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INVESTIGATION OF SHALE FROM THE VICINITY OF OTTAWA, ONTARIO, AS LIGHTWEIGHT CONCRETE AGGREGATE

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MINERAL PROCESSING DIVISION

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SUMMARY OF RESULTS

Two types of expanded shale aggregate were produced in pilot plant tests: product "A" was bloated at a temperature ranging from 1930 to 1960°F and weighed 45 lb/cu ft; product "B" was bloated in the range 2030 to 2050°F and weighed 39 lb/cu ft.

Structural lightweight concrete was produced with aggregate "A" and natural sand. The concrete ranged in weight from 106.7 to 115 lb/cu ft, in compressive strength from 2231 to 5247 psi and in flexural strength from 457 to 829 psi.

Lightweight masonry concrete was produced with all-shale aggregate "B". It ranged in weight from 76.4 to 85.3 lb/cu ft, in compressive strength from 616 to 2235 psi and in flexural strength from 247 to 477 psi.

Absorption of the masonry concrete ranged from 10 to 13 lb of water per cu ft of concrete, which is about double that of the structural concrete.

The 84-day drying shrinkage of the masonry concrete was about 25% higher than the 525μ in./in. shrinkage of the structural concrete, which in turn was 15-20% higher than similarly cured, conventional crushed limestone concrete.

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INTRODUCTION

A shale sample of approximately 1000 pounds was submitted by L. Sipolins Ltd., Ottawa, Ont., for evaluation as raw material for the production of lightweight concrete aggregate.

The sample was reported to be from Lot 3, Concession 5 (R.F.), 3000 feet west of the eastern boundary (Hawthorne Road), in the city of Ottawa. An area of considerable size, extending in a south-easterly direction from the eastern edge of the city, is underlain by shale of the Carlsbad formation. It is presumed that the sample was taken from this formation.

PURPOSE AND SCOPE OF THE INVESTIGATION

In the first part of this investigation, the possibility of producing lightweight aggregate from the shale submitted was determined. Small scale bloating tests and pilot plant rotary kiln tests were used and the physical properties of the aggregates were determined.

In the second part of the investigation, one of the two aggregates produced in the pilot plant tests was used to prepare lightweight structural concrete. The physical and structural properties of this concrete were then studied.

In the third part, the properties of lightweight masonry concrete were investigated using the other aggregate produced in the pilot plant tests. Tests were conducted on masonry concrete which was cured under similar conditions to the structural concrete. No attempt was made to apply either the low-or high-pressure steam curing procedures normally used for accelerated curing in concrete block plants.

PART I

LIGHTWEIGHT CONCRETE AGGREGATE

PREPARATION OF SHALE TEST SAMPLE

The submitted shale, minus 6 inch in size, was passed through a Pennsylvania impact crusher, which reduced it to about minus 3/4 inch in size. The product was separated by a double-deck Rotex screen into + 3/4 in., - 3/4 in. + No. 8 mesh, and - No. 8 mesh size fractions. The + 3/4 inch material was recirculated through the crusher until it all passed the 3/4 in. screen. The - 3/4 in. + No. 8 mesh fraction was retained for testing, and the - No. 8 mesh fraction was discarded. It was found that drying of the sized material was necessary to prevent decrepitation in the kilns.

PRELIMINARY BLOATING TESTS

About 5 pounds of the dried shale was tested in a 5 inch by 5 foot propane-fired rotary kiln, to obtain information on the bloating-temperature range and the approximate physical properties to be expected from a pilot-plant product. The inclination and rotational speed of the kiln were adjusted to result in a retention time of 6 to 7 minutes. The volume expansion of the shale was measured.

The bloated product was crushed and graded as follows:

75% minus 3/8 in. plus No. 4 mesh

25% minus 4 plus No. 8 mesh

The loose dry unit weight and the crushing strength were measured on the combined fractions.

The unit weight was measured in a 1/30 cubic foot metal container using the shovelling procedure outlined in ASTM standard C29-60. The crushing strength was obtained as two figures, that is, the pressures required to compact the graded aggregate 1 and 2 inches when placed to a depth of 5 inches in a 3 inch diameter cylinder. The firing temperatures and results are shown in Table 1.

TABLE 1

Preliminary Test Results

Temperature, °F	Volume expansion, per cent	Unit weight, lb/cu ft	Crushing strength, psi	
			1"	2"
1960-2050	80	46.3	640	2790

PILOT PLANT TESTS

Two tests were made in a 12 inch by 12 foot natural gas-fired rotary kiln. The firing conditions were adjusted to effect minimum as well as maximum bloating below the agglomerating temperature. Parts of the two products were crushed and graded as in the preliminary test. The unit weights and crushing strengths were measured. The test conditions and results are shown in Table 2.

TABLE 2

Pilot Plant Test Results

Test	Temperature, °F	Retention time, min	Unit weight, lb/cu ft	Crushing strength, psi	
				1"	2"
A	1930-1960	20	49.6	810	4150
B	2030-2050	20	38.4	620	1960

DISCUSSION OF RESULTS

The results of the preliminary and pilot plant tests indicate that this shale will bloat in these kilns through a temperature range of approximately 100 degrees, below the temperature at which agglomeration commences. The degree of bloating was greater at the upper end of the range than at the lower. The unit weights of all products graded within coarse aggregate limits were below the ASTM maximum of 55 lb/cu ft. The crushing strength of the aggregate produced in Test A is higher than that of some commercially produced aggregates, while that of the product from Test B was lower.

PREPARATION OF CONCRETE AGGREGATE

The two expanded shale materials produced in the pilot plant were crushed to meet the specified grading limits of coarse aggregate for lightweight structural and masonry concretes. The loose dry unit weights were obtained by the shovelling procedure outlined in ASTM standard C29-60.

Product "A", which was bloated to a lesser degree, weighed 45 pounds per cu ft when it was crushed to - 1 in. + No. 8 mesh size. This material was designed for use as coarse aggregate, together with natural sand as fine aggregate, in lightweight structural concrete.

Product "B", which was bloated to a higher degree, weighed 39 pounds per cu ft when crushed to - 3/4 in. + No. 8 mesh size. This material was designed for use in masonry concrete as coarse aggregate; the fine aggregate was the same material crushed to sand sizes and graded accordingly.

The gradings of both types of coarse aggregates are shown in Table 3, in comparison with the grading limits specified by the applicable ASTM standards.

TABLE 3

Grading of Expanded Shale Aggregate

Sieve Sizes	Coarse Aggregate, Per Cent Passing			
	For Structural Concrete		For Masonry Units	
	Product A	ASTM C330-60T	Product B	ASTM C331-59T
1 in.	100	100	-	-
3/4 in.	96	90-100	100	100
1/2 in.	70	-	91	90-100
3/8 in.	50	20-60	60	40-80
No. 4 mesh	20	0-10	40	0-20
No. 8 mesh	0	-	13	0-10

PART II

STRUCTURAL LIGHTWEIGHT CONCRETE

The prime considerations in producing lightweight concrete are structural strength and lightness in weight. A minimum 28-day compressive strength of 2000 psi and an air-dry unit weight of less than 115 lb/cu ft of hardened concrete are specified by the ASTM Standard Specification C330-60T.

AGGREGATES

To produce a high-strength, lightweight concrete, test mixes for structural concrete were made with lightweight coarse and natural sand fine aggregates. The natural sand, in place of lightweight fines, improved considerably the workability of the test mixes. The gradings of lightweight coarse aggregate "A", from minus 1 in. to plus No. 8 mesh size, and normal graded concrete sand of minus No. 4 mesh size, are shown in Table 4. Also shown in Table 4 are values of specific gravity and absorption.

A well graded combined fine and coarse aggregate will have a minimum void content and will require a minimum amount of cement paste to fill these voids. This will result in the most economical use of cement and will provide maximum strength with minimum volume change due to drying shrinkage.

