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ASSESSMENT OF AN EXPANDED CLAY LIGHTWEIGHT AGGREGATE IN STRUCTURAL CONCRETE

H.S. WILSON

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ASSESSMENT OF AN EXPANDED CLAY LIGHTWEIGHT AGGREGATE IN STRUCTURAL CONCRETE

by

H.S. Wilson*

SUMMARY

The physical and mechanical properties and durability of semi-lightweight concretes made with an expanded clay lightweight aggregate were evaluated. The concretes investigated, which had cement contents of between 275 and 448 kg/m^3, met CSA specifications for structural semi-low density concrete. They had 28-day air-dry densities of between 1990 and 2028 kg/m^3 and compressive strengths of between 25.8 and 36.0 MPa. The splitting-tensile strengths were 7.5 to 10.5% and the flexural strengths 16.7 to 19.8% of the compressive strengths. Young's moduli of elasticity were between 1.88 x 10^4 and 2.08 x 10^4 MPa. The lightweight aggregates tested could be used in structural concrete, but particular applications would depend on the specific properties required. Durability tests indicated that surface and structural damage occurred at 150 cycles of freezing and thawing, signifying that this aggregate should not be used in concrete exposed to freezing and thawing conditions.

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EVALUATION D'UN AGREGAT LEGER D'ARGILE DILATE
DANS UN BETON DE CONSTRUCTION

par

H.S. Wilson*

SOMMAIRE

Les propriétés physiques et mécaniques et la durabilité des bétons semi-légers fabriqués avec un agrégat léger d'argile dilaté ont été évaluées. Ces bétons avaient des teneurs de ciment de l'ordre de 275 à 448 kg/m^3 et rencontraient les normes de l'ACNOR sur les bétons de construction à mi-basse densité. Les densités mesurées à partir d'essais de séchage à l'air de 28 jours étaient de 1990 à 2028 kg/m^3 et les résistances à la compression étaient de 25.8 à 36.0 MPa. Les résistances à la rupture en traction étaient de 7.5 à 10.5% et les résistances à la flexion, 16.7 à 19.8% des résistances à la compression. Les modules d'élasticité de Young étaient entre 1.88 x 10^4 et 2.08 x 10^4 MPa. Les agrégats légers soumis aux essais peuvent être employés dans les bétons de construction, mais certaines applications pourraient dépendre des propriétés requises. Les essais de durabilité démontrent que le dommage en surface et structural se produit à 150 cycles de gel et de dégel; ceci indique que cet agrégat ne doit pas être employé dans les bétons exposés à des conditions de gel et de dégel.

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INTRODUCTION

Lightweight aggregates are produced from clay or shale at six locations in Canada: Calgary and Edmonton, in Alberta, Regina in Saskatchewan, St. Boniface in Manitoba, Mississauga in Ontario and Minto in New Brunswick. The plants at Edmonton, Regina and St. Boniface use clay, and those at Calgary, Mississauga and Minto use shale as raw materials; all use the rotary kiln method of manufacture. In 1978, more than 72% of the total production was used as aggregate in lightweight masonry units and 25% as aggregate in precast lightweight concrete and cast-in-place lightweight structural concrete (1).

Lightweight aggregates do not pose any problem when used in the manufacture of masonry units. Such units can be used in any application where normal-weight masonry units are used. The lightweight units have the advantage of lower density, lower thermal conductivity and consequently improved fire rating, and higher sound absorption.

In structural applications, the properties of lightweight concrete may differ appreciably from normal-weight concrete, and each lightweight aggregate should be evaluated to ascertain the properties it will impart to a structural concrete.

The properties of the five lightweight aggregates produced in Calgary, Edmonton, Minto, Mississauga and Regina and of the structural concretes incorporating them were determined by CANMET in a previous study and the results published (2). The lightweight aggregate produced by Kildonan Concrete Products Ltd. of St. Boniface, Manitoba was not received in time to be included in the initial study and was thus evaluated separately as described in the present report.

MATERIALS

The lightweight aggregate received from St. Boniface did not meet the standard grading used by CANMET for coarse aggregate and consequently was screened into three size fractions and recombined into the grading shown in Table 1. A local natural sand used in all mixes as the fine aggregate was also screened into different size fractions and these were recombined into the grading shown in Table 1. Normal portland cement CSA Type 10 (ASTM Type 1) was used in all mixes.

