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A COMPARATIVE STUDY OF LIGHTWEIGHT AGGREGATES IN STRUCTURAL CONCRETE

H.S. WILSON

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A COMPARATIVE STUDY OF LIGHTWEIGHT AGGREGATES IN STRUCTURAL CONCRETE

by

H.S. Wilson*

ABSTRACT

A study was made of the physical properties of five lightweight aggregates produced commercially in Canada from clays and shales, and of the properties of structural concretes incorporating these lightweight aggregates. The concretes were proportioned on the basis of three compressive strengths. The specimens were prepared, cured and tested in accordance with ASTM specifications.

The unit weights of the lightweight aggregates were between 636 and 952 kg/m^3; one had a unit weight higher than the 880 kg/m^3 permitted by ASTM. The 24-h absorptions were between 5.1 and 15.7%.

The densities of the concretes were between 1778 and 2035 kg/m^3, and the compressive strengths between 19.1 and 43.1 MPa. Using the boiling water method of accelerated curing resulted in average compressive strengths of 56, 61 and 71% of the 28-day compressive strengths for the three levels of strength. The splitting-tensile strengths were between 7 and 13% of the 28-day compressive strengths, and the flexural strengths were between 15 and 22% of the 28-day compressive strengths. The static moduli of elasticity were between 1.62 and 2.31 x 10^4 MPa. The specific creeps were between 1.66 and 5.00 mm/mm/MPa and the thermal conductivities between 0.68 and 0.77 W/m°C at ambient temperatures increasing 13 to 34% at about 300°C. All the concretes except one low-strength composition appeared to resist structural damage during freeze-thaw testing, but most exhibited some pop-outs of surface aggregates.

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ETUDE PAR LA METHODE COMPARATIVE DES AGREGATS LEGERS DANS LE BETON DE STRUCTURE

par

H.S. Wilson*

RESUME

Une étude a été effectuée sur les propriétés physiques de cinq agrégats légers produits commercialement au Canada à partir d'argiles et de schistes argileux et sur les propriétés des bétons de structure dans lesquels on incorpore des agrégats légers. Les bétons ont été dosés suivant trois valeurs de résistance à la pression. Les échantillons ont été préparés, traités et mis à l'essai en respectant les normes de l'ASTM.

Les agrégats légers avaient un poids unitaire pouvant varier entre 636 et 952 kg/m^3; un des agrégats avait un poids unitaire plus élevé que le 880 kg/m^3 permis par l'ASTM. Les valeurs d'absorption 24-h des agrégats légers se situaient entre 5.1 et 15.7%.

Les densités des bétons se situaient entre 1778 et 2035 kg/m^3 et les résistances à la pression entre 19.1 et 43.1 MPa. Lorsqu'on utilise la méthode de l'eau au point d'ébulition pour un traitement accéléré, on obtient des valeurs de résistance à la pression moyennes de 56, 61 et 71% des valeurs de résistance à la pression de 28 jours obtenues pour les trois niveaux de résistance. Les valeurs de résistance à la traction-fission se situaient entre 7 et 13% des valeurs de résistance à la pression de 28 jours et les valeurs de la résistance à la flexion se situaient entre 15 et 22% des valeurs de résistance à la pression de 28 jours. Les modules statiques d'élasticité se situaient entre 1.62 et 2.31 x 10^4 MPa. Les valeurs de fluage spécifique étaient entre 1.66 et 5.00 mm/mm/MPa et les conductivités thermiques étaient entre 0.68 et 0.77 W/m°C à la température ambiante et augmentaient de 13 à 34% à environ 300°C. Tous les bétons sauf un de composition à faible résistance, semblaient résister aux dommages structuraux occasionnés lors d'essais de gel-dégel, mais la plupart ont fait preuve d'écaillement des agrégats de surface.

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CONTENTS

TABLES

CONTENTS (cont'd)

FIGURES

INTRODUCTION

The first plant in Canada to produce lightweight concrete aggregate from shale was built in Cooksville (now Mississauga), Ontario in 1927, and the second in Calgary, Alberta in 1953. Growth since then has been considerable, with production increasing steadily to 421 000 m^3 by 1965 and fluctuating between 344 000 and 421 000 m^3 after that. The number of producers has varied between 10 in 1966 and 1969 to six in 1976. The trend has been to larger capacity plants (1). The companies presently producing lightweight aggregate from shale or clay are:

Avon Aggregates Ltd.	Minto, N.B.
Cindercrete Products Ltd.	Regina, Sask.
Consolidated Concrete Ltd.	Calgary, Alta.
Consolidated Concrete Ltd., Edcon Block Division	Edmonton, Alta.
Domtar Construction Materials Ltd.	Mississauga, Ont.
Kildonan Concrete Products Ltd.	St. Boniface, Man.

All these companies use the rotary-kiln method; the plants at Minto, Calgary and Mississauga use shale as the raw material; those at Regina, Edmonton and St. Boniface use clay.

The composition, properties and preparation of the raw materials and the pyro-processing methods at the various plants differ, consequently the products have different physical properties.

This study was undertaken to determine the physical properties of the various lightweight aggregates available in Canada and the properties of concretes made with these aggregates. Concretes of similar proportions of cement, aggregates and water were made with each of the aggregates so that their properties could be compared. To preserve anonymity of the producers, the aggregates supplied were arbitrarily assigned the designations A to E.

MATERIALS

LIGHTWEIGHT COARSE AGGREGATES

Coarse lightweight aggregates, nominally between 19 and 5 mm in size were obtained from five of the six plants. Aggregate from the sixth plant was not obtained in time to be included in this study. Because there was too much variation in the size of the different aggregates, they were separated into size fractions using 19.0-, 12.5-, 9.5- and 4.75-mm screens. For all concrete mixes, the three size-fractions, 19.0 to 12.5 mm, 12.5 to 9.5 mm and 9.5 to 4.74 mm were combined in equal proportions as the coarse aggregate.

NORMAL-WEIGHT FINE AGGREGATE

An Ottawa Valley sand was used as fine aggregate in all mixes. The sand was separated into size-fractions and recombined in specific proportions to give a grading common to all. The gradings of the coarse and fine aggregates are shown in Table 1.

CEMENT

Normal portland cement, ASTM Type 1 (CSA Type 10) was used in all mixes.

ADMIXTURE

An air-entraining agent was added in amounts to give an air content of about 6±1.5%.

PROPERTIES OF LIGHTWEIGHT COARSE AGGREGATE

The following properties of each of the lightweight aggregates were determined using standard ASTM testing:

(a) loose, dry unit weight (ASTM C29-76)
(b) bulk specific gravity (ASTM C127-77)
(c) 24-h absorption (ASTM C127-77)
(d) rate of absorption to 48 h
(e) per cent voids (ASTM C30-37)

Crushing strengths of the lightweight aggregates were also determined using a method

Table 1 - Gradings of aggregates

Lightweight coarse aggregate			Normal-weight fine aggregate		
Sieve size		Cumulative	Sieve size		Cumulative
in.	mm	% retained	No.	mm	% retained
0.75	19.0	0.0	4	4.75	0.0
0.5	12.5	33.3	8	2.36	10.0
0.38	9.5	66.6	16	1.18	32.5
No.4	4.75	100.0	30	600μm	57.5
			50	300μm	80.0
			100	150μm	94.0
			Pan		100.0

commonly employed in these laboratories. This is not a standard test and gives only relative values. A portion of each fraction was placed in a 76-mm diam steel cylinder to a depth of 127 mm. A plunger was placed on the aggregate and the aggregate compacted first by 25 mm and subsequently by a second of 25 mm by a hydraulic press. The pressures required to give these two stages of compaction are reported as the crushing strength. The physical properties of the lightweight coarse aggregates are shown in Table 2. The rates of absorption are shown in Table 3.

CONCRETE MIXES

It was planned originally to proportion the mixes on the basis of the unit weight of the concrete. Thus, the initial low-strength mixes were designed to produce concretes with hardened unit weights of about 1840 kg/m^3. However, for mix B-1, even with a coarse-to-fine aggregate ratio of 1.8:1, the unit weight of the fresh concrete was about 1950 kg/m^3. This showed that, because of the wide variation of the density of the lightweight aggregates, it was impossible to use density of concrete as the basis for proportioning. Therefore, three mixes of different strengths were proportioned for each aggregate using the same nominal cement content for each strength. Each mix of 0.1 m^3 was prepared in two identically-proportioned batches of 0.06 m^3 which were blended by shovel in a large metal tray. The aggregates were weighed 18 h before mixing. The 18-h absorptions were satisfied by flooding the coarse aggregate with water, and by adding 4.5 kg of water to each batch of fine aggregate. The coarse aggregates were drained just before mixing the concrete to remove unabsorbed water. The mix data and the physical properties of the fresh concretes are given in Tables 4 and 5.

Twelve 152 x 305-mm cylinders were made from each mix using the procedure outlined in ASTM C192-76, including internal vibration of the concrete after each of the two layers were placed in the moulds. Six 89 x 102 x 387-mm prisms were also made using a vibrating table to apply external vibration after each of two layers were placed in the moulds. Two 305 x 305 x 51-mm slabs were made from each mix for thermal conductivity determination using external vibration after the single layer of concrete had been placed in the wooden mould.

