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DURABILITY STUDY OF SEMI-LIGHTWEIGHT CONCRETE MADE WITH COATED HAYDITE AGGREGATE

by

N. G. ZOLDNERS AND H. S. WILSON

MINERAL PROCESSING DIVISION

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N.G. Zoldners* and H.S. Wilson**

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SUMMARY OF RESULTS

The durability of semi-lightweight concrete made with coated Haydite aggregate was assessed by exposing 3½ x 4 x 15-in. test beams to 1000 cycles of accelerated freezing and thawing.

After completion of freeze-thaw cycling no loss in weight was recorded, though a few popouts were evident. Expansion ranging from 0.006 to 0.01 per cent, (well below the specified maximum limit of 0.10 per cent) was observed only on the highest-strength (Series 3) specimens.

Non-destructive test methods did not reveal any general deterioration of concrete and the durability factor after 1000 cycles of freezing and thawing was over 100 per cent in all test series.

Flexural strength increased in all but Series 3 beams after 1000 cycles of exposure; however, it was up to 7 per cent lower than that of the companion standard moist-cured reference beams.

A few popouts, which started to develop after 700 cycles, appeared mainly in the test series for which the Haydite aggregate had been pre-soaked for 4 days. There was no unsound material found in popout aggregate particles. Spalling was caused by repeated freezing of trapped water in highly porous aggregate particles.

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INTRODUCTION

Until 1967, the lightweight aggregate produced by Domtar Construction Materials Limited at Cooksville, Ont., could be termed "crushed" Haydite. During the processing in rotary kilns, bloated shale agglomerated and discharged in clusters and lumps up to one foot in diameter. Therefore the product had to be crushed to required size.

In 1967 the Company modified the process and began producing a "semi-coated" Haydite aggregate. Under the new processing conditions, a considerably smaller proportion of the shale particles agglomerated in the kilns. The majority of expanded shale particles required no crushing and retained the glossy skin or coating.

In 1968 the Mines Branch was requested to assist in determining the durability of lightweight concrete, made with the semi-coated Haydite, when exposed to severe weathering conditions. The results of that study was reported in Mines Branch Investigation Report IR 69-18 (1). Semi-lightweight, air-entrained concrete made with Haydite coarse aggregate and natural sand fine aggregate maintained a high state of integrity during accelerated cycles of freezing and thawing. Its excellent frost resistance was confirmed by an increase in the relative dynamic modulus of elasticity and by the continued increase in flexural strength of freeze-thaw test specimens through 1000 cycles of exposure.

Since 1969, the Company has been producing a "coated" lightweight aggregate, with practically no agglomeration of the particles.

The Company requested the Mines Branch to repeat durability studies on concrete containing the new type of Haydite lightweight aggregate for comparison with the previous study.

CONCRETE MIXES

Materials

All materials used in these mixes were supplied by the Company.

Cement - normal (Type 1) Portland cement was used in all concrete mixes.

Admixtures - an air-entraining agent (Darex AEA) and a water-reducing, dispersing agent (WRDA), both in liquid form, were added in amounts prescribed by the manufacturer* to produce 6 $\pm$ 1% of entrained air in the mixes.

Aggregates - two sizes of coarse lightweight aggregate were submitted: ½-in. and 3/4-in. Haydite; a natural sand was also supplied for fine aggregate.

Representative samples of each aggregate were taken from the submitted material and tested for grading, unit weight, moisture content, absorption, and bulk specific gravity.

Gradings of the coarse and fine aggregates are given in Table 1 and are shown graphically in Appendices A and B. Other physical properties of the aggregates are given in Table 2.

The unit weight of the coated-Haydite coarse aggregate used in this investigation is lower than that of the semi-coated Haydite used in the previous investigation (see Table 3, ref. 1) as are the absorption and bulk specific gravity.

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* Dewey and Almy Chemical Division of W.R. Grace & Co. of Canada Limited.

TABLE 1

Gradings of Aggregates

(per cent passing)

Coarse Aggregates			Fine Aggregate	
Sieve Sizes	Haydite 3/4 in.	Haydite 1/2 in.	Sieve Sizes	Natural Sand
3/4 in.	100.0	-	No. 4	97.4
1/2 in.	42.7	100.0	No. 8	85.9
3/8 in.	21.5	39.8	No. 16	66.3
No. 4	10.0	5.0	No. 30	40.4
			No. 50	18.2
			No. 100	5.2

TABLE 2

Physical Properties of Coarse and Fine Aggregates

Properties	Coarse Aggregates Haydite 3/4 in.	Coarse Aggregates Haydite 1/2 in.	Fine Agg. Natural Sand
Unit Weight, lb/cu ft (loose, room-dry)	43.0	39.7	107.7
Moisture Content, per cent	2.6	10.1	3.7
Absorption, per cent	6.98	7.38	1.62
Bulk Specific Gravity (SSD*)	1.46	1.415	2.64

* SSD: Saturated, surface-dry condition.

Mix Design

Three series of semi-lightweight concrete mixes were designed for each of the ½-in. and 3/4-in. (maximum) sizes of Haydite to produce concrete in three strength levels between 2500 and 6000 psi, using 400, 500, and 700 lbs of cement per cu yd of concrete.

The mix proportions in this investigation were based on the results obtained from the previous study on the semi-coated Haydite. However, in order to reduce the unit weight of concrete, the proportion of natural sand in the mixes was drastically reduced. The sand amounts were reduced in the ½-in. mixes by 3 to 8% and in the 3/4-in. mixes by 6 to 11%. Consequently, the unit weight of concrete was also significantly lower.

Preparation of Mixes

Each mix produced 2 cu ft of concrete. The weights of aggregates were corrected for moisture content at the time of weighing. Actual mix proportions were calculated after the unit weight of a mixture was obtained and the amounts of absorbed and free water were determined for each batch. Mix proportions calculated on the SSD basis are given in Table 3 and are shown graphically in Appendix C.

In addition, two mixes were made with 3/4-in. Haydite that had been pre-soaked in water for 4 days and natural sand. One mix was in the low-strength and the other in the high-strength series.