PROPERTIES OF LIGHTWEIGHT AGGREGATE

The following properties were determined using appropriate ASTM procedures:

(a) dry, loose unit weight (ASTM C29-78) (3)*
(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 C29-78)
(f) crushing strength.

The crushing strength is not a standard test but is used routinely in the CANMET laboratory. Lightweight aggregate is placed in a 75-mm dia steel cylinder to a depth of 125 mm. A plunger is applied and the aggregate compacted first by 25 mm and then by an additional 25 mm using an hydraulic press. The pressures required to give 25- and 50-mm compaction are reported as the crushing strength. Physical properties are shown in Tables 2 and 3.

CONCRETE MIXES

Three mixes were proportioned on the same basis as used previously with the five other lightweight aggregates, containing nominal cement contents of 265, 355 and 415 kg/m^3 and with water:cement ratios of 0.55, 0.45 and 0.40 (2).

The coarse and fine aggregates were weighed about 18 hours prior to mixing. The absorption requirements were satisfied by flooding the lightweight coarse aggregate with water and by mixing about 10% water in the fine aggregate. Excess water was drained from the coarse aggregate just prior to mixing. Water retained by the coarse and fine aggregates was included in the total water in the mix proportions. Each mix

*All ASTM specifications: reference 3

Table 1 - Gradings of prepared aggregates

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

Table 2 - Physical properties of lightweight aggregate

Size range mm	Unit weight, kg/m^3	Bulk specific gravity	24-h absorption, %	Per cent voids	Crushing strength, MPa	
					25 mm	50 mm
19.0 to 12.5	820.2	1.90	10.6	56.8	3.2	22.9
12.5 to 9.5	842.7	1.94	10.6	56.4	4.0	31.1
9.5 to 4.75	887.5	1.93	10.6	54.0	4.5	34.8

Table 3 - Rates of absorption of lightweight aggregate

Size range, mm	Absorption, per cent					
	0.25 h	0.5 h	1 h	4 h	24 h	48 h
19.0 - 12.5	7.4	8.2	8.7	8.7	9.6	10.0
12.5 - 9.5	7.6	8.0	8.2	9.0	9.7	10.1
9.5 - 4.75	8.0	8.6	8.6	8.8	9.7	9.9
Average	7.7	8.3	8.5	8.8	9.7	10.0

was 0.1 m^3, adding in sequence to the mixer coarse aggregate, cement, 50% of the water, fine aggregate, almost all the balance of the water, and an air-entraining agent. Some water was held back in each mix until the slump and air content were determined. The slump was controlled at 50 ± 10 mm and the air content at 5 ± 1%. The total mixing time was 20 min. The mix data and the physical properties of the fresh concretes are shown in Tables 4 and 5 respectively.

From each mix, ten cylinders 152 x 305 mm, were made in steel moulds, following the procedure detailed in ASTM C192-76, including internal vibration of each of the three layers of concrete. Also, six prisms, 89 x 102 x 387 mm were made in brass moulds. A vibrating table was used to consolidate each of the two layers of concrete. Six of the prisms were cast with stainless steel studs embedded in the ends, two to be used in drying shrinkage determinations and four in the tests for resistance to freezing and thawing.

CONCRETE CURING

Two of the cylinders were used for accelerated curing (ASTM C684-74) and, when cast, had a steel plate clamped over the open end of the mould. For the first 24 h after casting, all the specimens were covered with plastic sheets to prevent evaporation of moisture. At 24 h, all specimens but the two cylinders to be used in accelerated curing were removed from the moulds, weighed in air and suspended in water to determine

Table 4 - Concrete mix proportions

	Mix proportions, (m^3)						
			Aggregates, SSD				
Mix no.	Cement kg/m^3	Water kg/m^3	Coarse lightweight, kg/m^3	Fine natural, kg/m^3	Coarse-fine ratio	Air entraining agent ml/m^3	Water-cement ratio
1	275	160	790	812	0.97	31	0.58
2	354	167	803	701	1.15	31	0.47
3	448	181	782	640	1.22	52	0.40

Table 5 - Properties of fresh concretes

	Temperature		Properties of Concrete			
Mix no.	Concrete, (°C)	Ambient, (°C)	Slump, (mm)	Unit weight, (kg/m^3)	Air pressure meter %	Water-cement ratio
1	20	19.5	40	2037.4	5.4	0.58
2	15	17	50	2024.9	4.6	0.47
3	18	19	55	2050.4	4.5	0.40

the 1-day density. They were then placed in the moist-curing room at 23.1 ± 1.7°C and 100% relative humidity.

