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MECHANICAL PROPERTIES AND FREEZING AND THAWING DURABILITY OF CONCRETE INCORPORATING A GROUND GRANULATED BLAST-FURNACE SLAG

V.M. Malhotra*

Abstract

This report gives results of laboratory investigations to determine the mechanical properties and freezing and thawing durability of concrete incorporating a granulated blast-furnace slag from a Canadian source. A series of fifteen 0.06 m^3 concrete mixtures were made with water-to-(cement + slag) ratios ranging from 0.70 to 0.45. The percentage of slag used as a replacement for normal portland cement ranged from 0 to 100% by weight. All mixtures were air entrained. A number of test cylinders and prisms were cast for determining the mechanical properties and freezing and thawing resistance of concrete.

The test results indicate that the ground-granulated blast-furnace slag can be used with advantage as a partial replacement for portland cement in concrete at 50% or lower replacement levels, especially at W/C + S of about 0.55 or lower.

At 7 days, irrespective of the W/C + S, and regardless of the percentage replacement of the cement by the slag investigated, the compressive strength of concrete incorporating slag is lower than that of the concrete made with normal portland cement.

At all W/C + S, and at all percentages of replacement, the flexural strength of slag concrete is comparable with, or greater than, the corresponding strength of the control concrete.

Durability of air-entrained slag concrete exposed to repeated cycles of freezing and thawing is satisfactory, as evidenced by the high durability factors achieved.

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Keywords: Granulated Slag, Bleeding, Time of Setting, Concrete, Strength, Freezing and Thawing, Shrinkage, Creep, Abrasion.

LES PROPRIÉTÉS MÉCANIQUES ET LA RÉSISTANCE AU GEL ET AU DÉGEL DU BÉTON EN Y INCORPORANT UN LAITIER DE HAUT FOURNEAU BROYÉ ET GRANULÉ

V.M. Malhotra*

Résumé

Le présent rapport expose les résultats de recherches en laboratoire afin de déterminer les propriétés mécaniques et la résistance au gel et au dégel du béton en y incorporant un laitier de haut fourneau granulé, de source canadienne. Une série de quinze mélanges de béton de 0,06 m^3 ont été préparés avec des rapports eau-(ciment+laitier) variant entre 0,70 et 0,45. Le pourcentage de laitier utilisé en remplacement du ciment Portland ordinaire variait entre 0 et 100 % en poids. Tous les mélanges ont été aérés. Un nombre de cylindres et de prismes d'essai ont été coulés afin de déterminer les propriétés mécaniques du béton et sa résistance au gel et au dégel.

Les résultats des essais ont démontré que le laitier de haut fourneau broyé et granulé pouvait avantageusement remplacer de façon partielle le ciment Portland dans le béton à des niveaux de remplacement de 50 % ou moins, particulièrement à un rapport E/C+L d'environ 0,55 ou moins.

Au bout de sept jours, sans tenir compte du rapport E/C+L ni du pourcentage de remplacement du ciment par le laitier étudié, la résistance à la compression du béton renfermant du laitier était inférieure à celle du béton fait de ciment Portland ordinaire.

À tous les rapports E/C+L et à tous les pourcentages de remplacement, la résistance à la flexion du béton fait de laitier était comparable ou supérieure à la résistance correspondante du béton témoin.

La résistance du béton de laitier aéré exposé à des cycles répétés de gel et de dégel est satisfaisante, comme l'ont démontré les facteurs de résistance atteints.

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Mots-clés : laitier granulé, ressuage, temps de prise, béton, résistance, gel et dégel, retrait, fluage, abrasion.

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INTRODUCTION

The Canada Centre for Mineral and Energy Technology (CANMET) has played a significant role in Canada for over thirty years in research associated with construction materials of mineral origin. In recent years greater emphasis has been given to research on fly ashes, ferrous and non-ferrous slags, condensed silica fume, and limestone dust aimed at conserving both resources and energy (1-30).

In 1985 CANMET funded a research project to encourage the production of granulated blast-furnace slag at the Algoma Steel Corporation plant at Sault Ste. Marie, Ontario. A granulation system using rotary filter dewatering was selected as the most suitable method of producing the slag. As a result, an experimental granulating unit was installed at the above steel plant and about 45 metric tons of granulated* slag was produced (25). The slag was ground to three different Blaine finenesses ranging from 3700 to 6080 cm^2/g. Characterization studies, and preliminary evaluation of the slag in mortar and concrete, indicated that it was comparable in performance with other slags (25). Autoclave expansion tests on mortar prisms, performed in accordance with ASTM C 151, indicated no deleterious expansion in spite of the high MgO content of the slag (24).

This paper describes a laboratory study undertaken to determine the mechanical properties and freezing and thawing resistance of concrete incorporating the above slag ground to a Blaine fineness of 6080 cm^2/g.

SCOPE

In this study, a total of fifteen 0.06 m^3 concrete mixtures involving 33 batches were made. The water:(cement + slag) ratio of the mixtures ranged from 0.45 to 0.70, and the percentage of slag used as a replacement for normal portland cement varied from 0 to 100% by weight of the cement. All mixtures were air entrained. A number of 152 x 305-mm cylinders were cast for testing in compression and for determining modulus of elasticity and creep. Test prisms, 76 x 102 x 390-mm in size were also cast for determining the drying shrinkage, flexural strength, and resistance to repeated cycles of freezing and thawing in accordance with ASTM standard, C 666 Procedure A. Test blocks, 305 x 305 x 102-mm in size, were also cast for determining the abrasion resistance of concrete.

CONCRETE MIXTURES

The concrete mixtures were made in the CANMET laboratory in early 1986 using the following materials.

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*Hereafter, the term slag, when used alone refers to the ground-granulated product.

Cement

Normal portland cement, ASTM Type I, was used. Its physical properties and chemical analysis are given in Table 1.

Slag

As described earlier, the slag was obtained from an experimental production facility installed at the Algoma Steel Corporation plant at Sault Ste. Marie, Ontario. The physical properties and chemical analysis of the slag are given in Table 1.

The Blaine fineness of the slag was 6080 cm^2/g and its relative density was 2.87. The slag activity index, when tested in accordance with ASTM C 989, was 81% at 7 days and 115.3% at 28 days.

Aggregates

Minus 19-mm crushed limestone was the coarse aggregate and local natural sand the fine aggregate. To keep the grading uniform for each mixture, 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 2 and 3.

Air-Entraining Admixture (AEA)

A sulphonated hydrocarbon-type air-entraining admixture was used in all the mixtures.

MIXTURE PROPORTIONS

The proportioning of the concrete mixtures is summarized in Table 4. For all mixtures, 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 the weight difference. A predetermined amount of water was added to the fine aggregate, which was then allowed to stand for 24 h.

Four series of concrete mixtures were made with W:(C + S) ratios of 0.70, 0.55, and 0.45. For mixtures in Series I, II, and III, the percentage level of the slag replacement for the cement was 25, 50, and 75%. The mixtures in series IV were made with 100% slag only, and incorporated no portland cement.

Two or three batches were made for each mixture of Series I, II, and III, in order to obtain sufficient test specimens for determining the mechanical properties and resistance to freezing and thawing. Only one batch was made for the mixtures of Series IV, and the test specimens were cast for compressive strength determination only (Table 5).

The concrete was mixed in a laboratory counter-current mixer for a total of six minutes, with slag being added as a separate ingredient.

Table 1 - Physical properties and chemical analysis of cement and granulated slag

Description of test	Portland cement*	Slag
Physical tests - general		
Time of set (Vicat needle): initial	2 hr : 10 min	-
: final	3 hr : 55 min	-
Fineness		
Passing 45 µm,	82.7	98%
Surface area, Blaine	3660 cm^2/g	6000 cm^2/g
Soundness, Autoclave	0.13	-
Physical tests - mortar strength		
Compressive strength of 51-mm cubes, at 3 days	22.6 MPa	-
7 days	27.0 MPa	21.7**MPa
28 days	32.9 MPa	-
		36.2**MPa
Chemical analysis		
Insoluble residue	0.80%	-
Silicon dioxide (SiO_2)	20.14%	37.8%
Aluminum oxide (Al_2O_3)	5.40%	8.8%
Ferric oxide (Fe_2O_3)	2.38%	0.60%
Calcium oxide (CaO) total	62.04%	31.8%
Magnesium oxide (MgO)	2.62%	18.4%
Sulphur trioxide (SO_3)	3.87%	2.28%
Loss on ignition	1.12%	-1.88%
K_2O	0.24%	-
Na_2O		
Glass content		
by QXRD	-	90.3%
Slag activity index (ASTM C 989)		
at 7 days	-	81.0%
28 days	-	115.3%
Compound composition		
C_3S	48.7%	
C_2S	21.0%	
C_3A	10.3%	
C_4AF	7.2%	

*Manufacturer's data.
**In accordance with ASTM C 989.

Table 2 - 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 3 - Physical properties of aggregates

	Coarse aggregate	Fine aggregate
Specific gravity	2.68	2.70
Absorption, %	0.80	1.00

Table 4 - Mixture proportions

Mixture series	Mixture no.	$\frac{W*}{C + S}$	Slag as replacement for cement, %	Quantities, kg /m^3					
				Water	Cement	Slag	C.A.	F.A.	AEA ** mL/m^3
I	1	0.70	0	140	199	-	1159	772	143
	2		25	140	149	50	1159	773	155
	3		50	140	100	100	1165	776	182
	4		75	141	50	151	1167	778	262
II	5	0.55	0	145	263	-	1131	755	160
	6		25	145	198	65	1134	756	161
	7		50	145	132	132	1132	755	233
	8		75	145	66	197	1124	749	364
III	9	0.45	0	150	334	-	1153	677	233
	10		25	151	252	84	1144	672	318
	11		50	149	166	166	1138	669	357
	12		75	150	84	250	1144	671	531
IV	13	0.70	100	137	-	196	1133	756	311
	14	0.55	100	145	-	263	1121	746	363
	15	0.45	100	154	-	342	1164	684	602

*Water:(Cement + slag) ratio by weight.
**Air-entraining admixture.

Table 5 - Number of batches per concrete mixture

Mixture series	Mixture no.	$\frac{W^*}{C + S}$	Slag as replacement for cement, %	Batches made per mixture		
I	1	0.70	0	A	B	C
	2		25	A	B	-
	3		50	A	B	C
	4		75	A	B	-
II	5	0.55	0	A	B	C
	6		25	A	B	-
	7		50	A	B	C
	8		75	A	B	-
III	9	0.45	0	A	B	C
	10		25	A	B	-
	11		50	A	B	C
	12		75	A	B	-
IV	13	0.70	100	-	B	-
	14	0.55	100	-	B	-
	15	0.45	100	-	B	-

*Water:(cement + slag) ratio by weight.

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. The bleeding of the concrete and the time of setting of fresh concrete are shown in Table 7.

PREPARATION AND CASTING OF TEST SPECIMENS

Batch A (Mixtures 1 to 12)

Four 152 x 305-mm cylinders and twelve 76 x 102 x 390-mm prisms were cast from batch A of each mixture.

The cylinders were used for the determination of compressive strength and Young's modulus of elasticity, and the prisms were used for determining the flexural strength, drying shrinkage, and freezing and thawing resistance of concrete. Both the cylinders and prisms were cast in two layers, with each layer compacted using an internal vibrator for the cylinders and a vibrating table for the prisms.

After casting, all the moulded specimens were covered with water-saturated burlap, then 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 at 100% relative humidity until required for testing, with the exception of the prisms for drying shrinkage tests. These prisms were stored in lime-satured water.

Batch B (All Mixtures)

Ten 152 x 305-mm cylinders were cast from batch B of each mixture. The cylinders were cast and cured in the manner outlined above, and were used for determining the compressive strength at various ages up to 365 days.

Batch C (Mixtures 1,3,5,7,9,11)

Ten 152 x 305-mm cylinders and one 305 x 305 x 102-mm block were cast. The cylinders were cast and cured in the manner outlined above, and the block was cast in one layer and compacted using a vibrating table. The cylinders were used for determination of the compressive strength and creep. The block was used for the determination of the abrasion resistance characteristics of the concrete.

