio of 0.56.

Durability studies indicated that regardless of the water to cement plus slag ratio and whether the concrete was air entrained or air entrained and superplasticized, the test prisms performed satisfactorily in freeze-thaw tests (ASTM C666 Procedure B) except for mixes with a high water to cement plus slag ratio and 65% slag content.

CARACTERISTIQUES DE RESISTANCE ET DE GEL-DEGEL DU BETON AUQUEL ON AJOUTE DES SCORIES GRANULEUSES DE HAUT-FOURNEAU

par

V.M. Malhotra*

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La fabrication du ciment portland entraîne une grande consommation d'énergie soit 6570 MJ par tonne de béton produit ce qui représente 42% du coût total de production de l'usine. Afin de réduire cette consommation d'énergie, les chercheurs essaient de trouver des matériaux plus économiques susceptibles de remplacer en partie le ciment dans le béton. Les scories, produit non-métallique normalement évacué après la production de la fonte brute dans le haut-fourneau, sont d'un intérêt particulier. Le présent rapport présente les résultats des études effectuées en laboratoire afin de déterminer les caractéristiques de résistance et de durabilité suite au gel-dégel du béton auquel on a ajouté des scories granuleuses de haut-fourneau.

Trente-deux mélanges de 0.062 m^3 ont été préparés ayant des rapports d'eau à ciment plus les scories pouvant varier de 0.30 à 0.65; le pourcentage des scories employées comme remplacement partiel au ciment portland normal peut varier de 25 à 65% par poids. Tous les mélanges étaient à air entraîné et à certains on a ajouté un superplastifiant en plus de l'agent d'entraînement de l'air. Plusieurs cylindres de 100 x 200 mm ont été coulés et soumis à des essais de résistance à la compression et à la fissuration pendant une durée d'un an. Des prismes d'essais de 90 x 100 x 405 mm ont aussi été coulés pour déterminer la résistance à la flexion et sa durabilité suite au gel-dégel.

Les données de l'essai ont démontré que la dose requise pour que l'agent puisse entraîner une quantité déterminée d'air augmentait de façon marquée avec l'augmentation du contenu de scories. Les résultats ont dévoilé par contre, que la teneur de superplastifiants requise pour obtenir un affaissement de 200 mm est plus basse pour le béton avec scories que pour le béton témoin.

Un examen visuel du béton frais et les essais d'affaissement ne démontrèrent aucun accroissement de la malléabilité du béton avec des scories; par contre, plus d'eau est nécessaire pour les mélanges de béton ayant un rapport d'eau à ciment plus scories plus bas.

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Malgré le rapport d'eau à ciment plus scories, il y avait généralement une grande différence entre la résistance du béton témoin et celle du béton avec scories; la première est plus grande. La différence de résistance diminue entre 7 et 91 jours selon le rapport d'eau à ciment plus scories; après 91 jours la différence recommence à croître. La tendance de la progression de la résistance ci-dessus est plus marquée dans le cas de béton ayant des rapports d'eau à ciment plus scories de 0.30 et 0.38.

La résistance à la flexion du béton ayant des rapports d'eau à ciment plus scories de 0.46 et 0.56 est comparable à ou plus élevée que la résistance à la flexion du béton témoin. Le contraire est aussi vrai dans le cas du béton ayant un rapport d'eau à ciment plus scories de 0.38 pour les bétons à air entraîné et les bétons à air entraîné et superplastifiés. Lorsque le remplacement avec les scories est de l'ordre de 65%, la résistance diminue de 20% si comparée avec le béton témoin. Les données des essais de résistance à la flexion de 14 jours du béton varient de 4.2 à 6.0 MPa pour un rapport d'eau à ciment plus scories de 0.56.

Les études de la durabilité indiquent que malgré le rapport d'eau à ciment plus scories ou qu'il s'agisse de béton à air entraîné ou de béton à air entraîné et superplastifié, les prismes d'essais ont bien réagi aux essais de gel-dégel (ASTM C666 Procédé B) sauf pour les mélanges ayant un rapport élevé d'eau à ciment plus scories et une teneur de scories de 65%.

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INTRODUCTION

CANMET has recently become increasingly involved in research on cementitious materials aimed at conserving both resources and energy. In particular, efforts have been directed at energy conservation by using less energy intensive materials such as fly ash, slags and pozzolan. Of the concrete making materials, cement is the most energy intensive component requiring 6570 MJ/tonne of product and the cost of energy to produce one tonne of portland cement accounts for 42% of the total plant production cost (1-5). Thus any attempt to reduce the amount of cement in concrete could result in considerable savings in energy. One of the most promising of the less energy intensive materials for replacing cement appears to be granulated slag, a byproduct of the blast furnace when making pig iron. The energy required to produce granulated slag is estimated at only 25 to 33% of that for portland cement (2,3,4,6). Considerable European data are available on the performance of slag cements in concrete when granulated iron ore blast furnace slag and cement clinker have been ground together in a cement plant (7). However, only recently, have data become available on the performance of concrete when granulated iron ore blast furnace slag is added as a separate ingredient along with other mix components at a concrete batch plant (8-11).

This report briefly describes the properties of slags and gives results of laboratory investigations undertaken to determine the mechanical properties and freeze-thaw durability of concrete incorporating this material.

IRON ORE BLAST FURNACE SLAG

HISTORICAL BACKGROUND

Slag is a byproduct resulting from the reduction of iron ore in the manufacture of pig iron. The silicious and aluminous residue remaining after the iron ore has been reduced by coke to metallic iron combines with the carbonates and magnesia of the fluxing medium to form slag. The slag collects at the top of the molten iron and may be tapped in the molten state at a temperature of between 1400 and 1500°C. The value of the slag depends upon its subsequent processing, i.e., whether it is air cooled or chilled very rapidly either by immersion in water or by subjecting it to jets of water or of air and water. The glassy granular product formed when molten slag is suddenly chilled by immersion in water is known as granulated slag.

The first documented studies of the hydraulic properties of blast furnace slags have been traced to Loriot in France in 1774 (12). This was followed by the discovery by Langens in 1863 in Germany of a cementitious binder comprising a mixture of ground chilled slag and lime (12). According to Lea, a slag-lime cement was first used commercially in Germany in 1865, whereas in 1883 slag was used as one of the raw materials for portland cement manufacture (13). A portland slag type of cement was first produced in Germany in 1892 by grinding together portland cement clinker and chilled slag. This laid the foundation for the modern day portland blast furnace slag cements.

HYDRAULIC ACTIVITY OF SLAGS*

The hydraulic properties of slags generally depend on the following:

(i) degree of vitrification achieved during rapid cooling
(ii) chemical composition
(iii) fineness

Degree of Vitrification

The degree of vitrification achieved in rapid cooling of slags primarily determines its latent hydraulicity (13). An increase in glass content results in greater reactivity and higher cementitious value. A minimum glass content of 90% is often specified though there are no standard methods of determining this and values as high as 95% have been mentioned in the literature.

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*Hereafter, the term slag, when used alone refers to the granulated product of the iron ore blast furnace.

Chemical Composition

Glass content and reactivity of slags are closely linked to slag chemistry. Various empirical formulae have evolved relating chemical composition of slags to their reactivity. German specification DIN 1164-1942 requires that the ratio M_1 of the percentage content of the oxides should be

$$M_1 = \frac{CaO + MgO + Al_2O_3}{SiO_2} \geq 1$$

The above ratio has also been adopted by Canadian preliminary Standard A363-M1977 (14); in Japan the corresponding value is 1.4 (7). The value of the above formulae has been questioned (13).

Table 1 gives the chemical composition of slags from various countries (7,13). According to Lea, portland blast furnace slag cements containing slags with up to 18% magnesia content have shown no soundness failures in the ASTM autoclave test whereas concretes made with them gained strength in the normal manner up to three years and showed no indication of dimensional instability (13,15).

The chemistry of slags is complex and the relationships between their hydraulic properties and chemical composition are of doubtful value at best because slags with similar composition may display different hydraulic properties after vitrification (7,13).

Fineness

The third important property after degree of vitrification and chemical composition is the fineness of ground slag which is of importance in developing strength of concrete. The slags are usually ground to a fineness of about 4000 cm^2/g as measured by the Blaine test which is somewhat higher than for normal portland cements. As energy requirements for grinding slags are from 10 to 15% higher than for normal portland cement clinker because of the harsher nature of their glassy structure, a fineness higher than 4000 cm^2/g may or may not be economical (16).

OUTPUT OF SLAGS IN THE U.S.A. AND CANADA

The annual output of iron ore blast furnace slags in the U.S.A. in 1977 was about 35 million tons but only a very small percentage of this was vitrified and finely ground for use in concrete. In Canada, the entire production is in the order of two million tons and of this only about 2 000 000 tons is being vitrified and finely ground for this purpose in the Hamilton area. The vitrified product is produced by expanding molten slag under water sprays and then passing it over a rotating drum. The fins mounted on the drum break up the material and throw it in the air for a sufficient length of time for it to granulate. A similar granulation process has been used in the U.S.S.R. (7). National Slag

Table 1 - Chemical composition of iron ore blast furnace slags*

Constituent, %	Canada**	U.K.	U.S.A.	Germany	South Africa	Australia	U.S.S.R.	Japan
CaO	38-41	38-53	39-47	40-48	28-37	35-42	42-44	39-42
SiO_2	36-41	29-35	32-38	31-38	32-33	32-35	36-38	35-36
Al_2O_3	7-9	7-22	10-13	8-17	11-18	18-23	9-11	13-15
MgO	9-12	2-6	2-10	2-6	14-18	1-2	5-16	3-5
FeO	0.4-1.3	0.4-1.1	0.4-2.0	0.2-1.5	0.6-2.5	1-2	N/A	N/A
MnO	0.5-1.2	0.5-1.8	0.2-1.3	0.4-4.0	0.2-0.9	0.5-1.0	N/A	N/A
S	1.0-2.0	0.6-1.9	0.8-1.7	0.8-2.5	0.7-1.4	0.4-0.6	N/A	N/A

*From references (7,13).