At 7 days, all the cylinders were removed from the moist-curing room and, except for those to be tested that day, were placed in a dry-curing room at 23 ± 1.1°C and a relative humidity of 50 ± 4%. Testing of these cylinders was done at 28 days.

The prisms containing the steel studs to be used in the determination of drying shrinkage, were also placed in the dry-curing room at 7 days for the duration of the test period.

The remainder of the prisms were transferred from the moist-curing room to the dry-curing room at 14 days, and returned to the moist-curing room at 25 days where they remained until tested.

CONCRETE TESTING

The following tests were made on the hardened concrete using standard ASTM methods:

1. Compressive strength test (ASTM C39-72)
   (a) at 28.5 h, after accelerated curing
   (b) at 7 days
   (c) at 28 days
2. Splitting-tensile strength test (ASTM C496-71)
3. Flexural strength test (ASTM C78-75)
4. Young's modulus of elasticity test (ASTM C469-65)
5. Drying shrinkage
6. Resistance to freezing and thawing.

Accelerated curing with boiling water is described in detail in ASTM C684-74. At 23 h, the two cylinders with mould and cover were placed in a tank of boiling water. After 3.5 h they were removed from the tank, the cylinders were removed from the moulds and allowed to cool for 1 h. They were then capped and broken in compression at 28.5 h.

At both 7 and 28 days, two cylinders were capped and broken in compression. The relationships between the accelerated and the 7- and 28-day compressive strengths are shown graphically in Fig. 1 and the relationship between the cement content and the 7- and 28-day compressive strengths is shown in Fig. 2.

Several other tests were made at 28 days. Two cylinders were used to determine the splitting-tensile strength and two to determine Young's modulus of elasticity, these two subsequently being broken in compression. Two prisms were used to determine the flexural strength. The compressive, splitting-tensile and flexural

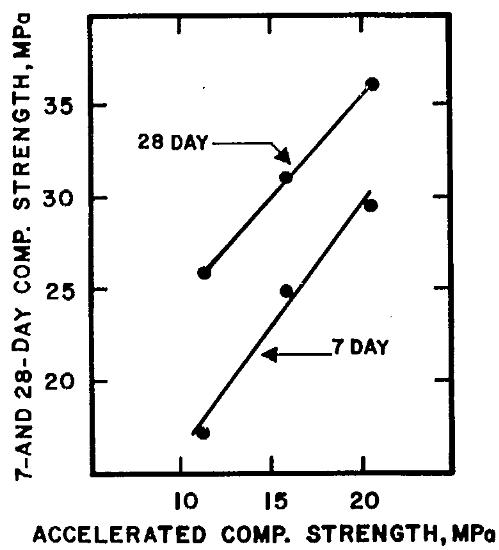

Fig. 1 - Relationship of accelerated to 7- and 28-day compressive strengths

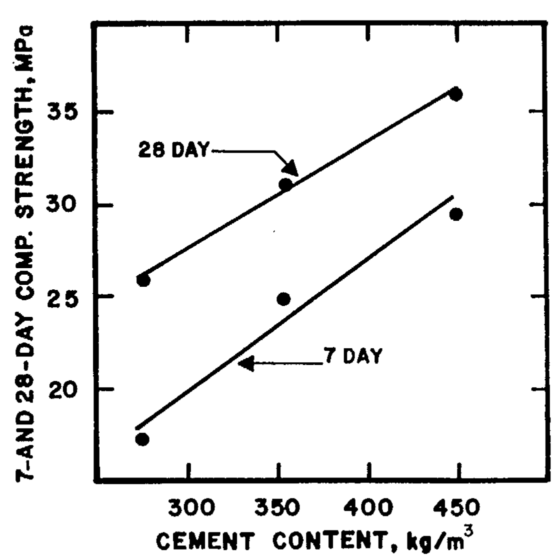

Fig. 2 - Relationship of cement content to 7- and 28-day compressive strengths

strengths, and the modulus of elasticity are given in Table 6. The relationships between the cement content and the splitting-tensile and flexural strengths are shown in Fig. 3, that between the cement content and the 28-day air-dry density in Fig. 4, and that between the cement content and the static modulus of elasticity in Fig. 5. Typical fracture surfaces of compressive strength specimens are shown in Fig. 6, and of splitting-tensile and flexural strength specimens in Fig. 7.