TESTING OF SPECIMENS

The testing schedule is shown in Table 8. All specimens for compression testing were capped with a sulphur and flint mixture before testing. Freezing and thawing tests were performed in an automatic freezing and thawing unit capable of performing six cycles per day - one complete cycle from 4.4° ± 1.7°C to -17.8° ± 1.7°C requires about four 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 them in the freezing and thawing unit at the thawing phase for one hour. The initial and all subsequent measurements

Table 6 - Properties of fresh concrete

Mixture series	Mixture no.	$\frac{W^*}{C + S}$	Slag as replacement for cement, %	Slump mm			Unit weight kg/m^3			Air content %			** Temp., °C
				Batch A	Batch B	Batch C	Batch A	Batch B	Batch C	Batch A	Batch B	Batch C	
I	1	0.70	0	50	55	70	2270	2275	2265	6.6	7.0	6.5	19
	2		25	70	75	-	2275	2265	-	6.0	6.7	-	18
	3		50	55	55	65	2290	2280	2270	5.9	6.5	6.7	20
	4		75	40	50	-	-	2285	-	6.1	6.5	-	19
II	5	0.55	0	70	75	65	2305	2295	2280	6.0	6.3	6.9	19
	6		25	45	65	-	2315	2285	-	6.0	6.8	-	20
	7		50	65	65	50	2300	2295	2295	6.2	6.7	6.7	21
	8		75	60	75	-	2285	2275	-	6.7	6.9	-	20
III	9	0.45	0	70	60	65	2315	2320	2315	6.2	6.0	6.9	18
	10		25	75	70	-	2280	2320	-	7.1	6.1	-	21
	11		50	65	70	75	2295	2280	2295	6.7	6.7	6.6	19
	12		75	55	50	-	-	2315	-	6.0	6.6	-	20
IV	13	0.70	100	-	85	-	-	2225	-	-	7.7	-	19
	14	0.55	100	-	65	-	-	2275	-	-	6.7	-	19
	15	0.45	100	-	50	-	-	2345	-	-	4.8	-	19

*Water:(cement + slag) ratio by weight.

**Average value for the batches made.

Table 7 - Bleeding and time of setting of fresh concrete

Mixture series	Mixture no.	$\frac{W^*}{C + S}$	Slag as replacement for cement, %	Bleeding, $cm^3/cm^2 \times 10^{-2}$	Time of set hr:min Initial	Time of set hr:min Final
I	1	0.70	0	18.5	6:00	10:18
	3	0.70	50	19.5	6:51	11:45
II	5	0.55	0	11.1	4:51	7:33
	7	0.55	50	2.8	5:09	8:57
III	9	0.45	0	1.6	5:06	7:24
	11	0.45	50	3.4	5:18	8:09

*Water:(cement + slag) ratio by weight.

Note: Bleeding and time of setting lists were performed in accordance with ASTM C 232 and C 403.

Table 8 - Testing schedule for hardened concrete

Batch No.	Type of testing	Age of testing, days					
		7	14	28	91	1 year	3 year
A(Mixture no. 1-12)	Compression (ASTM C 39)	-	-	2 cylinders	-	-	-
	Young's modulus of elasticity (ASTM C 469)	-	-	2 cylinders	-	-	-
	Flexural (ASTM C 78)	-	2 prisms	-	-	-	-
	Freezing and thawing (ASTM C 666), procedure A	Two prisms exposed to repeated cycles of freezing and thawing after 14 days of moist curing, and two prisms kept as reference in the moist-curing room until the end of freezing and thawing cycling					
	Drying shrinkage (ASTM C 157)	Two prisms each exposed to air drying at 23°C and 50% R.H. at the end of 7 days of curing in water					
B(Mixture no. 1-12)	Compression (ASTM C 39)	2 cylinders		2 cylinders	2 cylinders	2 cylinders	2 cylinders
B(Mixture no. 13-15)	Compression (ASTM C 39)	2 cylinders		2 cylinders	2 cylinders	2 cylinders	2 cylinders
C(Mixture no. 1,3,5, 7,9,11)	Compression (ASTM C 39)	-		2 cylinders	-	-	-
	Creep (ASTM C 512)	Four cylinders subjected to creep tests after 126 to 130 days of moist-curing					
	Abrasion (ASTM C 779)	One slab tested for abrasion after 120 days of moist-curing					

Note: Up to 3 concrete batches per mixture were made in order to cast all the specimens needed.

of the freezing and thawing test specimens, as well as the reference specimens, were made at this temperature. After initial measurements of the prisms had been taken, two test specimens were placed in the freezing and thawing machine, and the two companion prisms were placed in the moist-curing room for reference purposes.

The freezing and thawing 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 ultrasonic pulse velocity methods at approximately every 100-cycle interval. The freezing and thawing testing was terminated at the completion of 310 ± 10 cycles. Following this, both the reference and the freezing and thawing prisms were tested in flexure.

TEST RESULTS AND THEIR ANALYSIS

A total of 234 cylinders, 120 prisms, and 6 slabs were tested. Densities of the test cylinders were taken at one day and the data are shown in Table 9. The increased demand for AEA with increasing percentages of the slag is shown in Figure 1. A summary of the compressive and flexural strengths is given in Table 9, and the data are illustrated in Figures 2 to 5.

The drying shrinkage tests on the test prisms were commenced after an initial curing period of 7 days in lime-saturated water. Shrinkage strains were monitored for a period of 224 days of air drying at 23 ± 1.7°C and 50 ± 4% relative humidity. The expansion of the companion prisms stored in water was also monitored over the same period as mentioned above.

The drying shrinkage/expansion data are shown in Tables 10 and 11 and are illustrated in Figures 6 to 8. A summary of the test results after 300 cycles of freezing and thawing, including durability factors, is given in Table 12. The creep tests on 152 x 305-mm cylinders were commenced after an initial moist-curing period of 125 ± 5 days, with a constant applied load of 7.63 MPa. This, in most cases, was equivalent to about 30% of the compressive strength of the concrete at the age of loading. The very limited data are shown in Table 13.

The data on air void parameters on the hardened concrete, and the flexural strengths of the reference prisms and the test prisms after 300 cycles of freezing and thawing, are shown in Tables 14 and 15. The changes in weight, length, pulse velocity, and resonant frequency of the reference prisms and the prisms subjected to freezing and thawing cycling are shown in Appendix Tables 1 to 4.

The abrasion characteristics of the concrete test blocks were determined after a moist-curing period of 300 ± 20 days and the data are shown in Table 16. As far as possible, all tests were performed according to ASTM C 779, Procedure C. The apparatus for this procedure consists of a motor-driven hollow vertical shaft resting on and turning ball bearings, which rest on the concrete surface.

Table 9 - Summary of densities, compressive and flexural strengths, and modulus of elasticity

Mixture series	Mixture no.	W / C + S	Slag as replacement for cement, %	Density* of cylinders at one day, kg/m³	Compressive strength of cylinders, MPa					14-day flexural strength of prisms	28-day E modulus of elasticity of cylinders
					7-day		28-day		91-day	MPa	GPa
				Batch B	Batch B	Batch A**	Batch B	Batch C	Batch B	Batch A	Batch A
I	1	0.70	0	2305	12.9	15.7	16.1	16.2	19.3	3.2	24.7
	2		25	2300	10.6	15.4	15.5	-	19.7	3.1	23.9
	3		50	2320	8.3	17.0	16.6	16.0	20.0	3.1	26.9
	4		75	2320	6.3	14.9	13.0	-	15.5	3.7	27.0
II	5	0.55	0	2325	19.7	24.4	24.3	22.5	28.2	4.7	29.4
	6		25	2300	18.0	28.4	25.8	-	28.4	5.0	29.1
	7		50	2310	14.4	24.8	25.2	26.5	28.6	4.8	30.0
	8		75	2310	10.8	19.8	19.7	-	21.8	4.0	26.5
III	9	0.45	0	2350	25.5	29.6	31.7	29.7	35.2	5.7	32.2
	10		25	2330	24.7	29.6	32.7	-	37.5	5.5	31.6
	11		50	2295	20.9	32.0	31.0	32.5	34.6	6.0	32.9
	12		75	2300	18.5	26.9	25.5	-	28.5	5.7	28.6
IV	13	0.70	100	2270	4.6	-	7.4	-	9.5	-	-
	14	0.55	100	2315	5.8	-	9.9	-	12.9	-	-
	15	0.45	100	2345	7.2	-	11.1	-	14.2	-	-

Note: Each value represents the average of two test results unless otherwise specified.
*Average of 10 test results.
**Average of 4 test results;
cylinder size = 152 x 305 mm;
prism size = 76 x 102 x 390 mm.

Table 10 - Summary of drying shrinkage test results after 7-day initial moist-curing

Mixture series	Mixture no.	$\frac{W}{C + S}$	Slag as replacement for cement, %	Shrinkage strain, x10^{-6} (prism size = 76 x 102 x 390 mm)					
				7-day	16-day	28-day	56-day	112-day	224-day
I	1	0.70	0	121	202	355	415	479	514
	2	0.70	25	96	156	270	397	418	447
	3	0.70	50	75	149	245	355	482	553
	4	0.70	75	32	117	209	298	457	582
II	5	0.55	0	174	234	333	443	486	546
	6	0.55	25	142	177	277	447	443	518
	7	0.55	50	67	156	220	365	397	478
	8	0.55	75	32	99	177	337	472	571
III	9	0.45	0	206	273	379	489	546	575
	10	0.45	25	117	206	287	454	443	539
	11	0.45	50	89	145	223	355	390	454
	12	0.45	75	82	117	234	312	429	546

Table 11 - Summary of expansion/shrinkage test results after continuous water storage

Mixture series	Mixture no.	$\frac{W}{C + S}$	Slag as replacement for cement %	Expansion/shrinkage strain, $x10^{-6}$ (prism size: 76 x 102 x 390 mm)						
				7-day	14-day	21-day	35-day	63-day	119-day	231-day
I	1	0.70	0	+50	+64	+53	+18	+28	+32	+18
	2	0.70	25	+7	+4	-17	-17	-25	+4	+7
	3	0.70	50	+64	+67	+74	+60	+71	+75	+82
	4	0.70	75	+96	+85	+75	+60	+92	+75	+85
II	5	0.55	0	+28	+36	+46	+32	+46	+71	+53
	6	0.55	25	+39	+28	+18	+21	+4	+39	+46
	7	0.55	50	+46	+39	+14	+18	+25	+57	+53
	8	0.55	75	+92	+113	+92	+135	+113	+121	+124
III	9	0.45	0	+21	+21	+25	+53	+43	+60	+57
	10	0.45	25	+67	+64	+67	+82	+75	+89	+43
	11	0.45	50	-21	-14	0	+28	0	+39	-14
	12	0.45	75	+96	+67	+106	+106	+85	+121	+145

Table 12 - Summary of test results on concrete prisms after 300 cycles* of freezing and thawing

Mixture series	Mixture no.	$\frac{W}{C + S}$	Slag as replacement for cement, %	Air content in fresh concrete, %	Per cent change at the end of freeze-thaw cycling				Durability factor
					Weight	Length	Pulse velocity	Resonant frequency	
I	1	0.70	0	6.6	-1.47	-0.005	+0.42	-0.92	98
	2	0.70	25	6.0	-2.43	-0.014	-1.25	-2.34	95
	3	0.70	50	5.9	-1.85	-0.006	-2.22	-2.46	95
	4	0.70	75	6.1	-1.52	-0.001	+4.84	-2.70	95
II	5	0.55	0	6.0	-0.49	+0.004	-2.10	-0.61	99
	6	0.55	25	6.0	-0.61	+0.001	+1.06	-1.43	97
	7	0.55	50	6.2	-1.36	+0.012	+0.45	-1.85	96
	8	0.55	75	6.7	-0.62	-0.011	+0.42	-3.42	93

*Actual number of cycles of freezing and thawing at the termination of the test varied between 310 ± 10.

