Louisiana Highway Research

DURABILITY OF LIGHTWEIGHT CONCRETE

PHASE II-WETTING AND DRYING TESTS

PHASE III-FREEZING AND THAWING TESTS

Louisiana Department of Highways – Research & Development Section

DURABILITY OF LIGHTWEIGHT CONCRETE
PHASE II-WETTING AND DRYING TESTS
PHASE III-FREEZING AND THAWING TESTS

by

HOLLIS B. RUSHING
Concrete Research Engineer

Research Report No. 18

Research Project No. 61-8C
Louisiana HPR 1(4)

Conducted by
LOUISIANA DEPARTMENT OF HIGHWAYS
Research and Development Section
In Cooperation with
U. S. Department of Commerce
BUREAU OF PUBLIC ROADS

December, 1966

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

SYNOPSIS

This report describes a laboratory research program on the durability of lightweight concrete. Two phases of a three phase study are covered by this report, while the remaining phase is still under study. The two phases being reported are Phase II - Wetting and Drying Tests of Lightweight Concrete and Phase III - Freezing and Thawing Tests of Lightweight Concrete.

The testing program covered three sources of lightweight aggregate and one source of gravel and sand. The tests consisted of subjecting specimens made from concrete mixes containing various cement contents and aggregate gradations, with the moisture condition of the aggregates varied, to rapid freezing in air and thawing in water to determine freeze and thaw durability and to repeated cycles of submerging in water and drying in an oven for wetting and drying durability. In addition, complete physical tests were run on the aggregates such as, gradation, unit weight, abrasion and soundness loss.

The results of the freezing and thawing tests indicates that the lightweight concrete mixes were more resistant to freeze and thaw damage than the sand and gravel mix used as a reference in this study. The results of the wetting and drying tests were not as clearly defined, with one source of lightweight aggregate performing better than the reference sand and gravel mix, while the other two sources of lightweight aggregate were less durable.

It should be pointed out that the tests results received from these studies are applicable only to the material sources which were studied.

DURABILITY OF LIGHTWEIGHT CONCRETE

INTRODUCTION

The Louisiana Department of Highways has undertaken an extensive program to study the properties of lightweight concrete. This program was started in 1961 with the awarding of a contract to Louisiana State University to study the shrinkage properties of various lightweight concrete mixes. The next study was conducted by the Research & Development Section of the Department and consisted of two projects. The first being determination of the abrasion characteristics of lightweight aggregates and the development of a more comprehensive method of performing the abrasion test. The second was established to study the durability characteristics of lightweight concrete. This study was divided into three phases. Phase I consisted of installing a recording thermometer in both lightweight concrete and sand and gravel concrete bridge decks to determine the range of temperature encountered during a one year period. Phase II of the study consisted of studying various lightweight mixes when subjected to 300 cycles of wetting and drying. Phase III consisted of studying the effects of freezing and thawing of lightweight concrete mixes. The next step in this program was the awarding of a contract to Louisiana State University to make a field evaluation of all lightweight bridges built in the State.

As of this writing, the project on shrinkage, and the evaluation of lightweight bridges conducted by Louisiana State Universtiy and the abrasion study performed by the Department have been completed and reports published. Phase I of the Durability Study is in progress and reports will be published as soon as possible.

It is hoped that a much better understanding and knowledge of lightweight concrete will evolve when the results of these studies are evaluated and analyzed.

SCOPE

The use of lightweight aggregate in concrete is increasing rapidly; this is particularly true in structural application. Because of this, as much information as possible needs to be gathered concerning this material. Although several studies have been made by other agencies of freeze and thaw characteristics of lightweight concrete, it has become apparent that every source of lightweight aggregate will have to be studied for its particular properties. Because it is a manufactured product, results from one source cannot be used for another source.

The principal objectives of this study were to determine the effect of repeated cycles of wetting and drying on lightweight concrete durability and the effect of repeated cycles of freezing and thawing on lightweight concrete durability. This information should be very useful in establishing a test criteria for acceptance of a source of lightweight aggregate.

Three lightweight aggregates and one normal weight sand and gravel aggregate were used in this study. One lightweight coarse aggregate was also used in combination with sand in concrete mixes.

Cement contents of 5.5 and 6.0 bags per cubic yard were studied for each parameter. Two lightweight fine aggregate gradations were used, (1) approximately 15 per cent passing the No. 100 sieve, and (2) approximately 25 per cent passing the No. 100 sieve. The lightweight aggregates were used at two different moisture conditions, (1) at approximately 50% saturation (2) after 24 hours of immersion in water. The moisture content that approximated 50 per cent saturation, was found by immersing samples of the lightweight aggregates in water for various periods of time. The moisture content was then plotted versus the immersed time. From the curve, a value was selected which most nearly represented 50 per cent saturation. The moisture content was in the range of 15-18 per cent by weight. It was also found that the largest per cent of absorption occurred during the first 24 hours. After 24 hours, the rate of absorption is very slow and very little change in moisture content occurs. An air entraining agent and a water reducing agent were used in all lightweight mixes, and in one sand and gravel mix. The air content was maintained between 6 to 9 per cent total air in the lightweight concrete and 3 to 6 per cent entrained air in the sand and gravel mix.

MATERIALS

The cement used in all the concrete mixes was Type I produced in Baton Rouge, Louisiana.

The three lightweight aggregates and the sand and gravel used in this study are briefly described as follows:

Aggregate 1 - An expanded clay produced in a rotary kiln. The raw material is passed through a 3 inch screen prior to introduction into the 160 foot long kiln in which the maximum temperature is near 2000°F. Some crushing is necessary to produce fine aggregate.

Aggregate 2 - An expanded clay produced in a rotary kiln. The raw material is passed through a 5 inch screen prior to introduction into a 40 foot long kiln in which the maximum temperature is near 2000°F. Some crushing is necessary to produce fine aggregate.

Aggregate 3 - An expanded clay produced by the sintering process. The raw material is compressed into small briquettes approximately one inch in diameter and eight inches long. The briquettes are then placed on a continuously moving sintering grate and screeded off to a depth of approximately 8 inches before entering the kiln where the temperature is maintained at approximately 2000°F. All aggregates, both coarse and fine are produced by crushing the briquettes.

Aggregate 4 - The sand and gravel aggregates are natural uncrushed material obtained from the Amite River in Louisiana. They are both predominantly siliceous materials. These aggregates have a good service record in this area.

The admixtures used in the study consisted of a water reducing, set retarding agent (calcium lignosulfonate) and an air entraining agent (neutralized vinsol resin). The water reducing, set retarding admixture was used at a rate of 0.25 lb. per sack of cement, while the air entraining agent was used at a rate necessary to produce the required amount of air. This rate varied from 0.75 oz. to 1.25 ozs. per sack of cement, depending on the mix being used.

TEST PROCEDURES FOR AGGREGATES

The aggregates were prepared and tested in accordance with the methods listed below:

AASHO T 27-60 Method of Test for Sieve Analysis of Fine and Coarse Aggregate.

AASHO T 19-56 Method of Test for Unit Weight of Aggregate.

AASHO T 96-60 Method of Test for Abrasion of Coarse Aggregate by Use of the Los Angeles Machine.

AASHO T 104-57 Method of Test for Soundness of Aggregates by Use of Sodium Sulfate or Magnesium Sulfate.

LDH TR 103-63 Method of Test for Sand Equivalent.

PHASE II - WETTING AND DRYING TESTS

GENERAL

This phase of the project was started in March, 1962. The aggregates were collected from the various sources and stockpiled at the laboratory preparatory to beginning tests of the aggregate properties. After completion of the tests of the aggregate properties, the mixing of concrete and molding of test specimens was started.

TEST RESULTS FOR AGGREGATES

The gradations and the unit weights of the aggregates are shown in Table 1.

The results of all other tests performed on the aggregates are given in Table 2. The sand equivalent test was run on all the fine aggregates in an effort to determine the amount of colloids that may be present.