The drying shrinkage determinations were started at 7 days when the prisms were moved from the moist-curing room to the dry-curing room. Subsequent measurements to 0.001 mm were made at 14, 21, 28, 45, 60, 90 and 120 days. The changes in length and weight during drying are shown in Tables 7 and 8.

At 28 days, tests for resistance to freezing and thawing were started. The weight, length, pulse velocity (ASTM C597-71) and resonant frequency (ASTM C215-60) of four prisms were determined. Two of the prisms, as control specimens, were returned to the moist-curing room after the readings were taken. The other two prisms were exposed to freeze-thaw cycling using Procedure B of ASTM C666-77 (freezing in air and thawing in water, a cycle being completed in 171 min). The properties were measured on both the prisms in the freeze-thaw testing and on the control prisms after 100 and 150 cycles, at which time testing was terminated, and the prisms broken in flexure. The results are shown in Tables 9 to 14. The medium strength specimens in mix 2 at termination of testing are shown in Fig. 8.

Table 6 - Properties of hardened concretes

Mix no.	Density, kg/m^3		Compressive strength, MPa		Splitting tensile strength, MPa	Flexural strength, MPa	Accelerated curing strength, MPa	Static Modulus of elasticity, x 10^4 MPa	
	1 day	28 day	7 day	28 day				actual	theoretical
1	2039.3	1989.7	17.2	25.8	2.7	5.1	11.2	1.88	1.94
2	2040.9	2002.5	24.8	31.0	2.9	5.6	15.9	1.93	2.13
3	2052.2	2028.1	29.5	36.0	2.8	6.0	20.5	2.08	2.37

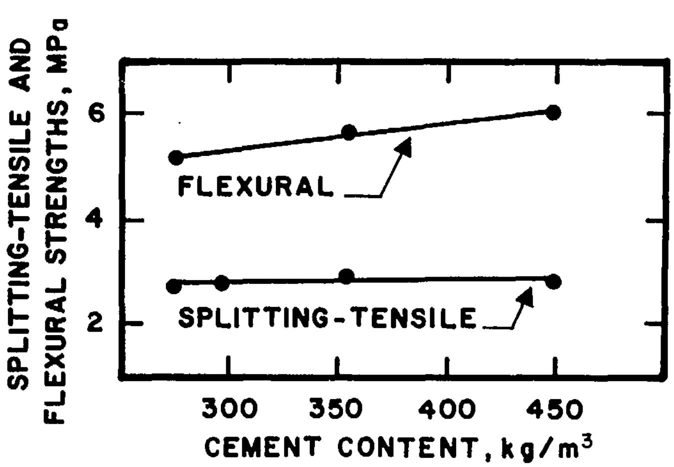

Fig. 3 - Relationship of cement content to splitting-tensile and flexural strengths