Table 13 - Summary of creep test results

Mixture series	Mixture no.	$\frac{W}{C+S}$	Age at loading, days	Applied stress, MPa	Stress/ strength ratio*, %	Duration of loading, days	Initial elastic strain, $x10^{-6}$	Creep strain**, $x10^{-6}$
I	1	0.70	128	7.63	40.0	28	280	434
	3	0.70	128	7.63	38.2	28	247	275
II	5	0.55	130	7.63	27.1	22	224	266
	7	0.55	126	7.63	26.7	21	195	174
III	9	0.45	126	7.63	21.7	14	202	168
	11	0.45	126	7.63	22.1	7	203	100

* Applied stress as a percentage of compressive strength of companion specimen at 126 to 130 days.

**Creep strain = total load-induced strain - initial elastic strain.

Note: All tests were discontinued after the duration of loading shown above because of overloading of the test system.

Table 14 - Air-void parameters of hardened concrete

Mixture series	Mixture no.	$\frac{W}{C + S}$	Slag as replacement for cement, %	Air content in fresh concrete, %	Air-void parameters of hardened concrete*			
					Air content, %	Specific surface, mm^{-1}	Spacing factor, mm	Voids per mm
I	1	0.70	0	6.6	9.7	22.8	0.084	0.552
	2	0.70	25	6.0	10.4	17.5	0.078	0.453
	3	0.70	50	5.9	9.9	22.3	0.078	0.552
	4	0.70	75	6.1	8.8	26.7	0.083	0.586
II	5	0.55	0	6.0	6.6	25.9	0.116	0.427
	6	0.55	25	6.0	6.3	26.7	0.126	0.419
	7	0.55	50	6.2	8.7	22.2	0.114	0.483
	8	0.55	75	6.7	7.0	32.4	0.087	0.571

*From report of CANMET contract: 23440-4-9337.

Table 15 - Flexural strengths of reference prisms and test prisms after freezing and thawing cycling

Mixture series	Mixture no.	$\frac{W}{C + S}$	Slag as replacement for cement, %	Flexural strength of 76 x 102 x 390-mm prisms,* MPa			
				Reference moist-cured		Test prisms after 300 freezing and thawing cycles	Residual flexural strength, %
				After 14-day moist curing	At the end of freezing and thawing cycles**		
I	1	0.70	0	3.2	3.6	3.2	89
	2	0.70	25	3.1	3.9	2.9	74
	3	0.70	50	3.1	4.4	2.9	66
	4	0.70	75	3.7	4.5	3.1	69
II	5	0.55	0	4.7	5.1	4.6	90
	6	0.55	25	5.0	5.5	4.2	76
	7	0.55	50	4.8	6.1	4.1	67
	8	0.55	75	4.0	4.4	3.6	82

*Each value represents average of two test results.

**Moist curing duration = 66 ± 2 days.

Table 16 - Abrasion resistance of control and slag concretes (ASTM C 779, procedure C)

Time, Sec.	Depth of wear, mm					
	W/C + S = 0.70		W/C + S = 0.55		W/C + SF = 0.45	
	Control	50% Slag	Control	50% Slag	Control	50% Slag
0	0	0	0	0	0	0
50	1.235	1.205	1.085	0.956	0.680	0.605
100	1.805	1.875	1.440	1.360	1.250	0.745
150	2.235	2.265	1.670	1.570	1.530	1.060
200	2.680	2.675	1.860	1.760	1.605	1.140
250	2.675	3.305	2.080	1.825	1.660	1.310
300	2.939	3.360	2.270	2.210	1.795	1.325
350	3.095	-	2.395	2.260	1.855	1.435
400	3.225	-	2.530	2.355	2.090	1.555
450	-	-	2.670	2.470	2.155	1.695
500	-	-	2.775	2.575	2.295	1.875
550	-	-	2.895	2.660	2.445	1.910
600	-	-	3.020	2.635	2.685	1.990
650	-	-	3.075	2.825	2.655	2.145
700	-	-	3.210	2.930	2.770	2.265
750	-	-	-	3.005	2.875	2.330
800	-	-	-	3.000	2.970	2.440
850	-	-	-	3.140	3.075	2.570
900	-	-	-	-	3.130	2.635
950	-	-	-	-	-	2.730
1000	-	-	-	-	-	2.745
1050	-	-	-	-	-	2.875
1100	-	-	-	-	-	2.990
1150	-	-	-	-	-	3.045
1200	-	-	-	-	-	3.085

Note: Age of concrete at testing = 300 ± 20 days.