TABLE 2

LOS ANGELES ABRASION, SOUNDNESS AND SAND EQUIVALENT RESULTS

	Los Angeles Abrasion Grade B-Per Cent Loss	Magnesium Sulfate Soundness Per Cent Loss	Sand Equivalent
Aggregate 1			
Coarse	27.8	9.3	
Fine 1A		10.0	85
Fine 1B		11.8	71
Aggregate 2			
Coarse	41.1	6.4	
Fine 2A		11.1	87
Fine 2B		11.8	75
Aggregate 3			
Coarse	37.0	17.5	
Fine 3A		32.4	56
Aggregate 4			
Gravel	21.7	6.7	
Sand		2.3	97

TABLE 1

GRADATION AND UNIT WEIGHT OF AGGREGATES

U. S. Sieve	Percentage Passing Sieve Indicated, By Weight										
	Lightweight Aggregates									Normal Weight Agg.	
	No. 1			No. 2			No. 3				
	Coarse	Fine 1A	Fine 1B	Coarse	Fine 2A	Fine 2B	Coarse	Fine 3A	Fine 3B*	Sand	Gravel
1 1/2 Inch											100
3/4 Inch	100			100			100				73
1/2 Inch	95			98			95				29
3/8 Inch	70	100	100	77	100	100	74	100		100	11
No. 4	6	100	100	5	100	100	7	100		98	0
No. 8	3	92	93	2	90	95	2	91		94	
No. 16		63	72		67	75		67		88	
No. 30		39	50		42	51		43		73	
No. 50		27	38		28	37		28		22	
No. 100		18	28		18	26		16		1	
DRY UNIT WEIGHT - LBS/CU FT											
Loose	39.0	56.0	58.0	42.5	60.0	62.0	52	66.0		100.00	89.0
Rodded	42.5	62.0	64.0	47.0	68.0	70.0	57.5	74.0		108.00	98.0

* Material with 25% passing No. 100 sieve was not available

CONCRETE

As stated before, cement contents of 5.5 and 6.0 sacks per cubic yard were used for all variables tested. The concrete was mixed in a 3.5 cu. ft. revolving drum mixer. The aggregate and approximately two-thirds of the water including the admixtures when required were added and mixed for 1 minute. The cement and remaining water were then added and mixing continued for 4 additional minutes.

In order to control the moisture content of the lightweight aggregate in the range desired, the aggregate was brought to the moisture condition desired the day previous to mixing concrete and stored in sealed containers to prevent any loss in moisture. Immediately prior to making the concrete mix, the moisture content of the aggregate was determined for correcting the batch weights

The lightweight mixes were designed by trial and error based on the unit weight of concrete. An estimated fresh unit weight was predicted and the mix designed from this figure. A trial mix was then made and the fresh unit weight determined. If the measured unit weight varied from the estimated unit weight, then the mix was redesigned using the measured unit weight. This procedure was followed for all lightweight mixes. No attempt was made to determine specific gravities of the lightweight aggregates. It was felt that since lightweight aggregates are manufactured products their gravities would change from day to day and hence could not be used as a basis for design. In addition, it is almost impossible to obtain a saturated surface dry condition because of the highly absorptive characteristic of the lightweight aggregates. The sand and gravel mixes were designed by absolute volume.

The consistency of the concrete was generally held in a range of 2 to 4 inches in slump. Air content was determined by AASHO T 152-57.

The specimens used in the wetting and drying test, were 3in. by 4in. by 16in. concrete prisms. Cylinders used for determining compressive strength were 6in. by 12in. All specimens were made and cured in accordance with AASHO T 126-60 except as otherwise noted.

Table 3 shows the data for all of the concrete mixtures. The condition of the aggregate is shown either by (1) 50%, which means approximately 50 per cent saturated, or (2) saturated meaning immersed for 24 hours prior to use. The compressive strength results shown are an average of 3 cylinders tested at 28 days age.

TABLE 3
CONCRETE MIX DATA

Aggregate: Coarse Agg. No.	Aggregate: Cond.	Aggregate: Fine Agg. No.	Mix No.	Quantities Per Sack of Cement: Cem. Lbs.	Quantities Per Sack of Cement: Aggregate Fine Lbs.	Quantities Per Sack of Cement: Aggregate Coarse Lbs.	Quantities Per Sack of Cement: Total Water Lbs.	Quantities Per Sack of Cement: Admixtures Air Entraining Ozs.	Quantities Per Sack of Cement: Admixtures Water Reducer Lbs.	Slumps In.	Air Content Per Cent	Unit Wt. of Plastic Concrete lbs./cu. ft.	Actual Cement Content Bags/Yard	Comp. Strength 28 days p.s.i.
							5.5 Sack Mix							
1	50%	1A	1-A	94	132.5	100.5	100.0	.50	.25	2 3/4	9.0	88.0	5.60	4204
1	50%	1B	3-A	94	126.5	126.5	95.0	.50	.25	3	6.5	90.4	5.52	4288
1	Sat.	1A	5-A	94	135.5	102.5	110.0	.50	.25	2 1/4	8.3	90.8	5.52	3798
1	Sat.	1B	7-A	94	124.0	124.0	110.0	.50	.25	3	6.5	94.0	5.60	4452
1	50%	Sand	17-A	94	205.0	137.0	65.0	.50	.25	3 1/4	8.3	102.8	5.55	4340
1	Sat.	Sand	19-A	94	206.5	138.5	77.0	.50	.25	3	7.5	107.6	5.60	4017
2	50%	2A	9-A	94	163.5	133.5	105.0	1.00	.25	2 3/4	8.0	100.8	5.51	3233
2	50%	2B	11-A	94	160.5	131.5	105.0	1.00	.25	2 3/4	7.5	100.8	5.54	3922
2	Sat.	2A	13-A	94	160.5	131.5	110.0	1.00	.25	2 1/4	8.0	101.2	5.50	2901
2	Sat.	2B	15-A	94	159.0	130.0	108.0	1.00	.25	2 3/4	8.0	100.8	5.58	3599
3	50%	3A	22-A	94	166.0	135.5	110.0	2.00	.25	3 3/4	6.5	104.0	5.55	3649
3	Sat.	3A	24-A	94	168.5	138.0	115.0	2.00	.25	3 1/2	7.5	104.0	5.47	3414
4	-	-	21-A	94	222.0	352.0	50.0	-	-	2 1/2	1.6	146.4	5.55	4558
							6.0 Sack Mix							
1	50%	1A	2-A	94	126.5	95.0	85.0	.50	.25	2 1/4	9.0	88.0	5.93	4039
1	50%	1B	4-A	94	111.0	110.5	85.0	.50	.25	2 1/4	6.3	90.8	6.10	4216
1	Sat.	1A	6-A	94	120.5	90.5	100.0	.50	.25	2 1/2	8.5	92.0	6.10	4334
1	Sat.	1B	8-A	94	112.5	112.5	100.0	.50	.25	2 3/4	6.0	95.2	6.10	4787
1	50%	Sand	18-A	94	188.5	126.0	55.0	.50	.25	2 1/2	7.2	103.6	6.00	4629
1	Sat.	Sand	20-A	94	192.5	128.0	67.0	.50	.25	3 1/2	7.5	107.2	5.98	4346
2	50%	2A	10-A	94	146.0	119.5	95.0	1.00	.25	3	8.4	100.8	6.00	3900
2	50%	2B	12-A	94	143.5	117.0	95.0	1.00	.25	3	7.0	102.0	6.13	4576
2	Sat.	2A	14-A	94	143.5	117.0	100.0	1.00	.25	2 1/2	7.8	101.6	6.02	3463
2	Sat.	2B	16-A	94	146.0	119.5	95.0	1.00	.25	2 1/2	7.5	101.2	5.99	3909
3	50%	3A	23-A	94	150.5	123.5	100.0	2.00	.25	3 1/4	6.0	105.2	6.09	4170
3	Sat.	3A	25-A	94	148.0	121.0	105.0	2.00	.25	3 1/4	7.0	104.0	6.03	3816

WETTING AND DRYING TESTS

The specimens for wetting and drying tests were cured for 7 days in a moist room at 73.4±2°F. and 100 per cent relative humidity. The specimens were then tested for modulus of elasticity in accordance with ASTM C 215-60. After determining the initial modulus of elasticity the wetting and drying cycles were started.

The test procedure for the wetting and drying cycles was as follows. The specimens were first immersed in water for 24 hours. After the 24 hour immersion period, the specimens were removed from the water, surface dried and placed in an oven at 130°F for 24 hours. This procedure was repeated until the required number of cycles were obtained. The water in which the specimens were immersed was maintained at 73.4±2°F throughout the test cycles.

The criteria used for comparing the durability of the concrete specimens was dynamic modulus of elasticity. The transverse frequency method was used for this study. The equipment for determining the dynamic modulus is shown in Figure 7 of Phase III in this report.

The modulus of elasticity readings were taken after each ten cycles of wetting and drying until a significant reduction in modulus had occurred. As the modulus of elasticity approached 60 percent of the original value, which was considered the failing point, the readings were taken more often.

In addition to subjecting the 3in. by 4in. by 16in. beams to the wetting and drying cycles, two 6 by 12 inch cylinders representing each mix under study were also subjected to the same treatment. When the tests were completed on the beams, the cylinders were tested for compressive strength for comparison with the standard 28 day cylinders. Photograph were taken of all test beams at the completion of the test. These photographs are shown in Appendix A.

DISCUSSION OF RESULTS

The results of the wetting and drying tests are shown in Table 4. Each mix is shown with the percent of original modulus of elasticity remaining at the conclusion of the test, the durability factor, and the relative durability factor. The relative durability factor was computed by using the durability factor of the 5.5 bag sand and gravel mix as 100 and determining what percent the durability factor of the lightweight mixes were of the reference mix.