TABLE 4

Grading of Combined Aggregate

Type of Aggregate	Sieve Sizes	Gradings, Separate Aggregate, % Passing	Grading Fractions, Separate Aggregate, % Retained	Grading Fractions, Combined Aggregate, % Retained	Gradings, Combined Aggregate, % Passing
				(F.A./C.A. = 68/32)	
Coarse Aggregate "A"	1 in.	100.0			100.0
(Expanded Shale)	3/4 in.	96.0	4.0	1.3	98.7
Average	1/2 in.	70.0	26.0	8.3	90.4
Spec.Grav.-1.35	3/8 in.	50.0	20.0	6.4	84.0
Absorption -8.0%	No. 4 M	20.0	30.0	9.6	74.4
	Pan		20.0	6.4	
	No. 4 M	100.0			
Fine Aggregate	No. 8 M	90.0	10.0	6.8	61.2
(Natural Sand)	No.16M	67.5	22.5	15.3	45.9
Average	No.30M	42.5	25.0	17.0	28.9
Spec.Grav.-2.64	No.50M	20.0	22.5	15.3	13.6
Absorption -1.2%	No.100M	6.0	14.0	9.5	4.1
	Pan		6.0	4.1	
				100.0	

Note: grading percentages by weight.

PROPORTIONS OF FINE AND COARSE AGGREGATE

To produce a workable mix and a dense structural concrete the proportion of fine aggregate should be between 40 and 60 per cent of the total aggregate, based on dry loose volume (I).

As the specific gravities of the coarse and fine aggregates differ greatly (see Table 4) it is the volume occupied by each material and size fraction, and not the weight, that determines the correct proportions of both aggregates in concrete mixes.

Assuming the ratio of fine to coarse aggregate by volume to be F.A./C.A. = 50/50, the ratio by weight can be calculated, using the values of specific gravity and absorption of both materials (see Table 4). The computed value of the above ratio by weight for the room-dry materials will be F.A./C.A. = 68/32.

Fine and coarse aggregate prepared for the investigation and blended in this proportion by weight will result in a satisfactory combined grading, as shown in the last column of Table 4. To assure uniform grading in all test mixes the produced coarse and fine aggregate were separated into size fractions and recombined according to the gradings shown in Table 4.

DESIGN OF MIXES FOR STRUCTURAL CONCRETE

Test mixes were designed with cement factors ranging from 5 to 9 bags of cement per cubic yard of concrete, and a slump of 2 ± 1/2 inch. The quantity of coarse aggregate in all mixes was maintained constant.

The mix design procedure based on the absolute volume method, can be used in lightweight aggregate concrete mixes only with certain reservations. The difficulties involved in obtaining accurate values for specific gravity and absorption of the aggregate necessitated preparation of actual trial mixes to establish the unit weight of fresh concrete and the water requirement for these mixes.

The correct ratio of fine to coarse aggregate in each mix was adjusted when the test mixes were prepared. The amount of fine aggregate was kept as low as possible while still providing a margin of safety for good workability. This resulted in decreasing the volume of fine aggregate in mixes from 46% in the 5.4 bag mix to 41% in the 9 bag mix (see Table 5).

Air entrainment was used to improve the workability of concrete and to decrease the bleeding of the mixture. Although the durability of lightweight aggregate concrete has been considered to be very good even without air entrainment, the addition of entrained air is recommended [1].

An air-entraining admixture (A.E.A. Darex) was used in all test mixes in amounts required to produce 5.5 $\pm$ 0.5 per cent entrained air. In addition a cement dispersing agent (D.A.-Pozzolith) was added to one series of test mixes.

PREPARATION OF TEST MIXES

In Test Series 1 three mixes (Nos. 183, 185 and 186) were prepared containing 5.4, 7 and 9 bags of cement respectively; Test Series 2 consisted of two mixes (Nos. 184 and 187) containing 5.5 and 9 bags of cement, respectively, per cu yd of concrete.

The weighed coarse aggregate was pre-soaked in water overnight and drained for one hour before mixing. The fine aggregate was wetted sufficiently but not soaked. The weight of water contained in each aggregate portion was determined before mixing was started. The balance of the total water required was added after all components of the mixture were placed in the mixer.

After mixing for two minutes, the mixer was allowed to rest for two minutes, then mixing was continued for an additional two minutes. During the time of rest the mixture was checked, and water was adjusted as needed to obtain a two-inch slump.

When mixing was completed the slump was measured, and the unit weight of the plastic concrete mixture was determined, using the air meter bowl as the volume measure.

The amount of entrained air was determined by the volumetric method described in ASTM C 173-55T, using a Roll-A-Meter* apparatus.

*Roll-A-Meter is manufactured by Concrete Specialties Company of Spokane and is distributed by the Charles R. Watts Company, Seattle, Wash.

The mix proportions and characteristics of the fresh concrete are compiled in Table 5.

The column "free water" shows that no water reduction resulted in concrete mixes of the second series (Mixes No. 4 and 5), although in these a lignosulfonate admixture, which is a water reducer, was used and a denser concrete was obtained.

MOULDING AND CURING OF TEST SPECIMENS

Nine 4 x 8 in. test cylinders and six 3 1/2 x 4 x 16 in. test beams were moulded from each test mix and tested at the age of 28 and 90 days. Also one 6 x 12 in. test cylinder was prepared from each of mixes Nos. 185 and 186 for determination of the static modules of elasticity E.

Test specimens were moulded and cured for 7 days in standard moist conditions in accordance with ASTM Standard Method C 330-60, and then were placed in a dry-storage room at a temperature of 75 $\pm$ 5°F and a relative humidity of 38 $\pm$ 4 per cent, until tested.

Specimens were pre-soaked 24 hours before testing and were crushed in a saturated surface-dry condition. The wet-testing, following dry-curing, tended to eliminate surface tension stresses caused by dry-curing of beam and cylinder test specimens.

TABLE 5

Structural Lightweight Concrete Mix Data

Mix No.	Test No.	Mix Proportions per 1 cu yd of Concrete: Cement, pounds (bags)[a]	SSD Aggregate[e]: Fine (natural), lb	SSD Aggregate[e]: Coarse (lightweight), lb	Free Water, lb	Admixtures: AEA[b], oz	Admixtures: DA[c], lb	Mix Characteristics: Slump, in.	Air, %	Unit Weight, lb per cu ft
				Test Series 1						
1	183	470 (5.4)	1393 (46%)	837 (54%)	300	2.0	-	2.0	6.0	111.1
2	185	615 (7.0)	1310 (45%)	838 (55%)	302	2.8	-	2.0	5.5	113.5
3	186	784 (9.0)	1126 (41%)	839 (59%)	308	3.6	-	3.0	5.0	113.2
				Test Series 2						
4	184	477 (5.5)	1420 (46%)	842 (54%)	306	1.0	1 1/4	2.0	5.0	112.7
5	187	789 (9.0)	1162 (42%)	844 (58%)	310	1.2	2 1/4	2.0	4.5	115.0

Note: a - Canadian bag of cement = 87 1/2 lb
b - Air-Entraining-Agent (Darex, double-strength)
c - Cement Dispensing Agent (Pozzolith)
d - Aggregate proportions in per cent by volume
e - Saturated surface dry aggregate

PROPERTIES OF STRUCTURAL LIGHTWEIGHT CONCRETE

The physical properties of structural lightweight concrete were investigated to provide data for design purposes. The following properties of hardened concrete were studied at different ages in both test series:

1. Unit weight and absorption
2. Loss of moisture and drying shrinkage
3. Compressive and flexural strengths
4. Modulus of elasticity

Unit Weight and Absorption

Determinations of unit weight and absorption were made in accordance with the Standard Methods of Testing for Concrete-Making Properties, as specified by ASTM Designation C 330-60T, para 8.