**For one plant only.

Limited, Hamilton, Ontario, now has licences for the process in many countries including the U.S.A., England, France, Finland, Sweden, Japan and Australia, in addition to its own operation at Hamilton (6).

USE OF SLAG AS A SITE BATCHED MATERIAL

In the present investigation, slag has been treated as another ingredient of the concrete mix, being blended with cement by hand just before mixing. The slag can also be added directly to the mixer, a method which appears to have a number of advantages, the principal one being that the ratio of cement to slag can be varied as desired. As slags are harsher and require more energy to grind, intergrinding with portland cement clinker, which is softer, can result in excessive fineness of the portland cement component. Furthermore, from energy saving considerations, intergrinding may also be less attractive as energy consumption varies approximately with the square of the Blaine value for fineness (17).

SCOPE OF INVESTIGATION

In this study a total of thirty-two 0.062-m^3 mixes were made. The water:cement + slag (W:C+S) ratio of the mixes ranged from 0.30 to 0.65 and the percentage of slag used as a replacement for normal portland cement varied from 25 to 65% by weight of cement. All mixes were air entrained and some mixes incorporated a superplasticizer in addition to the air entraining agent. A number of 100 x 200-mm cylinders were cast for testing in compression and splitting tension at ages up to one year. Test prisms, 90 x 100 x 405 mm, were also cast for determining flexural strength and resistance to freeze-thaw cycling in accordance with Procedure B, ASTM Standard C666.

CONCRETE MIXES

The concrete mixes were made in the CANMET laboratory between March and July 1978 using the following materials.

CEMENT

Normal portland cement, CSA Type 10 (ASTM Type I) was used. Its physical properties and chemical analysis are given in Table 2.

AGGREGATES

Minus 19-mm crushed limestone was the coarse aggregate and local natural sand the fine aggregate. To keep the grading uniform for each mix, the sand was separated into different size fractions which were then combined to a specified grading. The grading and physical properties of the coarse and fine aggregates are given in Tables 3 and 4.

AIR ENTRAINING AGENT

A sulphonated hydrocarbon type air entraining agent (AEA) was used in all mixes.

SUPERPLASTICIZER

A sulphonated melamine formaldehyde condensate of German origin was used. It is available as a 20% aqueous solution with a density of (1100 kg/m^3) and is limpid to slightly turbid or milky in appearance.

GRANULATED BLAST FURNACE SLAG

Slag from a plant in Hamilton, Ontario, was used as a partial replacement for cement. The slag and cement were blended by hand before adding to the mixer. The physical properties and chemical analysis of the slag is given in Table 2.

The fineness of the slag was 4656 cm^2/g and the specific gravity 2.7.

MIX PROPORTIONING

The proportioning of the concrete mixes is summarized in Table 5. For all mixes, the graded coarse and fine aggregates were weighed in the room dry condition. The coarse aggregate was then immersed in water for 24 h; the excess water was decanted and the water retained by the aggregate was determined by weight difference. A predetermined amount of water was added to the fine aggregate which was then allowed to stand for 24 h.

Table 2 - Physical properties and chemical analysis of cement and slag

Description of test		Portland cement*	Slag*
Physical tests - general			
Time of set (Vicat needle):	initial	2 h 00 min	
:	final	3 h 00 min	
Fineness			
Passing 45 µm,		-	83%
Surface area, Blaine,		3730 cm^2/g	4656 cm^2/g
Soundness, Autoclave		0.04%	-
Physical tests - Mortar strength			
Compressive strength of 51-mm cubes,			
at 3-day		24.4 MPa	-
7-day		29.6 MPa	9.1 MPa
14-day		-	14.5 MPa
28-day		35.6 MPa	19.6 MPa
Chemical analysis			
Insoluble residue		0.28%	-
Silicon dioxide (SiO_2)		21.88%	36.56
Aluminum oxide (Al_2O_3)		4.50%	9.49
Ferric oxide (Fe_2O_3)		2.16%	2.03
Calcium oxide (CaO) total		62.67%	38.66
Magnesium oxide (MgO)		2.50%	10.73
Sulphur trioxide (SO_3)		3.24%	4.74+
Loss on ignition		1.22%	++
Others		1.55%	-
Glass content			
By South African Method			96%

*Manufacturer's data

+Includes sulphide sulphur

++Gained weight on ignition

Table 3 - Grading of aggregates

Coarse Aggregate		Fine Aggregate	
Sieve size	Cumulative percentage retained	Sieve size	Cumulative percentage retained
19 mm	33.4	4.75 mm	0.0
9.5 mm	66.6	2.36 mm	10.0
4.75 mm	100.0	1.18 mm	32.5
		1.40 mm	57.5
		300 µm	80.0
		150 µm	94.0
		Pan	100.0

Table 4 - Physical properties of aggregates

	Coarse aggregate	Fine aggregate
Specific gravity	2.68	2.70
Absorption, %	0.40	1.0

Table 5 - Mix proportions

Mix series	Mix No.	W:C+S* ratio	A:C+S** ratio	Quantities, kg/m^3			A.E.A., cc/m^3***	SP^+, % by weight of (C+S)
				Water	Cement	Slag		
A	1	0.30	2.6	186	618	0	370^{++}	0
	2	0.30	2.6	186	463	155	300	0
	3	0.30	2.3	198	362	297	510	0
	4	0.30	2.1	210	264	455	670	0
B	5	0.38	4.0	164	437	0	177	0
	6	0.38	4.0	161	428	0	241	1.3
	7	0.38	4.0	164	328	110	241	0
	8	0.38	4.0	161	320	107	321	1.2
	9	0.38	3.8	168	246	200	369	0
	10	0.38	3.9	164	241	196	369	1.1
	11	0.38	3.7	174	162	300	562	0
	12	0.38	3.7	168	157	291	514	1.0
C	13	0.46	5.3	161	347	0	153	0
	14	0.46	5.4	157	338	0	145	1.1
	15	0.46	5.4	157	255	85	177	0
	16	0.46	5.3	160	257	86	177	1.2
	17	0.46	5.1	165	196	160	241	0
	18	0.46	5.1	164	192	159	209	1.2
	19	0.46	5.2	161	121	225	241	0
	20	0.46	5.0	164	122	227	209	1.0
D	21	0.56	7.0	152	273	0	96	0
	22	0.56	6.5	160	287	0	88	1.2
	23	0.56	7.0	155	209	70	128	0
	24	0.56	6.4	162	218	73	112	1.2
	25	0.56	6.8	155	154	126	128	0
	26	0.56	6.8	154	152	125	128	1.1
	27	0.56	6.5	162	102	189	154	0
	28	0.56	6.5	161	101	187	96	1.2
E	29	0.65	8.3	152	234	0	115	0
	30	0.65	8.3	152	176	59	125	0
	31	0.65	8.3	152	129	105	105	0
	32	0.65	8.3	153	83	153	175	0

*Water:cement+slag ratio (by weight)

**Aggregate:cement+slag ratio (by weight)

***Air entraining agent

$^+$Superplasticizer

$^{++}$This high value is due to the additional AEA to obtain the required air content and has not been plotted in Fig. 1.

Five series of concrete mixes were made. Test mixes in Series A and E had a W:C+S ratio of 0.30 and 0.65 respectively. The test mixes in Series B, C and D covered W:C+S ratios of 0.38, 0.46 and 0.56, respectively. The test specimens from mix Series A and E were used for compressive strength determination at early ages, whereas those from mix Series B, C and D were used for the determination of compressive strength at ages up to one year as well as for the determination of flexural and splitting-tensile strengths and freeze-thaw durability.

Concrete was mixed in a laboratory counter current mixer for a total of six minutes except for those incorporating superplasticizers. In the latter mixes, the superplasticizer was added at the end of six minutes and the concrete was then mixed for an additional two minutes.

PROPERTIES OF FRESH CONCRETE

The properties of the freshly mixed concrete, i.e., temperature, slump, unit weight and air content are given in Table 6.