TABLE 4

RESULTS OF WETTING AND DRYING TESTS

Aggregate: Coarse Agg. No.	Aggregate: Cond.	Aggregate: Fine Agg. No.	Mix No.	Per Cent of Original *E* at Approximately 300 Cycles	Durability Factor at 300 Cycles	Relative Durability Factor at Approximately 300 Cycles
				5.5 Sack Mix		
1	50%	1A	1A	85.5 (300)	85.5	82
1	50%	1B	3A	92.8 (300)	92.8	89
1	Sat.	1A	5A	82.9 (300)	82.9	79
1	Sat.	1B	7A	77.2 (300)	77.2	74
1	50%	Sand	17A	95.0 (300)	95.0	91
1	Sat.	Sand	19A	92.8 (300)	92.8	89
2	50%	2A	9A	118.5 (300)	118.5	114
2	50%	2B	11A	114.6 (300)	114.6	110
2	Sat.	2A	13A	115.7 (300)	115.7	111
2	Sat.	2B	15A	111.2 (300)	111.2	107
3	50%	3A	22A	75.4 (160)	-	-
3	Sat.	3A	24A	89.9 (300)	89.9	86
4	-	-	21A	104.4 (300)	104.4	100

Numbers in parentheses refer to cycles of wetting and drying.

TABLE 4 (Continued)

RESULTS OF WETTING AND DRYING TESTS

Aggregate						
Coarse Agg. No.	Cond.	Fine Agg. No.	Mix No.	Per Cent of Original E at Approximately 300 Cycles	Durability Factor at 300 Cycles	Relative Durability Factor at Approximately 300 Cycles
			6.0 Sack Mix			
1	50%	1A	2A	89.9 (300)	89.9	86
1	50%	1B	4A	93.7 (300)	93.7	90
1	Sat.	1A	6A	69.3 (280)	-	-
1	Sat.	1B	8A	93.8 (300)	93.8	90
1	50%	Sand	18A	95.3 (300)	95.3	91
1	Sat.	Sand	20A	93.2 (300)	93.2	89
2	50%	2A	10A	115.5 (300)	115.5	111
2	50%	2B	12A	114.5 (300)	114.5	110
2	Sat.	2A	14A	112.8 (300)	112.8	108
2	Sat.	2B	16A	111.3 (300)	111.3	107
3	50%	3A	23A	88.5 (300)	88.5	85
3	Sat.	3A	25A	94.4 (195)	-	-

Numbers in parentheses refer to cycles of wetting and drying.

The overall results of the study indicated that lightweight concrete is not materially effected by cycles of wetting and drying.

The main problem encountered during this testing program was the breaking of test specimens due to repeated handling. Every twenty-four hours the specimens were all removed from the water and placed in the oven, or vice versa and this resulted in the loss of a good number of specimens due to breakage during these transfer procedures. It can be noted from the results of Table 4 that the tests were ended on certain mixes prior to failure or the completion of 300 cycles. These cases were due to all three specimens having been broken during handling.

The variables under study were (1) cement content, (2) the amount of material passing the No. 100 sieve, (3) moisture content of the aggregates and (4) sand used as a replacement for lightweight fine aggregate. The effects of each of these variables will be discussed briefly.

Cement Content

Cement contents of 5.5 and 6.0 sacks per cubic yard were used in this study. Figure 1 shows graphically the effect of cement content on wetting and drying durability. The durability factors are plotted for each mix under study. Aggregate No. 1 showed a slight increase in durability with the increased cement content, Aggregate No. 2 showed a slight decrease in durability with the increased cement content, Coarse Aggregate No. 1 when used in conjunction with concrete sand showed practically no difference in durability and no comparison could be made with Aggregate No. 3. From these results it would appear that the effect on durability due to an increase or decrease of cement content of the magnitude tested in this study is insignificant.

Fine Aggregate Gradation

Two gradations of fine lightweight aggregate were obtained from each source tested if possible. One gradation was such that approximately 15 percent of the fine aggregate was minus No. 100 material, and the other gradation produced approximately 25 percent minus No. 100 material. The effect of these gradations on wetting and drying durability is shown in Figure 2. With the exception of mixes 3A and 4A, it appears that a slight detremental effect is produced by the fine gradation. This was true for both cement contents and aggregate moisture conditions studied.