CONCRETE CURING

When the two cylinders to be used in the accelerated strength test were cast, metal plates were clamped over the tops of the moulds. For the first 24 h after casting all the specimens remained covered with plastic sheets to prevent evaporation. Except the two specimens for accelerated curing, the others were removed from the moulds after 24 h. They were weighed in air and

Table 2 - Physical properties of lightweight aggregates

Aggregate	Size range in. (mm)	Unit weight, lb/ft^3 (kg/m^3)	Bulk specific gravity	24-h absorption, %	% voids	Crushing strength psi (MPa) 1 in. (25 mm)	2 in. (51 mm)
A	-0.75 + 0.5	45.2	1.59	14.7	54.4	450	2640
	(-19.0 + 12.5)	(724.1)				(3.1)	(18.2)
	-0.5 + 0.38	46.6	1.62	15.7	53.8	810	6360
	(-12.5 + 9.5)	(746.5)				(5.6)	(43.8)
	-0.38 + 4M	46.6	1.64	15.7	54.4	950	5970
	(-9.5 + 4.75)	(746.5)				(6.5)	(41.1)
	-0.75 + 4M	--	--	--	--	930	6940
	(-19.0 + 4.75)					(6.4)	(47.8)
B	-0.75 + 0.5	56.4	1.82	10.9	50.3	620	4200
	(-19.0 + 12.5)	(903.5)				(4.3)	(28.9)
	-0.5 + 0.38	48.8	1.76	9.7	55.5	770	5210
	(-12.5 + 9.5)	(781.8)				(5.3)	(35.9)
	-0.38 + 4M	59.4	1.99	12.1	52.1	1380	>8500
	(-9.5 + 4.75)	(951.6)				(9.5)	(>58.6)
	-0.75 + 4M	--	--	--	--	1180	>8500
	(-19.0 + 4.75					(8.1)	(>58.6)
C	-0.75 + 0.5	45.6	1.48	8.1	50.6	380	1340
	(-19.0 + 12.5)	(730.5)				(2.6)	(9.2)
	-0.5 + 0.38	48.4	1.55	8.5	49.9	590	2310
	(-12.5 + 9.5)	(775.4)				(4.1)	(15.9)
	-0.38 + 4M	44.9	1.43	8.9	49.6	650	2890
	(-9.5 + 4.75)	(719.3)				(4.5)	(19.9)
	-0.75 + 4M	--	--	--	--	520	2150
	(-19.0 + 4.75)					(3.6)	(14.8)
D	-0.75 + 0.5	49.2	1.52	6.8	48.1	560	2400
	(-19.0 + 12.5)	(788.1)				(3.9)	(16.5)
	-0.5 + 0.38	47.4	1.58	6.9	51.9	780	3580
	(-12.5 + 9.5)	(759.3)				(5.4)	(24.7)
	-0.38 + 4M	53.3	1.70	6.9	49.7	1160	6380
	(-9.5 + 4.75)	(853.9)				(8.0)	(44.0)
	-0.75 + 4M	--	--	--	--	840	4220
	(-19.0 + 4.75)					(5.8)	(29.1)
E	-0.75 + 0.5	42.5	1.45	5.1	53.0	350	1580
	(-19.0 + 12.5)	(680.9)				(2.4)	(10.9)
	-0.5 + 0.38	39.7	1.45	5.5	56.2	360	1560
	(-12.5 + 9.5)	(636.0)				(2.5)	(10.7)
	-0.38 + 4M	45.3	1.52	5.9	52.3	710	3180
	(-9.5 + 4.75)	(725.7)				(4.9)	(21.9)
	-0.75 + 4M	--	--	--	--	470	2450
	(-19.0 + 4.75)					(3.2)	(16.9)

Table 3 - Rates of absorption of lightweight aggregates

Aggregate	Size range in.(mm)	Absorption, %					
		0.25 h	0.50 h	1 h	4 h	24 h	48 h
A	-0.75 + 0.5 (-19.0 + 12.5)	8.5	9.8	10.2	12.3	14.7	16.2
	-0.5 + 0.38 (-12.5 + 9.5)	9.9	10.6	11.9	12.4	15.7	16.4
	-0.38 + 4M (-9.5 + 4.75	9.3	10.4	10.8	11.8	15.7	16.3
B	-0.75 + 0.5 (-19.0 + 12.5)	7.5	8.8	9.4	9.6	10.9	11.4
	-0.5 + 0.38 (-12.5 + 9.5)	8.3	8.8	9.2	9.4	9.7	10.6
	-0.38 + 4M (-9.5 + 4.75)	8.6	9.1	9.9	10.7	12.1	12.6
C	-0.75 + 0.5 (-19.0 + 12.5)	6.2	6.5	6.5	7.6	8.1	8.3
	-0.5 + 0.38 (-12.5 + 9.5)	5.3	5.8	6.2	7.0	8.5	9.2
	-0.38 + 4M (-9.5 + 4.75)	5.8	6.1	6.7	7.1	8.9	8.9
D	-0.75 + 0.5 (-19.0 + 12.5)	2.9	3.1	3.3	4.2	5.5	5.5
	-0.5 + 0.38 (-12.5 + 9.5)	2.2	2.7	3.0	3.3	4.5	5.3
	-0.38 + 4M (-9.5 + 4.75)	2.8	2.9	3.2	3.8	5.0	6.0
E	-0.75 + 0.5 (-19.0 + 12.5)	3.9	4.3	4.4	5.1	6.8	7.4
	-0.5 + 0.38 (-12.5 + 9.5)	3.8	3.9	4.2	5.5	6.9	7.8
	-0.38 + 4M (-9.5 + -4.75)	3.9	4.2	4.7	5.9	6.9	7.9
		Average absorption, %					
A		9.2	10.3	11.0	12.2	15.4	16.3
B		8.1	8.9	9.5	9.9	10.9	11.5
C		5.8	6.9	6.5	7.2	8.5	8.8
D		2.6	2.9	3.2	3.8	5.0	5.6
E		3.9	4.1	4.4	5.5	6.9	7.7

Table 4 - Concrete mix proportions

Aggregate	Mix No.	Cement, lb/yd^3 (kg/m^3)	Water lb/yd^3 (kg/m^3)	Aggregates, SSD: Coarse lightweight, lb/yd^3 (kg/m^3)	Aggregates, SSD: Fine natural, lb/yd^3 (kg/m^3)	Coarse-fine ratio	Air entraining agent (mL/m^3)	Water: cement ratio
A	1	464 (275.3)	276 (163.8)	1293 (767.1)	1121 (665.1)	1.15	24	0.59
	2	582 (345.3)	265 (157.2)	1219 (723.2)	1131 (671.0)	1.08	54	0.46
	3	709 (420.6)	278 (164.9)	1189 (705.4)	1042 (618.2)	1.14	54	0.39
B	1A	485 (287.8)	252 (149.5)	1652 (980.1)	910 (539.9)	1.81	44	0.52
	1B	449 (266.4)	247 (146.5)	1337 (793.2)	1326 (786.7)	1.01	54	0.55
	2	590 (350.0)	256 (151.9)	1390 (824.7)	1171 (694.8)	1.19	54	0.43
	3	710 (421.2)	279 (165.5)	1354 (803.3)	1070 (634.8)	1.27	54	0.39
C	1	452 (268.2)	260 (154.3)	1123 (666.3)	1194 (708.4)	0.94	54	0.58
	2	583 (345.9)	263 (156.0)	1091 (647.3)	1130 (670.4)	0.97	54	0.45
	3	703 (417.1)	285 (169.1)	1071 (635.4)	1014 (601.6)	1.06	54	0.41
D	1	470 (278.9)	269 (159.6)	1166 (691.8)	1330 (789.1)	0.88	54	0.57
	2	586 (347.7)	268 (159.0)	1132 (671.6)	1211 (718.5)	0.93	54	0.46
	3	719 (426.6)	277 (164.3)	1173 (695.9)	1157 (686.4)	1.01	54	0.39
E	1A	437 (259.3)	295 (175.0)	1014 (601.6)	1332 (790.3)	0.76	27	0.68
	1B	440 (261.1)	281 (166.7)	1021 (605.8)	1304 (773.7)	0.78	41	0.64
	2	555 (329.3)	297 (176.2)	1020 (605.2)	1206 (715.5)	0.85	54	0.54
	3	670 (397.5)	298 (176.8)	1021 (605.8)	1111 (659.2)	0.92	68	0.44

Table 5 - Properties of fresh concretes

Aggregate	Mix No.	Temperature: Concrete, °F (°C)	Temperature: Ambient °F (°C)	Properties of concrete: Slump, in. (mm)	Unit weight lb/ft^3 (kg/m^3)	Air: Pressure meter, %	Air: Roll-a-meter, %	Water cement ratio
A	1	77 (25)	73 (23)	3 (75)	116.8 (1871.2)	3.9	--	0.59
	2	75 (24)	73 (23)	2 (50)	118.4 (1896.8)	5.2	4.8	0.46
	3	77 (25)	79 (26)	1.75 (45)	119.2 (1909.6)	5.2	3.1	0.39
B	1A	77 (25)	75 (24)	2 (50)	122.2 (1957.6)	3.7	4.7	0.52
	1B	72 (22)	73 (23)	1.5 (40)	124.4 (1992.9)	4.8	--	0.55
	2	75 (24)	72 (23)	2 (50)	126.2 (2021.7)	4.6	4.4	0.43
	3	77 (25)	77 (25)	1.75 (45)	126.4 (2024.9)	4.4	3.5	0.39
C	1	73 (23)	72 (22)	1.75 (45)	112.2 (1797.4)	6.1	--	0.58
	2	75 (24)	72 (22)	1.75 (45)	113.6 (1819.9)	5.5	4.5	0.45
	3	82 (28)	79 (26)	2 (50)	113.8 (1823.1)	5.1	3.2	0.40
D	1	77 (25)	75 (24)	2.25 (55)	119.8 (1919.2)	6.5	7.0	0.57
	2	77 (25)	75 (24)	2.25 (55)	118.4 (1896.8)	5.3	5.1	0.46
	3	75 (24)	73 (23)	2.25 (55)	123.2 (1973.7)	4.0	--	0.39
E	1A	75 (24)	70 (21)	1.5 (40)	114.0 (1826.3)	3.5	2.8	0.68
	1B	73 (23)	73 (23)	1.5 (40)	112.8 (1807.1)	5.5	5.8	0.64
	2	75 (24)	70 (21)	2 (50)	114.0 (1826.3)	4.4	4.3	0.54
	3	75 (24)	70 (21)	2.5 (65)	114.8 (1839.1)	5.8	--	0.44

in water to obtain the 1-day densities, and then placed in a moist room at 23±1.7°C and 100% relative humidity.