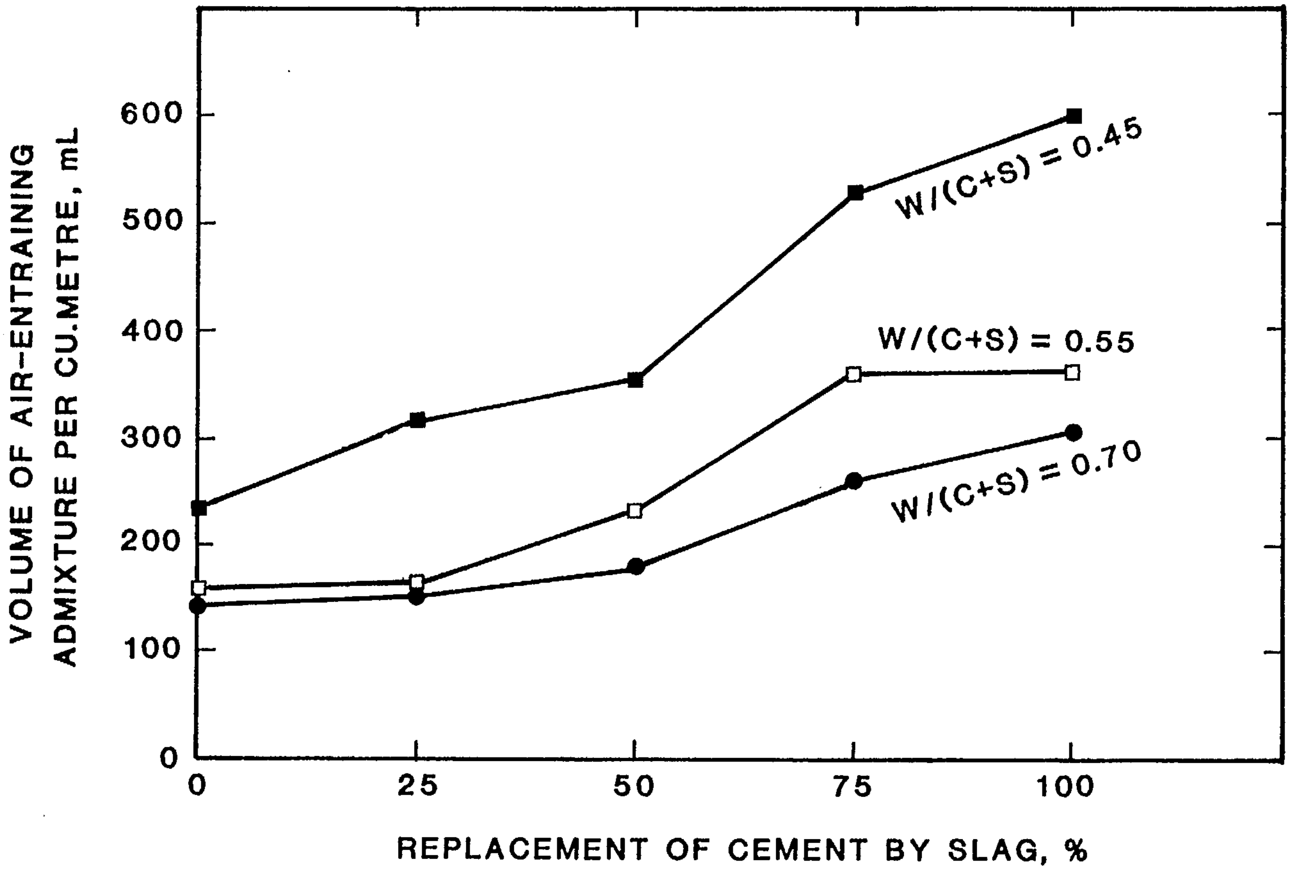

Fig. 1 - Volume of air-entraining admixture versus slag content

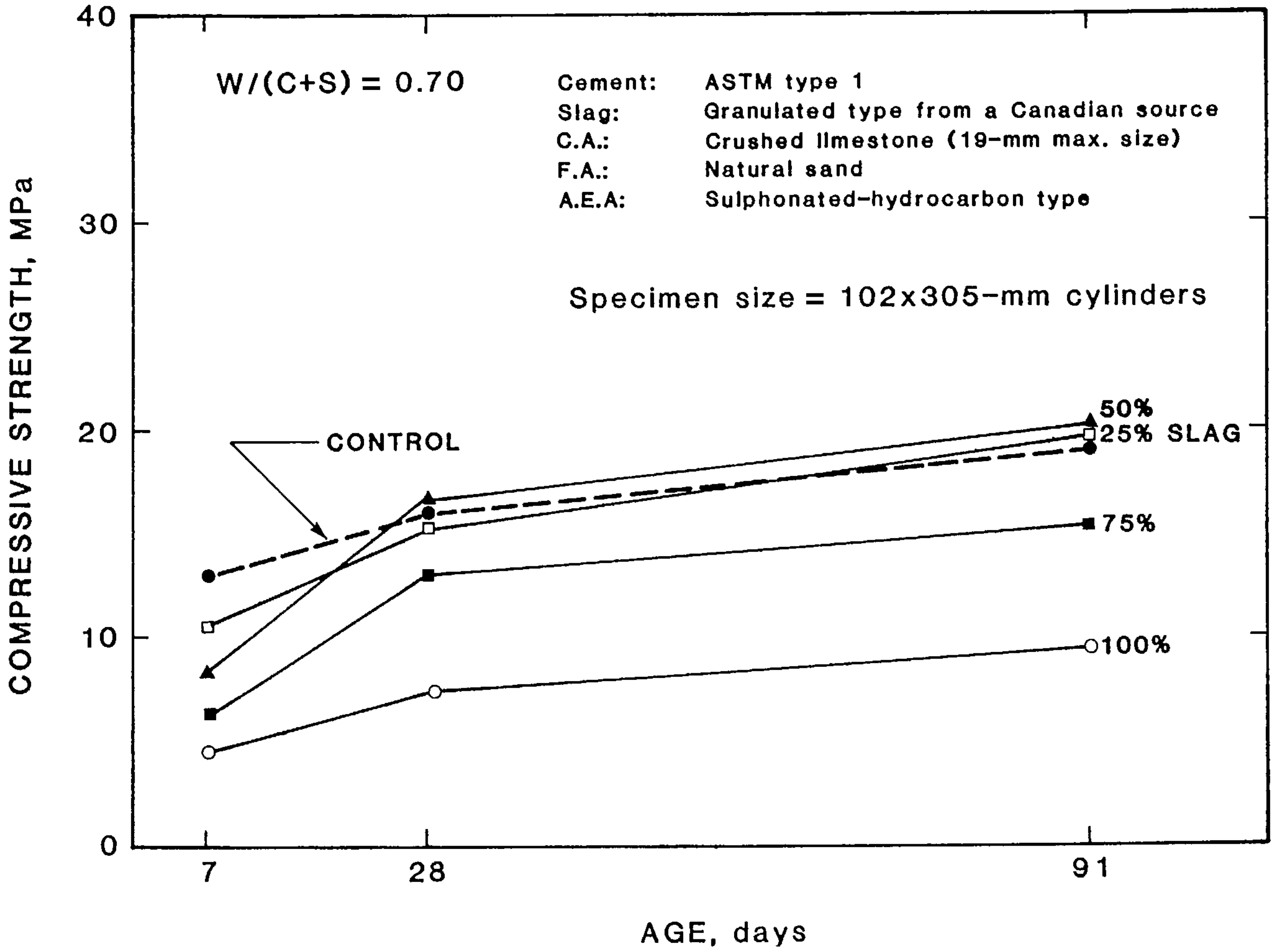

Fig. 2 - Compressive strength versus age for concrete with W/(C + S) of 0.70

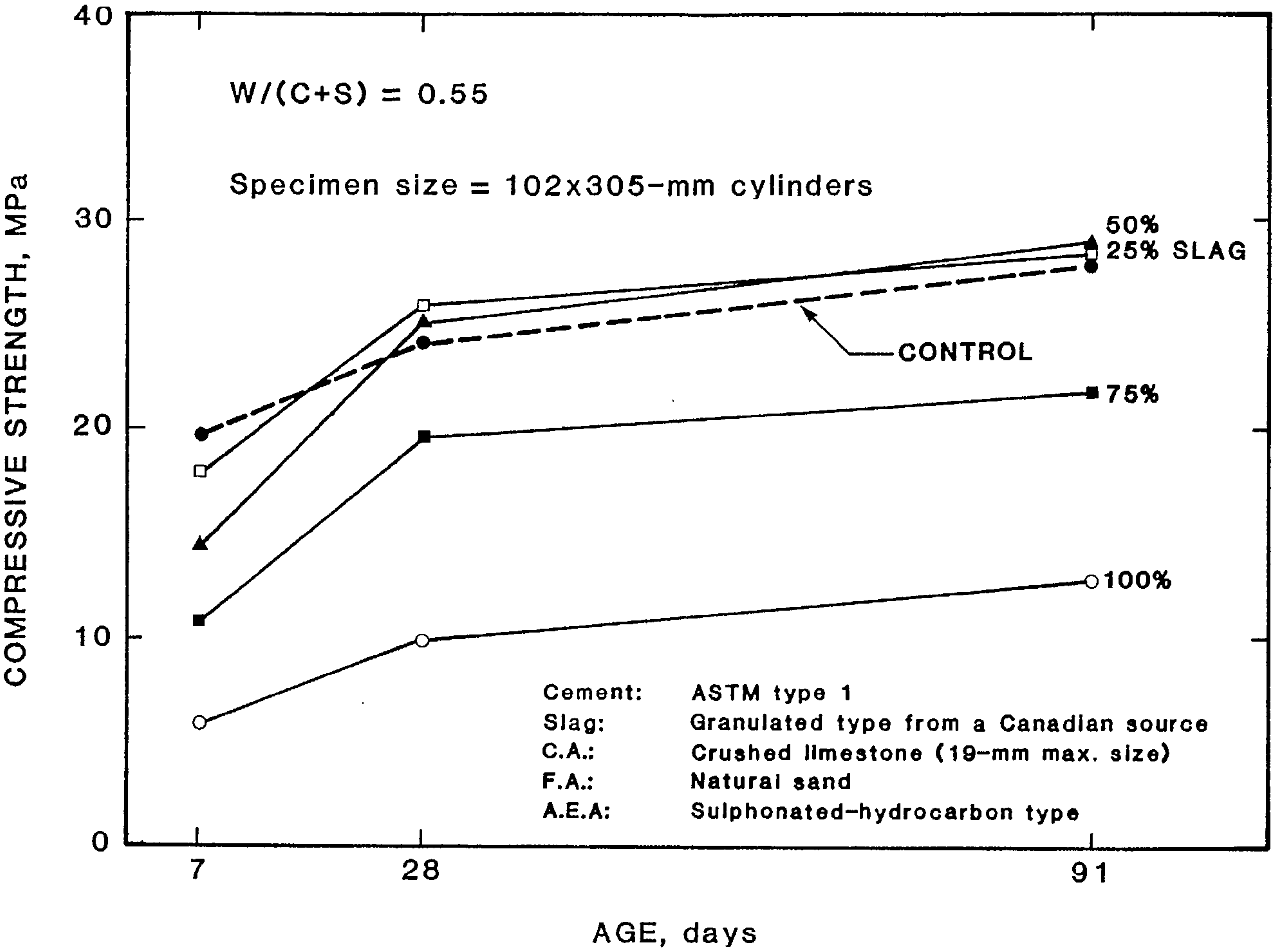

Fig. 3 - Compressive strength versus age for concrete with W/(C + S) of 0.55

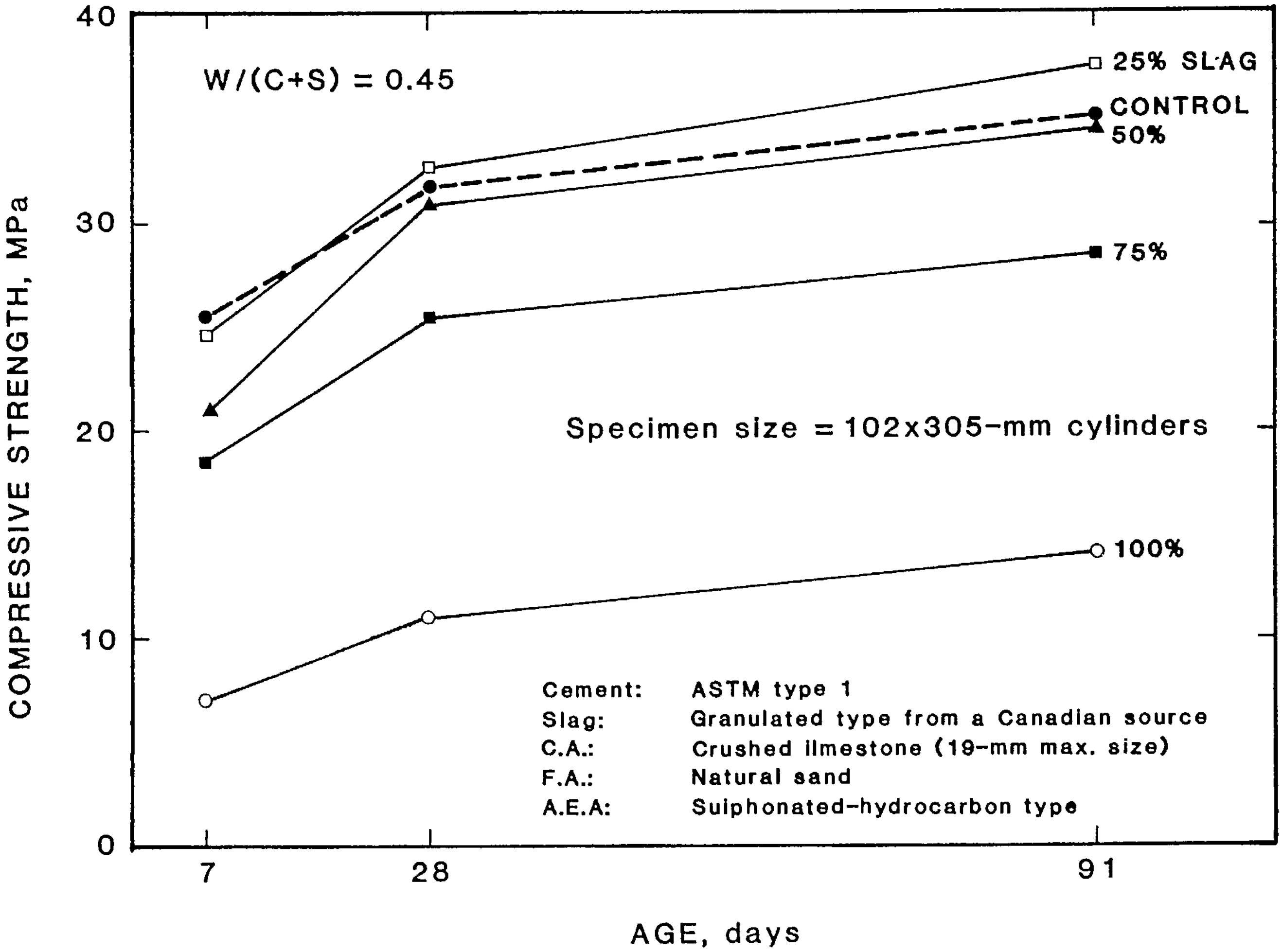

Fig. 4 - Compressive strength versus age for concrete with W/(C + S) of 0.45

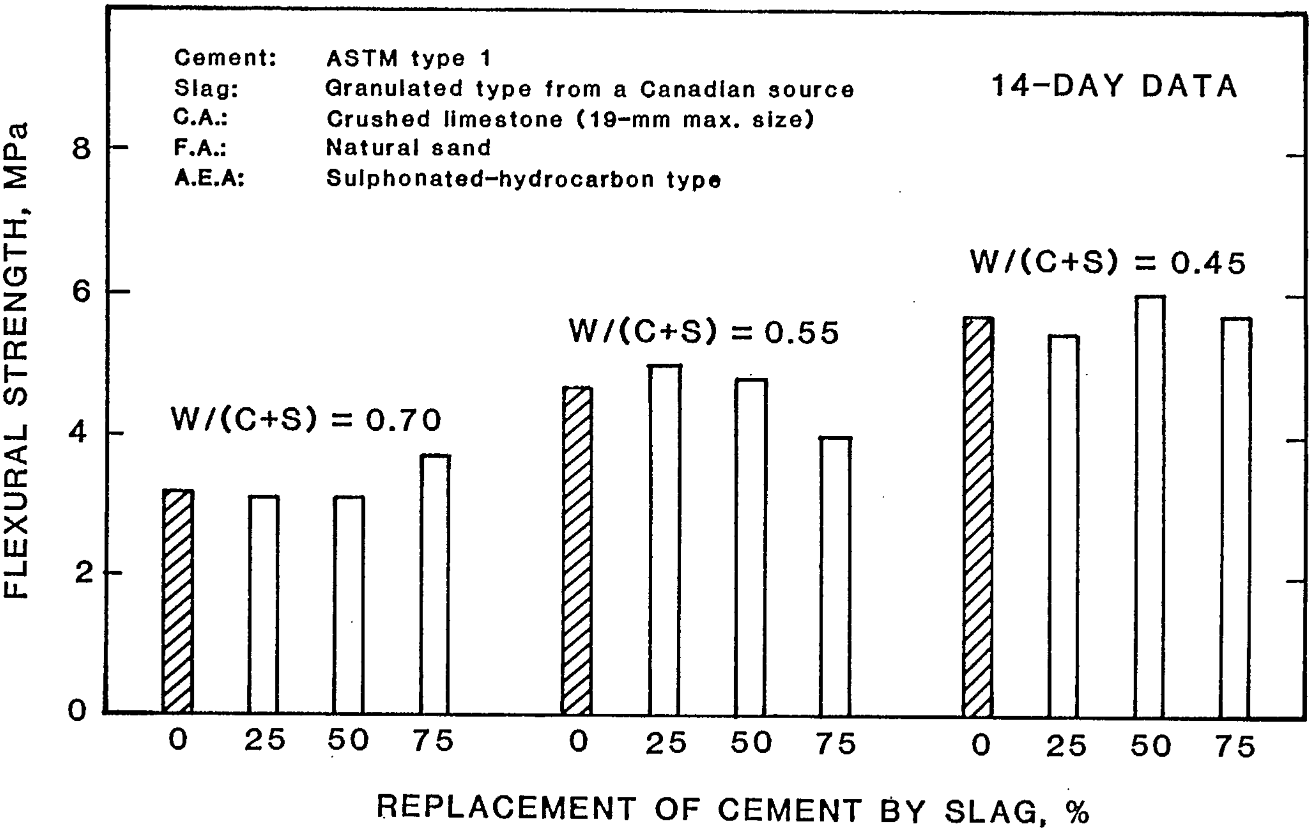

Fig. 5 - Flexural strength of concrete at 14 days

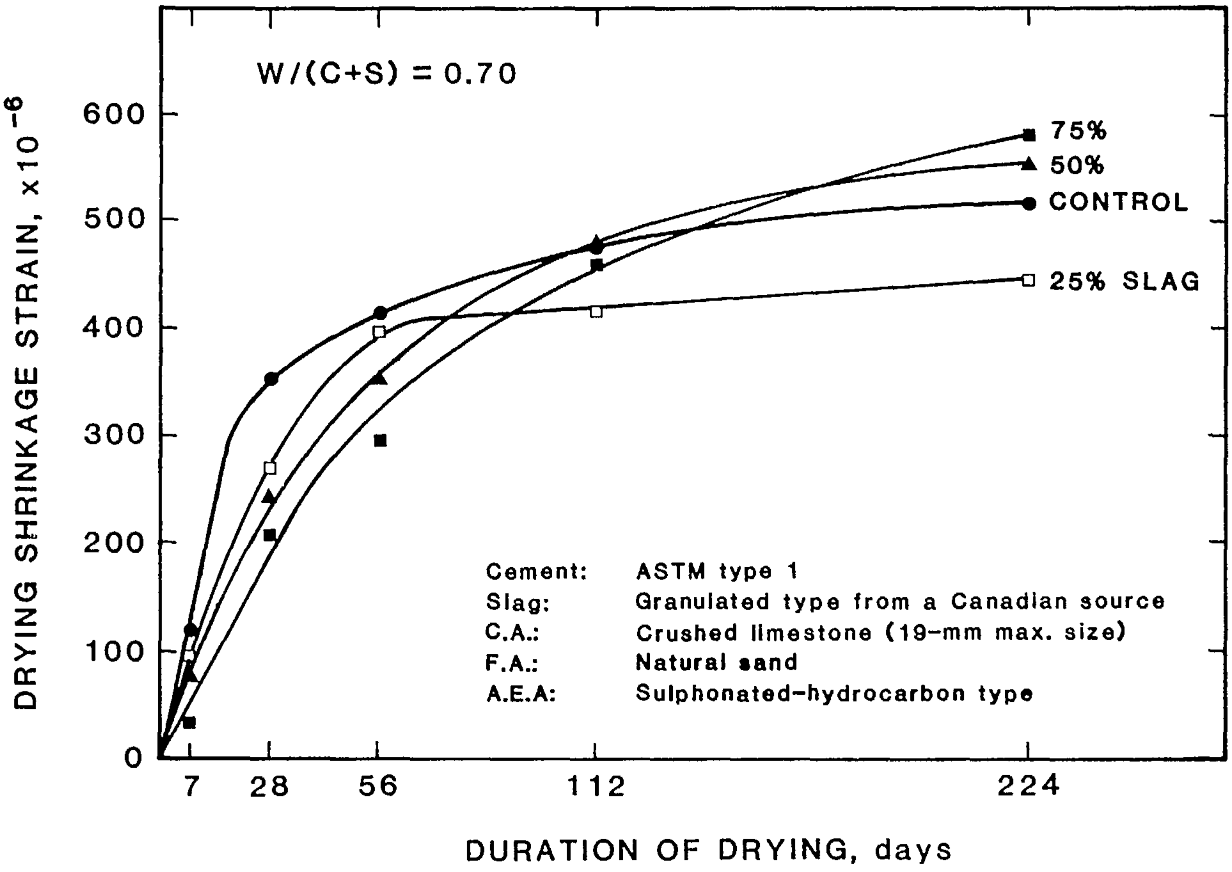

Fig. 6 - Drying shrinkage strains of concrete with W/(C + S) of 0.70

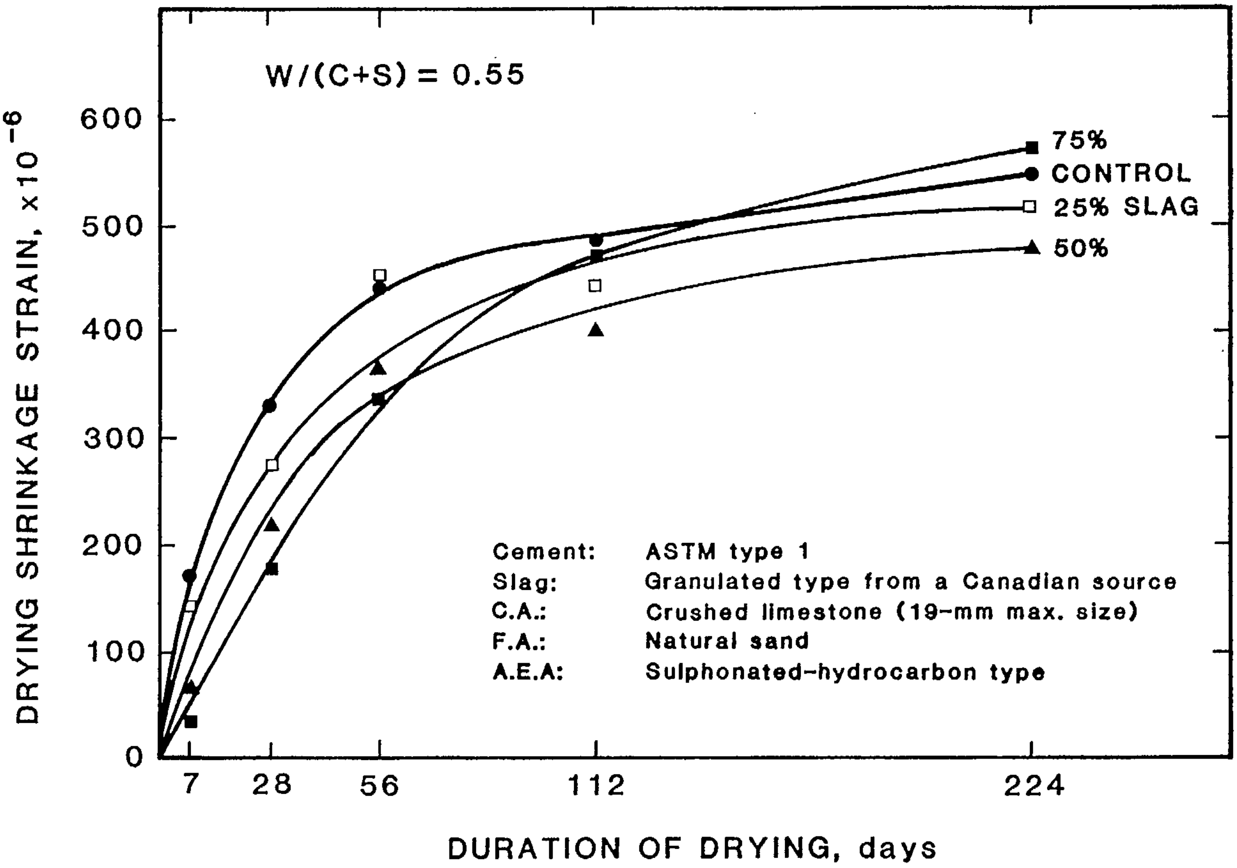

Fig. 7 - Drying shrinkage strains of concrete with W/(C + S) of 0.55

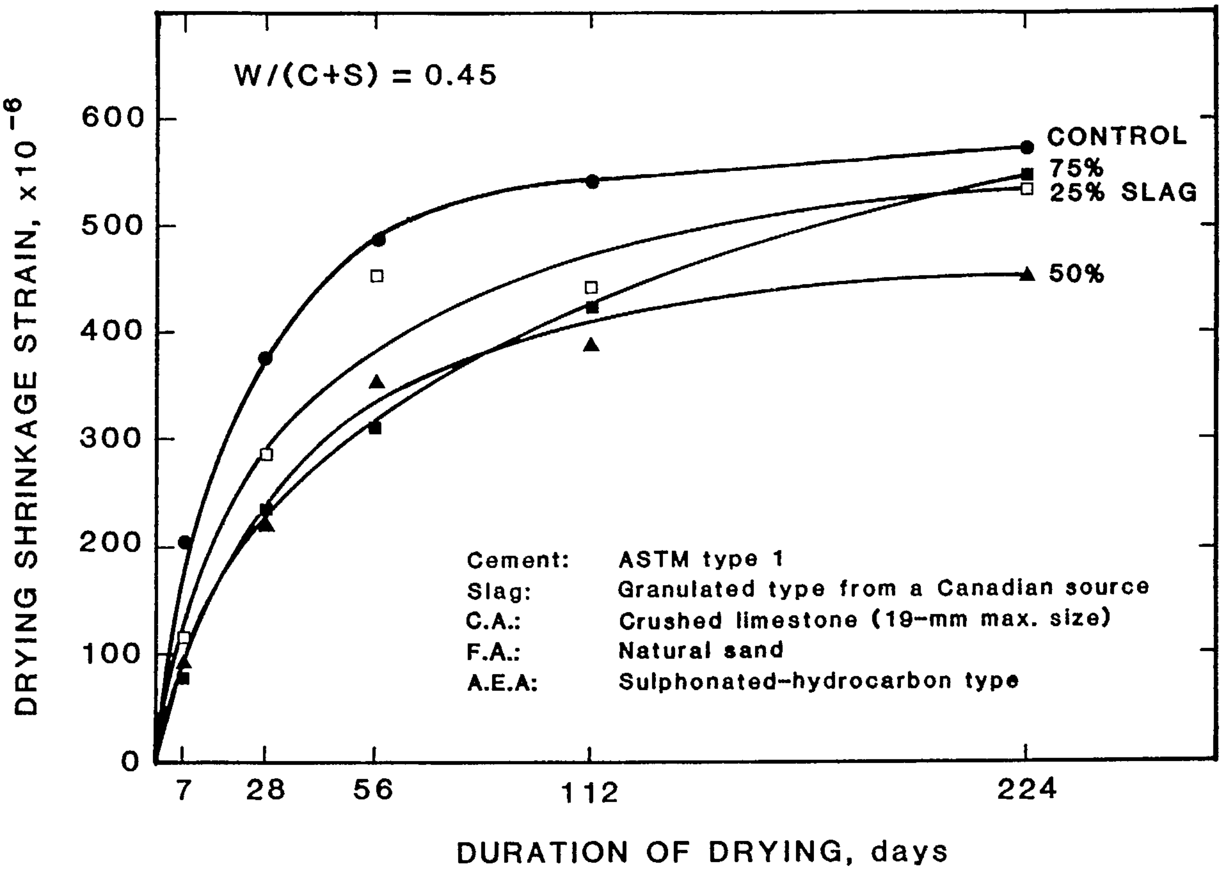

Fig. 8 - Drying shrinkage strains of concrete with W/(C + S) of 0.45

DISCUSSION

Air Content and Dosage of an Air-Entraining Admixture

The mixtures were proportioned to have an air content of 6.5 ± 0.5%, and this was achieved without any serious difficulty except for mixtures incorporating 100% slag. However, regardless of the W/C + S, the dosage required for an AEA to entrain the desired volume of air increased markedly with increase in the percentage of the slag used. For example, for concrete with a W/C + S of 0.55, the AEA needed to entrain 6.5 ± 0.5% air, increased from 160 mL/m^3 for the control mixture to 364 mL/m^3 for the mixture incorporating 75% slag. At W/C + S of 0.70, the increase was not as marked as for W/C + S of 0.55.

Water Requirement and Slump

The test program was designed to maintain the W/C + S constant within each series, with the added requirement that the slump be 60 ± 15 mm. The mixture proportioning data in Table 4, and properties of fresh concrete in Table 6, indicate that this was generally achieved. The only exception was batch A of mixture series I with W/C + S 0.70 and 75% slag as replacement for cement. In this instance, the slump was only 40 mm. Even though there were indications that there was some slump loss with decreasing W/C + S and increasing percentages of the slag, this did not appear to affect the workability of concrete as visually examined. On the contrary, the concretes incorporating slag appeared to be more workable and more responsive to vibration when casting cylinders.

Colour of Hardened Concrete

The centre portions of the specimens tested in compression or flexure were characterized by a bluish-green colour that faded after being left in the laboratory air for several days. The colour was attributed to the formation of calcium sulphide in the slag and its fading was due to the oxidation of the sulphide in dry air.

Compressive Strength

The data on the compressive strength development are presented in Table 9 and in Figures 2 to 4. The strength development pattern for each W/C + S will be discussed separately.