A counter-current, Lancaster-type mixer was used. After all materials were added, the constituents were mixed for 2 min., allowed to rest in the mixer for 1 min., then remixed for an additional 2 min. Normally, two mixes were made every alternate day before noon.

Properties of Freshly Mixed Concrete

The characteristic properties of the freshly mixed concrete, i.e., slump, air content, unit weight, and temperatures of concrete and atmosphere for all test mixes are given in Table 3. The air content of the concrete was determined twice by the pressure method using a pressure air meter (ASTM Standard Method C 231) and by the volumetric method using a roll-a-meter (ASTM Standard Method C 173).

The bowl (0.25 cu ft) of the pressure meter was used as a measure to determine the unit weights. Concrete was placed into the measuring container in two layers. Each layer was compacted by inserting a 1 1/8-in.-diameter inter al vibrator for 4 to 6 seconds.

PREPARATION OF TEST SPECIMENS

For the durability study, test beams are required in sizes to fit into cells of the freeze-thaw cabinet. Nine 3½ x 4 x 15¼-in. test beams were cast from each mix in heavy brass moulds. A stainless steel reference plug was cast in each end of the six beam specimens to be used for length measurements in the durability study; three control beams for determinations of flexural strength were left without plugs. The beams were moulded by placing concrete in the moulds in two layers and vibrating them on a vibrating table for 10 and 20 sec for the bottom and top layers, respectively.

As control specimens for the compressive-strength determinations, five 4 x 8-in. test cylinders were made from each batch in heavy steel moulds filled with two layers of concrete and compacted by an internal vibrator.

TABLE 3

Mix Data for Semi-Lightweight Structural Concrete

(coated Haydite as coarse aggregate)

Type of Mix		Mix No.	Mix Proportions, per 1 cu yd of Concrete: Cement, lb	Free Water, lb	Aggregates, SSD: Coarse Ltw, lb	Aggregates, SSD: Fine Nat, lb	Admixtures: AEA,(1) ml	Admixtures: WRDA(2) ml	Characteristics of Freshly Mixed Concrete: Slump, in.	Air, %: Press. Meter	Air, %: Roll-A-Meter	Unit Weight lb/cu ft	Water-Cement ratio	Temperature °F: Concr. Mix temp	Temperature °F: Ambient temp
Series 1 Low Strength	½-in. Haydite	500	402	302	763	1490	4	62	3	6.9	8.5	109.6	0.75	76	71
	¾-in. Haydite	501	407	267	882	1424	4	62	2½	6.9	8.0	110.4	0.66	76	76
	¾-in. Haydite (soaked)	506	409	256	885	1430	3	60	2½	7.0	7.8	110.4	0.63	70	71
Series 2 Medium Strength	½-in. Haydite	502	557	290	763	1490	5	80	2½	6.9	6.5	114.8	0.52	72	74
	¾-in. Haydite	503	544	262	868	1416	4	80	2¼	6.4	7.0	114.4	0.48	72	74
Series 3 High Strength	½-in. Haydite	504	714	292	765	1415	4	100	2½	6.0	5.3	118.0	0.41	70	68
	¾-in. Haydite	505	693	270	834	1357	3	100	2½	5.8	4.3	116.8	0.39	70	66
	¾-in. Haydite (soaked)	507	681	276	840	1333	4	100	2½	6.3	4.5	116.0	0.41	71	71

(1) AEA: Air-entraining agent (Darex)
(2) WRDA: Water-reducing and dispersing agent.

CURING OF TEST SPECIMENS

The test specimens in moulds, covered with glass plates and water-saturated burlap, were left in the mixing room for 24 hr. Then, the specimens were removed from the moulds and transferred immediately to a moist-curing room maintained at standard conditions, (73.4 $\pm$ 3°F and 100% RH), where they were kept for 14 days.

After 14 days of moist-curing all test cylinders were weighed in air and under water for determination of exact volume. Three cylinders were returned to the moist-curing room and two were placed in the drying room (73°F and 50% RH) until the time for determining 28-day strength density under wet and dry conditions.

Three test beams were kept in the moist-curing room until tested for 28-day flexural strength. The other three beams after 14-days of moist curing were transferred into the drying room and allowed to dry for 11 days and then returned to the moist-curing room for 3 days before commencing freeze-thaw cycling at the age of 28 days. The remaining three companion beams were left in the moist-curing room until the end of the freeze-thaw cycling period for use as reference test specimens.

DURABILITY STUDIES

Though the durability of concrete cannot be predetermined directly, prolonged exposure to accelerated cycles of freezing and thawing may produce measurable changes and visible damage on test specimens. These changes and observations can be used for evaluating the relative frost resistance or durability of the concrete under study.

The durability of the concrete made with "coated" Haydite aggregate was assessed by comparing the test results obtained on concrete specimens subjected to freezing and thawing with those obtained on the reference test specimens.

Freezing and Thawing Procedure

After 14 days of initial moist-curing, 11 days of drying and 3 days of soaking, the freeze-thaw test specimens were exposed to repeated cycles of freezing in air and thawing in water according to ASTM Standard Method C666-70. The automatic freeze-thaw unit* used can make 8 cycles per day. One complete cycle, from 40 $\pm$ 3°F to 0 $\pm$ 3°F and back to 40 $\pm$ 3°F, requires about three hours. The freeze-thaw cycling was started on May 25, 1970 and was terminated on November 3, 1970, after an exposure period of 147 days for each set of specimens.

Tests

The following tests were made to evaluate the resistance of the concrete test beams to accelerated cycles of freezing and thawing:

1. Weight determinations
2. Length determinations
3. Pulse-velocity determinations (2)
4. Longitudinal resonant-frequency determinations (3)
5. Flexural-strength determinations of:
    - (a) Test beams after freeze-thaw cycling
    - (b) Reference beams after standard curing
6. Visual examination of test specimens.

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* Manufactured by the Canadian Ice Machine Company Ltd., Toronto, Ontario.

Specimens of both series, the standard-cured and that exposed to freezing and thawing, were weighed, measured, and tested by the non-destructive techniques at the beginning, and after 1000 cyles (Tables 6 and 7). Pulse velocity and longitudinal resonant-frequency measurements were also made after 300 cycles (Table 7). After cycling, the test beams of both groups were tested for flexural strength, using the third-point loading method.