Table 6 - Properties of fresh concrete

				Properties of fresh concrete			
Mix series	Mix No.	Type of mix	W:C+S* ratio	Temp, °C	Slump, mm	Unit weight, kg/m^3	Air content %
A	1	Control + AEA	0.30	21	25	2434	3.6
	2	25% slag + AEA	0.30	20	25	2434	3.5
	3	45% slag + AEA	0.30	19	25	2395	3.5
	4	65% slag + AEA	0.30	19	40	2376	3.4
B	5	Control + AEA	0.38	24	65	2350	4.8
	6	Control + AEA + SP	0.38	25	205	2310	6.0
	7	25% slag + AEA	0.38	24	65	2360	4.5
	8	25% slag + AEA + SP	0.38	25	190	2310	6.2
	9	45% slag + AEA	0.38	23	70	2330	5.2
	10	45% slag + AEA + SP	0.38	23	190	2290	6.3
	11	65% slag + AEA	0.38	24	65	2340	4.6
	12	65% slag + AEA + SP	0.38	24	205	2280	6.4
C	13	Control + AEA	0.46	24	70	2340	6.0
	14	Control + AEA + SP	0.46	25	190	2320	6.7
	15	25% slag + AEA	0.46	23	75	2330	6.0
	16	25% slag + AEA + SP	0.46	25	215	2320	6.1
	17	45% slag + AEA	0.46	25	60	2320	6.1
	18	45% slag + AEA + SP	0.46	25	205	2290	6.9
	19	65% slag + AEA	0.46	24	95	2290	6.7
	20	65% slag + AEA + SP	0.46	24	200	2310	6.2
D	21	Control + AEA	0.56	24	95	2330	6.2
	22	Control + AEA + SP	0.56	25	205	2320	6.3
	23	25% slag + AEA	0.56	24	75	2330	6.2
	24	25% slag + AEA + SP	0.56	26	205	2330	5.6
	25	45% slag + AEA	0.56	24	75	2330	5.8
	26	45% slag + AEA + SP	0.56	24	205	2320	5.5
	27	65% slag + AEA	0.56	24	80	2244	5.1
	28	65% slag + AEA + SP	0.56	21	215	2331	7.5
E	29	Control + AEA	0.65	19	65	2318	6.2
	30	25% slag + AEA	0.65	20	45	2318	7.0
	31	45% slag + AEA	0.65	19	50	2318	6.8
	32	65% slag + AEA	0.65	21	30	2338	6.0

*Water:cement+slag ratio (by weight)

PREPARATION AND CASTING OF TEST SPECIMENS

CONCRETE MIXES NO. 1 TO 4 (SERIES A) AND 29 TO 32 (SERIES E)

Twenty 100 x 200-mm cylinders were cast from each mix. All cylinders were cast in two layers; each layer being compacted using a vibrating table. After casting, all the moulded specimens were covered with a water-saturated burlap and were left in the casting room at 24 ± 1.3°C and 50% relative humidity for 24 h. They were then demoulded and transferred to the moist-curing room until required for testing in compression at the ages of 1, 2, 3, 5, 7, 21 and 28 days.

CONCRETE MIXES NO. 5 TO 28 (SERIES B, C AND D)

Twenty-five 100 x 100-mm cylinders and 90 x 100 x 405-mm prisms were cast from each mix. All cylinders and prisms were cast in two layers and the moulds were compacted using a vibrating table. After casting, all the moulded specimens were covered with a water-saturated burlap and were left in the casting room at 24 ± 1.3°C and 50% relative humidity for 24 h. They were then demoulded and transferred to the moist-curing room until required for testing.

TESTING OF SPECIMENS

The cast specimens were tested in compression, flexure, splitting-tension and freeze-thaw tests at various ages in accordance with the plan in Table 7. All specimens for compression testing were capped with a sulphur and flint mixture before testing. Compression and splitting-tension tests were performed in a 272,000-kg machine and flexure tests in a 27,200-kg machine.

Freezing and thawing tests were performed in an automatic freeze-thaw unit capable of performing eight cycles per day - one complete cycle from 4.4 ± 1.7°C to -17.8 ± 1.7°C and back to 4.4 ± 1.7°C, requiring about three hours. At the end of the initial moist-curing period of 14 days, the temperature of each set of prisms was reduced to a uniform 4.4 ± 1.7°C by placing in the freeze-thaw cabinet at the thawing phase for one hour. The initial and all subsequent measurements of the freeze-thaw and reference test specimens were made at this temperature. After initial measurements of the prisms were taken, two test prisms were placed in the freeze-thaw cabinet and the two companion prisms in the moist-curing room for reference purposes.

The freeze-thaw test specimens were visually examined at the end of every 50-cycle interval. Their lengths were measured and they were weighed and tested by resonant frequency and by the ultrasonic pulse velocity method at approximately every 100-cycle interval. The freeze-thaw test was terminated at 700 cycles in each case unless the test prisms had failed earlier. Following this, both the reference and freeze-thaw prisms were tested in flexure.

Table 7 - Testing schedule

Mix		Age of testing								
series	Type of testing	1-day	3-day	5-day	7-day	14-day	21-day	28-day	91-day	365-day
A and E	Compression (ASTM C39-72)	3 cylinders	3 cylinders	3 cylinders	3 cylinders	-	3 cylinders	3 cylinders	-	-
B, C and D	Compression (ASTM C39-72)	3 cylinders	-	-	3 cylinders	-	-	3 cylinders	3 cylinders	3 cylinders
	Flexure (ASTM C78-75)	-	-	-	-	2 prisms	-	2 prisms*	2 prisms*	-
	Splitting-tension (ASTM C496-71)	-	-	-	-	-	-	3 cylinders	3 cylinders	-
	Freezing and thawing** (ASTM C666-77 Procedure B)	Two prisms were exposed to freeze thaw cycling at the end of 14 days. Two companion prisms were kept in moist-curing room and tested at the same time at the end of the test as those from the freeze thaw test.								

*For mix No. 9, 10, 17, 18, 25 and 26.

**Freezing and thawing test was performed for mixes with a W:C+S ratio of 0.38 and 0.56 and containing 25 and 65% slag. (Mix No.: 5, 6, 7, 8, 11, 12, 13, 14, 15, 16, 19 and 20).

TEST RESULTS AND THEIR ANALYSIS

The number of cylinders tested was 760 and of prisms 144. Densities of test cylinders were taken at one day and immediately before testing; selected data are shown in Table 8. The increased demand for AEA with increasing percentages of slag is shown in Fig. 1 and 2. A summary of compressive, flexural and splitting-tensile strengths is given in Tables 9 to 12, and the data are illustrated in Fig. 3 to 13. The within-batch variation of the strength data is given in Appendix Tables A1 and A2.

Changes in weight, length, pulse velocity and resonant frequencies of reference prisms and prisms subjected to freeze-thaw cycling are shown in Table 13, and a summary of the associated flexural strength is given in Table 14.

Table 8 - Density of test cylinders

Mix series	Mix No.	Type of mix	W:C+S ratio*	Density of 100 x 200-mm cylinders at 1 day**, kg/m^3
B	5	Control + AEA	0.38	2366
	6	Control + AEA + SP		2337
	7	25% slag + AEA		2367
	8	25% slag + AEA + SP		2347
	9	45% slag + AEA		2341
	10	45% slag + AEA + SP		2303
	11	65% slag + AEA		2347
	12	65% slag + AEA + SP		2301
C	13	Control + AEA	0.46	2362
	14	Control + AEA + SP		2352
	15	25% slag + AEA		2354
	16	25% slag + AEA + SP		2352
	17	45% slag + AEA		2346
	18	45% slag + AEA + SP		2344
	19	65% slag + AEA		2309
	20	65% slag + AEA + SP		2296
D	21	Control + AEA	0.56	2330
	22	Control + AEA + SP		2349
	23	25% slag + AEA		2330
	24	25% slag + AEA + SP		2357
	25	45% slag + AEA		2350
	26	45% slag + AEA + SP		2361
	27	65% slag + AEA		2362
	28	65% slag + AEA + SP		2333

*Water:cement+slag ratio

**Each value is the average of 21 test results

DISCUSSION OF TEST RESULTS

COLOUR

Immediately after testing, the centre portion of the broken slag test specimens was characterized by bluish green colour which faded away after being left in the laboratory air for several days. The colour was attributed to the presence of calcium sulphide in the slag and its fading away is due to oxidization of sulphides in dry air (18).

WATER REQUIREMENT

The test program was designed to maintain the W:C+S ratio constant for each series with the added requirement that the slump be 75 ± 10 mm. The mix proportioning data in Table 5 indicate that in general, the water demand of the mixes incorporating slag increased slightly with increasing slag content. This was particularly so for concrete with a W:C+S ratio of 0.30.

Reasons for the higher water demand may be due to the higher total surface area of slag particles at 1.98 m^2/g, compared with 0.99 m^2/g for the portland cement as determined by nitrogen adsorption technique.

There was no increased workability of the concrete mixes incorporating slag as sometimes reported (11).

DOSAGE FOR AN AIR ENTRAINING AGENT

The dosage required for an AEA to entrain the desired volume of air increased markedly with slag content (Fig. 1 and 2). This confirms published data (19). For example, for concrete with a W:C+S ratio of 0.30, the AEA needed to entrain approximately 3.5% air increased from 370 mL/m^3 for the control mix to 670 mL/m^3 for the concrete mix incorporating 65% slag. However, at higher ratios the increase required was not as marked as at lower ratios. The increased demand for the AEA with increasing amounts of slag is, stated once again, probably due to the higher total surface area of slag particles.