At seven days, the cylinders were removed from the moist room. Those not being tested at that time were placed in a dry room at 23°±1.1°C and 50±4% relative humidity until testing.

The prisms to be used in measuring drying shrinkage were cast with stainless steel plugs embedded in the ends. At seven days, they were transferred from the moist room to the dryer environment for the duration of the test period.

The prisms for testing of freezing and thawing were removed from the moist room to the dry room at 14 days, and returned to the moist room at 25 days. The actual testing of the prisms began at 28 days.

The slabs for thermal conductivity testing were left in the moist room for 28 days and then removed to the dry environment until testing.

CONCRETE TESTING

The following properties of the hardened concrete were determined using standard ASTM methods:

1. Compressive strength
   (a) at 28.5 h, using accelerated curing
   (b) at 7 days
   (c) at 28 days
2. Splitting tensile strength
3. Flexural strength
4. Static modulus of elasticity
5. Drying shrinkage
6. Creep in compression
7. Resistance to freezing and thawing
8. Thermal conductivity by the guarded hot plate method.

1. The accelerated-curing test, using the boiling water method, is described in ASTM C684-74. The specimens, complete with mould and cover, at 23 h were placed in the curing tank in which the water had been heated to boiling. After 3.5 h they were removed from the tank and the moulds were stripped. The cylinders were allowed to cool for 1 h, capped, and broken in compression at 28.5 h.

2,3,4. At 7 and 28 days, two cylinders were capped and broken in compression, as described in ASTM C39-72. The compressive strengths are shown in Table 6, and are compared graphically in Fig. 1 to 3. The relation of density to cement content is illustrated in Fig. 4.

At 28 days, several tests were made. The static modulus of elasticity as described in ASTM C469-65 was determined on two cylinders, which in turn was used to determine the compressive strength as described in ASTM C39-72. Two cylinders were used to determine the splitting tensile strength using the procedure outlined in ASTM C496-71. Two of the prisms were used for determining the flexural strength as described in ASTM C78-75. Splitting tensile and flexural strengths are shown in Table 6 and compared graphically in Fig. 5 and 6.

5. The initial length measurements were made on the two prisms used in determining drying shrinkage upon removal from the moist room at 7 days. Subsequent measurements were made at 14, 28, 45, 60, 90 and 120 days. The changes in length and weight are shown in Tables 7 and 8.

6. Four cylinders of each mix were used to determine the creep of the concrete while under compression*. The preparation and testing of the specimens as outlined in ASTM C512-76 was modified as follows:

On days 22 and 23 after casting, two pairs of holes, 7.9 mm in diam by 12.7 mm deep, were drilled in each cylinder at 203.2-mm centres along lines parallel to the longitudinal axis. Metal studs, drilled to accept a 203.2 mm long demountable strain gauge, were set in epoxy resin in the holes. This provided the means for measuring longitudinal deformation. Each cylinder was weighed to determine its density in the as-received condition, and zero strains were recorded.

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*The preparation and testing was done under contract by Prof. R.H. Mills, Dept. of Civil Engineering, University of Toronto, Toronto, Ontario.

Table 6 - Properties of hardened concretes

Aggregate	Mix No.	Density lb/ft^3 (kg/m^3) 1 day	28 day	Compressive strength, psi (MPa) 7 day	28 day	Splitting tensile strength, (MPa)	Flexural strength, psi (MPa)	Accelerated curing strength, psi (MPa)	Static modulus of elasticity x 10^6 psi (x 10^4 MPa) actual	theoretical
A	1	117.5	114.5	2460	3500	390	725	--	2.34	2.39
		(1882.4)	(1834.3)	(16.9)	(24.1)	(2.7)	(5.0)		(1.62)	(1.65)
	2	119.5	116.6	3610	4320	415	795	2060	2.61	2.73
		(1914.4)	(1867.9)	(24.9)	(29.8)	(2.9)	(5.5)	(14.2)	(1.79)	1.88)
	3	120.4	118.1	4590	5700	405	860	3290	2.66	3.20
		(1928.9)	(1892.0)	(31.6)	(39.3)	(2.8)	(5.9)	(22.7)	(1.83)	(2.20)
B	1A	123.1	120.9	2790	4150	400	850*	--	2.72	2.83
		(1927.1)	(1936.8)	(19.2)	(28.6)	(2.8)	(5.9)		(1.86)	(1.95)
	1B	127.6	125.1	2500	3670	460	--	--	3.05	2.80
		(2044.2)	(2004.1)	(17.2)	(25.2)	(3.2)			(2.10)	(1.93)
	2	128.5	127.0	3920	5370	475*	910	2280	3.40	3.46
		(2058.6)	(2034.5)	(27.0)	(37.0)	(3.3)	(6.3)	(15.7)	(2.34)	(2.38)
	3	127.8	126.1	5200	6260	510	945	3830	3.02	3.70
		(2047.4)	(2020.1)	(35.8)	(43.1)	(3.5)	(6.5)	(26.4)	(2.08)	(2.55)
C	1	114.1	111.3	2620	3250	350	670	1535	2.53	2.21
		(1827.9)	(1783.0)	(18.1)	(22.4)	(2.4)	(4.6)	(10.6)	(1.76)	(1.52)
	2	115.0	113.1	3060	3555	450	785	1800	2.69	2.37
		(1842.3)	(1811.9)	(21.1)	(24.5)	(3.1)	(5.4)	(12.4)	(1.83)	(1.63)
	3	114.7	113.0	3310	3820	375	750*	2310	2.58	2.45
		(1837.5)	(1810.3)	(22.8)	(26.3)	(2.6)	(5.2)	(15.9)	(1.79)	(1.69)
D	1	122.3	119.5	2490	3480	360*	675	1600	2.97	2.54
		(1959.2)	(1914.4)	(17.2)	(24.0)	(2.5)	(4.7)	(11.0)	(2.07)	(1.75)
	2	120.55	118.8	3170	4260	445	810	2140	3.17	2.79
		(1931.2)	(1903.2)	(21.8)	(29.4)	(3.1)	(5.6)	(14.7)	(2.14)	(1.92)
	3	124.9	123.2	4300	5460	405	925	2550	3.34	3.34
		(2000.9)	(1973.7)	(29.6)	(37.6)	(2.8)	(6.4)	(17.6)	(2.31)	(2.30)
E	1A	116.2	113.0	2440	3220	400*	--	1160	2.59	2.25
		(1861.5)	(1810.3)	(16.8)	(22.2)	(2.8)		(8.0)	(1.76)	(1.55)
	1B	114.8	112.7	2100	2770	370*	--	1130	2.71	2.08
		(1839.1)	(1805.5)	(14.5)	(19.1)	(2.5)		(7.8)	(1.89)	(1.43)
	2	115.5	113.6	2530	3490	365*	--	1610	2.75	2.36
		(1850.3)	(1819.9)	(17.4)	(24.0)	(2.5)		(11.1)	(1.89)	(1.63)
	3	116.4	115.1	2830	3490	345*	--	1930	2.74	2.41
		(1864.7)	(1843.9)	(19.5)	(24.0)	(2.4)				