TEST RESULTS

Strength Tests

The 28-day compressive strengths of 4 x 8-in. cylinders, tested in both wet and dry conditions, and the 28-day flexural strengths of 3½ x 4 x 15¼-in. beams, tested wet, are shown for each mix in Table 4.

Also shown are the flexural to compressive strength ratios (Fl./Compr.) for each mix, expressed in per cent.

Including in Table 4 are density values for both wet and dry concrete.

TABLE 4

Concrete Strengths

Type of Concrete		Mix No.	28-d. Compressive Strength, psi		Flexural Strength 28 d. moist curing		Concrete Density, lb/cu ft	
			14 d. moist & 14 d. dry cured; tested dry (1)	28-d. moist cured; tested wet (2)	Tested wet, psi (3)	Fl/Comp Ratio, % (4)	14 d. moist + 14 d. dry-cured; concrete	28 d. stand. moist-cured concrete
Series 1 Low Strength	½-in. Haydite	500	2775	2550	605	23.7	110.01	114.2
	¾-in. Haydite	501	2795	2530	555	21.9	110.01	114.6
	¾-in. Haydite (soaked)	506	3115	2815	630	22.4	111.27	114.4
Series 2 Medium Strength	½-in. Haydite	502	5530	5300	660	12.4	115.92	118.9
	¾-in. Haydite	503	4900	4740	710	15.0	114.63	120.0
Series 3 High Strength	½-in. Haydite	504	6155	5915	835	14.1	117.96	121.2
	¾-in. Haydite	505	5385	5040	820	16.3	117.80	119.3
	¾-in. Haydite (soaked)	507	6085	5370	850	15.8	120.95	122.3

(1) Average of 2 results
(2) Average of 3 results
(3) Average of 3 results
(4) Flexural to compressive strength ratio in per cent.

Durability Test Results

Visual examination of the freeze-thaw test specimens after 1000 cycles of freezing and thawing revealed no signs of deterioration other than a few scattered popouts ranging in diameter from 1/8-in. to 1½-in. and are shown in Figures 1 and 2.

The number of popouts were counted on all the specimens. The numbers of popouts, in each of the three lightweight concrete series, are shown in Table 5.

TABLE 5

Number of Popouts on Freeze-Thaw Beams

(after 1000 Fr/Th cycles)

Concrete Test Series	Number of Popouts			
	Standard Cured		Freeze-Thaw Tests	
	½" Haydite	¾" Haydite	½" Haydite	¾" Haydite
Series 1 Low Strength	Nil	Nil	1	1
Soaked aggr.	-	1	-	9
Series 2 Med. Strength	Nil	Nil	1	1
Series 3 High Strength	2	Nil	2	1
Soaked aggr.	-	1	-	3

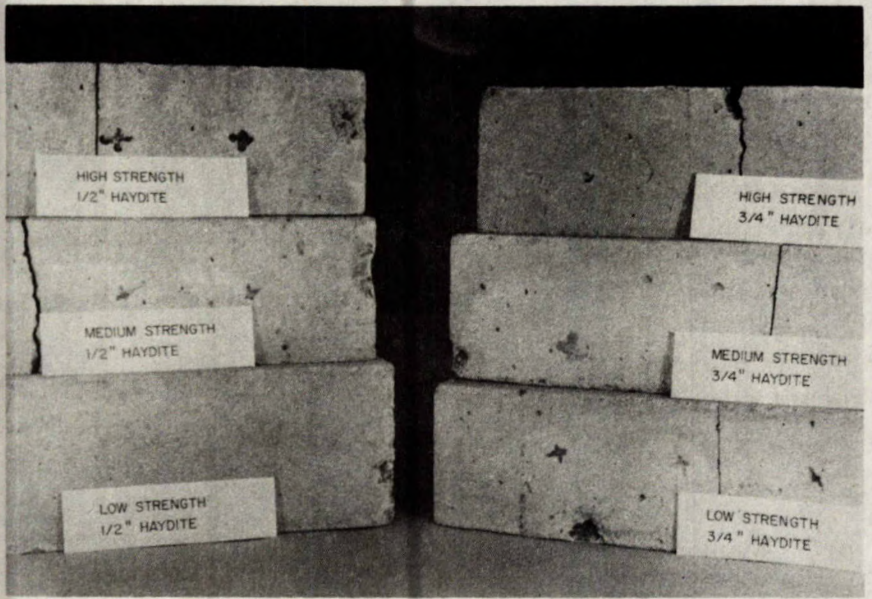

Fig. 1 - Popouts on ½" and ¾" Coated Haydite Concrete.

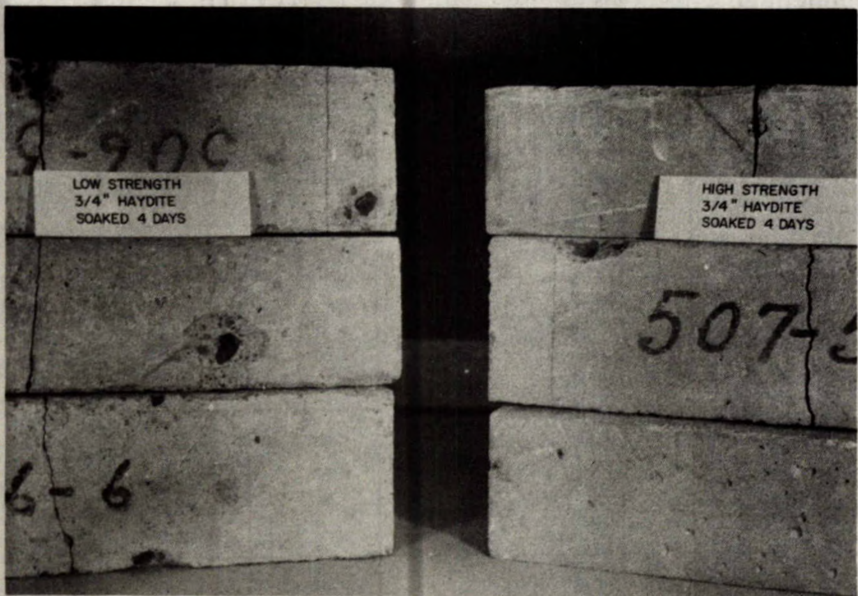

Fig. 2 - Popouts on Haydite Concrete Made With Soaked ¾" Aggregate.