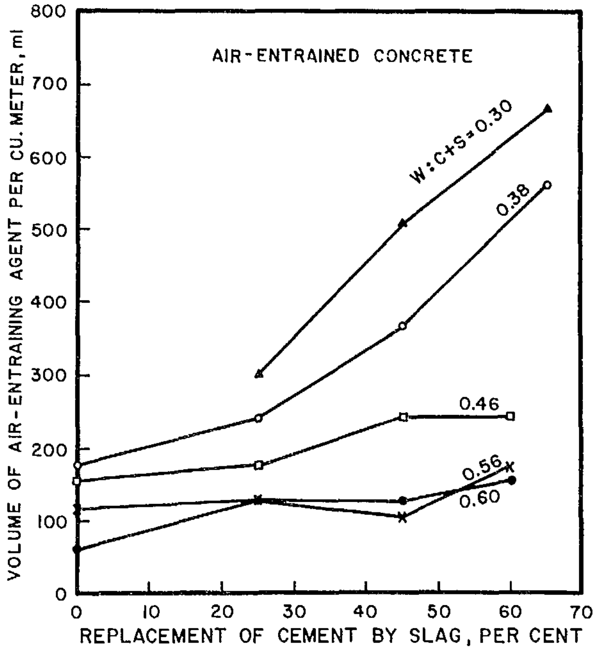

Fig. 1 - Dosage of air entraining agent versus slag content for air entrained concrete

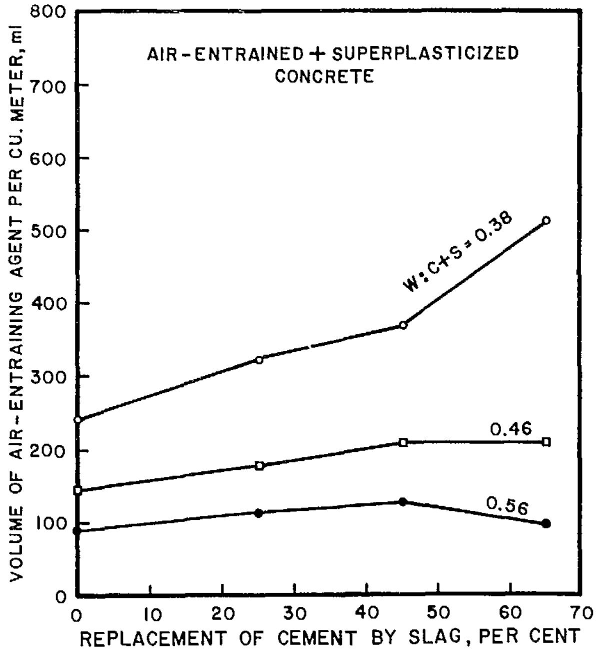

Fig. 2 - Dosage of air entraining agent versus slag content for air entrained and superplasticized concrete

DOSAGE FOR A SUPERPLASTICIZER

The superplasticizer was added to concrete at the end of the 6 min of mixing to obtain a slump of 200 ± 10 mm. At a W:C+S ratio of 0.30, the dosage required for the superplasticizer to achieve the above slump decreased from 1.3% by weight of cement for the control mix to 1.0% by weight of cement for the concrete mix incorporating 65% slag. At ratios of 0.46 and 0.56, there was no significant change in the dosage required for the superplasticizer for mixes with and without slag.

At first glance, it appears that the above data are at variance with the higher water and AEA demand for concrete incorporating slag. A closer look at the interaction of the superplasticizers and cementitious materials suggest that the rate of hydration characteristic of the cementing materials may be masking the real effects. It is hypothesized that if the hydration effects are eliminated and the flow characteristics of the mixes are measured instantly after incorporating the superplasticizer, it may be found that for equal flow, the superplasticizer demand is higher for concretes incorporating slag than for the control concrete. Ryan and Munn have reported results of investigations in which all or part of the cement had been replaced by the same volume of fly ash in an endeavour to ascertain whether the superplasticized concrete properties were primarily affected by physical or chemical changes in unit constituents (20). The tests showed that reversion of the flowing concrete to its original state was dependent on the presence of some portland cement. However, when no cement was present at all a typical initial increase in fluidity took place on introduction of the superplasticizer, but reversion to the original slump was a very gradual stiffening of the mix over many hours. Malhotra has shown that in superplasticized high alumina cement concrete reversion to the original slump took place extremely rapidly compared with superplasticized normal portland cement concrete (21). For example, for the former the reversion time was about 5 min compared with about 30 min for the latter depending on dosage.

SLAG AS A SITE BATCH MATERIAL

In this investigation the use of slag as another ingredient of concrete mix did not pose any difficulties in the laboratory mixing program. The slag and cement were mixed by hand just prior to the mixing of concrete and no attempt was made to add slag directly to the mixer. In a normal ready-mixed concrete operation, the mixing of fine powders like slag and cement is not possible and the slag will have to be added directly to the mixer.

COMPRESSIVE STRENGTH

The data on the compressive strength development are presented in Tables 9 and 10 and in Fig. 3 to 10. The compressive strengths expressed as a percentage of 28-day values are given in Table 11. The strength development pattern appears to be different for low, medium and high W:C+S ratios and these will be discussed separately.

Low W:C+S Ratio Concrete

The test cylinders for concrete with a ratio of 0.30 were tested for early age strength development (Fig. 3). At ages up to three days, the strength of concrete incorporating various percentages of slag are considerably lower than the strength of control specimens. At 28-days, the gap between the strength of control specimens and those cast from concrete incorporating slag does narrow, nevertheless, there is still a wide difference between the two. For example, the 28-day strength of control cylinders is 60.1 MPa, compared with 47.0 MPa for concrete containing 65% slag, indicating that the strength of the latter may never catch up regardless of the percentage of slag used.

The test specimens for concrete with a ratio of 0.38 were tested at ages up to one year. Regardless of the age and slag content, the strength of test specimens cast from concrete incorporating slag were always considerably lower than the strength of control specimens. For example, at 365 days, the strength of control cylinders was 60.7 MPa compared with 47.5 MPa for concrete incorporating 65% slag. The difference between the strength of control specimens and of those incorporating slag increases with slag content and decreases with age.

From the foregoing discussion, it becomes apparent that at low ratios the strength development of concrete incorporating slag is less than desirable. The reasons for this are not clear. It is probable that the slag is not being fully activated and research is needed to explain this phenomenon.

Table 9 - Compressive strength test results at early ages - Mix Series A and E

Mix series	Mix No.	Type of mix	W:C+S ratio*	Compressive strength of 100 x 200-mm cylinders, MPa 1-day	2-day	3-day	5-day	7-day	21-day	28-day
A	1	Control + AEA	0.30	36.1	41.9	42.4	46.7	-	60.0	60.7
	2	25% slag + AEA		27.8	36.5	39.5	42.4	-	53.1	55.1
	3	45% slag + AEA		20.1	29.5	35.0	-	40.8	51.2	51.1
	4	65% slag + AEA		9.4	16.4	25.2	-	36.9	46.9	46.8
E	29	Control + AEA	0.65	8.1	13.1	16.1	19.4	20.0	24.1	25.7
	30	25% slag + AEA		3.7	8.2	10.2	12.9	15.2	22.3	23.9
	31	45% slag + AEA		2.6	4.8	6.6	9.7	11.5	18.7	21.3
	32	65% slag + AEA		1.5	3.0	4.9	8.0	10.2	18.4	20.1

*Water:cement+slag ratio (by weight)

Table 10 - Compressive and flexural strength at various ages - Mix Series B, C and D

Mix series	Mix No.	Type of mix	W:C+S ratio*	Compressive strength of 100 x 200-mm cylinders, MPa 1-day	7-day	28-day	91-day	365-day	Flexural strength of 90 x 100 x 405-mm prisms, MPa 14-day	Splitting-tensile strength of 100 x 200-mm cylinders, MPa 28-day	91-day
B	5	Control + AEA	0.38	25.5	38.1	47.9	53.6	60.7	8.1	4.1	4.6
	6	Control + AEA + SP		28.3	38.3	44.5	53.3	56.5	8.0	4.1	4.1
	7	25% slag + AEA		17.2	34.1	43.3	50.0	54.4	7.8	3.9	4.5
	8	25% slag + AEA + SP		21.2	33.8	40.6	46.1	49.8	7.5	3.2	4.0
	9	45% slag + AEA		10.6	32.2	39.9	45.9	50.1	7.5	4.5	4.1
	10	45% slag + AEA + SP		10.2	31.2	36.6	42.5	46.5	6.8	3.7	4.0
	11	65% slag + AEA		6.7	29.6	35.1	41.8	47.5	6.7	4.0	4.1
	12	65% slag + AEA + SP		5.6	26.1	31.8	40.3	44.3	6.5	3.3	3.9
C	13	Control + AEA	0.46	16.6	28.4	36.7	43.1	49.9	5.4	3.7	4.1
	14	Control + AEA + SP		17.9	29.2	35.9	44.4	51.3	6.0	3.7	4.5
	15	25% slag + AEA		11.0	27.0	35.9	41.5	46.4	6.1	3.7	4.7
	16	25% slag + AEA + SP		12.4	27.1	37.8	44.0	47.7	5.9	3.9	4.6
	17	45% slag + AEA		8.2	23.5	34.0	41.4	44.8	6.1	3.7	4.2
	18	45% slag + AEA + SP		8.0	23.4	36.4	40.2	47.2	6.8	3.2	4.5
	19	65% slag + AEA		2.9	17.4	29.6	35.6	40.6	5.5	3.5	3.2
	20	65% slag + AEA + SP		3.1	18.8	29.3	34.1	39.2	5.6	3.4	3.3
D	21	Control + AEA	0.56	11.1	23.4	29.1	31.4	36.0	4.7	3.0	3.9
	22	Control + AEA + SP		13.7	22.8	28.4	36.1	42.9	5.2	3.3	4.3
	23	25% slag + AEA		8.2	20.0	27.0	32.0	36.8	5.5	3.3	3.7
	24	25% slag + AEA + SP		8.9	20.9	28.7	34.0	41.1	5.9	3.6	4.1
	25	45% slag + AEA		4.6	16.3	27.1	30.1	32.8	5.5	3.4	3.7
	26	45% slag + AEA + SP		4.1	20.7	26.2	35.3	38.8	6.0	3.8	3.5
	27	65% slag + AEA		1.8	13.8	26.2	28.4	31.3	5.4	3.4	3.3
	28	65% slag + AEA + SP		1.8	13.1	23.7	27.0	32.5	4.3	3.2	3.5

*Water:cement+slag ratio (by weight)

Note: Each compressive strength value is average of 3 tests.
Each flexural strength value is average of 2 tests.