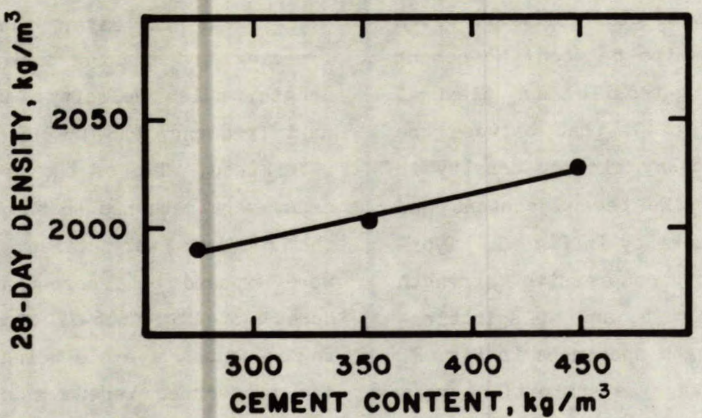

Fig. 4 - Relationship of cement content to 28-day density

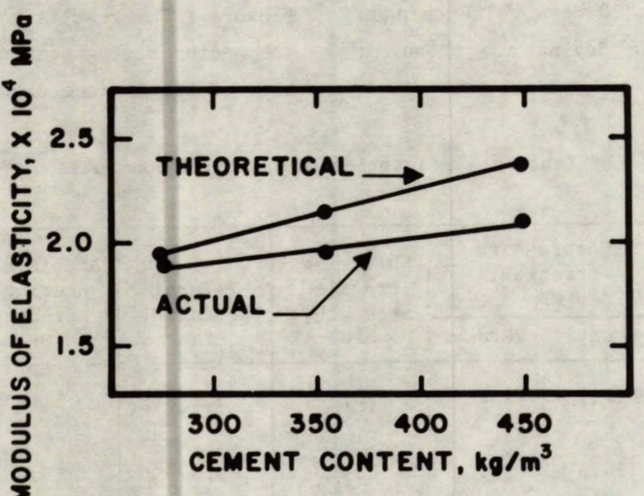

Fig. 5 - Relationship of cement content to static modulus of elasticity

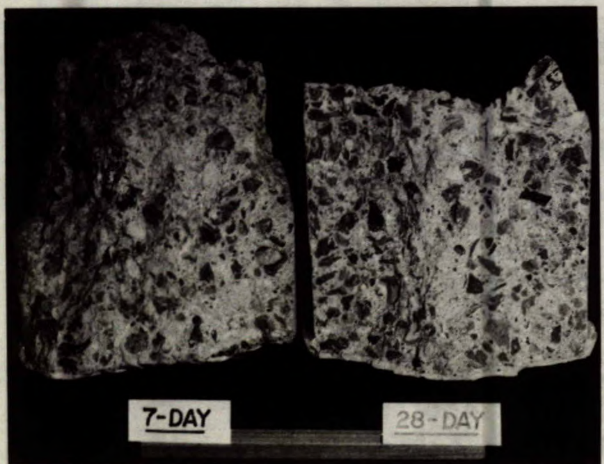

Fig. 6 - Fracture surfaces of 7- and 28-day compressive strength cylinders

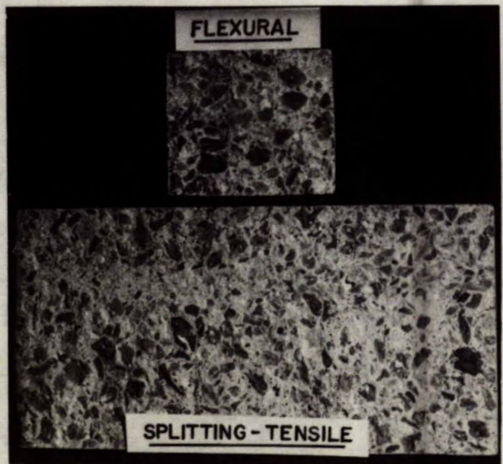

Fig. 7 - Fracture surfaces of splitting-tensile and flexural strength specimens

Table 7 -Changes in length of test prisms during drying

Mix no.	Cumulative length change							
	14 day, mm	21 day, mm	28 day, mm	45 day, mm	60 day, mm	90 day, mm	120 day, mm	120 day, mm/mm x 10^{-4}*
1	0.043	0.071	0.091	0.119	0.152	0.178	0.211	5.8
2	0.031	0.069	0.086	0.122	0.165	0.206	0.241	6.7
3	0.036	0.053	0.071	0.102	0.130	0.180	0.224	6.2

*Gauge length: 360 mm.

Table 8 - Changes in weight of test prisms during drying

Mix no.	7 day weight, kg	Cumulative weight change							
		14 day, kg	21 day, kg	28 day, kg	45 day, kg	60 day, kg	90 day, kg	120 day, kg	120 day, Per cent
1	7.477	0.210	0.262	0.295	0.345	0.386	0.445	0.458	6.13
2	7.457	0.160	0.213	0.242	0.293	0.328	0.388	0.403	5.40
3	7.649	0.149	0.186	0.214	0.279	0.293	0.342	0.354	4.63