The weight and length determinations on beams were made at the beginning of the test and after 1000 freeze-thaw cycles; the results are shown in Table 6. The table also gives weight and length changes of the standard moist-cured reference test beams during the same period (175 days). For the length-change calculations, a gauge length of 13.6-in., the distance between the inner ends of beams reference plugs, was used.

The values of ultrasonic-pulse velocity "V" and longitudinal resonant frequency "N" measured on the freeze-thaw test beams at the beginning of cycling and after 300 and 1000 cycles are shown in Table 7. Also shown are the "V" and "N" values of the standard moist-cured test beams determined at the beginning (28 days) and at the end (175 days) of the freeze-thaw cycling period.

The changes in these values are expressed as percentages of their initial values.

Flexural strengths of both the freeze-thaw and standard moist-cured beam specimens after completion of the freeze-thaw cycling are shown in Table 8.

TABLE 6

Weight and Length Changes of Beams

Test Series		Weight Change of Beams[1]						Length Change of Beams[1]					
		Standard (moist-cured)			Freeze-Thaw			Standard (moist-cured)			Freeze-Thaw		
								Gauge Readings			Gauge Readings		
Series No.	Mix No.	Weight, 28-day, lb	Weight, 175-day, lb	Weight Change, %	Weight, 0 cycle, lb	Weight, 1000 cycles, lb	Weight Change, %	L_{28}	L_{175}	Length Change, % (2)	L at 0 cycles	L after 1000 cycles	Length Change, % (2)
Series 1 Low Strength	500	14.136	14.188	+0.37	14.008	14.206	+1.41	0.0538	0.0527	-0.008	0.0481	0.0479	-0.001
	501	14.432	14.501	+0.47	14.121	14.121	+1.26	0.0409	0.0399	-0.007	0.0361	0.0358	-0.002
	506	14.493	14.549	+0.39	14.160	14.328	+1.19	0.0808	0.0804	-0.003	0.0661	0.0661	-0.001
Series 2 Medium Strength	502	14.745	14.508	+0.43	14.706	14.774	+0.46	0.0381	0.0380	-0.001	0.0662	0.0657	-0.004
	503	15.041	15.126	+0.57	14.940	15.104	+1.10	0.0370	0.0369	-0.001	0.0596	0.0591	-0.004
Series 3 High Strength	504	15.317	15.380	+0.41	15.206	15.234	+0.18	0.0487	0.0496	+0.007	0.0541	0.0552	+0.008
	505	15.126	15.205	+0.52	14.836	14.884	+0.32	0.0706	0.0718	+0.009	0.0631	0.0644	+0.010
	507	15.081	15.038	-0.28	14.957	14.983	+0.17	0.0657	0.0655	-0.001	0.0616	0.0624	+0.006

(1) Average of measurements on three test specimens.
(2) Gauge length 13.6 in.

TABLE 7

Ultrasonic Pulse Velocities and Longitudinal Frequencies of Beams

Test Series		Ultrasonic Pulse Velocity, fps									Longitudinal Resonant Frequency, cps								
		Standard (moist-cured)			Freeze-Thaw						Standard (moist cured)			Freeze-Thaw					
Series No.	Mix No.	V_{28}	V_{175}	% Change	V_0	V_{300}	% Change 300 c	V_{1000}	% Change 1000 c		N_{28}	N_{175}	% Change	N_0	N_{300}	% Change 300 c	N_{1000}	% Change 1000 c	
Series 1 Low Strength	500	12,850	12,910 14,380	+0.46 +11.9	12,630	12,820	+1.50	12,820	+1.42		4400	4500	+2.27	4320	4390	+1.62	4450	+3.00	
	501	13,140	13,320	+1.36	12,820	12,990	+1.32	12,950	+1.01		4470	4600	+2.90	4440	4530	+2.02	4550	+2.47	
	506	13,100	13,290	+1.45	12,860	12,930	+0.54	12,950	+0.69		4450	4550	+2.24	4400	4460	+1.36	4470	+1.59	
Series 2 Medium Strength	502	13,840	14.040	+1.44	13,700	13,810	+0.80	13,720	+0.14		4770	4860	+1.88	4760	4770	+0.21	4800	+0.84	
	503	13,890	13,860	-0.21	13,650	13,740	+0.65	13,620	-0.21		4760	4880	+2.52	4750	4740	-0.21	4780	+0.63	
Series 3 High Strength	504	14,200	14,440	+1.69	13,970	14,060	+0.64	13,970	0.00		4830	4960	+2.69	4770	4790	+0.41	4830	+1.25	
	505	14,040	14,380	+2.42	13,770	13,950	+1.30	13,870	+0.72		4800	4920	+2.50	2760	4770	+0.21	4810	+1.05	
	507	13,830	13,950	+0.86	13,740	13,720	-0.41	13,610	-0.80		4770	4870	+2.09	4700	4700	0.00	4760	+1.27	

TABLE 8

Flexural Strengths of Test Beams

Test Series	Test Mix No.	Type of Exposure	Flexural Strength		
			At 28-day Age, psi	At 175-day Age	
				psi	%*
Series 1 Low Strength	500	Stand. cured------	605	700	100
		1000 Fr-Th cycles--	-	650	93
	501	Stand. cured------	555	720	100
		1000 Fr-Th cycles--	-	670	93
	506	Stand. cured-------	630	710	100
		1000 Fr-Th cycles--	-	660	93
Series 2 Medium Strength	502	Stand. cured-------	660	900	100
		1000 Fr-Th cycles--	-	800	89
	503	Stand. cured-------	710	950	100
		1000 Fr-Th cycles--	-	930	98
Series 3 High Strength	504	Stand. cured-------	835	910	100
		1000 Fr-Th cycles--	-	780	86
	505	Stand. cured-------	820	830	100
		1000 Fr-Th cycles--	-	800	96
	507	Stand. cured-------	850	830	100
		1000 Fr-Th cycles--	-	770	93

* Strength of freeze-thaw test beams after 1000 cycles as a percentage of the strength of companion standard-cured test beams.