Moisture Content of Aggregates

The two moisture conditions studied were (1) approximately 50 per cent

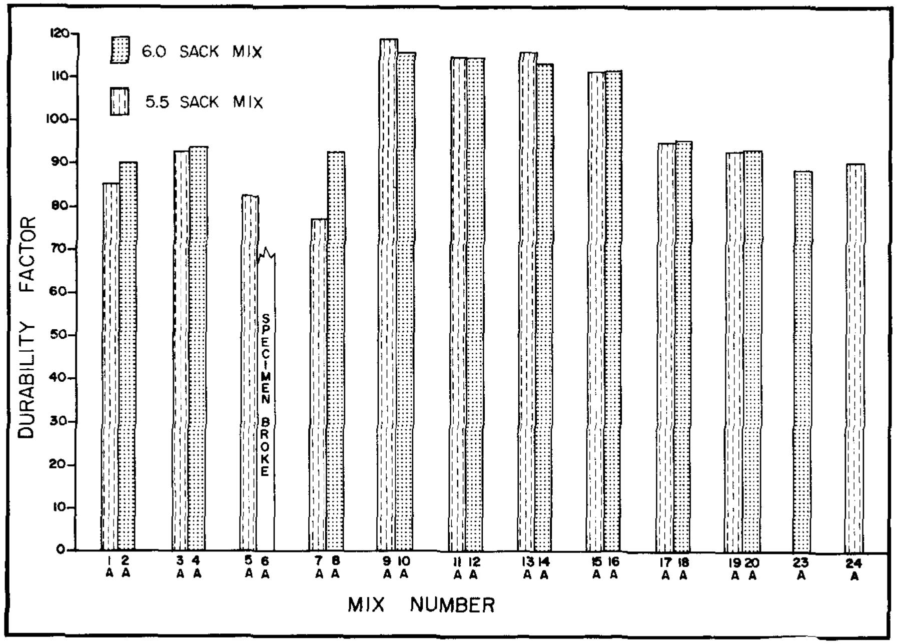


Figure 1 - Influence of Cement Content on Durability

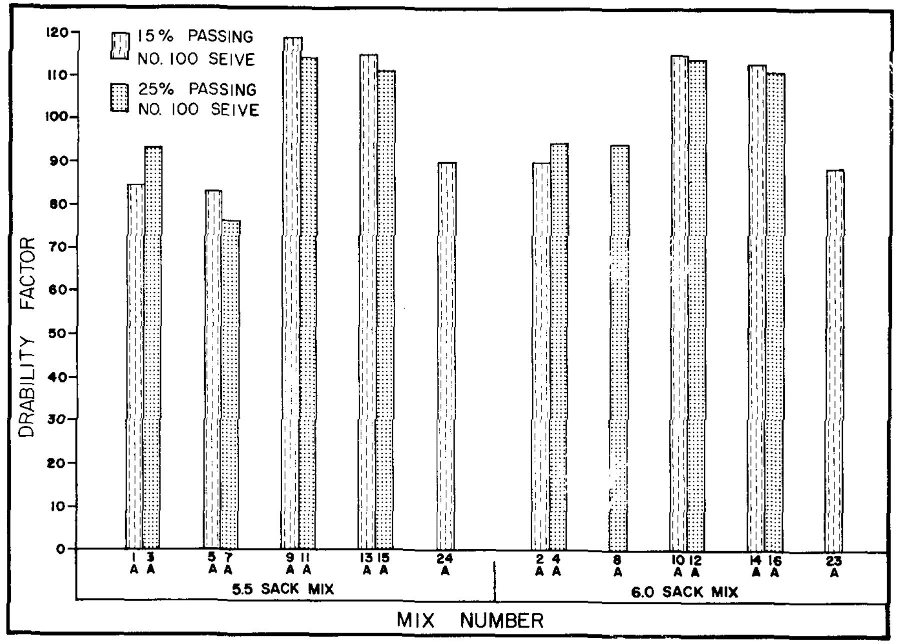


Figure 2 - Influence of Fine Aggregate Gradation on Durability

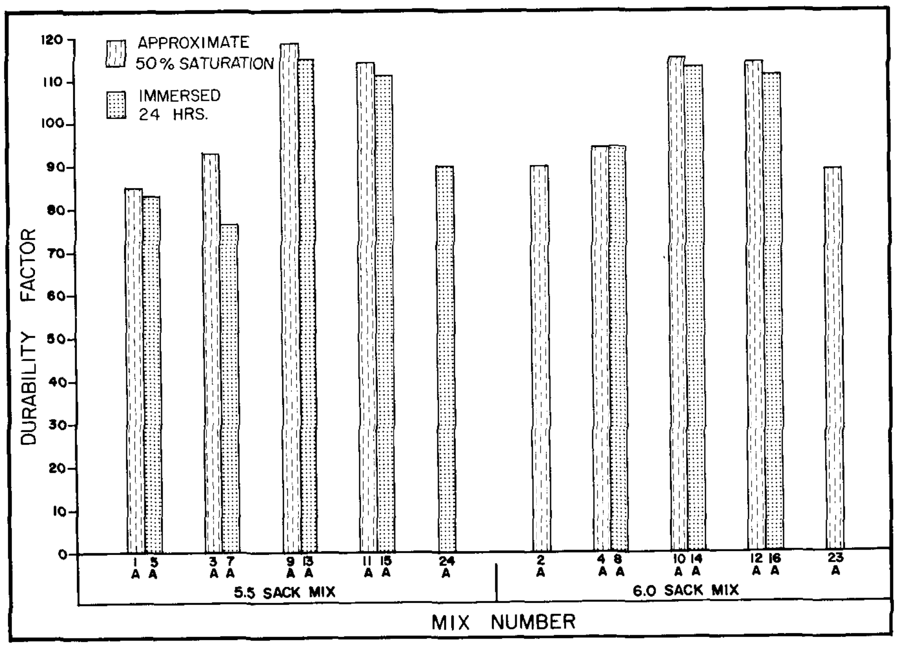


Figure 3 - Influence of Moisture Content of Aggregate on Durability

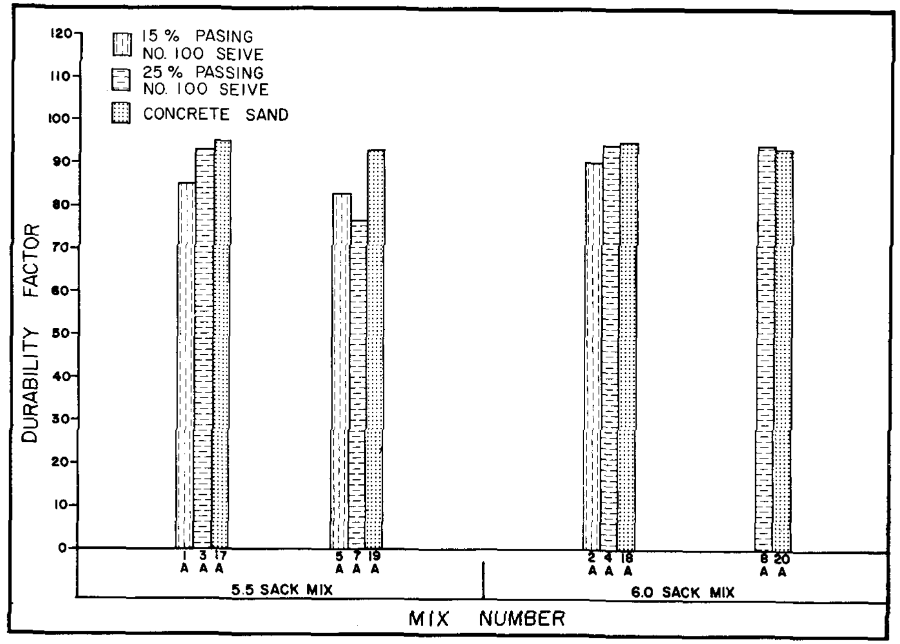


Figure 4 - Influence of Sand Used to Replace Lightweight Fines on Durability

saturated and (2) immersed in water for 24 hours prior to use. Figure 3 shows graphically the effect of initial moisture content of the aggregate on wetting and drying durability. It is evident from these results that higher initial moisture content was detremental to the concrete.

Sand Used to Replace Lightweight Fines

Natural sand was used to replace the lightweight fine aggregate in four concrete mixes to determine the effect this would have on wetting and drying durability. Figure 4 illustrates the comparison of durability found between mixes made with lightweight fine aggregate and those made with natural concrete sand. The results indicate that an improvement in wetting and drying durability is obtained by using concrete sand to replace lightweight fine aggregate in lightweight concrete.

In addition to the determination of durability by dynamic modulus, compressive strength tests were performed on 6 inch by 12 inch cylinders which had been subjected to the same number of wetting of drying cycles as the beams. Table 5 shows a comparison between the compressive strength at 28 days on standard cured cylinders and the compressive strength at the conclusion of the wetting and drying tests. A total of seven mixes had a loss of compressive strength due to the wetting and drying cycles. However, no pattern was established as to what conditions caused the reduction in compressive strength.

TABLE V

COMPRESSIVE STRENGTH RESULTS

Mix No.	Compressive Strength 28 days, Standard Cure P.S.I.	Compressive Strength At Conclusion of Tests P.S.I.
	5.5 Sack Mix	
1-A	4204	3798
3-A	4288	4681
5-A	3798	3886
7-A	4452	4346
17-A	4340	3780
19-A	4017	3692
9-A	3233	3975
11-A	3922	4708
13-A	2901	3957
15-A	3599	4487
22-A	3649	3869
24-A	3414	3825
21-A	4558	5300
	6.0 Sack Mix	
2-A	4039	-
4-A	4216	4841
6-A	4334	3851
8-A	4787	4800
18-A	4629	4364
20-A	4346	3780
10-A	3900	4708
12-A	4576	5265
14-A	3463	4045
16-A	3909	4955
23-A	4170	4523
25-A	3816	3825

PHASE III - FREEZING AND THAWING TESTS

GENERAL

This phase of the project was begun in May, 1963. The same procedure was followed in obtaining aggregates and performing the necessary tests prior to beginning the molding of test specimens as was described in Phase II.

TEST RESULTS FOR AGGREGATES

The gradations and the unit weights of the aggregates are shown in Table 6.

The results of all other tests performed on the aggregates are given in Table 7. The sand equivalent test was run on all the fine aggregates in an effort to determine the amount of colloids that may be present.

TABLE 7

LOS ANGELES ABRASION, SOUNDNESS AND SAND EQUIVALENT RESULTS

	Los Angeles Abrasion Grade B-Per Cent Loss	Magnesium Sulfate Soundness Per Cent Loss	Sand Equivalent
Aggregate 1			
Coarse	26.3	3.0	
Fine 1A		10.3	76
Fine 1B		11.8	67
Aggregate 2			
Coarse	41.1	6.4	
Fine 2A		4.0	87
Fine 2B		4.4	79
Aggregate 3			
Coarse	37.0	17.5	
Fine 3A		32.3	56
Aggregate 4			
Gravel	21.7	6.7	
Sand		2.3	92

TABLE 6

GRADATION AND UNIT WEIGHT OF AGGREGATES

U. S. Sieve	Percentage Passing Sieve Indicated, By Weight										
	Lightweight Aggregates									Normal Weight Agg.	
	No. 1			No. 2			No. 3				
	Coarse	Fine 1A	Fine 1B	Coarse	Fine 2A	Fine 2B	Coarse	Fine 3A	Fine 3B*	Sand	Gravel
1 1/2 Inch											100
3/4 Inch	100			100			100				73
1/2 Inch	95			98			94				29
3/8 Inch	73	100	100	77	100	100	74	100		100	11
No. 4	5	100	100	5	100	100	7	100		97	0
No. 8	1	94	96	2	90	90	2	91		94	
No. 16		69	75		67	75		67		88	
No. 30		44	53		42	51		43		73	
No. 50		29	39		28	37		28		22	
No. 100		20	30		18	26		16		1	
DRY UNIT WEIGHT - LBS /CU FT											
Loose	38.0	52.0	56.0	42.5		62.0	52.0	66.0		100.0	89.0
Rodded	41.0	60.0	64.0	47.0		70.0	57.5	74.0		108.0	98.0

* Material with 25% passing No. 100 sieve was not available.

CONCRETE

As stated before, cement content of 5.5 and 6.0 sacks per cubic yard were used for all variables tested. The concrete was designed, mixed, and controlled in the same manner as described in Phase II of this report.

The specimens for freeze and thaw testing were 3in. by 4in. by 16in concrete prisms. Cylinders used for determining compressive strength were 6 in. by 12 in. All specimens were made and cured in accordance with AASHO T 126-60 except as otherwise noted.

Table 8 shows the data for all the concrete mixtures. The condition of the aggregate is shown either by (1) 50%, which means approximately 50 percent saturated, or (2) saturated meaning immersed for 24 hours prior to use. The compressive strength results shown are an average of 3 cylinders tested at 28 days age.