Table 11 - Compressive strength as a percentage of 28-day values

Mix	Mix		W:C+S	Compressive strength as a % of 28-day values				
series	No.	Type of mix	ratio*	1-day	7-day	28-day	91-day	365-day
B	5	Control + AEA	0.38	53.2	79.5	100	111.9	126.9
	6	Control + AEA + SP		59.1	80.0	92.9	111.3	113.7
	7	25% slag + AEA		35.9	71.2	90.4	104.4	118.1
	8	25% slag + AEA + SP		44.3	70.6	84.8	96.2	103.9
	9	45% slag + AEA		22.1	67.2	83.3	95.8	104.7
	10	45% slag + AEA + SP		21.3	65.1	76.4	88.7	97.1
	11	65% slag + AEA		14.0	61.8	73.3	87.3	99.1
	12	65% slag + AEA + SP		11.7	54.5	66.4	84.1	92.6
C	13	Control + AEA	0.46	45.2	77.4	100	117.4	136.0
	14	Control + AEA + SP		48.8	79.6	97.8	121.0	139.8
	15	25% slag + AEA		30.0	73.6	97.8	113.1	126.4
	16	25% slag + AEA + SP		33.8	73.8	103.0	119.9	130.0
	17	45% slag + AEA		22.3	64.0	92.6	113.1	122.1
	18	45% slag + AEA + SP		21.8	63.8	99.2	109.5	128.6
	19	65% slag + AEA		7.9	47.4	80.7	97.0	110.6
	20	65% slag + AEA + SP		8.4	51.2	79.8	92.9	106.8
D	21	Control + AEA	0.56	38.1	80.4	100	107.2	123.6
	22	Control + AEA + SP		47.1	78.4	97.6	124.1	126.4
	23	25% slag + AEA		28.2	68.7	92.8	110.0	147.4
	24	25% slag + AEA + SP		30.6	71.8	98.6	116.8	141.0
	25	45% slag + AEA		15.8	56.0	93.1	103.4	112.4
	26	45% slag + AEA + SP		14.1	71.1	90.0	121.3	133.2
	27	65% slag + AEA		6.2	47.4	90.0	97.6	107.4
	28	65% slag + AEA + SP		6.2	45.0	81.4	92.8	111.5

*Water:cement+slag ratio (by weight)

Medium W:C+S Ratio Concrete

For concrete with ratios of 0.46 and 0.56, regardless of the age and whether the concretes were superplasticized or not, the compressive strength of test cylinders incorporating 65% slag is always considerably lower than the strength of control cylinders (Table 10).

For concrete with a ratio of 0.46 and incorporating AEA and 45% slag, the strength of slag concrete is lower than that of control concrete at ages up to 365 days (Fig. 6). However, for superplasticized concrete, the strength of control concrete and that incorporating 45% slag reach equal values at 28 and 91 days (Fig. 7). The latter has marginally higher strength. For concrete incorporating AEA and 25% slag, the strength of the slag concrete is always lower than that of control concrete at ages up to 365 days. For concrete incorporating superplasticizers, the strength of slag concrete is somewhat lower than that of control concrete at ages up to 7 days; beyond this the strength of the two types reach equal values at about 15 days; following this, the strengths deviate from each other slightly and once again, reach equal values at 91 days (Fig. 6).

For concrete with a ratio of 0.56 and incorporating AEA and 45% slag, the strength of

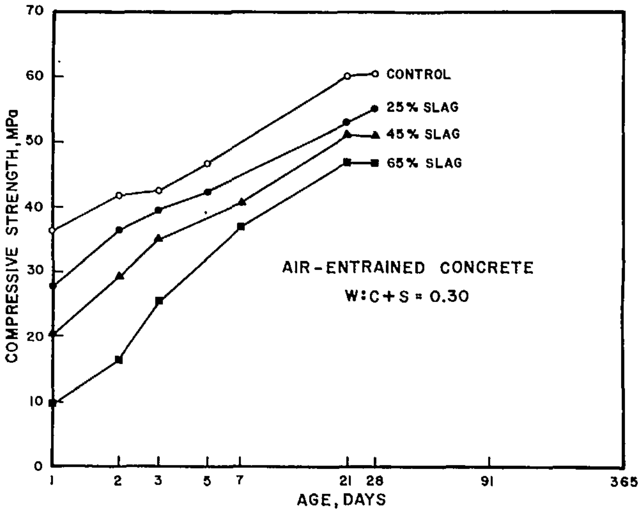

Fig. 3 - Age versus compressive strength relationship for air entrained concrete, W:C+S ratio = 0.30

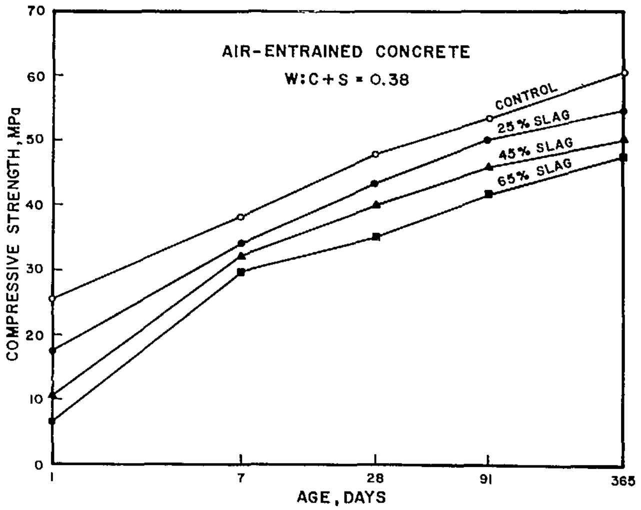

Fig. 4 - Age versus compressive strength relationship for air entrained concrete, W:C+S ratio = 0.38

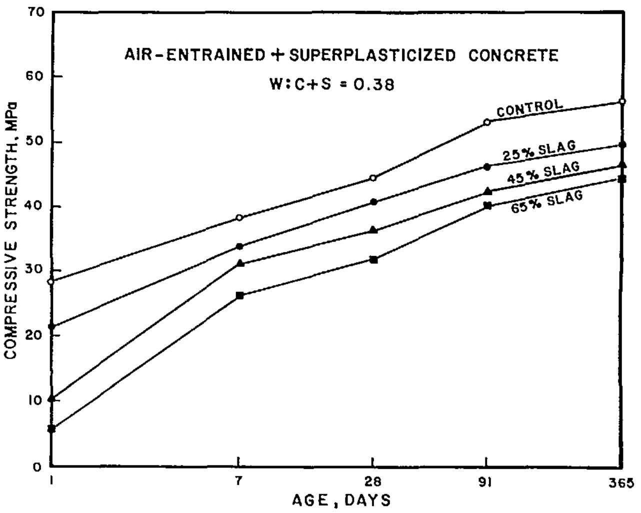

Fig. 5 - Age versus compressive strength relationship for air entrained and superplasticized concrete, W:C+S ratio 0.38

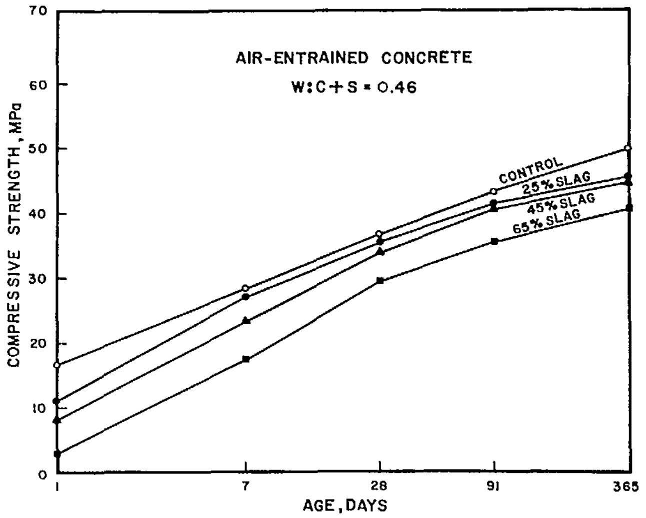

Fig. 6 - Age versus compressive strength relationship for air entrained concrete, W:C+S ratio = 0.46

control concrete is considerably higher than that of slag concrete at ages up to about 28 days; beyond this, the two strength values are comparable (Fig. 8). For superplasticized concrete, the strength of control concrete is also considerably higher than that of slag concrete at ages up to 28 days. At 91 days, the two types have nearly equal strength; however, beyond this, the control concrete once again shows higher strength (Fig. 9). For concrete incorporating AEA and 25% slag, the strength of slag concrete is somewhat lower than that of control concrete at ages up to about 80 days, beyond which the trend reverses (Fig. 8). For superplasticized concrete, the strength of slag concrete is lower than that of control concrete at ages up to 20 days; beyond this, the two strength values are comparable (Fig. 9).