DISCUSSION

Mix Design

The high proportion of natural sand used for concrete mixes in the previous investigation had resulted in excessively high density of the lightweight concrete ranging from about 121 to 125 lb/cu ft when determined in wet condition (see Table 5, Ref. 1).

By reducing the proportion of natural sand in the concrete and using the "coated" Haydite coarse aggregate a lighter concrete was produced, the density of which ranged from about 114 to 121 lb/cu ft when measured wet (or, from 110 to 118 lb/cu ft in the room-dry condition). A weight reduction of about 4 to 7 lb/cu ft of concrete is quite significant, and may be of prime importance for lighter weight concrete.

The mix design used in this investigation is shown graphically in Appendix C. The corresponding amounts of both fine (F.A.) and coarse aggregates (C.A.) and the water can be determined for each cement content ranging from 400 to 700 lb/cu yd of concrete. The weight of aggregates is given in SSD condition and the unit weight is that of freshly mixed concrete.

Strength

The data given in Table 2 indicate that the lightweight aggregate used in this study is more expanded than that used in the previous investigation (see Table 3, Ref. 1). Its bulk specific gravity and unit weight are lower and the crushing strength of the expanded particles is therefore lower too. As the proportion of the weaker component in the concrete mixes has been increased, owing to the reduced amount of natural sand, a slightly lower compressive strength of concrete has to be expected.

The 28-day compressive strength data compiled in Table 4 indicate that about 5 to 10 per cent higher strength values were obtained on test cylinders that were dried after 14 days of initial moist-curing, compared with the standard 28-day moist-cured test specimens.

The flexural strength/compressive strength ratio averaged from about 15% for high-strength concrete to about 22% for low-strength concrete.

Mixes Nos. 506 and 507, in which pre-soaked ¾-in. Haydite was used, showed remarkably higher strengths and higher wet densities than corresponding mixes Nos. 501 and 505, in which the aggregates were not pre-soaked.

The 28-day dry compressive strength curves for both the ½- and ¾-in. concrete show the relationship of strength to cement content. In order to meet the designed compressive strength with a 15 per cent overstrength for three selected concrete strength levels, the required amount of cement per cu yd of concrete is shown in Table 9.

TABLE 9

Cement Requirements for Concrete

Compressive Strength		Cement Requirement lb/cu yd	
Designed psi	Specified psi	½-in mix	¾-in mix
3000	3450	420	425
4000	4600	460	500
5000	5750	590	-

The compressive strength curves in Appendix C show that concrete with higher strength can be produced when smaller aggregate sizes are used. In this investigation, concrete with dry strength of 6155 psi was produced with 714 lb of cement using ½-in. aggregate, whereas only 5385 psi was achieved with 693 lb of cement when ¾-in. aggregate was used.

Durability

No significant damage was sustained by the concrete test specimens after exposure to 1000 cycles of freezing and thawing.

(a) Popouts. The only visible damage observed on the freeze-thaw test beams was spalling and pitting caused by aggregate popouts. They appeared first after 700 cycles and increased in number with continuing freeze-thaw cycling. The final numbers of popouts counted after 1000 cycles of freeze-thaw exposure in each test series are given in Table 5 and are shown in photographs Figs. 1 and 2. They indicate that most of the popouts were produced by the pre-soaked ¾-in. aggregate particles located near the concrete surfaces. Petrographic examination of these particles did not reveal any unsound material. It seems most likely that the spalling was caused by the expansion of freezing water trapped in the more permeable and highly porous aggregate particles.

A mineralogical report of November 5, 1970, on probable causes of local spalling and aggregate popouts has been prepared by Dr. J.A. Soles and is attached to this report as Appendix D.

(b) Weight Change. The measured weight changes of test beams compiled in Table 5 indicate no losses in weight after exposure to freeze-thaw cycling. On the contrary, there was a gain in weight due to absorption, averaging more than 1% for freeze-thaw specimens and about 0.4% for standard moist-cured test beams. As a result of popouts the gain in weight for freeze-thaw test specimens was reduced for test specimens No. 504 and 507 to 0.18 and 0.17%, respectively.

It is interesting to note that the absorption of standard moist-cured beams was, on the average, less than half of that measured on beams after undergoing freezing and thawing.

(c) Length Change. The results compiled in Table 5 show that, after exposure to 1000 cycles of freezing and thawing, most test beams shrank and only test specimens in the 3rd series developed some expansion ranging from 0.006 to 0.010%. This is well below the generally accepted maximum expansion limit of 0.10% for durable concrete (4). The expansion of standard moist-cured expansion test specimens during the same period was of about the same order. This may indicate that the expansion was merely due to absorption by Haydite, not because of detrimental expansion of unsound aggregate.

(d) Non-Destructive Testing. The test results shown in Table 6 indicate that both the ultrasonic pulse velocity and the longitudinal resonant-frequency measurements increased during the standard moist-curing as well as during exposure to freeze-thaw cycling, for concrete of all strength levels. Percentage gains after 300 and 1000 cycles of exposure, as calculated from the initial values, are summarized in Table 10.

Gains in pulse velocity were significantly larger for the standard-cured beams than for the corresponding freeze-thaw test specimens, in which pulse velocity first increased up to 300 cycles and then decreased during further exposure of up to 1000 cycles of freezing and thawing. Losses in pulse velocity were recorded in freeze-thaw test specimens Nos. 503 and 507.

Gains in resonant frequency, on the average, were significantly larger for standard-cured than for freeze-thaw test specimens. No retrogression in resonant frequency occurred during prolonged exposure from 300 to 1000 cycles. Either there was no deterioration of the concrete, or it was of such insignificant magnitude that it was not detectable by the equipment used.

Durability of concrete test specimens after exposure to freeze-thaw cycling may be expressed by the durability factor DF, which is equal to the relative dynamic modulus of elasticity P if it has not decreased to the specified minimum value within the specified number of cycles at which the exposure is to be terminated (60% of the initial modulus after 300 cycles).