Table 9 - Changes in weight in test prisms during freeze-thaw cycling

Mix no.	Weight, kg			% change, 0- 135 cycles	Remarks
	0 cycles	100 cycles	135 cycles		
1	7.469	7.519	7.488	+ 0.25	Pop-outs and scaling at 100 cycles
2	7.349	7.392	7.366	+ 0.23	Pop-outs on corners at 100 cycles
3	7.514	7.503	7.450	- 0.85	Cracking at ends at 117 cycles
1 control	7.362	7.407	7.416	+ 0.73	
2 control	7.475	7.508	7.515	+ 0.54	
3 control	7.519	7.536	7.541	+ 0.30	

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

Mix no.	Cumulative length change, mm		% change, * 0- 135 cycles	Remarks
	100 cycles	135 cycles		
1	+ 0.208	+ 0.666	+ 0.185	Testing stopped at 136 cycles
2	+ 0.076	+ 0.335	+ 0.093	Testing stopped at 148 cycles
3	+ 0.079	+ 0.125	+ 0.035	Testing stopped at 117 cycles
1 control	+ 0.005	+ 0.005	+ 0.001	
2 control	- 0.015	0.000	0.000	
3 control	+ 0.003	- 0.013	- 0.004	

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

Mix no.	Resonant Frequency			% change, 0- 135 cycles	Remarks
	0 cycles	100 cycles	135 cycles		
1	4 435	3 390	2 860	- 35.5	Testing stopped at 136 cycles
2	4 465	4 290	3 600	- 19.4	Testing stopped at 148 cycles
3	4 505	4 340	4 380	- 2.8	Testing stopped at 117 cycles
1 control	4 415	4 405	4 425	+ 0.2	
2 control	4 475	4 245	4 495	+ 0.4	
3 control	4 490	4 500	4 515	+ 0.6	

Table 12 - Changes in pulse velocity of test prisms during freeze-thaw cycling

Mix no.	Pulse velocity, m/s			% change, 0- 135 cycles	Remarks
	0 cycles	100 cycles	135 cycles		
1	3 910	3 480	2 340*	- 40.2	Testing stopped at 136 cycles
2	3 930	3 550	3 320	- 15.5	Testing stopped at 148 cycles
3	3 980	3 880	3 830	- 3.8	Testing stopped at 117 cycles
1 control	3 880	3 900	3 930	+ 1.3	
2 control	3 930	3 870	3 970	+ 1.0	
3 control	3 960	4 000	4 010	+ 1.3	

* one prism only

Table 13 - Changes in relative dynamic modulus of elasticity of test prisms during freeze-thaw cycling

Mix no.	Modulus of elasticity, x 10^4 MPa			% change, 0- 135 cycles	Remarks
	0 cycles	100 cycles	135 cycles		
1	2.51	1.99	1.05	- 58.2	Testing stopped at 136 cycles
2	2.51	2.33	1.64	- 34.7	Testing stopped at 148 cycles
3	2.60	2.43	2.45	- 5.8	Testing stopped at 117 cycles
1 control	2.46	2.47	2.49	+ 1.2	
2 control	2.47	2.32	2.60	+ 5.3	
3 control	2.60	2.61	2.63	+ 1.2	

Table 14 - Changes in flexural strength of test prisms during freeze-thaw cycling

Mix no.	Flexural strength, MPa		% change, 0- 135 cycles	Remarks
	control	after 135 cycles		
1	5.5	-	-	F-T prisms broke near one end
2	5.9	1.8	- 69.5	
3	6.4	5.1	- 20.3	

Fig. 8 - Medium strength specimens after 148 cycles of freezing and thawing

DISCUSSION OF RESULTS

PROPERTIES OF LIGHTWEIGHT AGGREGATE

The unit weight of this lightweight aggregate was greater than that of four of the five aggregates reported previously (2). The 9.5- to 4.75-mm fraction had a unit weight of 887.5 kg/m^3, slightly greater than the limit of 880 kg/m^3 specified by ASTM for structural lightweight concrete. The unit weights of the five other aggregates tested previously ranged from 719.3 to 951.6 kg/m^3. The crushing strength of a lightweight aggregate is usually related to its unit weight but although the unit weight of this aggregate was near the upper end of those of the others, its crushing strength was only about the middle of the range of the others. The crushing strengths of those aggregates sized 9.5 to 4.75 mm were between 4.5 and 9.5 MPa for 25-mm compaction and from 19.9 to > 58.6 MPa for 50-mm compaction. This aggregate absorbed water rapidly - about 85% of the 48-h absorption of 10% was absorbed in one hour.