FREEZE AND THAW TESTS

The specimens for freeze and thaw testing were cured for 7 days in a moist room at 73.4±2°F. and 100 per cent relative humidity. They were then placed in a curing room maintained at 73.4±2°F. and 50 per cent relative humidity for 14 days. The specimens were then moved to the moist room for 7 additional days. At the completion of this curing procedure, which took 28 days, the freeze and thaw tests were started. This curing procedure is the one recommended by the Bureau of Public Roads for freeze and thaw specimens.

The test procedure used for the freeze and thaw tests was ASTM Designation C 291-57T, Test for Resistance of Concrete Specimens to Rapid Freezing in Air and Thawing in Water.

The freeze and thaw cabinet used in this study is capable of producing from one cycle of freezing and thawing in 48 hours to eight cycles of freezing and thawing in 24 hours. Sixty specimens can be tested at one time. The temperature range is from 0°F. to 40°F. at the center of the specimens. The cycle consists of approximately two hours freezing and one hour thawing, when eight cycles are performed per day. Figures 5 and 6 show the freeze and thaw cabinet used in this study.

TABLE 8
CONCRETE MIX DATA

Aggregate: Coarse Agg. No.	Aggregate: Cond.	Aggregate: Fine Agg. No.	Mix No.	Quantities Per Sack of Cement: Cem. Lbs.	Quantities Per Sack of Cement: Aggregate Fine Lbs.	Quantities Per Sack of Cement: Aggregate Coarse Lbs.	Quantities Per Sack of Cement: Total Water Lbs.	Quantities Per Sack of Cement: Admixtures Air Entraining Ozs.	Quantities Per Sack of Cement: Admixtures Water Reducer Lbs.	Slumps In.	Air Content Per Cent	Unit Wt. of Plastic Concrete lbs./cu. ft.	Actual Cement Content Bags/Yard	Comp. Strength 28 days p.s.i.
							5.5 Sack Mix							
1	50%	1A	1-A	94	132.5	100.5	100.0	.50	.25	2 3/4	9.0	88.0	5.60	4204
1	50%	1B	3-A	94	126.5	126.5	95.0	.50	.25	3	6.5	90.4	5.52	4288
1	Sat.	1A	5-A	94	135.5	102.5	110.0	.50	.25	2 1/4	8.3	90.8	5.52	3798
1	Sat.	1B	7-A	94	124.0	124.0	110.0	.50	.25	3	6.5	94.0	5.60	4452
1	50%	Sand	17-A	94	205.0	137.0	65.0	.50	.25	3 1/4	8.3	102.8	5.55	4340
1	Sat.	Sand	19-A	94	206.5	138.5	77.0	.50	.25	3	7.5	107.6	5.60	4017
2	50%	2A	9-A	94	163.5	133.5	105.0	1.00	.25	2 3/4	8.0	100.8	5.51	3233
2	50%	2B	11-A	94	160.5	131.5	105.0	1.00	.25	2 3/4	7.5	100.8	5.54	3922
2	Sat.	2A	13-A	94	160.5	131.5	110.0	1.00	.25	2 1/4	8.0	101.2	5.50	2901
2	Sat.	2B	15-A	94	159.0	130.0	108.0	1.00	.25	2 3/4	8.0	100.8	5.58	3599
3	50%	3A	22-A	94	166.0	135.5	110.0	2.00	.25	3 3/4	6.5	104.0	5.55	3649
3	Sat.	3A	24-A	94	168.5	138.0	115.0	2.00	.25	3 1/2	7.5	104.0	5.47	3414
4	-	-	21-A	94	222.0	352.0	50.0	-	-	2 1/2	1.6	146.4	5.55	4558
							6.0 Sack Mix							
1	50%	1A	2-A	94	126.5	95.0	85.0	.50	.25	2 1/4	9.0	88.0	5.93	4039
1	50%	1B	4-A	94	111.0	110.5	85.0	.50	.25	2 1/4	6.3	90.8	6.10	4216
1	Sat.	1A	6-A	94	120.5	90.5	100.0	.50	.25	2 1/2	8.5	92.0	6.10	4334
1	Sat.	1B	8-A	94	112.5	112.5	100.0	.50	.25	2 3/4	6.0	95.2	6.10	4787
1	50%	Sand	18-A	94	188.5	126.0	55.0	.50	.25	2 1/2	7.2	103.6	6.00	4629
1	Sat.	Sand	20-A	94	192.5	128.0	67.0	.50	.25	3 1/2	7.5	107.2	5.98	4346
2	50%	2A	10-A	94	146.0	119.5	95.0	1.00	.25	3	8.4	100.8	6.00	3900
2	50%	2B	12-A	94	143.5	117.0	95.0	1.00	.25	3	7.0	102.0	6.13	4576
2	Sat.	2A	14-A	94	143.5	117.0	100.0	1.00	.25	2 1/2	7.8	101.6	6.02	3463
2	Sat.	2B	16-A	94	146.0	119.5	95.0	1.00	.25	2 1/2	7.5	101.2	5.99	3909
3	50%	3A	23-A	94	150.5	123.5	100.0	2.00	.25	3 1/4	6.0	105.2	6.09	4170
3	Sat.	3A	25-A	94	148.0	121.0	105.0	2.00	.25	3 1/4	7.0	104.0	6.03	3816

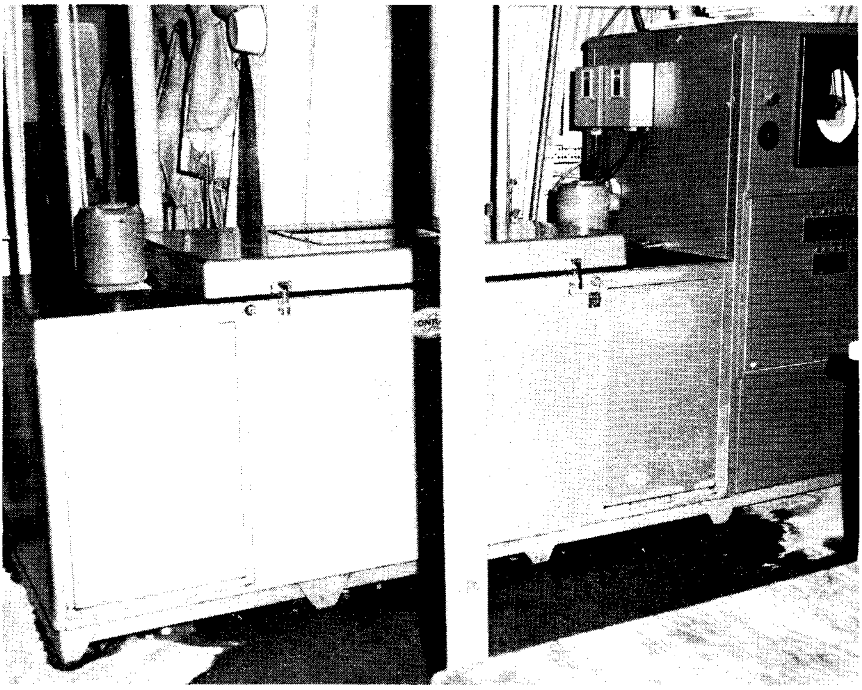


Figure 5 - Freeze and Thaw Machine used in this study

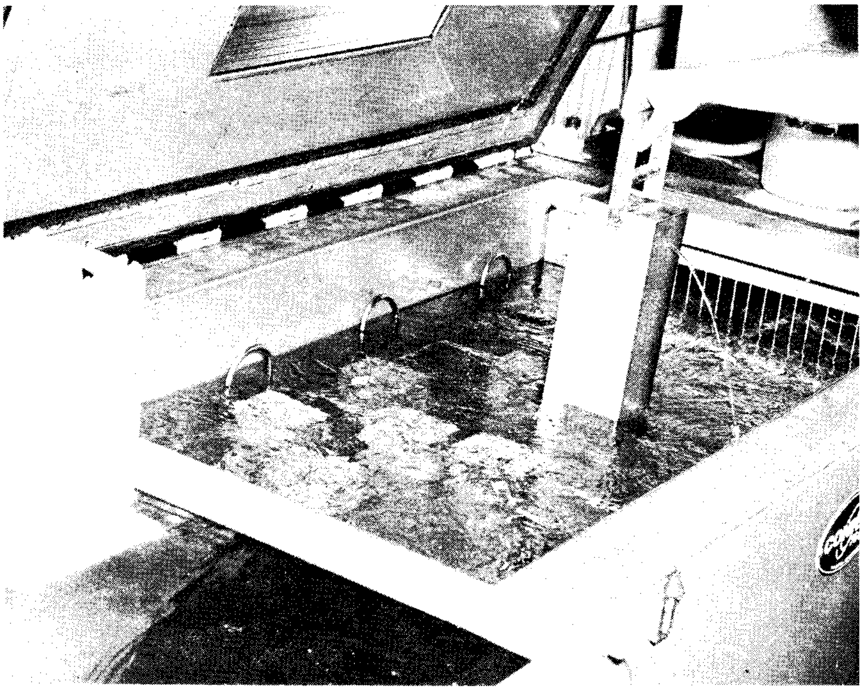


Figure 6 - Inside View of Freeze and Thaw Machine

DRYING SHRINKAGE TESTS

The measurement of drying shrinkage of concrete specimens was included in study in order to gain as much information as possible about lightweight concrete mixes.