The relative dynamic modulus P is calculated using the following formula: $P_c = \frac{N_c^2}{N_o^2} \times 100$ - - - (2), where:

P_c = relative dynamic modulus of elasticity, per cent, after c cycles of freezing and thawing,

N_o = fundamental longitudinal frequency at 0 cycles of freezing and thawing, and

N_c = fundamental longitudinal frequency at c cycles of freezing and thawing.

TABLE 10

Summary of Non-Destructive Test Results

Test Series	Mix No.	Test Beams	Ultrasonic Pulse Velocity Percentage Gain		Resonant Frequency (longitudinal) Percentage Gain		Relative Dynamic Modulus of Elastic P % = DF	
			300 cyc	1000 cyc	300 cyc	1000 cyc	300 cyc	1000 cyc
Series 1 Low Strength	500	Std	-	11.9	-	2.27	-	105
		Fr-Th	1.50	1.42	1.62	3.00	103	106
	501	Std	-	1.36	-	2.90	-	106
		Fr-Th	1.32	1.01	2.02	2.47	104	105
	506	Std	-	1.45	-	2.24	-	105
		Fr-Th	0.54	0.69	1.36	1.59	103	103
Series 2 Medium Strength	502	Std	-	1.44	-	1.88	-	104
		Fr-Th	0.80	0.14	0.21	0.84	101	102
	503	Std	-	-0.21	-	2.52	-	105
		Fr-Th	0.65	-0.21	-0.21	0.63	100	101
Series 3 High Strength	504	Std	-	1.69	-	2.69	-	105
		Fr-Th	0.64	0.00	0.41	1.25	101	103
	505	Std	-	2.42	-	2.50	-	105
		Fr-Th	1.30	0.72	0.21	1.05	101	102
	507	Std	-	0.86	-	2.09	-	104
		Fr-Th	-0.41	-0.80	0.00	1.27	100	103

In evaluation of the P or DF values it must be borne in mind that the weight increase of test specimens due to absorption will contribute to the increase of resonant frequency readings, thus perhaps overshadow any small deterioration effects in concrete.

The summary of non-destructive test results compiled in Table 10 shows that the relative dynamic modulus of elasticity P, which in this case is equal to the durability factor DF, in all test series is over 100%.

This indicates that the lightweight concrete under investigation will meet the requirements for a durable concrete.

(e) Flexural Strength. The results of flexural strength tests shown in Table 8 indicate that for Series 1 and 2, the final strengths of both the freeze-thaw and reference beams exceeded the strength of the reference beams at 28 days. However, the reference beams gained more strength than did the freeze-thaw specimens.

In Series 3, the high-strength mixes, the freeze-thaw beams all showed flexural strengths that were lower than the initial 28-day flexural strengths. No definite explanation of this phenomenon can be given by the authors. The only tangible factor common to these three mixes is the very high cement content (700 lb/cu yd) which may have caused microcracking of the concrete due to initial paste shrinkage. It is evident from the compressive strength graphs in Appendix C that the above proportion of cement is close to the saturation point, above which additional cement would not increase the strength of the concrete, particularly of the ¾-in. mixes.

CONCLUSIONS

Semi-lightweight, air-entrained concrete made with Haydite coated coarse aggregate showed excellent frost resistance. This is confirmed by the increase of the relative dynamic modulus of elasticity and general increase in flexural strength of freeze-thaw beam specimens after 1000 cycles of exposure.

This investigation has shown that, despite some scattered popouts, the coated Haydite aggregate is suitable for use in air-entrained structural concrete exposed to severe weathering conditions.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the assistance of Dr. J.A. Soles, who provided advice on the mineralogy of the aggregate particles causing popouts, and the co-operation of Mr. F.E. Hanes who provided the photographs for this investigation.