PROPERTIES OF FRESH CONCRETES

With cement contents of between 275 and 448 kg/m^3, water:cement ratios of 0.40 to 0.58 and air contents of between 4.5 and 5.5%, concretes were made having densities of between 2037.4 and 2050.4 kg/m^3. These unit weights were greater than was achieved using the other lightweight aggregates weighing 1800 to 2025 kg/m^3. Slumps of the concretes containing this aggregate were between 40 and 55 mm.

PROPERTIES OF HARDENED CONCRETES

The 28-day air-dry densities of between 1990 and 2028 kg/m^3 were between the limits of 1850 and 2150 kg/m^3, and the 28-day compressive strengths were above the minimum of 15 MPa as specified by CSA (4). The 28-day densities were between 1.2 and 2.4% lower than the 1-day densities. The 28-day densities of the other lightweight concretes were between 1783 and 2020 kg/m^3 and the 28-day compressive strengths were between 22.4 and 43.1 MPa.

The accelerated strengths were between 64 and 69% of the 7-day compressive strengths and between 43 and 57% of the 28-day compressive strengths, the proportions increasing with compressive strength. These values are comparable with those found previously with other lightweight concretes.

The splitting-tensile strengths were between 10.5 and 7.8% of the 28-day compressive strengths, the proportion decreasing with increasing compressive strength. With the other concretes the proportions were between 7 and 13%.

The flexural strengths, about double the splitting-tensile strengths, were between 19.8 and 16.7% of the 28-day compressive strength, decreasing with increasing compressive strength. The proportions with the other concretes were between 15 and 22%.

Table 6 shows the actual and theoretical values of the static modulus of elasticity. the actual values are about in the middle of the range of values for the other lightweight concretes which were between 1.62×10^4 and 2.34×10^4 MPa. The theoretical values are near the higher end which were between 1.43×10^4 and 2.55×10^4 MPa. The theoretical value is obtained from the equation (5):

$$E_c = 0.043\, w^{1.5} \sqrt{f'_c}$$

where E_c = static modulus of elasticity, MPa
w = air-dry density, kg/m^3
f'_c = compressive strength at time of test, MPa

This equation gives results which may be accurate to ± 15 to 20% of the actual value. In these determinations, the theoretical values were from 3 to 14% higher than the actual values, increasing with compressive strength.

With concretes containing the same aggregates and having similar water:cement ratios, drying shrinkage usually increases with cement content because of more water being available for evaporation (6). In these concretes, the drying shrinkage was relatively similar in spite of different cement contents. From low to high-strength concrete, the cement content was increased 63% and the water 13%, indicating less water was available for evaporation.

Changes in weight, length, resonant frequency and pulse velocity are all indications of durability of concrete exposed to freezing and thawing. Decreases in weight and resonant frequency denote surface deterioration, whereas decrease in pulse velocity and increase in length indicate structural deterioration.

All the concretes showed some deterioration after 100 cycles of freezing and thawing, through changes in their properties. The low- and medium-strength specimens also exhibited pop-outs, scaling of the surface, and spalling at the corners. By 136 cycles, the low-strength concrete showed drastic changes in all properties, indicating failure. Tests on the medium-strength concrete after 148 cycles indicated failure as shown by an expansion of 0.093% and a decrease in relative dynamic modulus of elasticity of 34.7%. The high strength concrete did not exhibit the same degree of change in properties as did the other concretes. However, testing was stopped after 117 cycles because a corner had spalled from one of the prisms because there was considerable cracking near the ends of both prisms, and because the expansion was 0.035%.

CONCLUSIONS

The unit weight of the lightweight aggregate studied in this investigation was near the upper range of other lightweight aggregates previously reported. For aggregate of 19.0 to 4.75 mm, the unit weight was below the maximum of 880 kg/m^3 specified by ASTM. Semi-lightweight structural concrete incorporating this lightweight coarse aggregate, natural sand and a maximum cement content of 448 kg/m^3 had a 28-day air-dry density of 2028 kg/m^3 and a compressive strength of 36.0 MPa. The concretes met the CSA requirements for structural semi-low density concrete (4). Concrete containing the lightweight aggregate under investigation should not be exposed to freezing and thawing conditions because of the poor durability found in this study. Other structural applications should be governed by concrete proportioning and properties.

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