Unit weights of hardened concrete were determined on beam specimens at the following ages:

(a) 1 day - as removed from the forms;

(b) 7 days - after 6 days of moist-curing, in saturated, surface-dry condition (SSD);

(c) 28 days - after 21 days of dry-curing, which followed the initial 6-day moist-curing

The volumetric data for unit weight calculations were obtained for each beam after 6 days of moist curing, from the SSD weight in air and from the immersed weight in water. Unit weight per cubic foot of concrete, as cured, was calculated in accordance with the following formula:

$$\text{Wt (per cu ft)} = \frac{A \times 62.4}{B - C}$$

where:

A = weight of concrete beam, as cured,

B = SSD weight of beam in air,

C = immersed weight of beam

Absorption was determined on 3 test cylinders (4 x 8 in.) of each type of concrete at 28 days' age. The dry cured cylinders were immersed in tap water for 24 hr. After the immersed weight and SSD weight of test specimens was obtained, the saturated cylinders were dried in an oven at 212 to 248°F and weighed at 24-hr intervals until the loss in weight did not exceed 1 per cent in a 24-hr period. Absorption was calculated in percentage by volume as follows:

$$\text{Absorption (\% by volume)} = \frac{B - D}{B - C} \times 100$$

where:

B = SSD weight of concrete cylinder,

C = immersed weight of cylinder,

D = weight of dried cylinder

Unit weights of the hardened concrete and of the corresponding fresh concrete mixture in the plastic state are shown in Table 6. Also shown are absorption values of the hardened concrete, after dry curing at 28 days' age, in per cent by volume and by weight.

TABLE 6

Unit Weights and Absorptions

Mix No.	Test No.	Unit Weights, lb/cu ft Plastic Concrete	1d Hardened	7d SSD	28d R-Dry	Absorption of concrete, per cent by wt.	by vol.
			Test Series 1				
1	183	111.1	112.2	113.0	106.7	8.0	14.4
2	185	113.5	114.8	115.8	112.5	7.8	14.2
3	186	113.2	113.8	115.0	112.2	7.9	14.3
			Test Series 2				
4	184	112.7	113.1	114.4	109.2	7.4	13.3
5	187	115.0	117.0	117.5	115.0	7.1	13.2

The results show that the freshly hardened concrete has a higher unit weight than the concrete mixture in the plastic state. This is characteristic of all air-entrained concretes, as rodding in the moulds expels air and reduces the volume by 1/2 to 1 per cent.

Addition of a water-reducing and cement-dispersing agent in the second series of mixes, Nos. 184 and 187, produced denser concrete, the unit weight of which was 1/2 to 2 per cent higher than that of the freshly mixed plastic concrete.

During the initial six days of standard moist-curing, concrete specimens absorbed additional moisture in amounts from 0.5 to 1.2 lb/cu ft, depending on the absorption characteristics of the moist-cured concrete.

Absorption tests on the dry-cured concrete cylinders produced results shown in Table 6. These results are in close agreement with data obtained by J.J. Shideler on lightweight structural concrete made with expanded shale aggregate produced in a rotary kiln (2).

Concrete test specimens of Series 1 show about 1 per cent higher absorption than corresponding specimens of Series 2.

Loss of Moisture and Drying Shrinkage

After the initial 6 days of moist-curing, test specimens were placed in a dry-curing room having a relative humidity of 38 ± 4 per cent and a temperature of 75 ± 5°F.

Beam specimens were used to study the effect of drying on the properties of concrete. Stainless steel reference plugs were provided on each end of the test beams for length measurements.

Test specimens exposed to prolonged drying in the storage room were weighed and measured for length changes once a week. Weighing was done with a accuracy of ± 0.001 lb. Length measurements of beams were made using a 16-in. length-change comparator, which was designed and built at the Mines Branch. The Ames dial gauge used with this instrument reads directly to 0.0001 inch.

The average values of moisture losses and shrinkage of dried beam specimens at 28, 56, and 84 days' age, are compiled in Table 7. The test results of two corresponding mixes of each series are shown: Nos. 183 and 186 of the first series (with A.E.A. only), and Nos. 184 and 187 of the second series (in which A.E.A. and D.A. was used).

TABLE 7

Loss of Moisture and Drying Shrinkage

Test No.	Cement Factor bg/cu yd	Loss of Moisture % by wt.			Drying Shrinkage μ in. /in.		
		28d	56d	84d	28d	56d	84d
		Test Series 1					
183	5.4	5.73	7.05	7.52	175	385	525
186	9.0	2.51	3.55	4.02	210	435	580
		Test Series 2					
184	5.5	4.46	5.62	6.07	240	480	630
187	9.0	2.05	2.82	3.37	282	518	643

The average drying shrinkage of beam specimens at the age of 84 days in Series 1 was 525 μ in. /in. for the 5.4-bag mix and 580 μ in. /in. for the 9.0-bag mix concrete. These results are lower than drying shrinkage results (625 μ in. /in.) given by Shideler [(2)] on similar concrete made with an all-lightweight aggregate produced from shale in a rotary kiln. The lower shrinkage of this concrete might be attributed to the use of natural sand as fine aggregate.

Test beams made with crushed limestone coarse aggregate and natural sand, and stored under the same drying conditions, showed an average shrinkage of 415 μ in. /in.

Drying shrinkage of lightweight concrete in this study, expressed as a per cent of the shrinkage of crushed limestone concrete, is 126 per cent, which is about normal for this type of concrete.

The drying shrinkage of test beams in the 84-day tests of Series 2 was 630 μ in. /in. for the 5.5-bag mix and 643 μ in. /in. for the 9.0-bag mix; this is 20 and 11 per cent larger than the shrinkage of corresponding test specimens in Series 1. The use of a lignosulfonate admixture, containing a certain amount of calcium chloride increased the drying shrinkage particularly at the earlier ages of concrete hardening. At 28 days of age this increase was 37 and 34 per cent in corresponding test specimens of Series 1 and 2.

In general, the drying shrinkage of this lightweight concrete is well below the limit specified by the ASTM Designation C 330-60T, which is 0.10 per cent (or 1000 μ in. /in.) after 100 days of storage at a temperature of 73.4 $\pm$ 2°F and a relative humidity of 50 $\pm$ 2 per cent.

Compressive and Flexural Strengths

The most important property of structural concrete is strength. A minimum 28-day compressive strength of 2000 psi is specified by the ASTM C 330-60T for the structural lightweight concrete.

After initial 6-day moist-curing the test cylinders and beams were dry-cured and tested for compressive and flexural strengths at ages of 28 and 90 days. Before crushing all test specimens were soaked in tap water for 24 hours.

Cylinders were capped with sulphur capping compound and broken in an Amsler compression machine of 600,000-lb capacity. Beams were tested in a Tinius Olsen compression testing machine of a lever-weighing type using the third-point loading attachment (ASTM Standard Method C 78-57).

Three cylinders (4 x 8 in.) were used for compressive strength and three beams (3 1/2 x 4 x 16 in.) for flexural strength determinations of each type of concrete at both test ages.

TABLE 8

Structural Lightweight Concrete Strength Test Results

Test No.	Cement Factor, bg/cu yd	Type of Admixt.	Room-Dry Unit Wt lb/cu ft	Compressive Strength psi		Flexural Strength psi			
				28d	90d	28d	% of Comp. St.	90d	% of Comp. St.
Test Series 1									
183	5.4	A.E.A.	106.7	2231	2180	457	20.5	421	18.9
185	7.0	A.E.A.	112.5	3803	3807	676	17.8	732	19.2
186	9.0	A.E.A.	112.2	4623	4322	734	15.9	762	16.5
Test Series 2									
184	5.5	A.E.A. and D.A.	109.2	3247	2642	524	16.1	430	13.2
187	9.0	A.E.A. and D.A.	115.0	5247	4685	829	15.8	692	13.2

Note: Abbreviations for admixtures are: - A.E.A. for air-entraining agent
- D.A. for cement dispersing agent

The average values of each set of three test results are compiled in Table 8. Photographs of broken test beams and crushed cylinders are shown in Figures 1 and 2.