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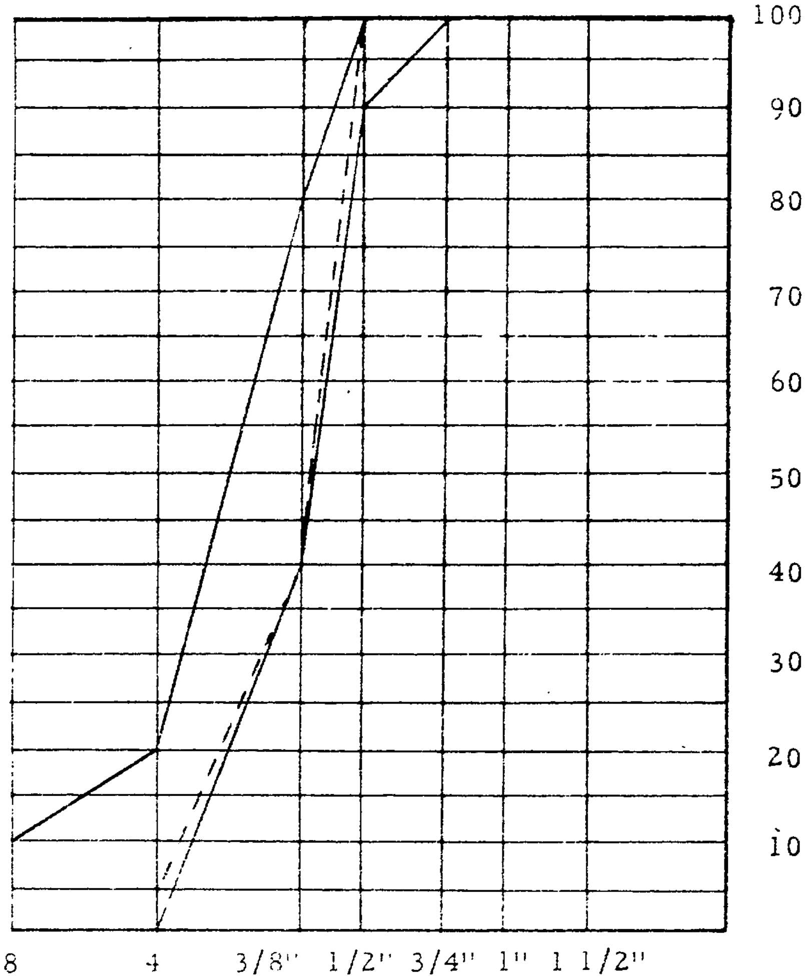
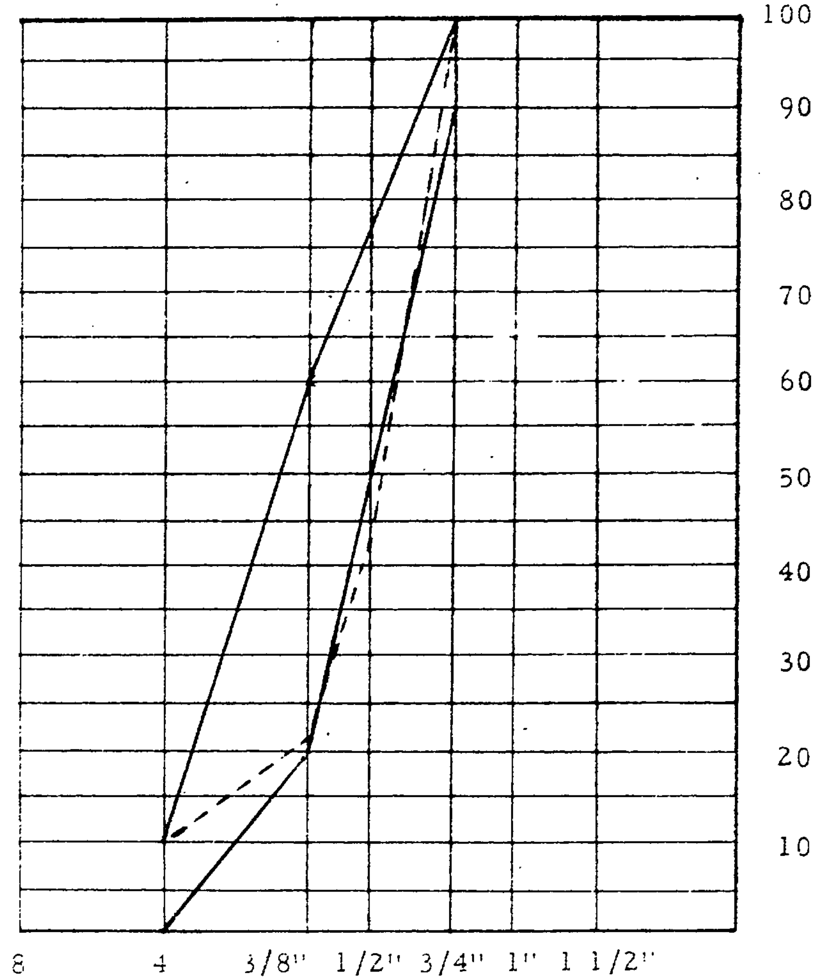
APPENDIX A