* One specimen only

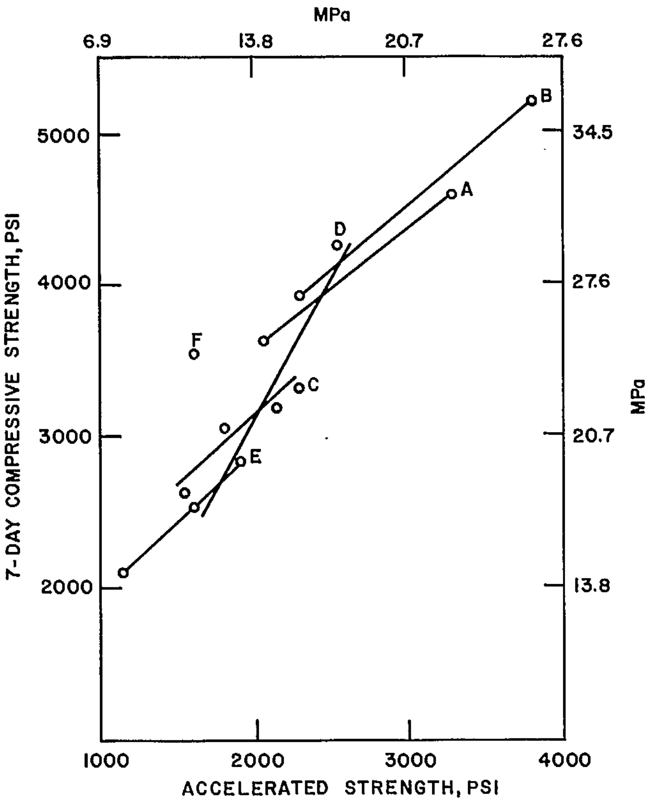


Fig. 1 - Relationship of accelerated to 7-day compressive strength

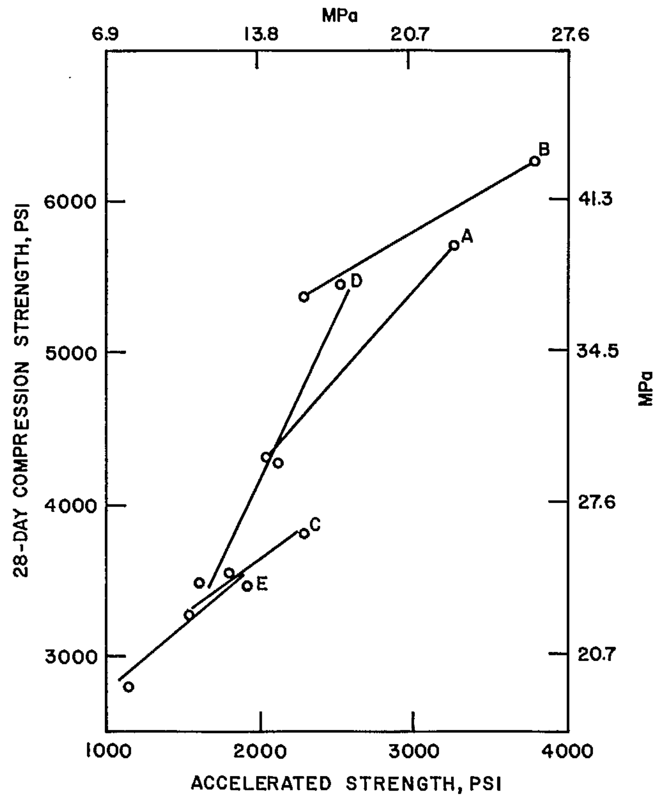


Fig. 2 - Relationship of accelerated to 28-day compressive strength

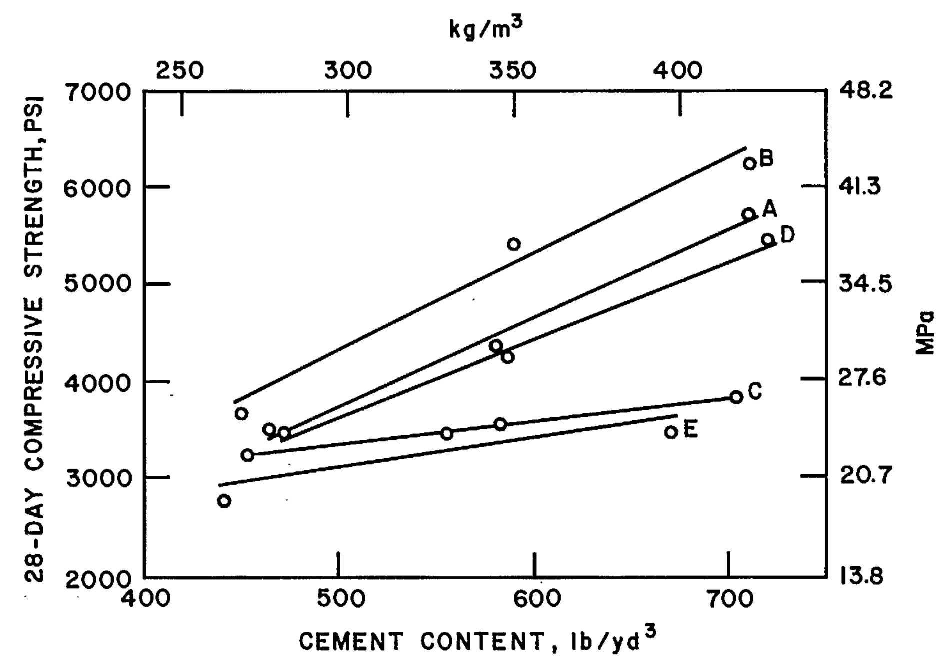


Fig. 3 - Relationship of 28-day compressive strength to cement content

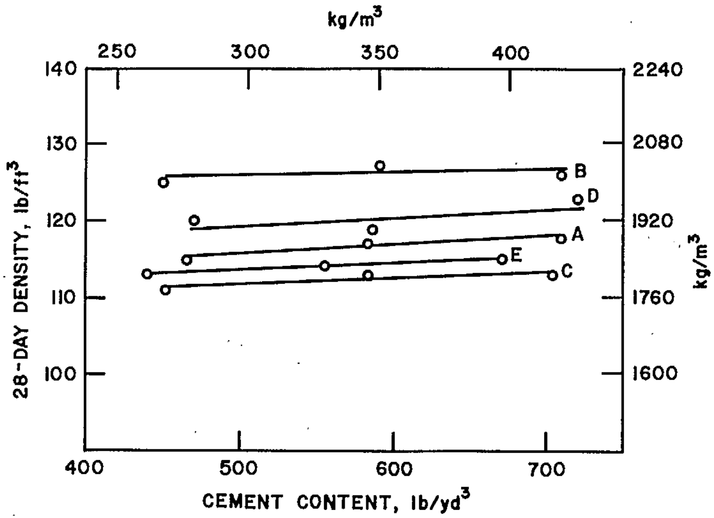


Fig. 4 - Relationship of 28-day density to cement content

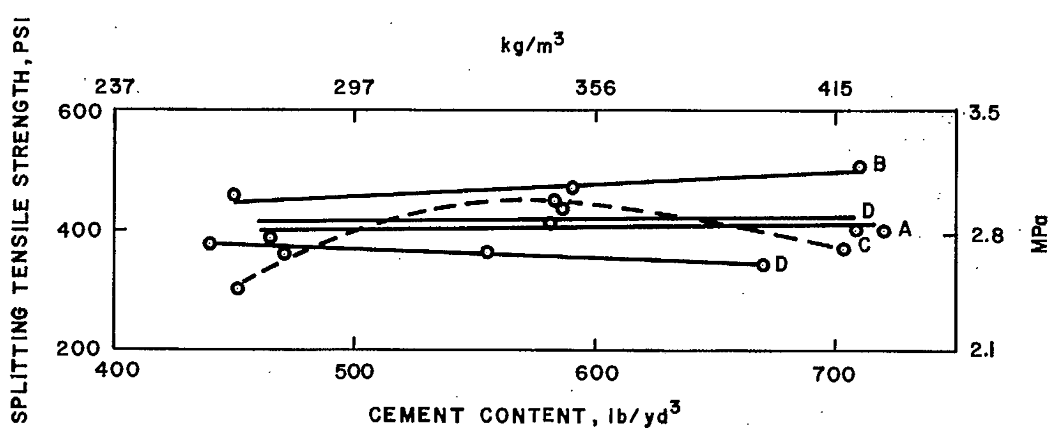


Fig. 5 - Relationship of splitting-tensile strength to cement content

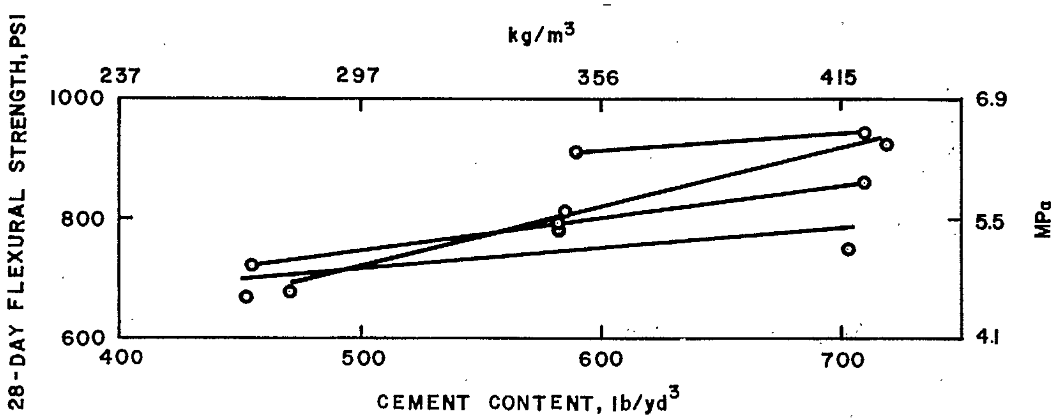


Fig. 6 - Relationship of flexural strength to cement content

Table 7 - Changes in length of test prisms during drying

		Cumulative length change							
Aggregate	Mix No.	14 day, in. (mm)	21 day, in. (mm)	28 day, in. (mm)	45 day, in. (mm)	60 day, in. (mm)	90 day, in. (mm)	120 day, in. (mm)	in./in. and mm/mm x 10^{-4}
A	1	+0.0003 (+0.0076)	--	-0.0042 (-0.1067)	-0.0064 (-0.1626)	-0.0062 (-0.1575)	-0.0090 (-0.2286)	-0.0104 (-0.2642)	-7.3
	2	--	--	--	--	--	--	--	--
	3	-0.0043 (-0.1092)	-0.0003 (-0.0076)	-0.0009 (-0.0229)	-0.0028 (-0.0711)	-0.0027 (-0.0686)	-0.0042 (-0.1067)	-0.0070 (-0.1778)	-4.9
B	1A	-0.0002 (-0.0051)	--	-0.0029 (-0.0737)	--	-0.0040 (-0.1016)	-0.0063 (-0.1600)	-0.0070 (-0.1778)	-4.9
	2	--	--	--	--	--	--	--	--
	3	-0.0049 (-0.1245)	-0.0008 (-0.0203)	-0.0007 (-0.0178)	-0.0024 (-0.0610)	-0.0025 (-0.0635)	-0.0041 (-0.1041)	-0.0063 (-0.1600)	-4.4
C	1	0.0000	-0.0060 (-0.1524)	-0.0073 (-0.1854)	-0.0099 (-0.2515)	-0.0103 (-0.2616)	-0.0118 (-0.2997)	-0.0131 (-0.3327)	-9.2
	2	-0.0015 (-0.0381)	-0.0013 -(0.0330)	-0.0028 (-0.0711)	-0.0031 (-0.0787)	-0.0055 (-0.1397)	-0.0067 (-0.1702)	-0.0088 (-0.2235)	-6.2
	3	0.0002 (-0.0051)	-0.0008 (-0.0203)	-0.0018 (-0.0457)	-0.0027 (-0.0686)	-0.0038 (-0.0965)	-0.0066 (-0.1676)	-0.0087 (-0.2210)	-6.1
D	1	-0.0018 (-0.0457)	-0.0059 (-0.1499)	-0.0066 (-0.1676)	-0.0070 (-0.1778)	-0.0091 (-0.2311)	-0.0111 (-0.2819)	-0.0118 (-0.2997)	-8.3
	2	-0.0017 (-0.0432)	-0.0030 (-0.0762)	-0.0040 (-0.1016)	-0.0054 (-0.1372)	-0.0068 (-0.1727)	-0.0089 (-0.2261)	-0.0104 (-0.2642)	-7.3
	3	-0.0006 (-0.0152)	-0.0022 (-0.0559)	-0.0023 (-0.0584)	-0.0031 (-0.0787)	-0.0042 (-0.1067)	-0.0053 (-0.1346)	-0.0074 (-0.1880)	-5.2

Table 8 - Changes in weight of test prisms during drying

Aggregate	Mix No.	1-day weight lb (kg)	Cumulative weight change, lb (kg) 7 day,	14 day,	21 day,	28 day,	45 day,	60 day,	90 day,	120 day,	%
A	1	14.783	+0.214	-0.289	-0.463	-0.566	-0.709	-0.764	-0.860	-0.998	6.75
		(6.711)	(+0.092)	(-0.131)	(-0.210)	-(0.257)	-(0.322)	-(0.347)	-(0.390)	(-0.453)	
	2	15.308	+0.139	-0.207	-0.340	-0.429	-0.533	-0.601	-0.731	-0.866	5.66
		(6.950)	(+0.063)	(-0.094)	(-0.154)	(-0.195)	(-0.241)	(-0.273)	(-0.332)	(-0.393)	
	3	15.259	+0.070	-0.154	-0.265	-0.327	-0.435	-0.482	-0.548	-0.722	4.73
		(6.928)	(+0.032)	(-0.070)	(-0.120)	(-0.148)	(-0.197)	(-0.219)	(-0.249)	(-0.327)	
B	1A	15.518	+0.215	-0.251	-0.379	-0.464	--	-0.642	-0.740	-0.888	5.73
		(7.045)	(+0.098)	(-0.114)	(-0.172)	(-0.210)		(-0.291)	(-0.336)	(-0.403)	
	2	16.606	+0.137	-0.166	-0.276	-0.356	-0.451	-0.506	-0.632	-0.760	4.57
		(7.539)	(+0.062)	(-0.075)	(-0.125)	(-0.161)	(-0.204)	(-0.230)	(-0.287)	(-0.345)	