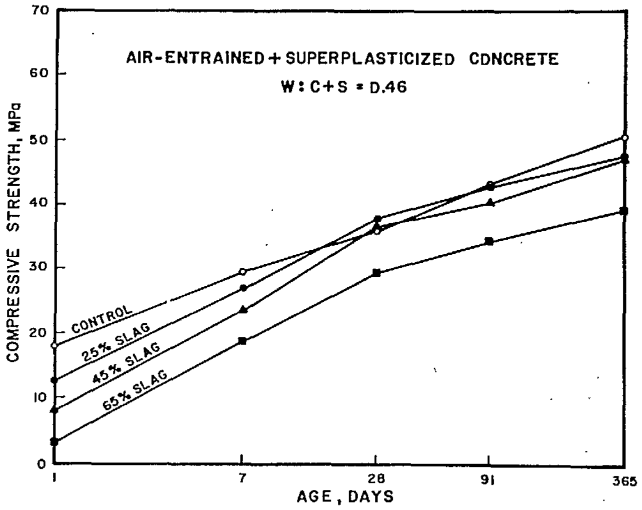

Fig. 7 - Age versus compressive strength relationship for air entrained and superplasticized concrete, W:C+S ratio = 0.46

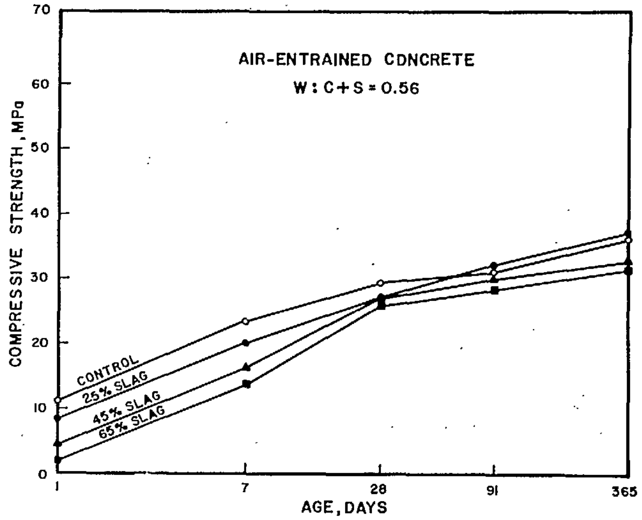

Fig. 8 - Age versus compressive strength relationship for air entrained concrete, W:C+S ratio = 0.56

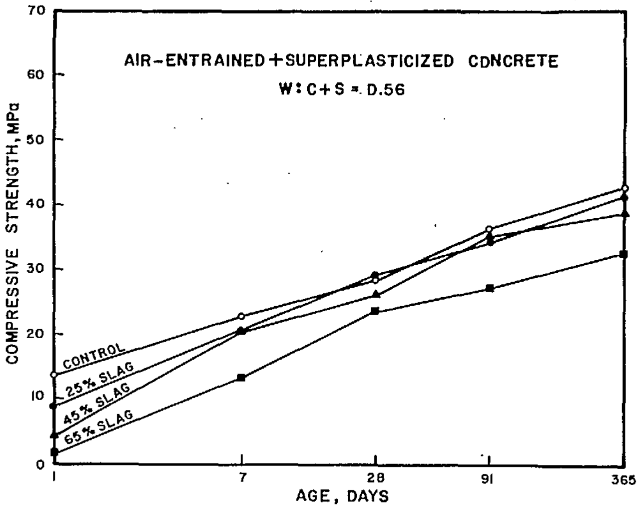

Fig. 9 - Age versus compressive strength relationship for air entrained and superplasticized concrete, W:C+S ratio = 0.56

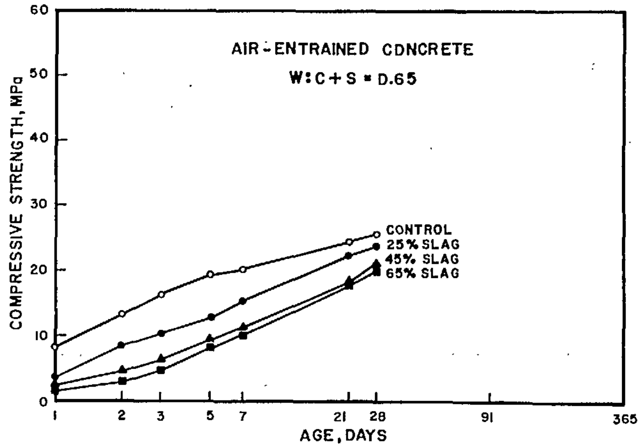

Fig. 10 - Age versus compressive strength relationship for air entrained concrete, W:C+S ratio = 0.65

High W:C+S Ratio Concrete

Like the concrete mixes having a ratio of 0.30, the specimens for concrete with a ratio of 0.65 were tested to determine early age strength development. For ages up to 28 days, the strength of cylinders cast from the control mix are considerably higher than the strength of cylinders cast from concrete mixes incorporating various percentages of slag (Fig. 10). The difference between the strength of control cylinders and those cast from concrete incorporating slag narrows with age. For example, at three days the strength of control concrete is 16.3 MPa compared with a value of 10 MPa for concrete incorporating

25% slag; the corresponding values at 28 days are 25.8 and 23.9 MPa respectively.

The low early age strength of concrete containing slag can pose difficulties in construction because the formwork will have to be left in place longer. This can become serious during winter construction in Canada.

FLEXURAL STRENGTH

The 14-day flexural strength of concrete ranged from 6.5 to 8.1, 5.4 to 6.1 and 4.2 to 6.0 MPa for concretes with ratios of 0.38, 0.46 and 0.56 respectively (Fig. 11,12,13). In general, for concrete with ratios of 0.46 and 0.56, the flexural strength of concrete incorpor-