W:(C + S) Ratio of 0.70

Regardless of the percentage of slag used, the 7-day compressive strength of concrete incorporating slag was always lower than that of the control concrete, and the difference in the strength of the two types of concrete increased with increasing percentage of the slag. For example, at 25, 50, and 75% of slag, the 7-day strengths of the slag concrete were 82.2, 64.3, and 48.8% of the control strength. The test cylinders cast from concrete made with 100% slag failed to reach 50% of the value of the control strength.

At 28 days and beyond, the strengths of the concretes incorporating 25 and 50% slag were comparable to the strength of the control concrete, the 91-day strengths of the concretes being approximately 20 MPa.

The rate of strength-gain of concrete incorporating 75% slag paralleled that of the control concrete, but the actual strength was much lower. For example, the strength of the slag concrete was only 80.7 and 80.3% of the control concrete at 28 and 91 days, respectively.

The concrete made with 100% slag continued to gain strength with time but at a much slower rate; the 28-day and 91-day strengths achieved were 7.4 and 9.5 MPa, respectively.

W:(C + S) Ratio of 0.55

At 25, 50, and 75% of cement replacements, the 7-day compressive strengths of the slag concrete were 91.3, 73.1, and 54.8% of the strength of the control concrete. The strength of the test cylinders cast from concrete made with 100% slag was approximately 25% that of the control cylinders.

At 28 days, the strength of the concretes incorporating 25 and 50% slag was of the order of 25 MPa, marginally higher than that of the strength of the control concrete. This was equally true at 91 days when the strength of the slag concrete was about 29 MPa.

The strength of concrete incorporating 75% slag was considerably lower than that of the control concrete, the 28-day strength values being 19.7 and 24.3 MPa, respectively. This trend continued beyond 28 days, and at 91 days the strength of the slag concrete was 77.3% of the control value (Table 9).

The concrete made with 100% slag continued to gain strength slowly, reaching only 9.9 and 12.9 MPa at 28 and 91 days, respectively.

W:(C + S) Ratio of 0.45

At 7 days, the strength of the concrete incorporating 25% slag was 24.7 MPa and was comparable with that of the control concrete. At 16 days, the strength of the former concrete surpassed that of the control concrete (Fig. 4). Beyond that, the difference in the strengths of the two concretes increased slightly. For example, at 91 days the strength of the slag concrete reached 37.5 MPa as compared with 35.2 MPa for the control concrete.

The strength of concrete incorporating 50% slag was considerably lower than that of the control concrete at 7 days. At 28 and 91 days, the strengths of the two concretes were comparable, with the corresponding strength values being 34.6 and 35.2 MPa, respectively.

As with higher W/C + S, the strength of concrete incorporating 75% slag was considerably lower than that of the control concrete at all ages. For example, at 91 days, the strength of the former concrete was 28.5 MPa as compared with 35.2 MPa for the latter concrete.

The concrete made with 100% slag continued to gain strength with time, reaching 11.1 and 14.2 MPa at 28 and 91 days, respectively.