Two shrinkage tests were performed. The first was the procedure described in ASTM C-330 60T Lightweight Aggregates for Structural Concrete and the second was the procedure described in AASHO M 195-62T, Interim Specification for Lightweight Aggregates for Structural Concrete.

In each case the mix was composed of one part of Portland Cement to six parts of aggregate by dry rodded volume. Two specimens were made for each mix. The average shrinkage of the two specimens are given in Table 9.

TABLE 9

DRYING SHRINKAGE DATA

Aggregate		Shrinkage	Shrinkage
Coarse Aggregate Number	Fine Aggregate Number	ASTM-C 330 Per Cent	AASHO-M 195 Per Cent
1	1A	0.060	0.053
1	1B	0.065	0.059
1	Sand	0.039	0.032
2	2A	0.076	0.051
2	2B	0.085	0.063
3	3A	0.141	0.099
4	Sand	0.040	-

DISCUSSION OF RESULTS

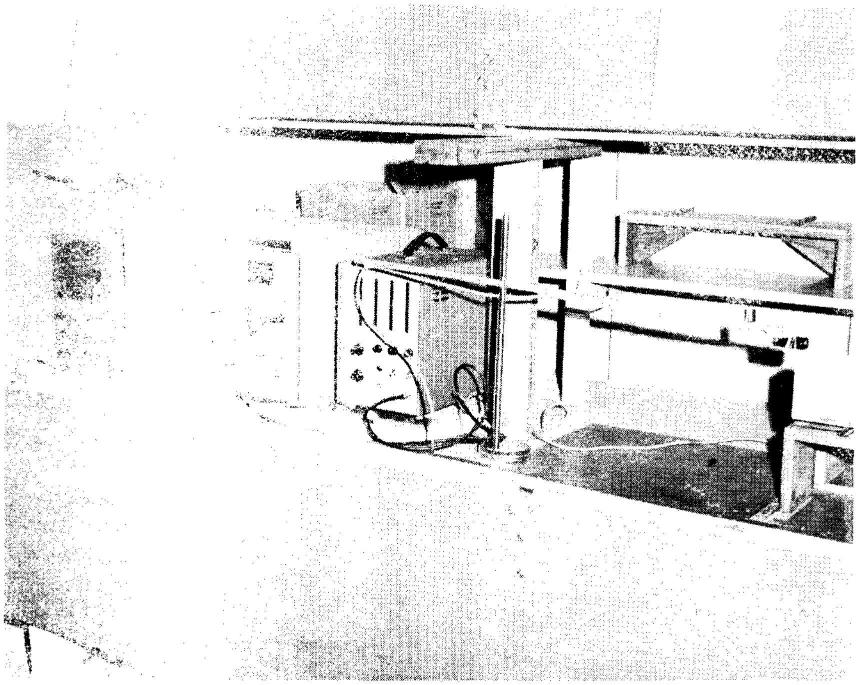
Freeze and Thaw Test

The criteria used for comparing the durability of the concrete specimens was dynamic modulus of elasticity. The dynamic modulus of elasticity was determined in accordance with ASTM C 215-60, Method of Test for Fundamental, Transverse Longitudinal, and Torsional Frequencies of Concrete Specimens. The transverse frequencies method was used for this study. The equipment for determining the dynamic modulus is shown in Figure 7.

At the completion of the curing period, the specimens were removed from the moist room, surface dried with cloth, weighed and then the dynamic modulus value was determined. After this step was completed, the specimens were placed in the freeze and thaw machine. Subsequent modulus readings were taken approximately every twenty cycles of freezing and thawing. This was changed to allow readings to be taken more often as the loss in modulus became greater and the specimens approached a failing condition. A specimen was considered to have failed when the original modulus was reduced by 40 percent. However, since the machine performs 8 cycles of freeze and thaw per day, it was impossible to get a reading exactly at the time the specimens had lost 40 percent of the originial modulus. Table 10 shows the results of the freeze and thaw test. The durability factors were calculated in accordance with ASTM C 291-57 T. In the cases where the dynamic modulus readings were not taken at exactly 300 cycles it was assumed that no change would have been evident at 300 cycles and, therefore, 300 cycles was used in determining the durability factors. The relative durability factor was determined by using the durability factory of the gravel and sand mix, containing no admixtures, as the reference and assuming this to be 100 per cent and then determining the other durability factors as based on a percentage of this value.

It became apparent after 300 cycles of freezing and thawing the lightweight concrete mixes, that very little loss in modulus was being obtained. Even the mixes made from the lightweight aggregate which had shown a poor service record had only lost approximately 6 per cent. Therefore, it was decided to continue the tests until 500 cycles were completed. This was done in all cases where possible. Photographs were taken of all specimens at the completion of the test. These photographs are given in Appendix B.

The reference concrete used in the study failed after 85 cycles of freezing and thawing. As seen in Table 10, all lightweight mixes were in excess of five times better as far as resistance to freeze and thaw cycles is concerned as was the gravel and sand mixes.



Modulus Equipment used in this study

TABLE 10

RESULTS OF FREEZING AND THAWING TESTS

Aggregate No.	Aggregate Cond.	Aggregate Agg.	Mix No.	Per Cent of Original E at Approximately 300 Cycles	Durability Factor at 300 Cycles	Relative Durability Factor at Approximately 300 Cycles	Per Cent of Original E at Completion of Test
				5.5 Sack Mix			
1	50%	1A	1-C	99.6 (301)	99.6	588	98.7 (504)
1	50%	1B	3-C	97.4 (305)	97.4	573	98.1 (503)
1	Sat.	1A	5-C	99.8 (318)	99.8	587	97.0 (502)
1	Sat.	1B	7-C	99.9 (318)	99.9	588	98.0 (502)
1	50%	Sand	25-C	99.4 (302)	99.4	585	98.0 (501)
1	Sat.	Sand	27-C	100.0 (373)	100.0	588	98.7 (502)
2	50%	2A	9-B	99.3 (304)	99.3	584	96.0 (504)
2	50%	2B	11-B	97.2 (297)	97.2	572	96.0 (504)
2	Sat.	2A	13-B	96.3 (302)	96.3	566	95.0 (502)
2	Sat.	2B	15-B	95.4 (308)	95.4	561	93.9 (500)
3	50%	3A	17-B	94.4 (250)	-	-	-
3	Sat.	3A	19-B	93.6 (299)	93.6	551	79.9 (463)
4	-	-	30-B	60.0 (85)	17.0	100	-
4	-	-	31-B	60.0 (83)	16.6	97.6	-

Numbers in parentheses refer to cycles of freezing and thawing.

TABLE 10 (Continued)

RESULTS OF FREEZING AND THAWING TESTS

Aggregate No.	Aggregate Cond.	Aggregate Agg.	Mix No.	Per Cent of Original E at Approximately 300 Cycles	Durability Factor at 300 Cycles	Relative Durability Factor at Approximately 300 Cycles	Per Cent of Original E at Completion of Test
6.0 Sack Mix							
1	50%	1A	2-C	97.6 (301)	97.6	574	97.6 (504)
1	50%	1B	4-C	97.7 (306)	97.7	575	97.3 (503)
1	Sat.	1A	6-C	97.7 (318)	97.7	575	95.1 (502)
1	Sat.	1B	8-C	98.7 (318)	98.7	581	96.9 (502)
1	50%	Sand	26-C	97.7 (302)	97.7	575	97.6 (501)
1	Sat.	Sand	28-C	99.7 (313)	99.7	586	97.7 (502)
2	50%	2A	10-B	98.6 (304)	98.6	580	96.6 (504)
2	50%	2B	12-B	98.1 (297)	98.1	577	95.7 (504)
2	Sat.	2A	14-B	99.1 (302)	99.1	583	99.0 (502)
2	Sat.	2B	16-B	95.4 (308)	95.4	561	93.8 (500)
3	50%	3A	18-B	91.8 (298)	91.8	540	84.4 (494)
3	Sat.	3A	20-B	91.5 (296)	91.5	538	88.2 (466)

Numbers in parentheses refer to cycles of freezing and thawing.