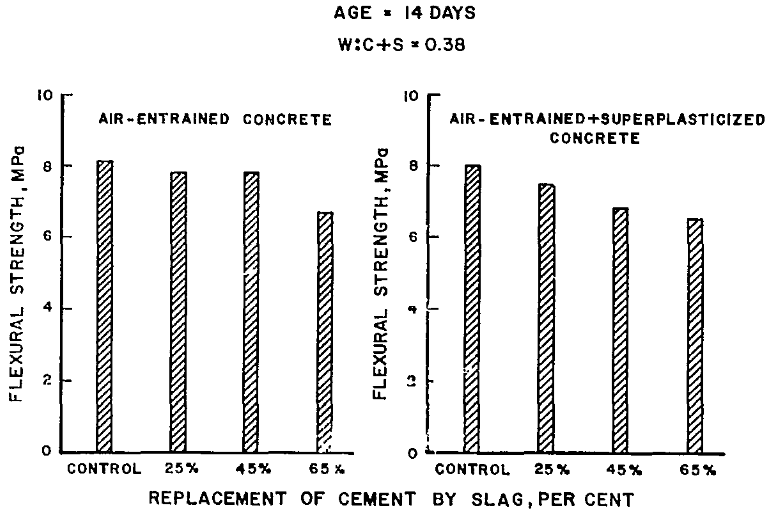

Fig. 11 - Flexural strength of concrete at 14 days, W:C+S ratio = 0.38

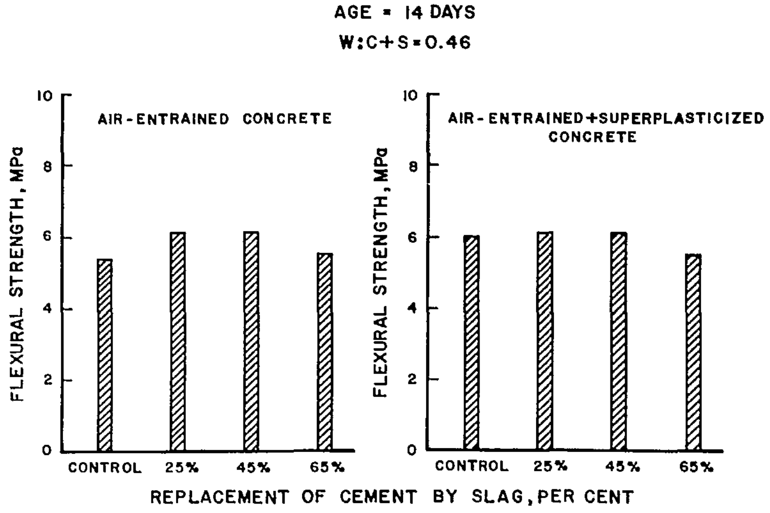

Fig. 12 - Flexural strength of concrete at 14 days, W:C+S ratio = 0.46

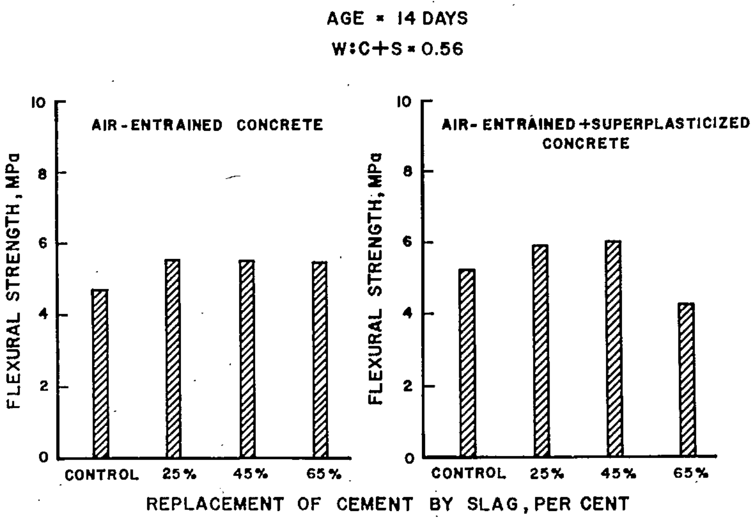

Fig. 13 - Flexural strength of concrete at 14 days, W:C+S ratio = 0.56

Table 12 - Summary of flexural strength of prisms at various ages

Mix series	Mix No.	Type of mix	W:C+S ratio*	Flexural strength of prisms**, MPa 14-day	28-day	91-day
B	5	Control + AEA	0.38	8.1	-	-
	6	Control + AEA + SP	0.38	8.0	-	-
	9	45% slag + AEA	0.38	7.5	8.6	8.2
	10	45% slag + AEA + SP	0.38	6.8	7.8	8.1
C	13	Control + AEA	0.46	5.4	-	-
	14	Control + AEA + SP	0.46	6.0	-	-
	17	45% slag + AEA	0.46	6.1	5.8	6.0
	18	45% slag + AEA + SP	0.46	6.8	6.1	6.7
D	21	Control + AEA	0.56	4.7	-	-
	22	Control + AEA + SP	0.56	5.2	-	-
	25	45% slag + AEA	0.56	5.3	5.5	6.6
	26	45% slag + AEA + SP	0.56	6.0	6.0	6.5

*Water:cement+slag ratio (by weight)

**Each flexural strength is the average of two 90 x 100 x 405-mm prisms ating slag is comparable with or greater than the corresponding strength of control concrete. This confirms the data published by others (11,12). However, for concrete with a ratio of 0.38, the reverse is true for both air entrained, and air entrained and superplasticized concrete; for example, for 65% slag content, there is a drop in strength in the order of 20% compared with strength of the control concrete (Fig. 11).

The high flexural strength of concrete even with up to 45% replacement of cement with slag suggests the possible uses of this type of concrete for airport and highway pavements.

The increased flexural strength of slag concrete is probably due to the stronger bonds in cement/slag/aggregate system because of the particle shape and surface texture of the slag particles.

SPLITTING-TENSILE STRENGTH

In general, the splitting-tensile strength of slag concrete is comparable with or lower than the strength of control concrete (Table 10); the trend appears to reverse itself at least for 28-day strength for concrete with a ratio of 0.56. The 28-day strength values range from 3.2 to 4.5, 3.2 to 3.9 and 3.0 to 3.8 MPa for concretes with ratios of 0.38, 0.46 and 0.56 respectively (Table 10).

DURABILITY OF CONCRETE PRISMS EXPOSED TO REPEATED CYCLES OF FREEZING AND THAWING

Durability of concrete prisms exposed to repeated cycles of freezing and thawing was determined from weight, length, resonant frequency and pulse velocity of test specimens before and after freeze-thaw cycling, and calculating relative durability factors (ASTM C666). Following the end of freeze-thaw cycling, the reference and test prisms were broken in flexure.

The test data indicate that regardless of the ratio and whether the concretes were air entrained or air entrained and superplasticized, the prisms performed excellently in freeze-thaw tests with relative durability factors being greater than 91% (Table 13). The only exceptions were Mixes No. 19 and 20 with a ratio of 0.56 containing 65% slag. Though the prisms did not show any distress up to 300 freeze-thaw cycles, the test specimens showed considerable damage

Table 13 - Summary of freeze-thaw test results for concrete Series B and D

			Summary of freeze-thaw test results									
			At zero cycles				At completion of 700 cycles					
Mix series	W:C+S ratio*	Type of mix	Weight kg	Length** mm	Longitudinal resonant frequency, Hz	Pulse velocity, m/sec	Weight kg	Length mm	Longitudinal resonant frequency, Hz	Pulse velocity, m/sec	Durability factor, %	Relative durability factor, %
B	0.38	Control + AEA	8.703	2.89	5150	4717	8.693	2.90	5200	4747	102	100
		Control + AEA + SP	8.499	2.70	5150	4684	8.486	2.72	5138	4661	99	97
		25% slag + AEA	8.697	3.00	5300	4788	8.673	3.05	5225	4788	97	95
		25% slag + AEA + SP$^+$	8.540	2.96	5125	4684	8.517	3.01	5100	4656	99	97
		65% slag + AEA	8.622	2.74	5140	4684	8.626	2.91	4950	4568	93	91
		65% slag + AEA + SP	8.302	1.59	5025	4589	8.302	1.68	4875	4531	94	92
D	0.56	Control + AEA	8.331	2.56	5000	4568	8.299	2.56	5010	4600	100	-
		Control + AEA + SP	8.443	2.76	4980	4568	8.394	2.76	4980	4504	100	100
		25% slag + AEA	8.451	2.85	5000	4573	8.416	2.88	5000	4606	100	100
		25% slag + AEA + SP	8.544	2.83	5040	4639	8.483	2.91	5050	4622	100	100
		65% slag + AEA	8.465	2.61	4950	4546	***	2.88	****	****	-	59
		65% slag + AEA + SP	8.471	2.52	4930	4563	****	2.75	****	****	-	70

*Water:cement+slag ratio

**Gauge length of 345 mm should be added to this value to arrive at the exact length

***Prisms failed at the end of 533 freeze-thaw cycles when the resonant frequency was 3840 Hz

****Prisms failed at the end of 450 freeze-thaw cycles when the resonant frequency was 4150 Hz

+Test results for one prism only

Table 14 - Flexural strength of reference prisms and those subjected to freeze-thaw cycling

				Flexural strength of 90 x 100 x 405-mm prisms, MPa					
						Prisms after exposure to freeze-thaw cycling			
				Prisms after moist-curing		No. of freeze-thaw cycles	Age at the end of freeze-thaw cycling	Strength,	Residual strength,
Mix series	Mix No.	W:C+S ratio$^+$	Type of mix	14-day	95-day*	700	95-day	MPa	%
B	5	0.38	Control + AEA	8.1	**	700	95	7.3	-
	6		Control + AEA + SP	8.0	8.1	700	95	7.8	96.1
	7		25% slag + AEA	7.8	**	700	95	6.5	-
	8		25% slag + AEA + SP	7.5	8.3	700	95	7.5***	90.8
	11		65% slag + AEA	6.7	8.6	700	95	5.3	61.7
	12		65% slag + AEA + SP	6.5	6.8	700	95	5.8	84.6
D	13	0.56	Control + AEA	4.7	6.1	700	95	5.7	94.9
	14		Control + AEA + SP	5.2	6.8	700	95	5.9	87.3
	15		25% slag + AEA	5.5	6.6	700	95	6.2	93.9
	16		25% slag + AEA + SP	5.9	7.3	700	95	6.3	85.3
	19		65% slag + AEA	5.4	6.5	533	75	3.1	47.5
	20		65% slag + AEA + SP	4.3	5.5	450	69	2.6	47.3

$^+$Water:cement + slag ratio (by weight)

*The 95-day period corresponds to the end of 700 freeze-thaw cycles

**Prisms damaged during laboratory handling and discarded

***Only one prism tested; other values are average of two results

after 533 and 450 cycles when the relative durability factors were 59 and 70% and the residual flexural strengths were 47.5 and 47.3% respectively. At the time of writing, air void data on the test prisms were unavailable. It may be argued that for the exceptions noted above, the freeze-thaw test may be biased against concrete incorporating slag because test prisms were subjected to freeze-thaw cycling at equal ages rather than at equal compressive strengths. This argument has validity and research is indicated in this direction.

WITHIN-BATCH VARIATION

The within-batch variation for the test result is given in Appendix Table A1 and A2. The coefficient of variation for compressive strength tests range from 0.5 to 9.9% but are generally less than 4.0% regardless of the ratio and age of the test. There appears to be no significant difference in the coefficients of variation values for control cylinders and those incorporating superplasticizers and slags.

The coefficients of variation for flexural strength range from 0.2 to 15.4% but are generally less than 8%. No significant trends are present for mixes with and without slags and superplasticizers.

The coefficients of variation for splitting-tensile strength range from 1.0 to 20.0% but are generally less than 10%. Once again, no significant trends are apparent for mixes with and without slags and superplasticizers.

CONCLUSIONS

The investigation reported herein indicates that slag has considerable potential as a partial replacement for portland cement in concrete. In general, regardless of age, the compressive strength of concrete incorporating slag is lower than that of concrete made of normal portland cement. This is particularly so at early ages and for concrete with a low W:C+S ratio. The low rate of strength development at early ages for concrete incorporating slag could mitigate against its use in winter concreting in Canada.

Regardless of the ratio, the compressive strength development pattern appears to be as follows:

> At early ages there appears to be a wide gap between the strength of control concrete and that incorporating slag. This difference in strength narrows between 7 and 91 days depending upon the ratio. Beyond 91 days the difference in the two strengths once again widens. No explanation can be offered for this.