	3	16.786	+0.094	-0.135	-0.240	-0.295	-0.408	-0.449	-0.511	-0.683	4.07
		(7.621)	(+0.043)	(-0.061)	(-0.109)	(-0.134)	(-0.185)	(-0.204)	(-0.232)	(-0.310)	
C	1	14.687	+0.105	-0.259	-0.355	-0.422	-0.514	-0.545	-0.601	-0.677	4.61
		(6.668)	(+0.048)	(-0.117)	(-0.161)	(-0.192)	(-0.233)	(-0.247)	(-0.273)	(-0.307)	
	2	14.850	+0.039	-0.210	-0.273	-0.332	-0.384	-0.433	-0.526	-0.645	4.34
		(6.742)	(+0.018)	(-0.095)	(-0.124)	(-0.151)	(-0.174)	(-0.196)	(-0.239)	(-0.293)	
	3	14.948	+0.085	-0.112	-0.177	-0.221	-0.293	-0.318	-0.366	-0.512	3.43
		(6.786)	(+0.039)	(-0.051)	(-0.080)	(-0.100)	(-0.313)	(-0.144)	(-0.166)	(-0.232)	
D	1	15.719	+0.080	-0.268	-0.415	-0.484	-0.581	-0.629	-0.754	-0.884	5.62
		(7.136)	(+0.036)	(-0.122)	(-0.188)	(-0.220)	(-0.264)	(-0.285)	(-0.342)	(-0.401)	
	2	15.564	+0.083	-0.202	-0.296	-0.338	-0.453	-0.482	-0.563	-0.688	4.62
		(7.066)	(+0.038)	(-0.092)	(-0.134)	(-0.153)	(-0.205)	(-0.219)	(-0.255)	(-0.312)	
	3	15.828	+0.041	-0.152	-0.225	-0.263	-0.372	-0.425	-0.489	-0.613	3.87
		(7.186)	(-0.019)	(-0.069)	(-0.102)	(-0.119)	(-0.169)	(-0.193)	(-0.222)	(-0.278)	

On day 27 after casting, two of each set of cylinders were further drilled along the longitudinal axis with a 25.4-mm diamond bit. All four cylinders were placed in water for 24 h, and on day 28 all specimens were weighed to determine moisture gain and measured to determine change in the longitudinal dimension.

On day 28 the two specimens with longitudinal holes were capped with plaster of Paris and fitted with end bearing plates and a prestressing tendon. The tendon was then tensioned to generate a nominal axial compressive stress of 25% of the 28-day compressive strength. One of these specimens was sealed against moisture loss by coating with a good quality wax and three thicknesses of heavy duty aluminum foil. The other was left to lose water in the laboratory atmosphere at about 50% relative humidity.

One of the other two specimens of each mix was sealed and the other exposed to laboratory atmosphere as described above. The results of the creep tests are summarized in Table 9 and the apparatus is illustrated in Fig. 7

7. At 28 days, testing for resistance to freezing and thawing was begun. The density, pulse velocity, and resonant frequency of two prisms from each mix were measured as described in ASTM C597-71 and C215-60. Procedure B of ASTM C666-77 (freezing in air and thawing in water, a cycle being completed in 171 min) was followed. The pulse velocity and resonant frequency were measured at 300, 600 and 1000 cycles. The dynamic modulus of elasticity was determined at each interval using the longitudinal frequency, as described in ASTM C215-60. The results are shown in Tables 10 to 14. Photographs of specimens after 300 cycles of freezing and thawing are shown in Fig. 8 to 11. The results of all the testing are shown in Tables 6 to 13.

8. The two slabs made from each mix for determining thermal conductivity were carefully cut and the surfaces ground to form discs 203 mm in diameter by 25.4 mm thick. Two grooves 0.64 mm wide and 0.64 to 0.76 mm deep were cut into each flat surface to accommodate thermocouples. The discs were heated at 100°C for 18 h to drive off moisture and remnants of the epoxy used to fasten the disc to a metal plate when the discs were being surfaced.