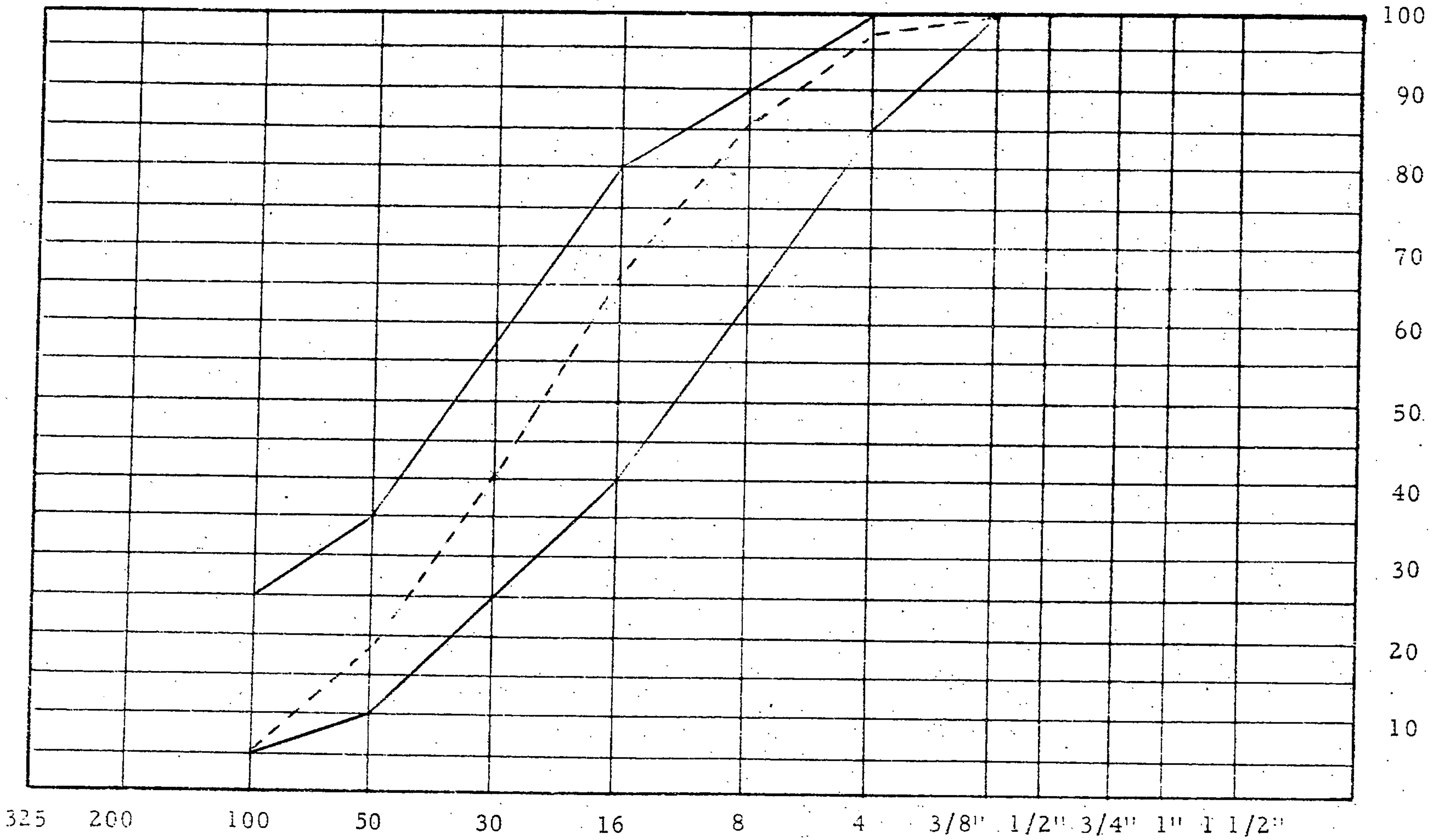
½-in. Haydite



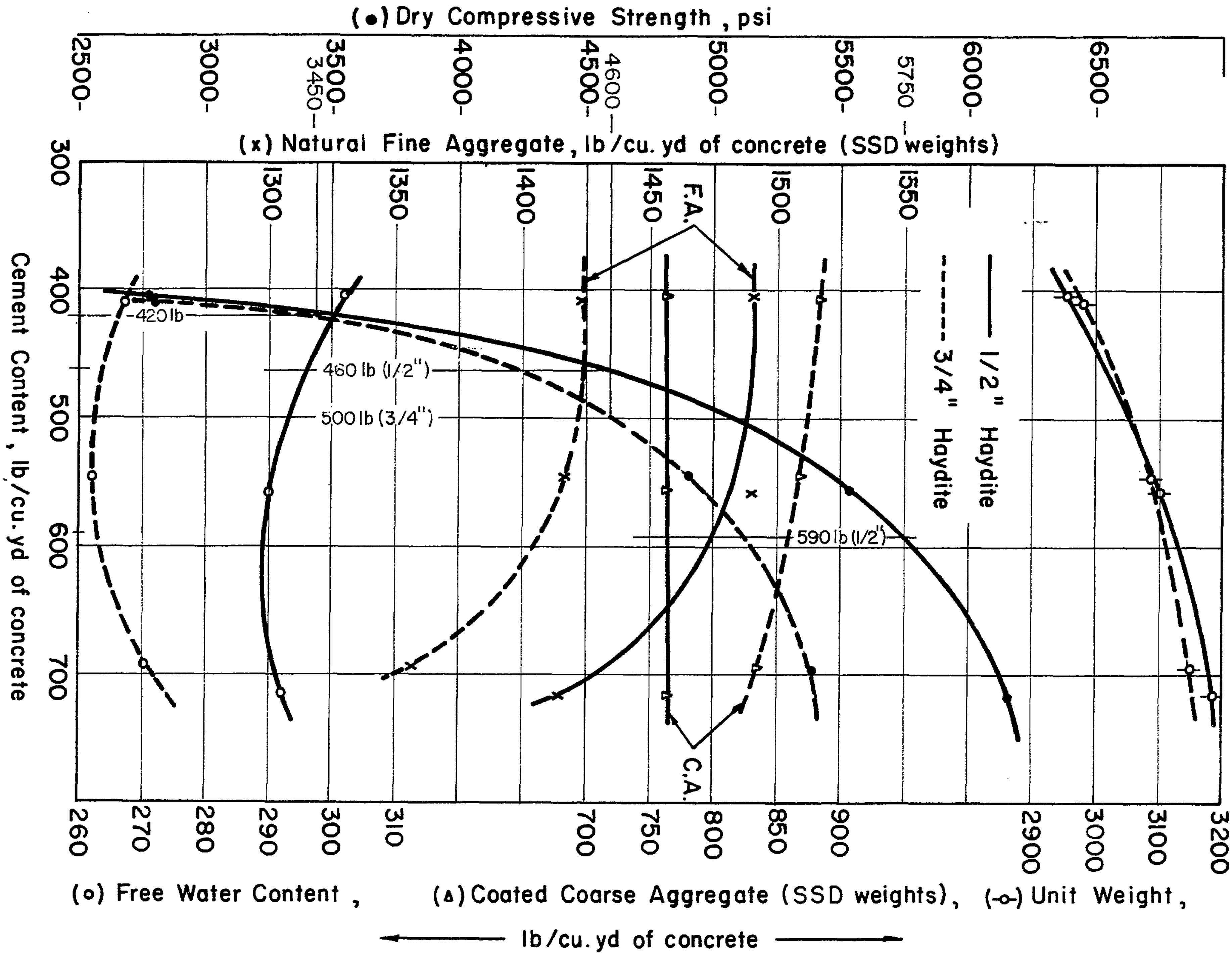
¾-in. Haydite

Gradings of Coarse Aggregates and ASTM Limits (per cent by weight passing).

APPENDIX B



Grading of Natural Sand and ASTM Limits
(Per cent by weight passing)



Mix Proportions and Concrete Strength.

MINERAL PROCESSING DIVISION

Mineralogical Report

Submitted by: H.S. Wilson, M.P.D.

Description and Source of Specimen: Concrete test beams which had been subjected to 1000 F-T cycles. Domtar 'Haydite' aggregate, pre-soaked for 4 days.

Information Requested: Cause of local spalling

Procedure and Results: Several beams were examined under stereomicroscope.

Large aggregate particles on ruptured sections were mostly dark grey to locally brownish, vesicular, partly vitrified, and dense to highly porous. Most were deeply crevassed and intruded by the surrounding cement matrix. A few smaller particles, light brown in color, were apparently poorly bloated; they contain carbonate and unvitrified silicate minerals.

Spalling occurred only where coarse aggregate particles were imbedded on corners or near the concrete surface. With one exception, the particles had coarsely vesicular, vitrified centers; the exception was a light brown, ferriferous, apparently poorly bloated particle containing carbonate.

Excepting the latter type of particle, the aggregate was vitrified and therefore probably inert. It seems most likely that the spalling was caused by the freezing of water trapped in the more permeable and highly porous aggregate particles. The fact that more popouts occurred with aggregate which had been soaked longer would support this suggestion. The features of disintegrated aggregate particles are little different from those described earlier in Investigation Report IR-70-16.

Mineralogist: [signature]
J.A. Soles

Date: Nov. 5/70

Sample No. CM-449