The 28-day test results indicate that the strength of all test specimens in Series 2 was about 12 to 15 per cent higher than the strength of the corresponding test specimens in Series 1. Addition of cement dispersing agent to concrete mixes in Series 2 obviously has boosted the strength of the hardened concrete.

The fact that 90-day strength in most instances was lower than the 28-day strength is rather unusual in concrete technology. Prolonged drying evidently had an adverse effect on the strength of the concrete. Shideler reported (2) that concrete made with lightweight aggregate, and air-dried in a relative humidity of 50 per cent, normally gained strength up to age of 90 days. A slight decrease in strength was observed at later ages.

The results of our tests (Table 8) indicate that the strength of lightweight concrete, particularly the flexural strength in Series 2, was significantly reduced at the 90 days' age after dry curing. This recession in strength may be attributed to differential shrinkage stresses resulting from moisture gradients between the interior and exterior of the concrete. Freshly broken sections of the 90-day test beams revealed darker concrete of higher humidity in the center of the section, followed by surrounding lighter, dry concrete, and a darker outer rim of moist concrete from pre-soaking of test specimen.

Stereo-microscopic examination of concrete beam sections did not reveal any macroscopic fissures or cracks in the concrete paste, nor any other evidence of internal deterioration.

Strength recovery is expected when moisture differences within the concrete diminish and equilibrium with the relative humidity of the environment is attained.

To evaluate the effect of pre-soaking on the dry-cured cylinders, a special test series was introduced. Four dry-cured test cylinders of Test No. 187 were tested at 90 days' age: two were broken dry and two were pre-soaked 24 hours prior to the testing. The results are shown in Table 9.

TABLE 9

Effect of Pre-Soaking on Dry-Cured Test Cylinder Strength

Test No.	Dry Test		Pre-Soaked	
	Cyl No.	psi	Cyl No.	psi
187	7	5250	9	4670
	8	5250	10	4700
Average, psi:		5250		4685

These results indicate that the dry-cured specimens should not have been pre-soaked prior to testing.

It must be noted that the effect of prolonged drying on the properties of concrete is not well known; more investigation on drying phenomena would be greatly appreciated by the concrete technologists.

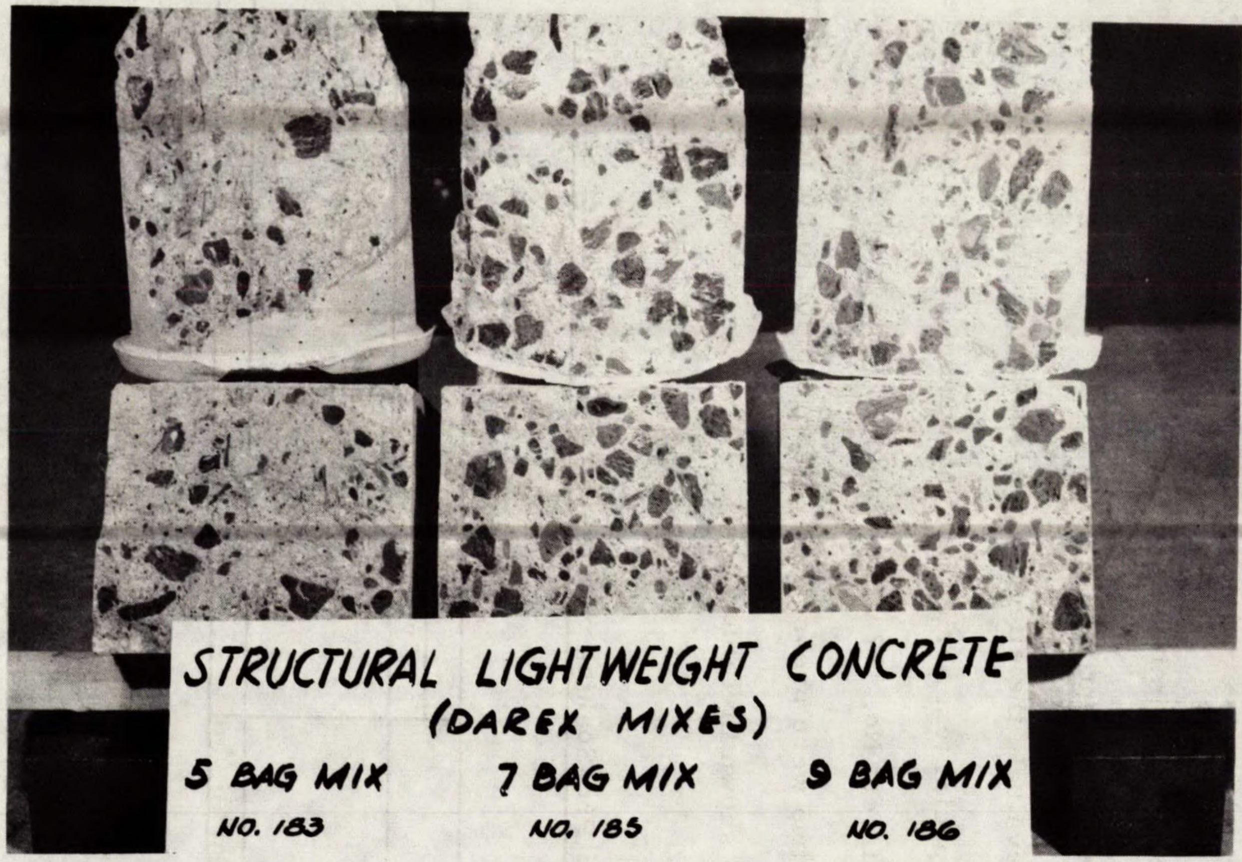

Figure 1. Broken test specimens from Series 1. Beam fractures are shown in the lower row, cylinder fractures in the upper row.