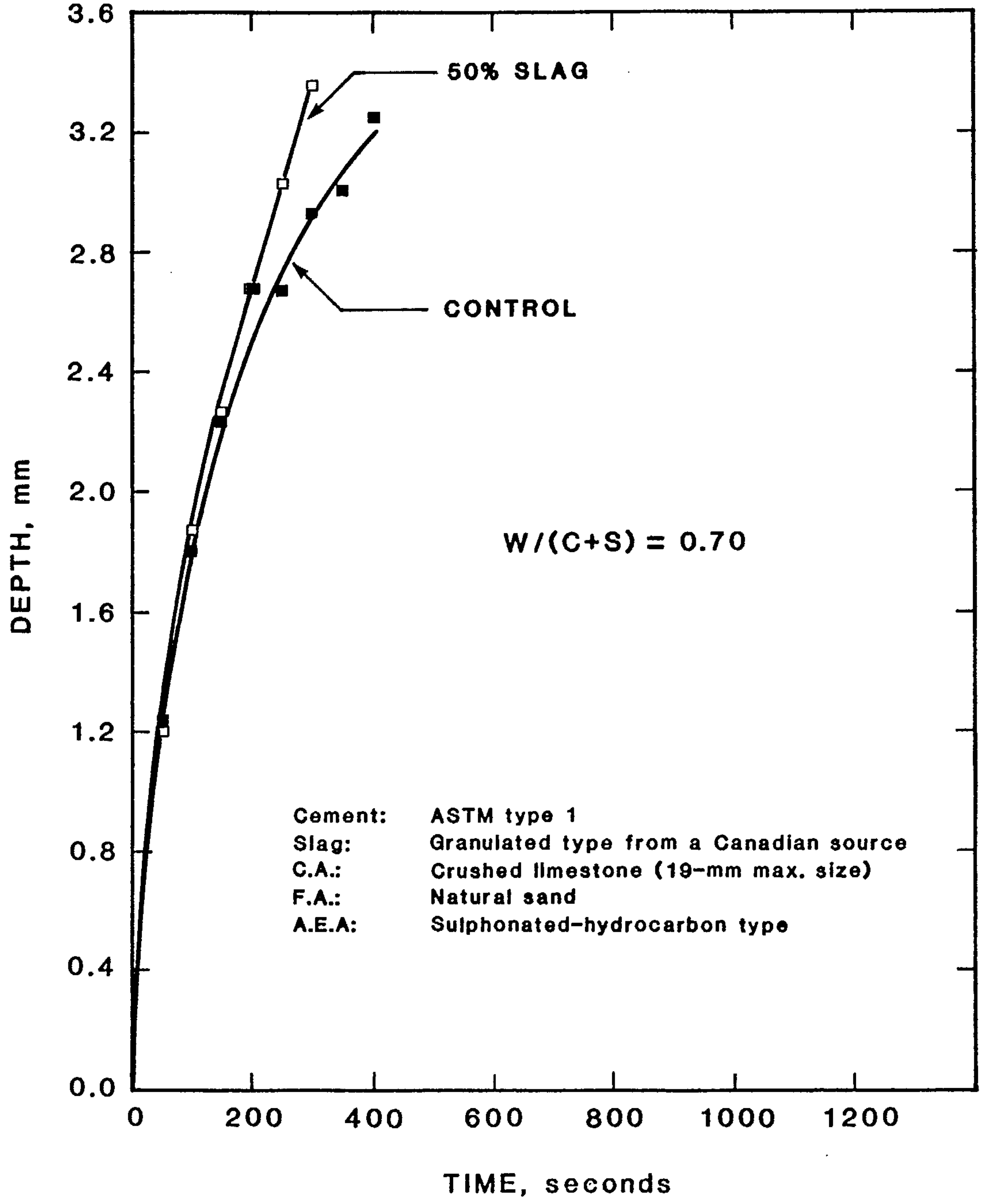

Fig. 9 - Abrasion resistance of control and slag concretes, W/C + S of 0.70

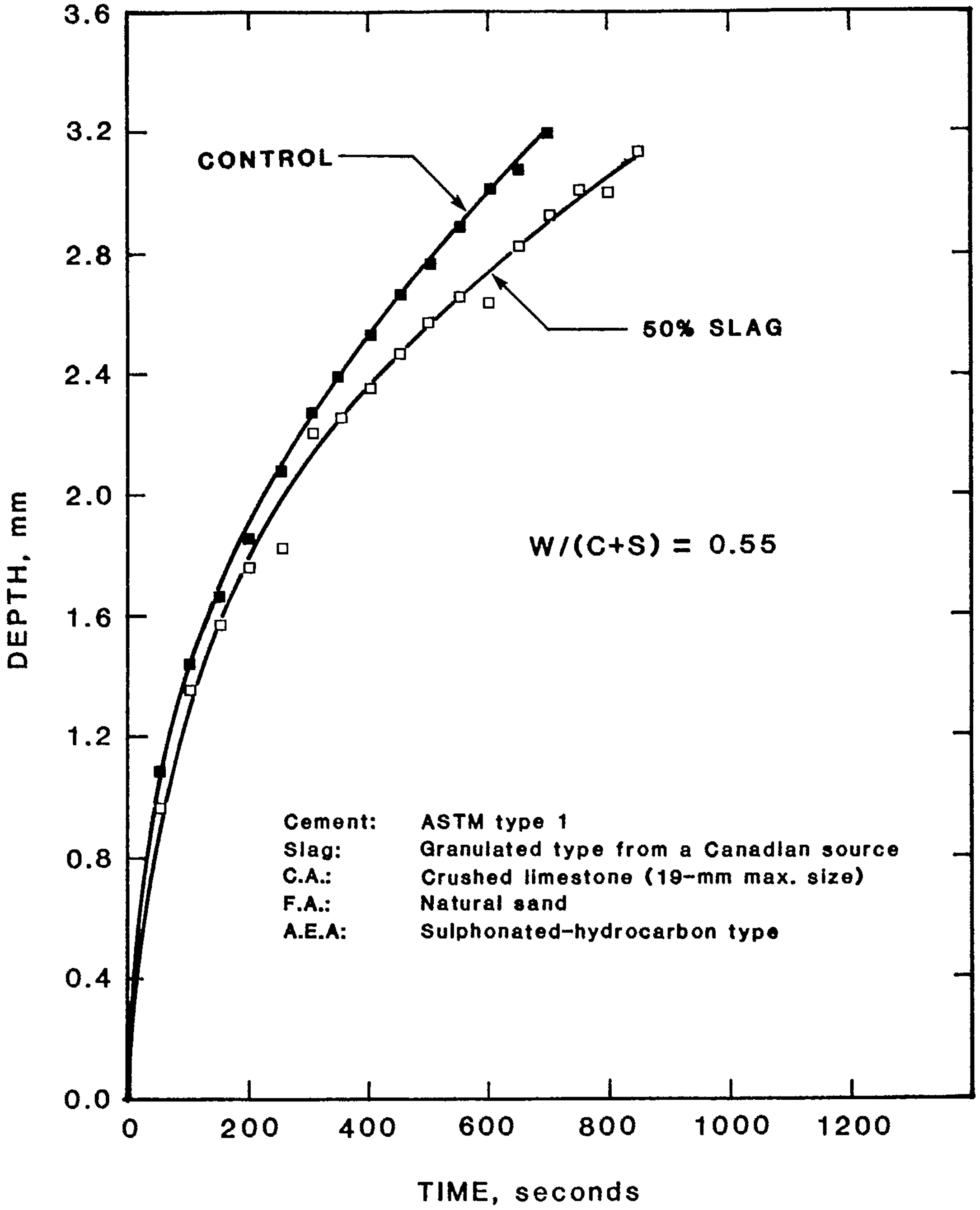

Fig. 10 - Abrasion resistance of control and slag concretes, W/C + S of 0.55

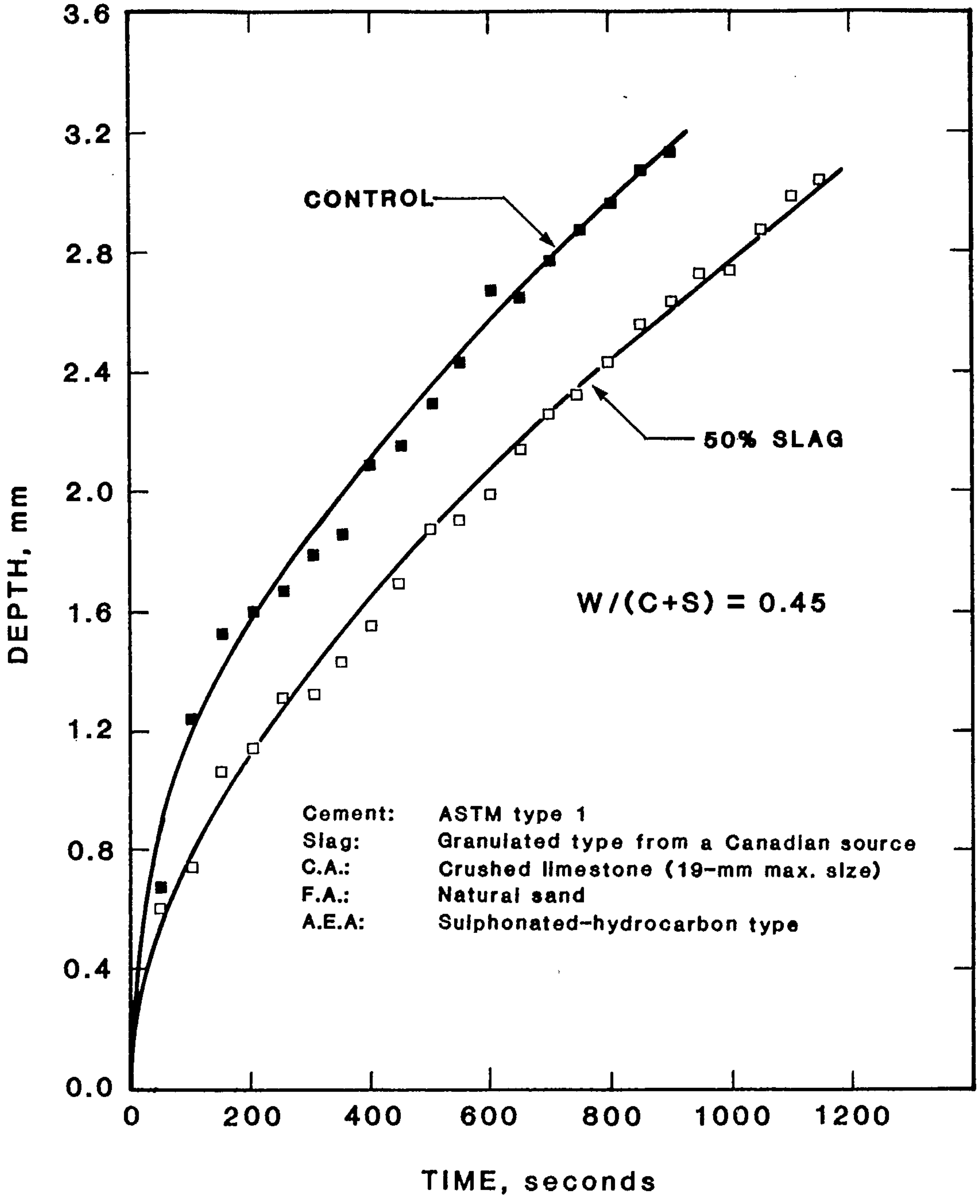

Fig. 11 - Abrasion resistance of control and slag concretes, W/C + S of 0.45

From the foregoing discussion of strength development of concrete with W/C + S ranging from 0.70 to 0.45, it becomes apparent that at low W/C + S, the use of very high percentages of slag as a replacement for cement is not desirable as far as strength development characteristics are concerned.

Flexural Strength

The 14-day flexural strength of concrete ranged from 3.1 to 3.7, 4.0 to 5.0, and 5.5 to 6.0 for concrete with W/C + S of 0.70, 0.55, and 0.45, respectively (Fig. 5). The flexural strength of the slag concrete, irrespective of the percentage of slag used, was comparable with that of the control concrete. Unlike the compressive strength, which showed marked loss at higher percentages of slag as replacement for cement, the flexural strength showed no such loss.

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

From the foregoing discussion, it can be concluded that in concrete construction where the design criterion is based on flexural rather than compressive strength, such as airport and highway pavements, the use of slag concrete can be advantageous.

Young's Modulus of Elasticity "E"

The 28-day Young's modulus of elasticity values are shown in Table 9. At W/C + S of 0.70, the "E" values of concrete incorporating slag were comparable to that of the control concrete. For example, the modulus values for concrete incorporating slag ranged from 23.9 to 27.0 GPa, with the value for the control concrete being 24.7 GPa. At W/C + S of 0.55 and 0.45, and at lower percentages of slag, the "E" values for the control concrete and that incorporating slag were comparable at about 30 GPa. However, at 75% slag, the "E" values for concrete incorporating slag were lower than that of the control concrete. For example, at W/C + S of 0.45, the "E" value for the former concrete was 28.6 GPa compared with 32.2 for the latter concrete. The lower "E" values correspond with the lower 28-day compressive strength of the former concrete.

Drying Shrinkage

Drying shrinkage strains were determined over a period of 224 days, following an initial curing period in lime-saturated water of 7 days (Tables 10, 11).

The drying shrinkage of the control concrete prisms and the test prisms was comparable regardless of the W/C + S, and irrespective of the percentage of the slag used. After 224 days, the drying shrinkage strains ranged from a low of 447 x 10^{-6} for concrete with W/C + S of 0.70 and 25% slag to a high of 582 x 10^{-6} for concrete with W/C + S of 0.70 and 75% slag.

Expansion/shrinkage strains were also determined over a period of 231 days during continuous curing of the concrete prisms in lime-saturated water. Somewhat higher expansions were obtained for the test prisms with lower

W/C + S and higher percentages of the slag. The highest expansion of 145 x 10^{-6} was obtained for the test prisms with a W/C + S of 0.45 and incorporating 75% slag.

Creep

Creep tests were initiated at 126 to 130 days at a stress of 7.63 MPa. However, because of the malfunction of the pressure system, the test specimens were overloaded shortly after the commencement of the tests and the tests had to be abandoned. Very limited data from the creep test are shown in Table 13.

Abrasion Resistance of Concrete

Abrasion tests on the control concrete and concrete incorporating the slag were performed in accordance with ASTM C 779, using Procedure C. The test results are shown in Table 16 and illustrated in Figures 9 to 11. At W/C + S of 0.70, the abrasion resistance of the control and the slag concretes is comparable; but at W/C + S of 0.55 and 0.45, the slag concretes show higher resistance compared with the control concrete. For example, for W/C + S of 0.45, the time required to reach 3.0-mm depth of wear is 800 seconds for the control concrete compared with 1130 seconds for the slag concrete.

Air-Void Parameters of Hardened Concrete

The air-void parameters of the hardened concrete are shown in Table 14. For concrete with W/C + S of 0.70 and slag content ranging from 0 to 75%, the specific surface ranged from 17.5 to 26.7 mm^2/mm^3, and the $\bar{L}$ values ranged from 0.078 to 0.084 mm. This indicates that even at the high W/C + S and high percentages of the slag, satisfactory $\bar{L}$ values (< 0.20 mm) can be achieved. However, the specific surface values are not always > 25 mm^2/mm^3.

Regardless of the percentage of slag used, for concrete with W/C + S of 0.55 the specific surface ranged from 22.2 to 32.4 mm^2/mm^3, and the $\bar{L}$ values ranged from 0.087 to 0.126 mm. Thus, the test data indicate that regardless of the W/C + S and irrespective of the percentage of the slag used, $\bar{L}$ values of < 0.20 mm can be achieved in hardened concrete. Once again, some of the specific surface values are lower than the usually recommended values of 25 mm^2/mm^3 (23). Somewhat similar data were obtained in concrete incorporating 20% fly ash (23). Further research is needed to obtain more data in this regard.

Durability of Concrete Prisms Exposed to Repeated Cycles of Freezing and Thawing

Durability of concrete prisms exposed to repeated cycles of freezing and thawing (ASTM C 666, Procedure A: Freezing in water and thawing in water) was determined from weight, length, resonant frequency, and pulse velocity of test specimens before and after freezing and thawing cycling, and by calculating the durability factors. Following the freezing and thawing cycling, the reference and test prisms were broken in flexure.

The test data indicate that regardless of the W/C + S and irrespective of the slag content, the test prisms performed excellently in freezing and thawing cycling, with durability factors equal to or greater than 93%. The control prisms and the prisms incorporating slag had been exposed to freezing and thawing cycling, at equal ages i.e., at the end of 14 days of moist-curing. Thus, the compressive strength of concrete incorporating slag was considerably less than that of the control concrete at the initiation of the freezing and thawing test (Fig. 2 to 4). This appears not to have affected the durability factors.

CONCLUSIONS

1. The tests performed indicate that the ground-granulated slag has excellent potential as a partial replacement for portland cement in concrete at 50% or lower levels of replacement of the cement by the slag.

2. Regardless of the W/C + S, the 75% replacement of the cement by the slag in concrete is not recommended because of the low rate of strength development at all ages.

3. At 7 days, for W/C + S of 0.70 and 0.55 and regardless of the percentage replacement levels of cement by slag, the compressive strength of the concrete incorporating the slag was lower than that of concrete made with normal portland cement. Therefore, caution should be exercised when using slag in concrete for structures where early-age strengths are critical, such as in winter construction in Canada.

4. At all W/C + S, and at all percentage levels of replacement of the cement by the slag, the flexural strength of the slag concrete was comparable with, or greater than, the corresponding strength of the control concrete. This can be of advantage for concrete in highway and airport pavements.

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

5. The high demand for the air-entraining admixture for concrete incorporating the slag is not a serious disadvantage because of the low cost of the admixture.

6. Durability of the slag concrete to repeated cycles of freezing and thawing is satisfactory as evidenced by the high durability factors (> 90), provided that concrete is properly air entrained and has satisfactory $\bar{L}$ and specific surface values.

7. Regardless of the W/C + S, the concrete incorporating 100% slag as replacement for cement showed some strength gain, but the rate of gain and strengths obtained at 28 and 91 days were too low to be of any practical significance.

8. At high W/C + S, the abrasion resistance of the slag concrete is comparable with the control concrete, but at low W/C + S the abrasion resistance of the former concrete is significantly higher than that of the latter concrete.

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REFERENCES

1. Malhotra, V.M.; Berry, E.E.; and Wheat, T.A., Editors. *Proceedings, Seminar on Energy and Resources Conservation in the Cement and Concrete Industry*; CANMET, Energy, Mines and Resources Canada; 1976.

2. Berry, E.E. "Fly ash for use in concrete. Part 1 - A critical review of the chemical, physical and pozzolanic properties of fly ash"; CANMET, Energy, Mines and Resources Canada; 1976.

3. Berry, E.E., and Malhotra, V.M. "Fly ash for use in concrete - A critical review"; *ACI Journal, Proceedings* 77:2:59-73; 1980.

4. Malhotra, V.M.; Carette, G.G.; and Bremner, T.W. "Durability of concrete in marine environment containing granulated blast furnace slag or fly ash or both"; *ACI Special Publication* SP 65, pp. 157-168; (Editor, V.M. Malhotra); 1980.

5. Malhotra, V.M., and Carette, G.G. "Silica fume - Its use in concrete"; *Concrete Construction* 27:5:443-446; Chicago, U.S.A.; May 1982.

6. Malhotra, V.M. "The use of fly ash, silica fume, slag and other mineral by-products in concrete"; *Int Journal for Development Technology* 1:307-315; 1983.

7. Malhotra, V.M. "Strength and durability characteristics of concrete incorporating a pelletized blast-furnace slag"; *ACI Special Publication* SP 79, 2:891-922; (Editor, V.M. Malhotra); 1983.

8. Mukherjee, P.K.; Loughborough, M.T.; and Malhotra, V.M. "Development of high-strength concrete incorporating a large percentage of fly ash and superplasticizers"; *ASTM Cement, Concrete and Aggregates* 4:2:81-86; 1983.

9. Carette, G.G., and Malhotra, V.M. "Mechanical properties, durability and drying shrinkage of portland cement concrete incorporating silica fume"; *ASTM Cement, Concrete and Aggregates* 5:1:3-13; 1983.

10. Malhotra, V.M., and Carette, G.G. "Silica fume concrete - Properties, applications and limitations"; *ACI Concrete International: Design and Construction* 5:5:40-46; May 1983.

11. Carette, G.G., and Malhotra, V.M. "Early-age strength development of concrete incorporating fly ash and condensed silica fume"; *ACI Special Publication* SP 79, 2:765-786; (Editor, V.M. Malhotra); 1984.