The test apparatus was designed to give

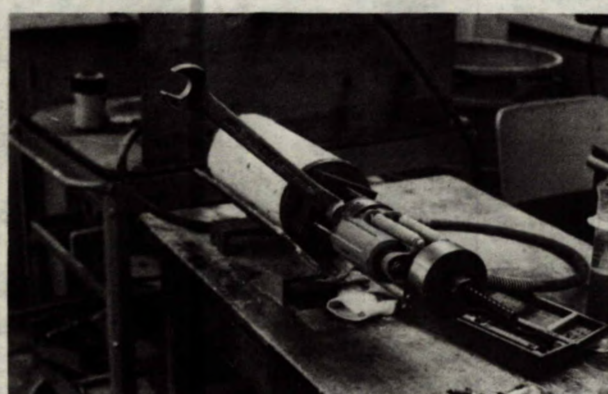
Table 9 - Summary of creep test data

		Compressive strength		Total stress		Duration of stress,	Drying conditions				Sealed conditions			
	Mix						Total creep		Specific creep		Total creep		Specific creep	
Aggregate	No.	psi	MPa	psi	MPa	(days)	in./in.x10^{-6}	mm/mm/10^{-3}	in./in./psi	mm/mm/MPa	in./in. x 10^{-6}	mm/mm x 10^{-3}	in./in./psi	mm/mm/MPa
A	1	3410	23.5	855	5.9	385	720	18.3	0.84	3.10	-50	-1.3	-0.06	-0.22
	2	4310	29.7	1080	7.4	368	890	22.6	0.82	3.05	395	10.0	0.37	1.35
	3	5700	39.3	1425	9.8	375	660	16.8	0.46	1.71	20	0.5	0.01	0.05
B	1A	4215	29.0	1055	7.3	385	720	18.3	0.68	2.51	75	1.9	0.07	0.26
	1B	3670	25.3	920	6.3	349	770	19.6	0.83	3.11	555	14.1	0.60	0.24
	2	5360	36.9	1340	9.2	368	760	19.3	0.57	2.10	310	7.9	0.23	0.86
	3	6280	43.3	1570	10.8	375	705	17.9	0.45	1.66	280	7.1	0.18	0.66
C	1	3250	22.4	815	5.6	383	755	19.2	0.93	3.43	690	17.5	0.85	3.13
	2	3550	24.5	890	6.1	361	825	21.0	0.93	3.43	375	9.6	0.42	1.57
	3	3820	26.3	955	6.6	373	815	20.7	0.85	3.14	-115	2.9	-0.12	-0.44
D	1	3480	24.0	870	6.0	362	810	20.6	0.93	3.43	385	9.8	0.44	1.63
	2	4260	29.4	1065	7.3	360	980	24.9	0.92	3.41	230	5.8	0.22	0.97
	3	5460	37.6	1365	9.4	360	635	16.1	0.47	1.71	165	4.2	0.12	0.45
E	1A	3220	22.2	805	5.5	353	1035	26.3	1.18	4.78	715	18.2	0.89	3.31
	1B	2770	19.1	695	4.8	349	945	24.0	1.36	5.00	155	3.9	0.22	0.81
	2	3490	24.0	875	6.0	353	880	22.4	1.01	3.73	510	13.0	0.58	2.17
	3	3490	24.0	875	6.0	353	915	23.2	1.05	3.87	605	15.4	0.69	2.57

precise readings of heat flow through the specimen, based on the guarded hot-plate method detailed in ASTM C177-76. The thermal conductivity of each disc was determined at seven or more temperatures between 30 and 350°C. The values obtained for the two discs of each mix were averaged.

The thermal conductivities of the low-, medium- and high-strength concretes at about 30, 100, 200 and 300°C are tabulated in Table 15.

(a) Cylinder with end bearing plate and prestressing tendon



(b) Apparatus applying compression to cylinder

(c) Arrangement of cylinders in laboratory

Fig. 7 - Apparatus for studying creep of concrete

Table 10 - Changes in weight of test prisms during freeze-thaw cycling

Aggregate	Mix No.	Weight lb (kg) 0 cycles	300 cycles	600 cycles	1000 cycles	% change, 0-1000 cycles	Remarks
A	1	14.904	14.910	14.584	14.078	-5.54	
		(6.760)	(6.763)	(6.615)	(6.386)		
	2	15.215	15.218	15.029	14.606	-4.00	
		(6.902)	(6.903)	(6.817)	(6.625)		
	3	15.448	15.406	15.333	15.202	-1.59	
		(7.007)	(6.988)	(6.955)	(6.896)		
B	1A	15.628	15.646	14.596	--	-6.60	Testing stopped after 600 cycles
		(7.089)	(7.097)	(6.621)			
	2	16.579	16.558	16.225	--	-2.14	Testing stopped after 600 cycles
		(7.520)	(7.511)	(7.360)			
	3	16.662	16.492	15.891	--	-4.63	Testing stopped after 600 cycles
		(7.558)	(7.481)	(7.208)			
C	1	14.618	14.623	14.604	14.558	-0.41	
		(6.631)	(6.633)	(6.624)	(6.604)		
	2	15.041	15.034	14.996	14.950	-0.61	
		(6.823)	(6.819)	(6.802)	(6.781)		
	3	14.904	14.858	14.856	14.820	-0.56	
		(6.760)	(6.740)	(6.739)	(6.722)		
D	1	15.501	15.524	15.495	15.496	-0.03	
		(7.031)	(7.042)	(7.029)	(7.029)		
	2	15.322	15.322	15.289	15.272	-0.33	
		(6.950)	(6.950)	(6.935)	(6.927)		
	3	15.953	15.940	15.905	15.875	-0.49	
		(7.236)	(7.230)	(7.215)	(7.201)		

Table - 11 Changes in length of test prisms during freeze-thaw cycling

Aggregate	Mix No.	Cumulative length change, in. (mm) 300 cycles	600 cycles	1000 cycles	% change 0-1000 cycles	Remarks
A	1	+0.0003	+0.0009*	+0.0006*	+0.004	
		(0.008)	(0.023)	(0.015)		
	2	-0.0014	-0.0022	-0.0025	-0.018	
		(0.036)	(0.056)	(0.064)		
	3	+0.0002	-0.0011	-0.0015	-0.011	
		(0.005)	(0.028)	(0.038)		
B	1A	+0.0282	--	--	+0.207	Measurements stopped after 300 cycles
		(0.716)				
	2	+0.0044	+0.0092	--	+0.068	Measurements stopped after 600 cycles
		(0.112)	(0.234)			
	3	-0.0031	+0.0046*	--	+0.034	Measurements stopped after 600 cycles
		(0.078)	(0.117)			
C	1	-0.0021	-0.0014	+0.0054	+0.040	
		(0.053)	(0.036)	(0.137)		
	2	+0.0018	+0.0027	+0.0034	+0.025	
		(0.046)	(-0.069)	(0.086)		
	3	+0.0039	+0.0056	+0.0066	+0.049	
		(0.099)	(0.142)	(0.168)		
D	1	+0.0008	+0.0008	+0.0028	+0.021	
		(0.020)	(0.020)	(0.071)		
	2	+0.0008	+0.0011	+0.0029	+0.021	
		(0.020)	(0.028)	(0.074)		
	3	+0.0026	+0.0035	+0.0056	+0.041	
		(0.066)	(0.089)	(0.142)		

*1 prism only

Table 12 - Changes in resonant frequency of test prisms during freeze-thaw cycling

Aggregate	Mix No.	Resonant frequency 0 cycles	300 cycles	600 cycles	1000 cycles	% change, 0-1000 cycles	Remarks
A	1	4170	4195	4150	4260*	+2.16*	Corners broken
	2	4370	4360	4335	4340	-0.69	
	3	4430	4425	4425	4415	-0.34	
B	1A	4290	4245	4195	--	-2.21	Measurements stopped after 600 cycles
	2	4500	4520	4460	--	-0.89	Measurements stopped after 600 cycles
	3	4500	4475	4520*	--	+0.44	Measurements stopped after 600 cycles
C	1	4400	4355	4355	4385	-0.34	
	2	4445	4440	4465	4475	+0.67	
	3	4430	4445	4440	4460	+0.68	
D	1	4570	4590	4550	4550	-0.44	
	2	4620	4660	4690	4650	+0.65	
	3	4750	4775	4770	4775	+0.53	

*1 prism only

Table 13 - Change in pulse velocity of test prisms during freeze-thaw cycling

Aggregate	Mix No.	Pulse velocity, ft/sec (m/s) 0 cycles	300 cycles	600 cycles	1000 cycles	% change, 0-1000 cycles	Remarks
A	1	11 980 (3 650)	11 890 (3 630)	11 760 (3 590)	--	-1.84	Measurements stopped after 600 cycles
	2	12 330 (3 760)	12 440 (3 790)	12 400 (3 780)	12 450 (3 800)	+0.97	
	3	12 450 (3 800)	12 570 (3 830)	12 760 (3 890)	12 640 (3 860)	+1.53	
B	1A	12 200 (3 720)	11 910 (3 630)	--	--	-2.38	Measurements stopped after 300 cycles
	2	12 560 (3 830)	12 890 (3 930)	13 010 (3 970)	--	+3.58*	Measurements stopped after 600 cycles
	3	12 970 (3 960)	12 600 (3 840)	11 840 (3 610)	--	-8.71	Measurements stopped after 600 cycles
C	1	12 540 (3 820)	12 520 (3 820)	12 390 (3 780)	12 510 (3 820)	-0.24	
	2	12 990 (3 960)	12 750 (3 890)	12 960 (3 950)	12 960 (3 950)	-0.23	
	3	12 790 (3 900)	12 840 (3 920)	12 880 (3 930)	12 760 (3 890)	-0.23	
D	1	13 080 (3 990)	13 150 (4 010)	13 120 (4 000)	13 060 (3 980)	-0.15	
	2	13 380 (4 080)	13 400 (4 090)	13 500 (4 120)	13 370 (4 080)	-0.07	
	3	13 600 (4 150)	13 640 (4 160)	13 690 (4 180)	13 580 (4 140)	-0.15	

*This increase in pulse velocity is unexplained.