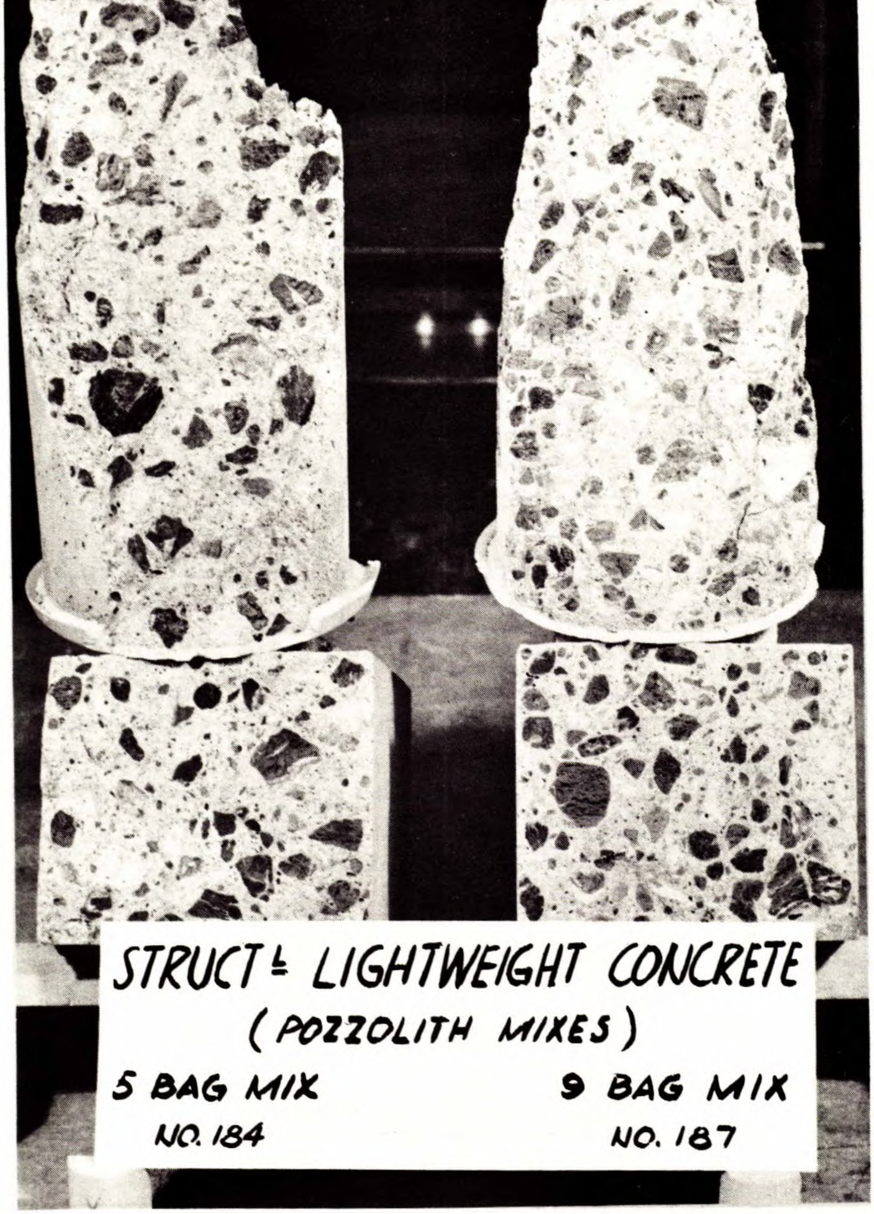

Figure 2. Broken test specimens from Series 2. Beam fractures are shown in the lower row, cylinder fractures in the upper row.

Modulus of Elasticity

The static modulus of elasticity E was determined according to the ASTM Standard Test Method E 111-59T. An averaging-type Baldwin collar compressometer Model PC-6M, equipped with a microformer, was used in conjunction with a Daytronic dial indicator for measuring deformations under applied loads.

Modulus E was determined at ages of 28 and 90 days on two 6 x 12 in. dry-cured, lightweight concrete cylinders made from mixes Nos. 185 and 186.

The modulus of elasticity reported herein is based on the slope of the secant drawn through the origin and the point (f_c = 2000 psi) on the stress-strain curve corresponding approximately to 45% of the ultimate compressive strength (f'_c) of the concrete cylinder. This value was chosen as it represents the maximum stress in compression allowed by the ACI Standard Building Code [3].

The test results are shown in Table 10.

TABLE 10

Modulus of Elasticity-E

Test No.	Cement Factors, bg/cu yd	Cylinder Compress. Strength, psi		Modulus of Elasticity, $E \times 10^6$, psi	
		28d	90d	28d	90d
185	7.0	3803	3807	2.97	2.76
186	9.0	4623	4322	3.08	2.76

The modulus of elasticity of this concrete is about 20 per cent higher than that obtained by the U. S. National Bureau of Standards on expanded shale concrete in which both fine and coarse aggregates were lightweight [4].

The E modulus of concrete made with all-expanded shale aggregate is normally about 55 per cent of that of corresponding sand and gravel concrete, but a 100 per cent replacement of lightweight fine aggregate by natural sand raises the modulus to approximately 75 per cent [5].

According to Richart and Jensen [6], the E values for conventional sand and gravel concrete of corresponding compressive strength and age would be 3.7×10^6 psi for Test No. 185, and 4.0×10^6 psi for Test No. 186. The modulus of elasticity would therefore be, for Tests No. 185 and 186, respectively 80 and 70% of that of corresponding sand and gravel concrete.

MIX DESIGN FOR DESIRED STRENGTH

Concrete mixes for structural purposes should be designed to produce the necessary workability in the fresh concrete, and to meet the specified strength of the hardened concrete.

Proportions of ingredients used in test mixes for this investigation and the 28-day compressive strengths obtained, as compiled in Tables 5 and 8, were plotted on the graph shown in Appendix "A" at the end of this report. This graph represents lightweight concrete mixes, having $2 \pm 1/2$ in. slump and a compressive strength ranging from 2000 to 4600 psi in Series 1, and from 3000 to 5750 psi in Series 2. The graph makes it possible to derive mix proportions for any strength specified within the above ranges.

Let us assume we wished to design a mix which will produce in 28 days a concrete of an average compressive strength of 3500 psi. The following procedure would be used in obtaining the mix proportions.

A dashed line is drawn horizontally through the desired strength mark (eg 3500 psi). This line crosses both strength curves - the solid one for Series 1 (Darex mixes) and the dashed one for Series 2 (Pozzolith mixes). By drawing vertical lines through the points of intersection, the amount of each mix ingredient in pounds may be obtained. The mix proportions for 3500 psi concrete were obtained in this way for both mix series, and are as follows:

Weight Proportions for 1 cu yd of 3500 psi Concrete

	Series 1 (Darex Mixes)	Series 2 (Pozzolith Mixes)
Cement	570 lb	500 lb
Natural Sand F.A.	1345 lb	1410 lb
Lightweight C.A.	837 lb	842 lb
Water	301 lb	306 lb
	3053 lb	3058 lb
Admixtures:		
Darex, A.E.A.	2.0 oz	1.0 oz
Pozzolith, D.A.	nil	1.4 lb

It must be borne in mind, that these mix designs are good only for concrete made with this particular aggregate, using admixtures as specified, and having a workability measure of 2 ± 1/2 in. slump.

PART III

LIGHTWEIGHT MASONRY CONCRETE

The prime consideration in producing lightweight concrete masonry units is lightness combined with load-bearing strength. Such concrete shall weigh not more than 100 lb and not less than 70 lb per cubic foot in an air-dry condition. The modular 8 x 8 x 16 in., hollow, load-bearing concrete block made with sand and gravel weighs approximately 45 lb. Its counterpart of lightweight aggregate averages about 30 lb and may weigh as little as 26 lb.

The minimum compressive strength requirements of the National Building Code of Canada, edition 1953, are based on the corresponding ASTM Specifications*. To meet these specifications, concrete mixes ranging in strength from 500 to 2000 psi, net area, are used in the manufacture of concrete masonry units.

Lightweight aggregates impart other properties to concrete masonry units and masonry construction which is perhaps of even greater importance than lightness in accounting for their demand. Some of these properties are reduced thermal conductivity, high sound absorption, fire resistance, and nailability. Some lightweight aggregate types may also contribute desirable colour or textural effects to concrete masonry units.

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*ASTM Designations C 55-55, C 90-59, C 129-59 and C 145-59

AGGREGATES

Lightweight aggregate properties for concrete masonry units are covered by ASTM Specification C 331-59T. In this investigation both coarse and fine aggregates were made of expanded shale. The coarse aggregate, graded from minus 3/4 to No. 8 mesh was the product "B", described in Part I of this report (p. 5). The fine aggregate consisted of the minus No. 8 material and crushed surplus coarse material. A grading was selected for combined coarse and fine aggregates within the specification limits given in Table 11. According to this grading, the proportion of fine aggregate (ie minus No. 8 mesh material) was 55 per cent by weight, or 48 per cent by absolute volume, of the total aggregate.

To assure uniform grading in all test mixes, the produced coarse and fine aggregates were screened into size fractions and recombined according to the gradings shown in Table 11.