12. Carette, G.G.; Malhotra, V.M.; and Aitcin, P.C. "Mechanical properties of portland cement concrete incorporating blast-furnace slag and condensed silica fume"; *Division Report* MRP/MSL 84-73 (OP&J); CANMET, Energy, Mines and Resources Canada; 1984.

13. Carette, G.G.; Wilson, H.S.; and Tan, C.W. "Development of superplasticized lightweight high-strength concrete incorporating fibres, silica fume and fly ash"; *Division Report* MRP/MSL 84-81 (IR); CANMET, Energy, Mines and Resources Canada; 1984.

14. Nebesar, B., and Carette, G.G. "Variations in the chemical composition, specific surface area, fineness and pozzolanic activity of a condensed silica fume; *Division Report* MRP/MSL 84-126 (J); CANMET, Energy, Mines and Resources Canada; 1984.

15. Douglas, E., and Mainwaring, P.R. "Hydration and pozzolanic activity of non-ferrous slags"; *American Ceramic Society Bulletin* 64:5:700-706; 1985.

16. Douglas, E.; Malhotra, V.M.; and Emergy, J.J. "Cementitious properties of non-ferrous slags from Canadian sources"; *ASTM Cement, Concrete and Aggregates* 17:1:3-14; 1985.

17. Malhotra, V.M. "Mechanical properties and freezing and thawing resistance of non air-entrained and air-entrained condensed silica-fume concrete using ASTM Test C 666, Procedures A and B"; *ACI Special Publication* SP 91 2:1069-1093; (Editor, V.M. Malhotra); 1986.

18. Berry, E.E., and Malhotra, V.M. *Fly Ash in Concrete*; CANMET Special Publication SP 85-3; Energy, Mines and Resources Canada; 178 pp.; 1986.

19. Carette, G.G.; Malhotra, V.M.; Bédard, C.; De Benedictis, V.; and Plumat, M. "Development of heat-curing cycles for portland cement/fly ash concrete for the precast industry"; *ACI Special Publication* SP 91, 1:249-272; (Editor, V.M. Malhotra); 1986.

20. Douglas, E.; Mainwaring, P.R.; and Hemmings, R.T. "Pozzolanic properties of Canadian non-ferrous slags"; *ACI Special Publication* SP 91, 2:1525-1551; (Editor, V.M. Malhotra); 1986.

21. Douglas, E., and Malhotra, V.M. "A review of the properties and strength development of non-ferrous slag - portland cement binders"; *CANMET Report* 85-7E; CANMET, Energy, Mines and Resources Canada; 1986.

22. Zerbino, R.; Carette, G.G.; and Malhotra, V.M. "Fineness and Particle Size Determination of Fly Ashes"; *Division Report* MRP/MSL 86-9 (IR); CANMET, Energy, Mines and Resources Canada; 1986.

23. Carette, G.G., and Malhotra, V.M. "Characterization of Canadian fly ashes and their performance in concrete"; *CANMET Report* No. 86-6E; Energy, Mines and Resources Canada; Ottawa; 48 pp.; 1986.

24. Sivasundaram, V., and Painter, K.E. "Autoclave expansion of slag-cement pastes"; *MSL-INT Report* 86-7 (TR); CANMET, Energy, Mines and Resources Canada; Ottawa; 9 pp.; 1986.

25. Douglas, E.; Wilson, H.S.; and Malhotra, V.M. "Production and Evaluation of a new source of granulated blast-furnace slag"; *MSL Division Report* MSL 86-126 (J); Energy, Mines and Resources Canada; Ottawa, Canada; 20 pp., 1986.

26. Johnston, C.D., and Malhotra, V.M. "High strength lightweight concrete with up to 50 per cent high calcium fly ash"; *MSL Division Report* MSL 86-19 (J); Energy, Mines and Resources Canada; Ottawa, Canada; 34 pp.; 1986.

27. Malhotra, V.M. "Superplasticized low cement/high volume fly ash concrete for structural applications"; *MSL Division Report* MSL 86-80 (J); Energy, Mines and Resources Canada; Ottawa, Canada; 10 pp.; 1986.

28. Malhotra, V.M.; Painter, K.E.; Bilodeau, A. "Mechanical properties and freezing and thawing resistance of high-strength concrete incorporating silica fume"; *MSL Division Report* MRP 86-96 (OP&J); Energy, Mines and Resources Canada; Ottawa, Canada; 25 pp.; 1986.

29. Malhotra, V.M. "Properties of fresh and hardened concrete incorporating ground granulated blast furnace slags"; *MSL Division Report* 86-136 (J); Energy, Mines and Resources Canada; Ottawa, Canada; 54 pp.; 1986.

30. Douglas, E., and Zerbino, R. "Characterization of granulated and pelletized blast furnace slag"; *Cement and Concrete Research* 16:5:662-670; 1986.

APPENDIX A

Table A1 - Changes in weight of test prisms during freezing and thawing cycling per ASTM C 666, procedure A

Mixture series	Mixture no.	$\frac{W}{C + S}$	Slag as replacement for cement, %	Air content %	Weight of 76 x 102 x 390-mm prisms "W", kg*							Relative change, percent
					Reference moist-cured prisms			Freeze-thaw test prims				
					At 14 days	At end of freeze -thaw cycling	Percent change	W**	W***	W****	Percent change	
I	1	0.70	0	6.6	6.865	6.950	+1.24	6.960	6.910(196)	6.858(305)	-1.47	2.71
	2	0.70	25	6.0	6.910	7.015	+1.52	6.910	6.823(196)	6.742(305)	-2.43	3.95
	3	0.70	50	5.9	7.005	7.030	+0.36	7.012	6.953(199)	6.882(310)	-1.85	2.21
	4	0.70	75	6.1	7.005	7.015	+0.14	7.040	6.978(199)	6.933(309)	-1.52	1.66
II	5	0.55	0	6.0	7.160	7.220	+0.84	7.110	7.098(196)	7.075(311)	-0.49	1.33
	6	0.55	25	6.0	7.080	7.120	+0.57	7.030	7.015(197)	6.987(318)	-0.61	1.18
	7	0.55	50	6.2	7.130	7.005	+1.75	7.122	7.095(206)	7.025(306)	-1.36	3.11
	8	0.55	75	6.7	6.975	7.000	+0.36	7.072	7.042(201)	7.028(311)	-0.62	0.98

*Each result represents the average of two tests.

**Average weight of prisms after 14 days of moist curing i.e., at the commencement of the freeze-thaw cycling.

***Number in parentheses represents the number of freeze-thaw cycles at which the given weights were taken.

****Number in parentheses represents the number of freeze-thaw cycles completed when test was terminated.

Table A2 - Changes in length of test prisms during freezing and thawing cycling per ASTM C 666, procedure A

Mixture series	Mixture no.	$\frac{W}{C + S}$	Slag as replacement for cement, %	Air content %	Length$^+$ of 76 x 102 x 390-mm prisms "L", mm*							Relative change, percent
					Reference moist-cured prisms			Freeze-thaw test prisms				
					At 14 days	At end of freeze -thaw cycling	Percent change	L**	L***	L****	Percent change	
I	1	0.70	0	6.6	360.699	360.690	-0.003	360.819	360.797(196)	360.801(305)	-0.005	-0.002
	2	0.70	25	6.0	360.940	360.809	-0.036	360.748	360.761(196)	360.698(305)	-0.014	+0.022
	3	0.70	50	5.9	360.885	360.876	-0.003	360.748	360.799(208)	360.770(310)	-0.006	-0.003
	4	0.70	75	6.1	361.082	361.063	-0.005	361.112	361.104(208)	361.115(309)	+0.001	+0.006
II	5	0.55	0	6.0	360.272	360.238	-0.009	360.903	360.932(196)	360.919(311)	+0.004	+0.013
	6	0.55	25	6.0	360.892	360.872	-0.006	360.778	360.776(197)	360.780(318)	+0.001	+0.007
	7	0.55	50	6.2	360.743	360.743	-0.000	360.648	360.597(206)	360.691(306)	+0.012	+0.012
	8	0.55	75	6.7	361.108	361.091	-0.005	361.193	361.186(201)	361.155(311)	-0.011	-0.006

*Each result represents the average of two tests.

**Average length of prisms after 14 days of moist curing i.e., at the commencement of the freezing-thawing cycling.

***Number in parentheses represents the number of freezing and thawing cycles at which measurements were taken.

****Number in parentheses represents the number of freezing and thawing cycles completed when test was terminated.

+gauge length = 358 mm.

Table A3 - Changes in ultrasonic pulse velocity of test prisms during freezing and thawing cycling per ASTM. C 666, procedure A

Mixture series	Mixture no.	$\frac{W}{C + S}$	Slag as replacement for cement, %	Air content %	Ultrasonic pulse velocity of 76 x 102 x 390-mm prisms "V", m/s*							Relative change, percent
					Reference moist-cured prisms			Freeze-thaw test prisms				
					At 14 days	At end of freeze-thaw cycling	Percent change	V**	V***	V****	Percent change	
I	1	0.70	0	6.6	4307	4456	+3.46	4311	4298(196)	4329(305)	+0.42	3.04
	2	0.70	25	6.0	4220	4443	+5.28	4246	4186(196)	4193(305)	-1.25	6.53
	3	0.70	50	5.9	4279	4516	+5.54	4281	4255(199)	4186(310)	-2.22	7.76
	4	0.70	75	6.1	4276	4378	+2.39	4281	4146(199)	4488(309)	+4.84	-2.45
II	5	0.55	0	6.0	4540	4629	+1.96	4518	4464(196)	4423(311)	-2.10	4.06
	6	0.55	25	6.0	4524	4643	+2.63	4508	4534(197)	4556(318)	+1.06	1.57
	7	0.55	50	6.2	4451	4613	+3.64	4446	4438(206)	4466(306)	+0.45	3.19
	8	0.55	75	6.7	4319	4456	+3.17	4272	4230(201)	4290(311)	+0.42	2.75

*Each result represents the average of two tests.

**Average pulse velocity of prisms after 14 days of moist curing i.e., at the commencement of the freezing and thawing cycling.

***Number in parentheses represents the number of freezing and thawing cycles at which measurements were taken.

****Number in parentheses represents the number of freezing and thawing cycles completed when test was terminated.

Table A4 - Changes in fundamental longitudinal resonant frequency of test prisms during freezing and thawing cycling per ASTM C 666, procedure A

Mixture series	Mixture no.	$\frac{W}{C + S}$	Slag as replacement for cement, %	Air content %	Fundamental longitudinal resonant frequency of 76 x 102 x 390-mm prisms "N", Hz*							Relative change, percent
					Reference moist-cured prisms			Freeze-thaw test prisms				
					At 14 days	At end of freeze -thaw cycling	Percent change	N**	N***	N****	Percent change	
I	1	0.70	0	6.6	4797	5009	+4.42	4776	4716(196)	4732(305)	-0.92	5.34
	2	0.70	25	6.0	4727	4996	+5.69	4783	4653(196)	4671(305)	-2.34	8.03
	3	0.70	50	5.9	4787	5078	+6.08	4807	4699(199)	4689(310)	-2.46	8.54
	4	0.70	75	6.1	4811	4985	+3.62	4822	4658(199)	4692(309)	-2.70	6.32
II	5	0.55	0	6.0	5101	5274	+3.39	5063	4991(196)	5032(311)	-0.61	4.00
	6	0.55	25	6.0	5134	5311	+3.45	5115	5048(197)	5042(318)	-1.43	4.88
	7	0.55	50	6.2	5070	5284	+4.22	5032	4942(206)	4939(306)	-1.85	6.07
	8	0.55	75	6.7	4892	5056	+3.35	4848	4734(201)	4682(311)	-3.42	6.77

*Each result represents the average of two tests.

**Average resonant frequency of prisms after 14 days of moist curing i.e., at the commencement of the freezing and thawing cycling.

***Number in parentheses represents the number of freezing and thawing cycles at which measurements were taken.

****Number in parentheses represents the number of freezing and thawing cycles completed when test was terminated.