Influence of Fine Aggregate Gradation on Durability

Figure 8 shows the durability factors compared for mixes which were identical except for the percentage of fine aggregate passing a No. 100 sieve. Of the mixes containing 5.5 sacks of cement per cubic yard, only one showed better results with approximately 25 per cent of the fine aggregate passing a 100 sieve. The other three comparative mixes showed better results with approximately 15 per cent of fine aggregates passing a 100 sieve.

The mixes containing 6.0 sacks of cement per cubic yard had two mixes which gave better results with 25 per cent of the fine aggregate passing a No. 100 sieve and two mixes which gave better results with approximately 15 per cent of the fine aggregate passing a No. 100 sieve.

The loss in modulus at 500 cycles is not shown graphically, however, the trend was the same as that observed at 300 cycles.

Analyzing all the results, it appears that the larger percentage of material passing the 100 sieve is detremental to the lightweight concrete. The loss in durability was greater than the slight increase which occurred in some cases.

Influence of Moisture Content of Aggregates on Durability

Figure 9 shows the durability factors arranged to compare similar mixes with only the moisture condition of the aggregate as the variable. The two moisture conditions were (1) aggregate at approximately 50 per cent saturation and (2) aggregate that had been immersed in water for 24 hours prior to use.

The results of this phase of the study gave no conclusive results. Aggregate 1 gave better results with a saturated aggregate. Aggregate 2 gave better results with the aggregate at approximately 50 per cent saturation, and Aggregate 3 gave almost identical results for both conditons.

Influence of Cement Content on Durability

Figure 10 shows the durability factors arranged to compare similar mixes with varying cement contents. The two cement contents used were 5.5 and 6.0 sacks of cement per cubic yard.

The mixes containing 5.5 sacks of cement per cubic yard performed better than did the mixes containing 6.0 sacks of cement per cubic yard for all but four mixes. This was a very interesting development which will be pursued further at a later date.

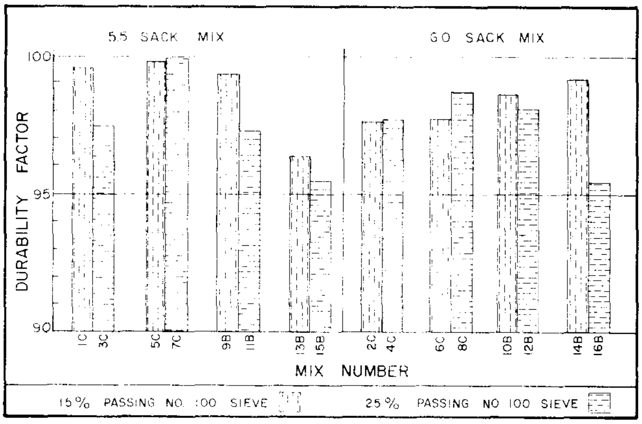


Figure 8 - Influence of Fine Aggregate Gradation on Durability

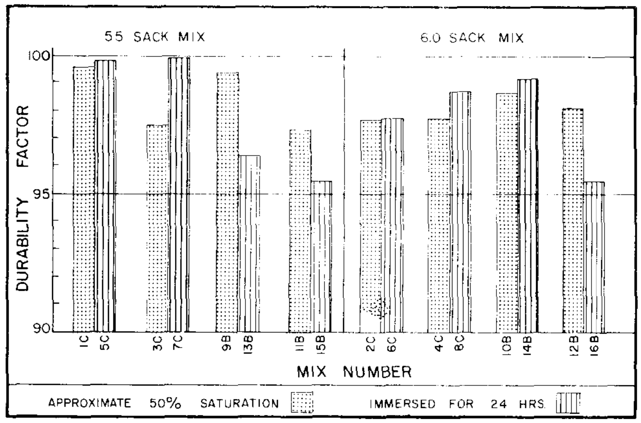


Figure 9 - Influence of Moisture Content of Aggregate on Durability

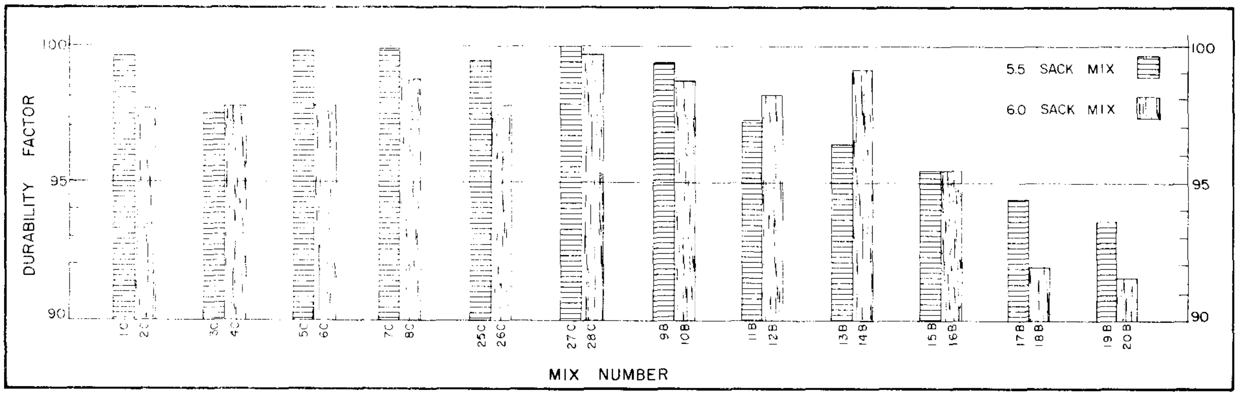


Figure 10 - Influence of Cement Content on Durability

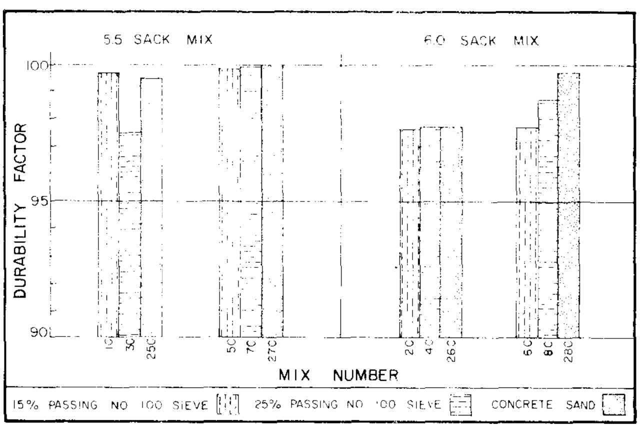


Figure 11 - Influence of Sand Used to Replace Lightweight Fines on Durability

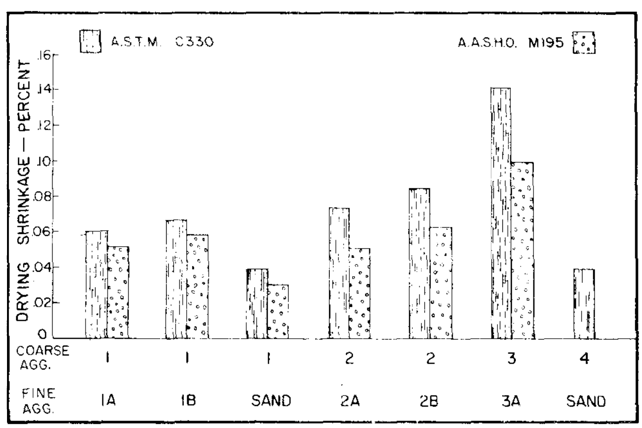


Figure 12 - Comparison of Drying Shrinkage

Influence of Sand Used to Replace Lightweight Fines on Durability

Figure 11 shows a comparison of the durability factors for mixes made with lightweight coarse and fine aggregate and lightweight coarse aggregate and sand. The coarse aggregate in all mixes was the same.

The results indicated that the replacement of fine lightweight aggregate with concrete sand had very little effect on the durability of the concrete. The most significant improvement was obtained on the 6.0 sack mix with the aggregate saturated.

Drying Shrinkage Test

The results of this phase of the study are shown graphically in Figure 12. Because of the test procedure called for in ASTM C330, it was impossible to compare the effects of moisture condition and cement content on drying shrinkage. The only comparisons that were made were the effect of the percent of fine aggregate passing the No. 100 sieve and the effect of sand when used as the fine aggregate.

In all cases, more shrinkage occurred when the fine aggregate had approximately 25 percent passing the No. 100 sieve. Also, the mix containing sand with lightweight coarse aggregate was comparable to a sand and gravel mix.

CONCLUSIONS

The results obtained from this study warrant the following conclusions:

1. It is evident that no general statement can be made concerning the comparison of wetting and drying durability of lightweight concrete to normal sand and gravel concrete. The results of this study indicated that one source of lightweight aggregate was more durable than normal sand and gravel concrete and that two sources were less durable.

2. The two cement contents studied (5.5 and 6.0 sacks/cu.yd.) produced no apparent difference of wetting and drying durability of lightweight concrete.