DESIGN OF MIXES FOR MASONRY UNITS

Test mixes were designed with cement content ranging from 4 to 6 bags per cu yd of concrete. The weight of coarse aggregate was held constant in all mixes. The proportion of fine to coarse aggregate in each mix was adjusted at the time of mixing, the amount of fine aggregate in the mix being kept as low as possible to produce concrete of required strength and of desired texture. Without impairing the workability of concrete mixes the proportion of fine aggregate eventually was reduced from the initial ratio of 48%

TABLE 11

Lightweight Aggregate Gradings for Concrete Masonry Units

Type of Aggregate	Sieve Sizes	ASTM C 331-59T Grading, % Passing	Selected Combined Grading, % Passing	Fractions of Combined Grading, % Retained	Gradings of Coarse and Fine Aggregates: Grading Fractions, % Retained	Gradings of Coarse and Fine Aggregates: Accumulat. Gradings, % Passing
					Coarse Aggregate	
Coarse Aggregate	3/4 in.	100	100			100
	1/2 in.	95 to 100	95	5	11	89
Average	3/8 in.		87	8	18	71
Specif. Grav. 1.35	No. 4 M	50 to 80	70	17	38	33
Absorption - 8.0%	No. 8 M		55	15	33	
				45%	100%	
					Fine Aggregate	
Fine Aggregate	No. 8 M		55			100
	No. 16 M		40	15	27	73
Average	No. 30 M		25	15	27	46
Specif. Grav. 1.90	No. 50 M	5 to 20	15	10	18	28
Absorption - 13.0%	No. 100 M	2 to 15	10	5	10	18
	Pan			10	18	
				55%	100%	

Note: grading percentages by weight.

to 46% in the 4 bag mix and to 45% in the 6 bag mix.

An air-entraining agent (A.E.A. Darex) was used in all mixes in amounts required to produce 5 $\pm$ 1% of entrained air. Air entrainment improved concrete mouldability and increased cohesiveness of the freshly moulded units.

No attempt was made to use other types of admixtures and additives, frequently used for concrete masonry, or to explore the effect of either low-or high-pressure steam curing, normally used for accelerated production in block plants.

PREPARATION OF TEST MIXES

Three test mixes were prepared with 4, 5 and 6 bags of cement per cubic yard of concrete. The weighed amounts of coarse and fine aggregate were pre-soaked in water overnight and drained for one hour prior to mixing. The exact amount of water contained by the aggregates was determined before mixing was started. After all ingredients were placed in the mixer, the balance of the water was added to produce a mouldable, cohesive no-slump concrete mixture. The same mixing and testing procedure as described in Part II of this report (p.10) for the structural concrete was used here.

The mix proportions and characteristics of the fresh concrete are compiled in Table 12.

TABLE 12

Lightweight Masonry Concrete Mix Data

Mix No.	Test No.	Mix Proportions per 1 cu yd Concrete: Cement, lb, (or bags)	SSD Aggregate: Fine, lb	SSD Aggregate: Coarse, lb	Free Water, lb	AEA Darex, oz	Entr. Air, %	Unit Weight, lb per cu ft
1	188	350 (4.00)	892 (46%)	667 (54%)	310	2	5.5	82.2
2	189	441 (5.05)	886 (45.5%)	668 (54.5%)	305	2.5	5.0	85.2
3	190	527 (6.01)	875 (45%)	668 (55%)	300	4	4.0	87.0

Note: Aggregate proportion in per cent by volume

MOULDING AND CURING OF TEST SPECIMENS

Seven 4 x 8 in. cylinders, five 3 1/2 x 4 x 16 in. beams, and one 13 x 17 1/2 x 3 in. slab were moulded from each test mix. The fairly dry, no-slump concrete mixture was compacted in the moulds, in three layers, each receiving 12 strokes of a nonabsorptive hardwood tamper.

Test specimens were standard moist-cured for 7 days and then stored in a dry-storage room at 50 ± 5% relative humidity and room temperature until tested.

Prior to testing, specimens were pre-soaked 24 hours and crushed in the moist condition at 28 and 90 days' age.

The slabs were dry-cured in the storage room for six months, after which time they were submitted to the National Research Council laboratories for thermal conductivity tests.

PROPERTIES OF LIGHTWEIGHT MASONRY CONCRETE

To evaluate its suitability for use in concrete masonry units, the following properties of the hardened concrete were studied at different ages:

1. Unit weight and absorption
2. Loss of moisture and drying shrinkage
3. Compressive and flexural strengths
4. Thermal conductivity

Unit Weight and Absorption

Determination of unit weight and absorption of the hardened concrete were made in accordance with the Standard Methods of Sampling and Testing Concrete Masonry Units, ASTM Designation C 140-56.

Unit weights were determined on beam specimens at the following ages:

(a) 1 day - as removed from the forms;

(b) 7 days - after 6 days of moist-curing, in the SSD condition;

(c) 28 days - after 21 days of dry-storage, which followed the initial 6-day moist-curing

The test procedure and calculations are given in Part II of this report (pp.7 and 8).

Unit weights of hardened concrete and of the corresponding fresh concrete are shown in Table 13. Also shown are absorption values of dry-stored concrete at 28 days' age, in per cent by weight and in pounds per cubic foot.

TABLE 13

Unit Weights and Absorption of Masonry Concrete

Mix No.	Test No.	Unit Weights, lb/cu ft				Absorption of Concrete	
		Concrete Mixture	1 day, Hardened	7 day, SSD	28 days, R-Dry	% by wt	lb per cu ft
1	188	82.2	82.5	85.5	76.4	16.4	12.5
2	189	85.2	85.4	89.0	81.3	14.5	11.8
3	190	87.0	87.4	90.6	85.3	11.9	10.2

Absorption of this concrete is at least 50 per cent higher than that of structural concrete with the same cement content. The largest absorption of the dry-cured test specimens was in Test No. 188 (4-bag mix), which was 12.5 pounds of water per cu ft of concrete. That is below the 15-pound maximum absorption limit specified for concrete masonry units.

Loss of Moisture and Drying Shrinkage

Moisture loss and drying shrinkage were obtained by the same test procedure used for the structural concrete, described in Part II of this report. The average values of weight and length changes from the initial measurements of the SSD test specimens, after 7 days of moist-curing, were obtained on beam specimens at

28, 56 and 84 days' age; the results are compiled in Table 14.

TABLE 14

Loss of Moisture and Drying Shrinkage

Test No.	Cement Factor, bg/cu yd	Loss of Moisture % by wt			Drying Shrinkage μ in./in.		
		28d	56d	84d	28d	56d	84d
188	4.0	12.5	14.1	15.0	262	465	605
189	5.0	10.5	12.3	13.4	249	490	662
190	6.0	6.7	8.7	9.7	256	505	656

The tests show that moisture losses on drying for this type of concrete were almost double the moisture losses for corresponding structural concrete (see Table 7, p.17, Test No. 183). The higher moisture losses also caused higher drying shrinkage of this concrete, which was 25 to 50 per cent more than that of the structural lightweight concrete cured under the same conditions.

Compressive and Flexural Strengths

Lightweight masonry concrete specimens were tested for compressive and flexural strengths after similar curing, and at the same age of 28 and 90 days, as were specimens of lightweight structural concrete, shown in Part II of this report. The computed average values for each set of tests are compiled in Table 15.

The tests indicate that the strength of dry-cured concrete specimens decreases at later ages, similar to that noted for the structural concrete (see Table 8). Another interesting feature in

TABLE 15

Lightweight Masonry Concrete Strength Test Results

Test No.	Cement Factor, bg/cu yd	Type of Admixt.	Unit Weight, lb/cu ft		Compressive Strength, psi		Flexural Strength, psi			
			28d Room-Dry	215°F Oven-Dry	28d	90d	28d	% Comp. Strength	90d	% Comp Strength
188	4.0	A.E.A. Darex	76.4	70.0	616	556	247	40.1	187	30.4
189	5.0	A.E.A. Darex	81.3	73.9	1136	1750	367	32.3	326	28.7
190	6.0	A.E.A. Darex	85.3	77.5	2235	2210	477	21.4	525	23.5

these test results is the high flexural to compressive strength ratio, which was 21.4% in the 6-bag mix and 40.1% in the 4-bag mix. This is characteristic of concrete made with aggregates of low crushing strength. In this type of concrete the flexural to compressive strength ratio is high, because the relatively weaker aggregate reduces the compressive strength of concrete more than the flexural strength, particularly when the concrete mixes are leaner.