Table 14 - Changes in dynamic modulus of elasticity during freeze-thaw cycling

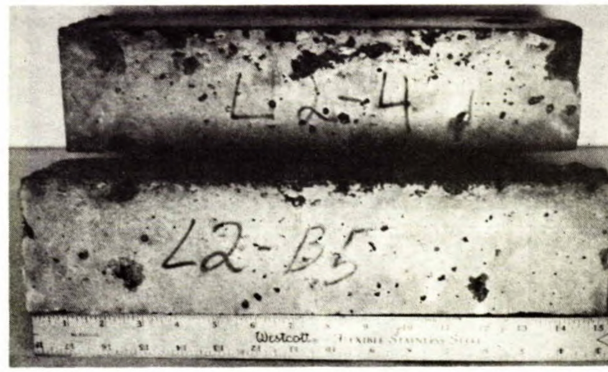
		Dynamic modulus of elasticity, x 10^6 psi (x 10^4 MPa)				% change, 0-1000 cycles	Remarks
		0 cycles	300 cycles	600 cycles	1000 cycles		
A	1	2.92	2.96	2.83	2.88	-1.4	
		(2.01)	(2.04)	(1.95)	(1.98)		
	2	3.28	3.26	3.18	3.10	-5.5	
		(2.26)	(2.25)	(2.19)	(2.14)		
	3	3.42	3.40	3.38	3.34	-2.3	
		(2.36)	(2.34)	(2.33)	(2.30)		
B	1A	3.24	3.18	2.90	-	-10.5	
		(2.23)	(2.19)	(2.00)			
	2	3.78	3.81	3.64	-	-3.7	Measurements stopped after 600 cycles
		(2.60)	(2.63)	(2.51)			
	3	3.80	3.72	3.66	-	-3.7	
		(2.62)	(2.56)	(2.52)			
C	1	3.19	3.13	3.12	3.16	-0.9	
		(2.20)	(2.16)	(2.15)	(2.18)		
	2	3.35	3.34	3.37	3.38	+0.9	
		(2.31)	(2.30)	(2.32)	(2.33)		
	3	3.30	3.31	3.30	3.32	+0.6	
		(2.27)	(2.28)	(2.27)	(2.29)		
D	1	3.65	3.69	3.62	3.62	-0.8	
		(2.51)	(2.54)	(2.49)	(2.49)		
	2	3.69	3.75	3.79	3.72	+0.8	
		(2.54)	(2.58)	(2.61)	(2.56)		
	3	4.06	4.10	4.08	4.08	+0.5	
		(2.80)	(2.82)	(2.81)	(2.81)		

A: Low strength

B: Medium strength

C: High strength

Fig. 8 - Concretes made with aggregate A after 300 cycles of freezing and thawing

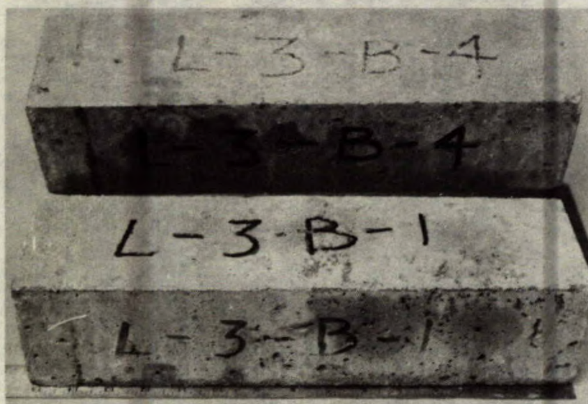


A: Low strength

B: Medium strength

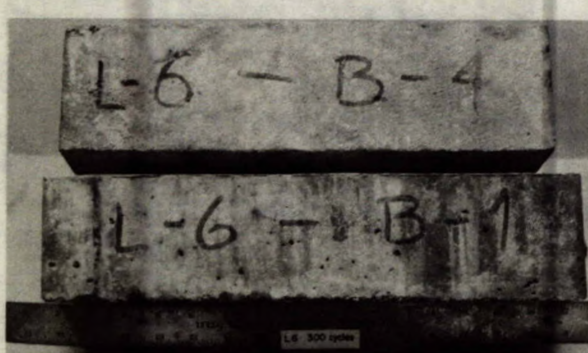
C: High strength

Fig. 9 - Concretes made with aggregate B after 300 cycles of freezing and thawing



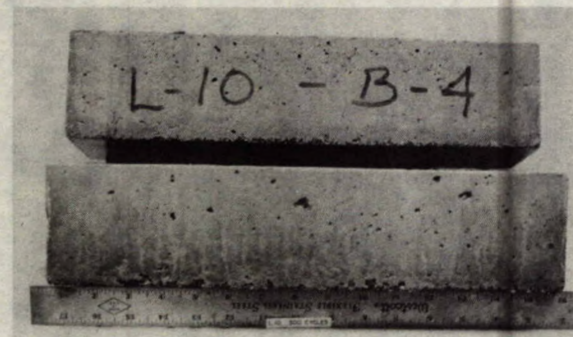
A: Low strength

B: Medium strength

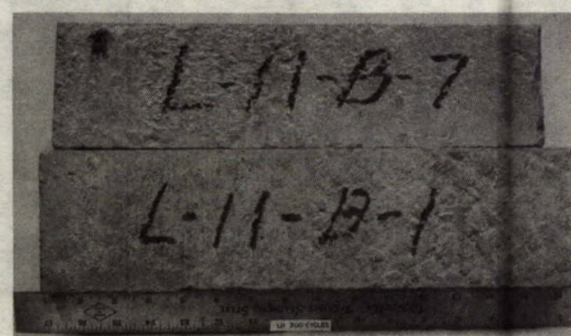


C: High strength

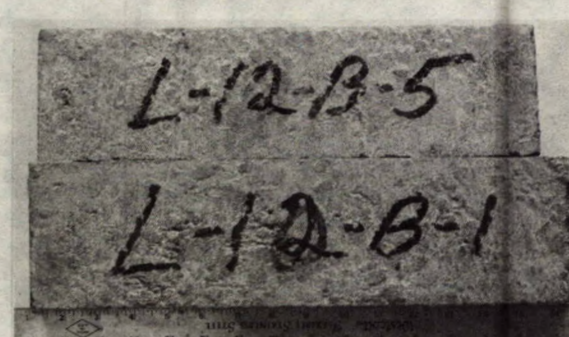
Fig. 10 - Concretes made with aggregate C after 300 cycles of freezing and thawing



A: Low strength



B: Medium strength



C: High strength

Fig. 11 - Concretes made with aggregate D after 300 cycles of freezing and thawing

Table 15 - Thermal conductivity

	Mix	Thermal conductivity (λ): W/(m°C) x 10^{-2} at temperature (T): °C							
Aggregate	No.	T	λ	T	λ	T	λ	T	λ
A	1	31.1	73	115.3	77	193.6	74	252.8	75
	2	33.2	70	107.2	81	220.7	85	301.4	87
	3	31.0	74	103.9	84	195.3	84	308.6	90
B	1A	32.9	68	122.9	79	210.8	78	303.1	80
	2	42.1	77	118.8	93	212.7	85	293.1	88
	3	30.8	75	99.4	83	199.6	88	309.5	89
C	1	32.1	70	121.8	73	206.8	77	312.5	79
	2	34.7	70	100.1	79	199.2	84	311.5	89
	3	32.8	72	97.0	79	191.7	84	309.6	84
D	1	32.9	71	118.1	87	209.8	91	252.4	93
	2*	32.6	71	116.6	89	208.6	98	290.8	95
	3	30.9	72	115.4	85	219.6	91	305.1	93
	3	30.9	72	115.4	85	219.6	91	305.1	93

*Disc thickness: 0.875 in. (22 mm).

DISCUSSION OF RESULTS

PROPERTIES OF LIGHTWEIGHT AGGREGATES

The properties of the lightweight aggregates varied considerably (Table 2). The unit weights of the various size-fractions were between 640 and 960 kg/m^3. The 19.0- to 12.5-mm and the 9.5- to 4.75-mm fractions of aggregate B exceeded the 880 kg/m^3 maximum specified by ASTM. The bulk specific gravities, which were determined on the saturated surface-dry basis, did not correspond to the respective unit weight in every case. Because of their higher absorptions, aggregates A and B had higher specific gravities than would have been expected from the unit weights. Aggregate E had the lowest unit weight and crushing strength. Aggregates B and D had the highest unit weights and aggregates A and B had the highest crushing strengths.

The average 48-h absorption of the aggregates was between 5.6 and 16.3%; aggregate A having the highest and aggregate D the lowest. The 4-h absorptions were between 68 and 86% of the 48-h absorptions. At 24 h, between 80 and 97% of the 48-h absorptions had been satisfied (Table 3).

PROPERTIES OF FRESH CONCRETES

The cement contents of the low-, medium- and high-strength concretes were about 205, 265 and 320 kg/m^3, respectively. The respective water-cement ratios were 0.6, 0.5 and 0.4 (Table 4).

The slumps were between 45 and 75 mm. The air contents were measured by both pressure meter and roll-a-meter. The results from the latter method were erratic and their validity is questionable. From the pressure meter, the air contents were between 3.5 and 6.5% (Table 5).

The unit weights of the fresh concretes were between 1790 and 1950 kg/m^3 for the low-strength mixes, between 1810 and 2020 kg/m^3 for the medium-strength mixes, and between 1825 and 2030 kg/m^3 for the high-strength mixes. They were related to the bulk specific gravities of the coarse aggregates; concretes made with aggregates E and C having the lowest unit weights, and with aggregate B the highest.

PROPERTIES OF HARDENED CONCRETES

Densities at 28 Days

The 28-day densities were between 1775 and 1935 kg/m^3 for specimens with the lowest cement content, and between 1810 and 2030 kg/m^3 for those with the highest cement content. They were between 1.25 and 2.5% lower than were one-day densities (Table 6). ASTM C330-77 does not specify a maximum density for structural lightweight concrete. CSA 23.1-77M, "Concrete materials and methods of concrete construction", defines a structural semi-low density concrete as having a minimum 28-day compressive strength of 15 MPa, and an air-dry density between 1850 and 2150 kg/m^3. All the concretes had compressive strengths well above the specified minimum.

Accelerated-Curing Strength

The accelerated strength averaged 56% of the 7-day strength for the low-strength, 61% for the medium-strength and 71% for the high-strength concretes. The accelerated strengths averaged 42, 47, and 59% of the 28-day strengths respectively (Table 6). The values for concretes made with different aggregates increased with cement content, except for aggregate D in high-strength concrete. In a similar study made 10 years ago on two different lightweight aggregates, the accelerated strengths averaged 63, 63, and 65% of the 7-day strengths and the accelerated strengths averaged 39, 45 and 51% of the 28-day strengths for similar strength levels (2).