For concrete with ratios of 0.46 and 0.56, the 91- and 365-day strength of cylinders cast from concrete incorporating various percentages of slag is generally higher than the 28-day strength of control cylinders. Thus on jobs where 91- or 365-day strength may be the governing criterion such as in massive bridge piers, abutment walls, harbour works, the use of slag can offer savings in construction.

At 25 and 45% replacement of cement by slag, the flexural strength of slag concrete is comparable with or greater than the corresponding strength of control concrete. This can be of a decided advantage for highway and airport pavements.

The flexural to compressive strength ratio of concrete incorporating slag increases with increasing percentages of slag. This can offer advantages in the design of structural elements requiring high flexural to compressive strength ratios.

The high demand for the air entraining agent for concrete incorporating slag is a decided disadvantage, whereas the apparent lower requirement for the superplasticizer to make flowing concrete is encouraging.

The modifications in mix proportioning methods in which an additional amount of slag is used to replace sand or the use of high-early strength cement instead of normal portland cement may overcome the problem of low strengths at early ages. However, this may or may not be economical, depending upon the relative prices of slag, normal portland and high-early strength cements.

The relatively poor strength of low W:C+S ratio concret remains unanswered and needs further research. Investigations are also needed to fully explain the low dosage requirements of superplasticizers for slag concrete and its high flexural to compressive strength ratio at early ages.

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APPENDIX A

Table A-1 - Within-batch standard deviation and coefficient of variation for compressive strength test results

Mix series	Mix No.	Type of mix	W:C+S ratio⁺	1-day			7-day			28-day			91-day		
				Compressive strength*	S.D.**	C.V.***	Compressive strength*	S.D.**	C.V.***	Compressive strength*	S.D.**	C.V.***	Compressive strength*	S.D.**	C.V.***
				MPa	MPa	%	MPa	MPa	%	MPa	MPa	%	MPa	MPa	%
B	5	Control + AEA	0.38	25.6	0.8	3.2	38.1	0.6	1.5	47.9	2.1	4.4	53.6	0.8	1.5
	6	Control + AEA + SP		28.3	0.8	2.7	38.3	0.4	1.1	44.5	1.9	4.3	53.3	0.6	1.2
	7	25% slag + AEA		17.2	0.7	3.8	34.1	1.2	3.5	43.3	1.8	4.2	50.0	2.5	4.9
	8	25% slag + AEA + SP		21.2	0.4	2.0	33.8	0.6	1.8	40.6	0.5	1.3	46.1	2.0	4.3
	9	45% slag + AEA		10.6	0.6	5.5	37.2	0.8	2.6	39.9	1.8	4.6	45.9	0.9	2.0
	10	45% slag + AEA + SP		10.2	0.7	7.0	31.2	1.9	6.2	36.6	2.0	5.6	42.5	0.6	1.5
	11	65% slag + AEA		6.7	0.1	0.9	29.6	0.8	2.6	35.1	1.5	4.3	41.8	0.6	1.5
	12	65% slag + AEA + SP		5.6	0.4	6.6	26.1	0.6	2.2	31.8	1.6	4.9	40.3	0.9	2.2
C	13	Control + AEA	0.46	16.6	0.4	2.3	28.4	0.5	1.7	36.7	0.3	0.9	43.2	0.3	0.8
	14	Control + AEA + SP		18.0	1.1	5.9	29.2	2.8	9.5	35.9	1.2	3.3	44.0	1.2	2.6
	15	25% slag + AEA		11.1	0.4	3.5	27.0	2.1	7.9	35.9	1.5	4.1	41.5	0.2	0.5
	16	25% slag + AEA + SP		12.4	0.4	3.4	27.1	0.5	1.7	37.8	1.7	4.6	44.0	2.1	4.8
	17	45% slag + AEA		8.2	0.1	1.2	23.6	0.7	3.2	34.0	2.0	5.8	41.4	3.1	7.5
	18	45% slag + AEA + SP		8.1	0.1	1.5	23.4	1.0	4.3	36.4	3.6	9.9	40.2	1.3	3.2
	19	65% slag + AEA		2.9	0.1	4.0	17.4	0.6	3.2	29.6	0.8	2.8	35.7	2.2	6.2
	20	65% slag + AEA + SP		3.1	0.1	2.4	18.8	0.3	1.6	29.3	0.5	1.6	34.1	1.0	2.9
D	21	Control + AEA	0.56	11.1	0.7	6.4	23.4	0.7	3.1	29.1	1.3	4.6	31.4	0.7	2.1
	22	Control + AEA + SP		13.7	0.4	3.0	22.8	0.6	2.5	28.4	0.2	0.7	36.1	0.5	1.5
	23	25% slag + AEA		8.2	0.5	6.4	20.0	0.4	1.9	27.0	0.5	2.0	32.0	0.7	2.2
	24	25% slag + AEA + SP		8.8	0.1	1.6	20.9	0.9	4.1	28.7	1.4	4.8	33.9	1.1	3.2
	25	45% slag + AEA		4.6	0.2	4.0	16.3	0.4	2.5	27.1	1.2	4.5	30.1	0.8	2.7
	26	45% slag + AEA + SP		4.1	0.03	0.6	20.7	0.4	2.0	26.2	1.4	5.2	35.3	1.3	3.8
	27	65% slag + AEA		1.9	0.03	1.5	13.8	0.4	3.0	26.1	0.8	3.0	28.4	2.0	7.0
	28	65% slag + AEA + SP		1.8	0.04	2.3	13.4	0.4	2.9	24.4	1.1	4.5	28.5	0.1	0.5

⁺Water:cement+slag ratio (by weight)

*Each strength value is average of tests on three 100 x 100-mm cylinders

**Standard deviation

***Coefficient of variation

Table A-2 - Within-batch standard deviation and coefficient of variation for splitting-tensile strength test results

				Splitting-tensile strength						Flexural strength***		
				28-day			91-day			14-day		
Mix series	Mix No.	Type of mix	W:C+S ratio*	Splitting-tensile strength** MPa	S.D.+ MPa	C.V.++ %	Splitting-tensile strength** MPa	S.D.+ MPa	C.V.++ %	Flexural strength*** MPa	S.D.+ MPa	C.V.++ %
B	5	Control + AEA	0.38	4.1	0.20	4.9	4.6	0.05	1.0	8.1	0.42	5.1
	6	Control + AEA + SP		4.1	0.43	10.6	4.1	0.41	9.7	8.0	0.78	9.7
	7	25% slag + AEA		3.9	0.62	15.6	4.5	0.50	11.2	7.8	1.20	15.4
	8	25% slag + AEA + SP		3.2	0.25	7.7	4.0	0.08	2.0	7.5	1.15	15.4
	9	45% slag + AEA		4.5	0.38	8.3	4.1	0.62	15.0	7.5	0.33	4.5
	10	45% slag + AEA + SP		3.7	0.67	5.9	4.0	0.57	14.3	6.8	0.37	5.5
	11	65% slag + AEA		4.0	0.26	6.4	4.1	0.26	6.1	6.7	0.37	5.6
	12	65% slag + AEA + SP		3.3	0.17	5.1	3.9	0.35	9.0	6.5	0.61	9.3
C	13	Control + AEA	0.46	3.7	0.49	13.4	4.1	0.27	6.5	5.4	0.41	7.5
	14	Control + AEA + SP		3.7	0.39	10.5	4.5	0.19	4.2	6.0	0.06	1.0
	15	25% slag + AEA		3.7	0.42	11.1	4.7	0.62	12.9	-	-	-
	16	25% slag + AEA + SP		3.9	0.39	10.0	4.6	0.31	6.7	5.9	0.03	0.5
	17	45% slag + AEA		3.7	0.76	20.0	4.2	0.36	8.4	6.1	0.28	4.5
	18	45% slag + AEA + SP		3.2	0.20	6.1	3.2	0.15	3.3	6.8	0.08	1.2
	19	65% slag + AEA		3.5	0.46	13.1	3.3	0.16	5.0	5.5	0.07	1.3
	20	65% slag + AEA + SP		3.4	0.15	4.4		0.25	7.5	5.6	0.14	2.5
D	21	Control + AEA	0.56	3.0	0.16	5.4	3.9	0.48	12.3	4.7	0.08	1.8
	22	Control + AEA + SP		3.3	0.10	12.9	4.3	0.36	8.1	5.2	0.76	14.6
	23	25% slag + AEA		3.3	0.41	12.3	3.7	0.33	8.9	5.5	0.40	7.1
	24	25% slag + AEA + SP		3.6	0.11	2.9	4.1	0.08	2.0	5.9	0.31	5.3
	25	45% slag + AEA		3.4	0.30	8.8	3.7	0.27	7.1	5.5	0.08	1.6
	26	45% slag + AEA + SP		3.8	0.33	8.7	3.5	0.33	9.3	6.0	0.21	3.5
	27	65% slag + AEA		3.4	0.25	7.4	3.3	0.19	5.5	5.4	0.13	2.3
	28	65% slag + AEA + SP		3.2	0.07	2.0	3.4	0.26	7.5	5.2	0.01	0.2

*Water:cement+slag ratio (by weight)

**Each splitting-tensile strength value is average of tests on three 100 x 200-mm cylinders

***Each flexural strength value is average of tests on two 90 x 100 x 405-mm prisms

+Standard deviation

++Coefficient of variation

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