The photograph in Figure 3 shows sections of broken test beams and crushed cylinders at 28 days' age. The larger number of pieces of coarse aggregate broken in the richer mixes indicate stronger mortar than in the leaner mixes. The same amount of coarse aggregate was used in all three test mixes.

Thermal Conductivity

From each of the three test mixes Nos. 188, 189 and 190 a slab 3 x 17 x 17 1/2 in. was moulded and cured under the same conditions as the other test specimens.

After 6 months of dry storage the three slabs were submitted by the owner of the shale deposit for thermal conductivity tests to the National Research Council laboratories in Ottawa.

Two specimens were cut from each of the original slabs, were ground to exact dimensions of 1 x 8 x 8 inches and were tested in oven-dry conditions.

Figure 3. Broken specimens of masonry concrete. Both beams (lower row) and cylinders show a greater proportion of broken aggregate in the richer mixes.

The results obtained were reported in NRC Test Report No. 553 S of May 10, 1961, which was submitted by Mr. L. Sipolins for inclusion in this report. These test results are shown in the following Table 16.

TABLE 16

Thermal Conductivity Test Results*

Test No.	Unit Weight, (6 mo) lb/cu ft		Mean Temp. °F	Thermal Conductivity (K), BTU/°F. ft^2. hr
	Air-Dry	Oven-Dry		
188	74.7	70.0	75.5	2.62
189	80.1	73.9	75.4	2.82
190	82.5	77.5	75.0	3.34

* Reproduced with consent of the National Research Council

Thermal conductivity (K) values obtained are in line with K values reported for similar concrete by P.H. Petersen[7], and are about 30 to 50 per cent of the K values for conventional sand and gravel concrete (140 lb/cu ft), which range from 6.0 to 9.0 [8, 9, 10].

It should be borne in mind that these values were obtained on oven-dried test specimens. The air-dry lightweight concrete in service normally contains residual moisture in equilibrium with the surrounding air. An increase in moisture content will cause an increase in the thermal conductivity. R.C. Valore reported that each 1 per cent increase in density of this type of concrete, due to the increased moisture content, increases the thermal conductivity by 4 per cent [8].

A 20% increase of the K values obtained in these tests is desirable to provide a more realistic base for calculating thermal transmittance of air-dry lightweight concrete masonry walls in service.

A relationship also exists between the oven-dried unit weight of the lightweight concrete and its thermal conductivity - the denser the concrete, the greater is its heat conductivity [4, 8, 9].

MIX DESIGN FOR DESIRED STRENGTH

Mix proportions used in test mixes for masonry concrete, and the resultant 28-day compressive strength data, as compiled in Tables 12 and 15, were plotted on the graph attached to this report as Appendix "B". This graph represents a fairly dry, no-slump masonry concrete ranging in strength from 500 to 2500 psi. Mix proportions of any desired strength within this range may be obtained from it by a method similar to that used for the structural concrete, described in Part II of this report (see p. 26).

The mix proportions for 2000 psi masonry concrete were obtained and are as follows:

Weight Proportions for 1 cy yd of 2000 psi Concrete

Cement		500 lb
Fine Aggregate (SSD)		879 lb
Coarse Aggregate (SSD)		668 lb
Water		302 lb
	Total Weight	2349 lb
A.E.A. (Darex)		4 oz

CONCLUSIONS

1. Pilot plant tests showed that this shale bloated in a rotary kiln through a temperature range of about 100 degrees F. Bloating shales of this firing range may be classed as excellent raw material for producing lightweight aggregate.
2. The degree of bloating determined the quality of the aggregate: the less bloated, heavier product "A" was suitable for structural concrete, and the more bloated, lighter product "B" was suitable for masonry concrete.
3. Structural lightweight concrete with compressive strength up to 5000 psi, and dry unit weight ranging from 100 to 115 lb/cu ft, may be produced, by combining the less bloated product "A" as coarse aggregate with natural sand as fine aggregate.
4. The use of natural sand as fine aggregate for structural lightweight concrete improved the workability of the mixes and the structural properties of the hardened concrete. The modulus of elasticity of all-shale aggregate concrete was raised from 55 per cent to an average of 78 per cent of that of corresponding sand and gravel concrete.
5. Concrete strength increased in compression by about 1000 psi, and in flexure by 100 psi, when a lignosulfonate admixture was used as a dispersing agent in the concrete mixes. However, this admixture effected an increase of the drying shrinkage, averaging 35 per cent for 28-day tests and 15 per cent for 84-day tests.

6. Unit weight, absorption and drying shrinkage values of the structural concrete were within the limits set by ASTM specifications.

7. Lightweight masonry concrete with a compressive strength up to 2500 psi and dry unit weight from 75 to 85 lb/cu ft may be produced using the more bloated product "B" as coarse aggregate and the same material crushed, as fine aggregate.

8. Two lightweight concretes of equal strength (2235 vs 2231 psi) were produced. One, of the masonry type made with all-shale aggregate, required 6.0 bags of cement; the other, of the structural type, using natural sand as fine aggregate, required only 5.4 bags.

9. The average unit weight of the lightweight masonry concrete was about 80 per cent of that of the structural concrete, and only about 60 per cent of that of conventional sand and gravel masonry concrete.

10. Absorption of the lightweight masonry concrete ranged from 10 to 13 lb of water per cu ft of concrete, or about double that of the structural concrete. This absorption is well below the maximum 15 lb limit specified by the ASTM for lightweight masonry products.

11. The thermal conductivity of the lightweight masonry concrete was about 30 to 50 per cent of that of conventional sand and gravel concrete.

12. The use of air-entraining admixtures is desirable in all types of lightweight concrete. Air entrainment improves workability and resistance to freezing and thawing; it decreases bleeding, and provides necessary plasticity to lean and otherwise harsh mixes.

The results of this investigation show that:

A. The raw material submitted is suitable for producing lightweight concrete aggregates.

B. Structural and masonry concretes made with these aggregates meet all ASTM specifications.

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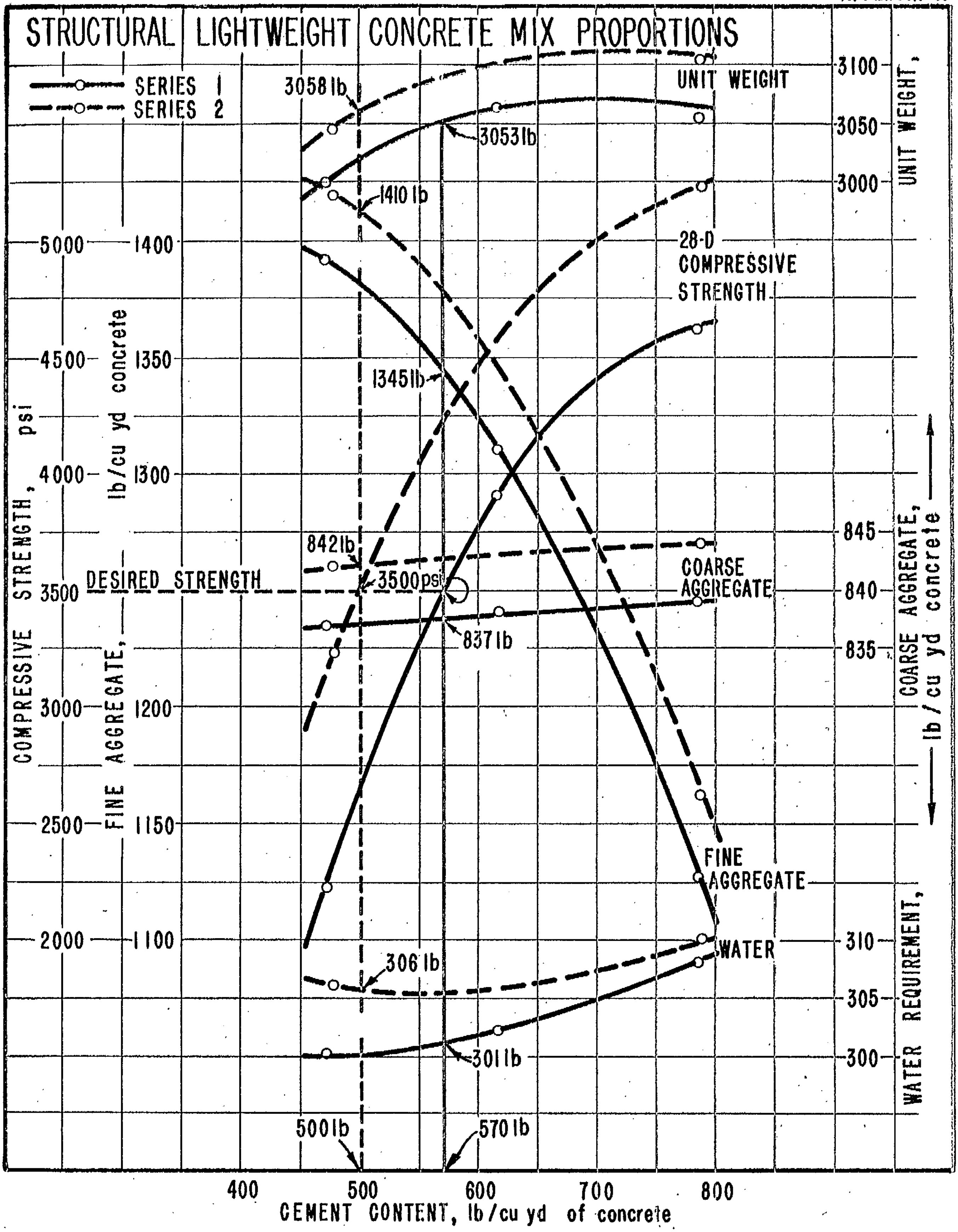
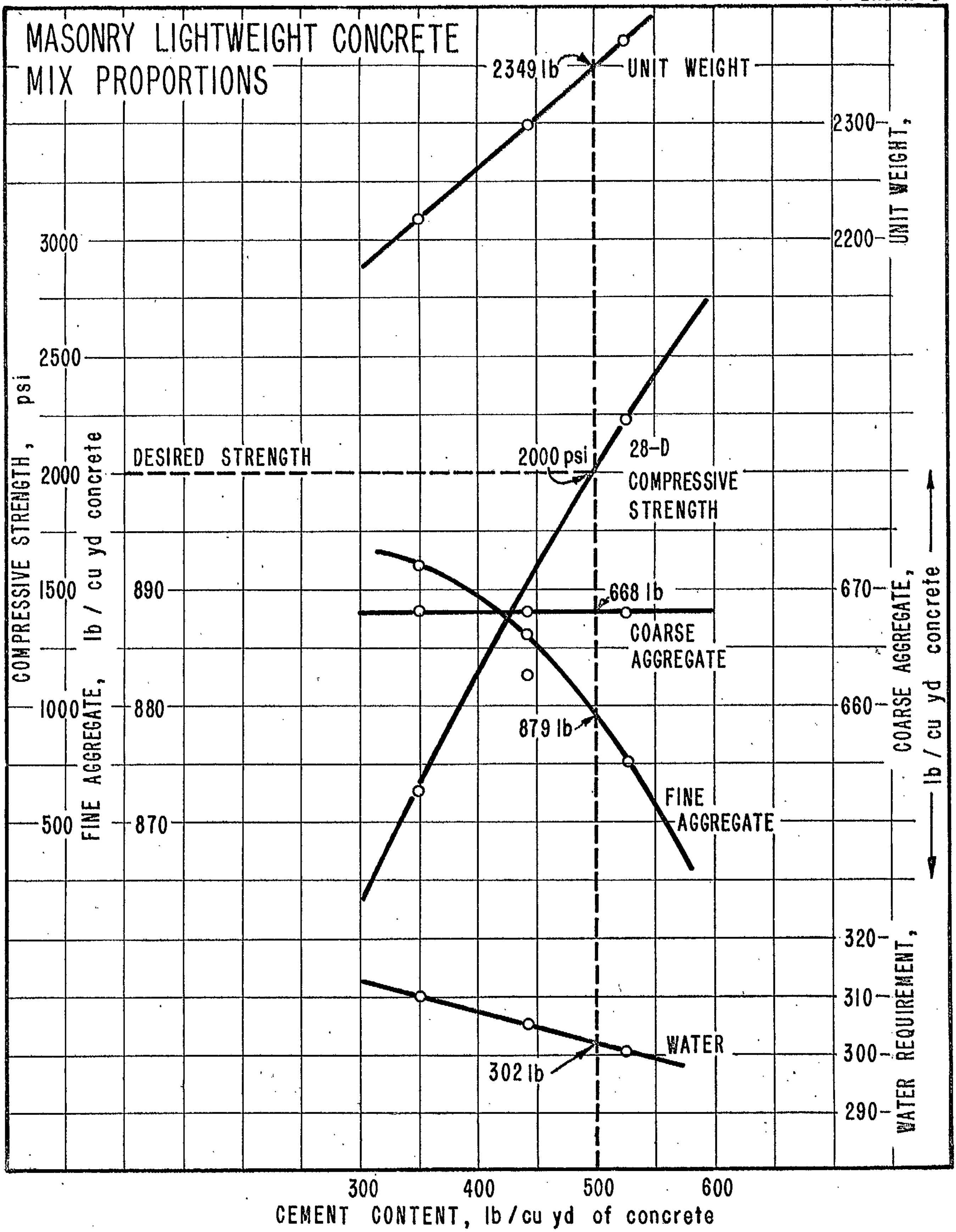
APPENDIX A



STRUCTURAL LIGHTWEIGHT CONCRETE MIX PROPORTIONS
SERIES 1
SERIES 2
3058 lb
UNIT WEIGHT
3053 lb
1410 lb
28-D COMPRESSIVE STRENGTH
1345 lb
842 lb
3500 psi
DESIRED STRENGTH
COARSE AGGREGATE
837 lb
FINE AGGREGATE
WATER
306 lb
301 lb
500 lb
570 lb
COMPRESSIVE STRENGTH, psi
5000
4500
4000
3500
3000
2500
2000
FINE AGGREGATE, lb/cu yd concrete
1400
1350
1300
1200
1150
1100
UNIT WEIGHT,
3100
3050
3000
COARSE AGGREGATE, lb/cu yd concrete
845
840
835
WATER REQUIREMENT,
310
305
300
400
500
600
700
800
CEMENT CONTENT, lb/cu yd of concrete


MASONRY LIGHTWEIGHT CONCRETE
MIX PROPORTIONS
2349 lb
UNIT WEIGHT
2300
2200
UNIT WEIGHT,
3000
2500
2000
1500
1000
500
COMPRESSIVE STRENGTH, psi
DESIRED STRENGTH
2000 psi
28-D
COMPRESSIVE
STRENGTH
890
880
870
FINE AGGREGATE, lb / cu yd concrete
668 lb
COARSE
AGGREGATE
670
660
COARSE AGGREGATE, lb / cu yd concrete
879 lb
FINE
AGGREGATE
320
310
300
290
WATER
302 lb
WATER REQUIREMENT,
300
400
500
600
CEMENT CONTENT, lb / cu yd of concrete