Compressive Strength

The 7-day compressive strengths were from 67 to 81% of the 28-day compressive strengths for the low-strength concretes and from 79 to 87% for high-strength concretes (Table 6). Concretes containing aggregate C had the highest proportion, and those containing aggregate B the lowest. The 28-day compressive strengths were between 24.0 and 43.1 MPa. The concretes containing aggregate B had the highest strengths and those with aggregates C and E the lowest. The strengths are in proportion to the relative crushing strengths of the lighweight aggregates (Table 2). If the cement contents of the concretes containing aggregate E had been higher, with a consequent lower water-cement ratio, the compressive strengths undoubtedly would have been higher. Concretes containing aggregates A, B and D showed greater increase in strength with increased cement content than those containing aggregates C and E.

Splitting-Tensile Strength

The splitting-tensile strengths were between 2.4 and 3.5 MPa, which were between 7 and 13% of the respective 28-day compressive strengths (Table 6). There appears to be an anomaly for concretes made with aggregate C in that the strength at the highest cement content is lower than at the medium content. Concretes made with aggregate B had the highest splitting-tensile strength and concretes made with aggregate E had the lowest, although the difference was only 1.1 MPa.

Flexural Strength

The flexural strength of the concretes was about double the splitting-tensile strength (Table 6). This was between 4.6 and 6.5 MPa, which is between 15 and 22% of the respective 28-day compressive strengths. The proportions of flexural to compressive strength tended to decrease with increasing cement content. As with the splitting-tensile strength, aggregate B gave the highest flexural strength, an with aggregate C the flexural strength at the highest cement content was lower than with the medium cement content.

Static Modulus of Elasticity

The static modulus of elasticity, shown in Table 6, was between 1.62 to 2.31 x 10^4 MPa.

The modulus for both lightweight and normal weight concrete can be determined approximately by the formula:

$$E_c = 0.043\ w^{1.5} \sqrt{f'_c}\ (3),$$ where

Ec = static modulus of elasticity, MPa

w = air-dry density of the concrete, kg/m^3

f'_c = compressive strength at the time of test, MPa

Table 6 gives the actual values obtained from the concrete specimens and also the theoretical values obtained from the formula. The formula is accurate only to ±15 to 20%. The only incongruity between the actual and theoretical values is in the high-strength concrete made with aggregate B. The actual value should not be lower than that of the medium-strength concrete. Concretes containing aggregates B and D, having the highest moduli, would have the greatest stiffness. Stiffness however, would not be necessarily a disadvantage, depending on the application.

Drying Shrinkage

In these tests the concrete specimens made with aggregates A and B warped during the early stages of drying, apparently from unequal drying of the upper and lower portions of the prisms. Problems were encountered with the length-measuring device during the early stages of the drying of the medium-strength concretes made with aggregates A and B. Consequently, the shrinkage values for these concretes is not recorded (Table 7). Concretes made with aggregate C had the highest drying shrinkage and those with aggregate B the lowest. As expected, the shrinkage lessened as the water-cement ratio was reduced and as the compressive strength increased.

The weight loss of the concretes during drying did not follow the same order as for the drying shrinkage (Table 8). The greatest losses were shown by the concretes containing aggregate A, and the least by those containing aggregate C. While most of the water lost during drying was from the cement paste, undoubtedly some was lost from the coarse aggregate. The relative weight losses are closely aligned with the relative absorptions.

Creep

Under drying conditions, the concretes had specific creep values of between 1.66 and 5.00 mm/mm/MPa and under sealed conditions, of between 0.05 and 3.31 mm/mm/MPa (Table 9). Two of the concretes expanded against the applied stress and thus had negative creep values (4).

RESISTANCE TO FREEZING AND THAWING

During freeze-thaw cycling, changes in weight, length, resonant frequency and ultra-sonic pulse velocity of the concrete prisms all provide information on the durability of the concrete. Decreases in weight, resonant frequency and pulse velocity indicate deterioration of the concrete, as does an increase in length. Decrease in weight and in resonant frequency indicates surface deterioration, whereas increase in length and decrease in pulse velocity indicate internal structural deterioration.

After 300 Cycles

The changes in weight did not correspond to the changes in resonant frequency for most of the concretes (Tables 10 and 12). With the medium-strength concrete made with aggregate B and the high-strength concretes made with aggregates C and D, the weights decreased whereas the resonant frequencies increased. Only the low-strength concrete with aggregate B had an increase in weight while the resonant frequency decreased. With the low-strength concrete containing aggregate C, the resonant frequency of one specimen dropped 1.8% whereas the other dropped only 0.2%. All the concretes made with aggregate D had increased resonant frequencies. Figures 10 and 11 show that only the high-strength concrete made with aggregate C and the low and high-strength concretes made with aggregate D exhibited no pop-outs after 300 cycles of freezing and thawing.

The high-strength concretes made with aggregates A, C and D showed increased pulse velocities (Table 13). The medium-strength concretes made with aggregates A, B and D also showed increases. Of the low-strength concretes only that made with aggregate D showed an increase.

After 600 Cycles

All concretes began losing weight at the completion of 600 cycles, those made from aggregates C and D losing less than 0.3% (Table 10). Concretes containing aggregate A lost between 0.7 and 2.1% in weight. The testing of concretes made with aggregate B was stopped because the weight losses were between 2.1 and 6.6%, and the ends of the specimens were so badly deteriorated that it was impossible to take accurate readings of the resonant frequency and pulse velocity. The resonant frequency of the other concretes had also begun to decrease, with the exception of those of medium strength made with aggregates C and D (Table 12).

The pulse velocities of the medium strength concretes made with aggregates C and D increased whereas the pulse velocities of the other concretes either remained constant or began to decrease (Table 13).

After 1000 Cycles

After 1000 cycles, all the prisms had lost some weight, the concretes containing aggregates C and D having lost less than 1% and those containing aggregate A between 1.5 and 5.5% (Table 10). Concretes made with aggregates C and D increased in length, but less than 0.05%. The medium- and high-strength concretes made with aggregate A continued to show decrease in length whereas the low-strength concrete showed a slight increase of 0.04% (Table 11). The resonant frequencies of the medium- and high-strength concretes made with aggregates C and D also showed increases in resonant frequency. The others showed decreases. The pulse velocities of the concretes made with aggregates C and D showed decreases, while the medium- and high-strength concrete made with aggregate A continued to show increases (Table 13).

At the start of the freeze-thaw cycling the dynamic moduli of elasticity of concretes were between 2.01 and 2.80 x 10^4 MPa, with aggregate A being the lowest and aggregate D the highest (Table 14). After 300 cycles of freezing and thawing, nine of the twelve concretes showed either an increase or a decrease of less than 1%. The low- and high-strength concretes made with aggregate B and the low-strength concrete made with aggregate C showed a decrease of more than 1%. After 600 cycles, all the concretes made with aggregates A and B and the low-strength concrete made with aggregate C showed a decrease of more than 1%. Testing of the concretes made with aggregate B was stopped because of the severe deterioration of the surfaces particularly at the ends. After 1000 cycles, the low-strength concretes made with aggregate C and D had decreases of less than 1% and the medium- and high-strength concretes had increases in moduli.

THERMAL CONDUCTIVITY*

All concretes had relatively similar thermal conductivities at about 30°C of between 0.68 and 0.77 W/(m°C); concrete B2, having a value of 0.77 W/(m°C), was measured at 42.1°C. The values were most diverse with the low-strength concretes, becoming less so with increase in strength. All concretes showed general increases in thermal conductivity with increased temperature. Ten of the twelve concretes showed decreases in conductivity between 100 and 200°C. This indicated that the concretes had not been thoroughly dried before testing. Moisture in concrete increases its thermal conductivity appreciably. Concretes made with aggregates A, B and C had similar conductivities at higher temperatures after the moisture had been driven off, whereas concretes made with aggregate D had higher

*Specimen preparation and determination were done by V.V. Mirkovich, Mineral Sciences Laboratories, CANMET, Ottawa, Canada.

conductivities.

Spratt, among others, states that thermal conductivity increases with density and gives a graphical relationship (5). The range of densities in this study was too narrow, and the thermal conductivities varied too much to draw a similar relationship. The variation in thermal conductivities was within the variation encountered by Spratt. In this study the variation might have been reduced if the specimens had been at least 76 rather than 25.4 mm thick.

CONCLUSIONS

The physical properties of the lightweight aggregates differed, hence the properties of the concretes also differed considerably. The unit weight of one of the aggregates was slightly above the maximum of 880 kg/m^3 specified by ASTM. The concretes were proportioned on the basis of compressive strength rather than on densities because of the variation between the unit weights of the aggregates.

Densities of the concretes were between 1778 and 2035 kg/m^3, which are below the maximum of 2150 kg/m^3 specified by CSA. Compressive strengths were between 19.1 and 43.1 MPa. All the concretes appeared to withstand 300 cycles of freezing and thawing without structural damage. All but two of the concretes exhibited pop-outs after 300 cycles. The thermal conductivities were between 0.68 and 0.77 W/(m°C) at ambient temperatures, rising to 0.75 to 0.95 W/(m°C) at 300°C.

These lightweight aggregates undoubtedly could be used in lightweight structural concrete. The proportioning and properties of the particular concrete would govern its application.

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