3. The larger the amount of minus No. 100 material present in lightweight fine aggregate, then, generally, the less durable is the concrete in regards to wetting and drying.

4. The higher the initial moisture content of the lightweight aggregate, the lower is the wetting and drying durability of the concrete.

5. Concrete sand used to replace lightweight fine aggregate improves the wetting and drying durability of lightweight concrete in most cases.

6. Lightweight concrete has much greater resistance to freeze and thaw damage than does the normal sand and gravel concrete used in this area.

7. Lightweight fine aggregate should not have more than 20 percent passing the No. 100 sieve.

8. The moisture condition of the aggregate has very little effect on the resistance to freeze and thaw damage, provided the concrete is properly cured before being subjected to freezing conditions.

9. The reduction in durability obtained when the cement content was increased from 5.5 to 6.0 sack per cubic yard cannot be explained at this time. However, further work will be done to try to determine the reasons.

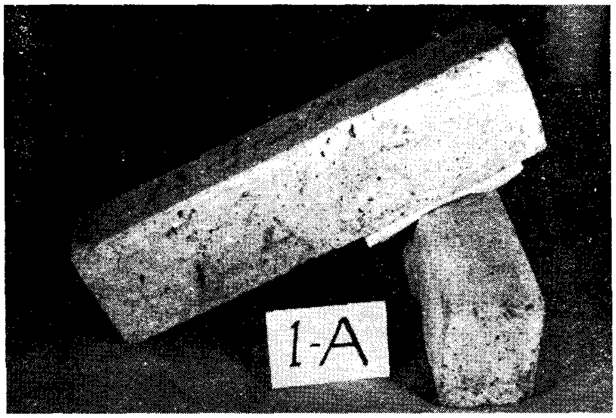
10. The use of concrete sand to replace lightweight fine aggregate had no significant effect on durability.

11. The drying shrinkage of lightweight concrete is different for each source of aggregate. Concrete sand used to replace lightweight fines reduces the

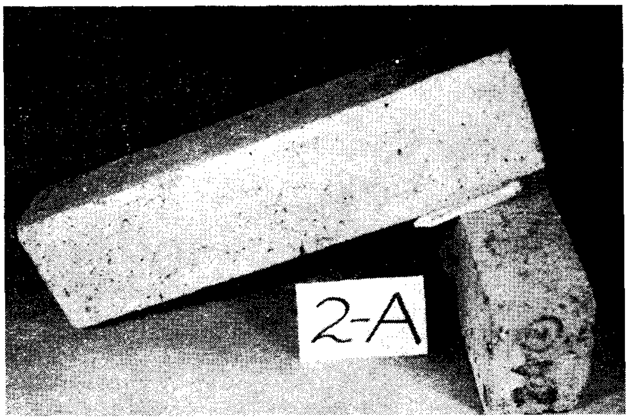
shrinkage to approach what is normally obtained for a sand and gravel mix.

The above conclusions are based on the results obtained from this study. It should be pointed out that each source of lightweight concrete may exhibit different characteristics and should be treated accordingly.

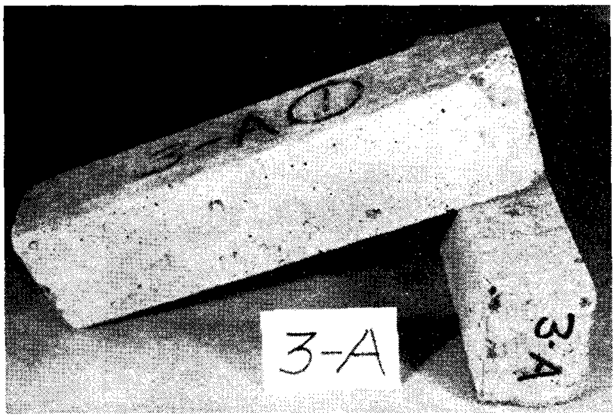
APPENDIX A



Mix No. 1 - A - 300 Cycles of Wetting and Drying

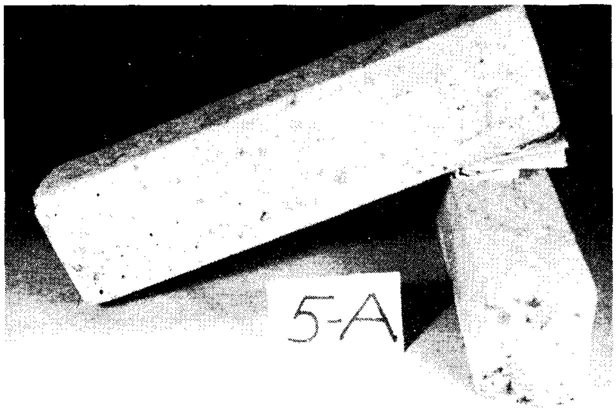


Mix No. 2 - A - 300 Cycles of Wetting and Drying

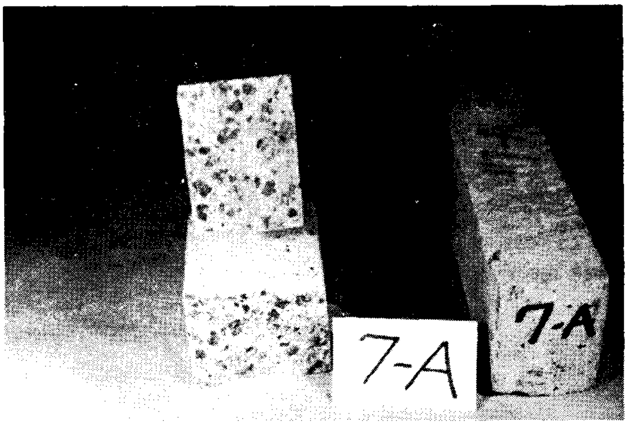


Mix No. 3 - A - 300 Cycles of Wetting and Drying

Mix No. 4 - A - 300 Cycles of Wetting and Drying

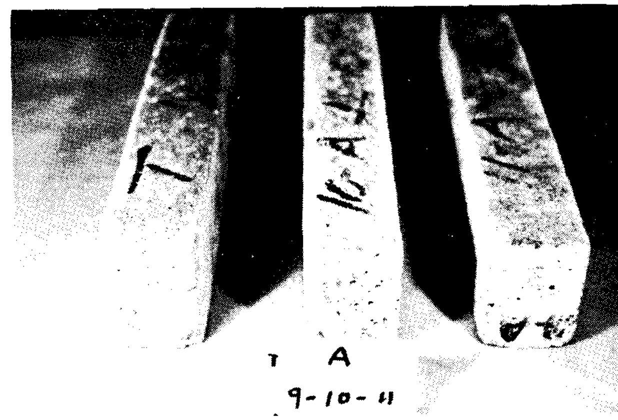


Mix No. 5 - A - 300 Cycles of Wetting and Drying

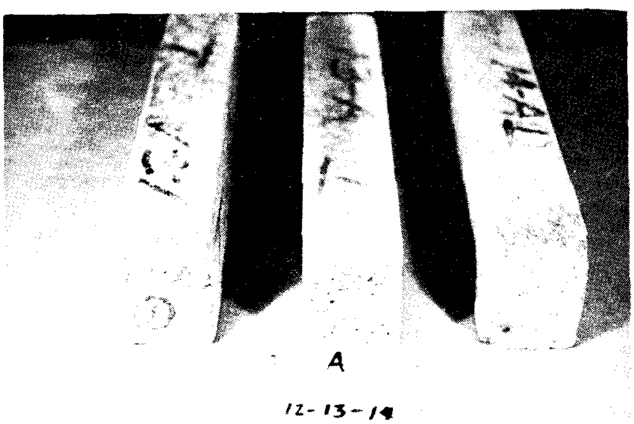


Mix No. 7 - A - 300 Cycles of Wetting and Drying

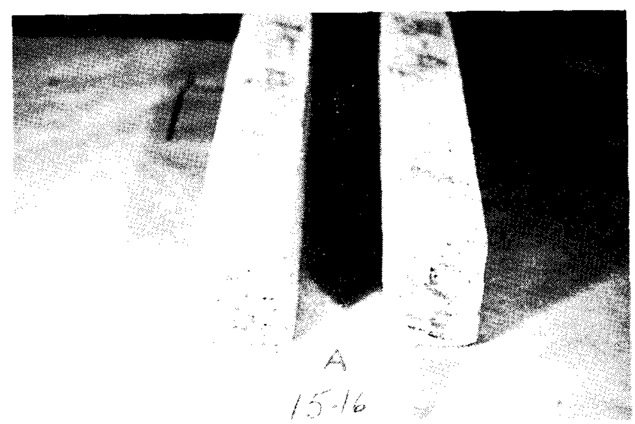
Mix No. 8 - A - 300 Cycles of Wetting and Drying



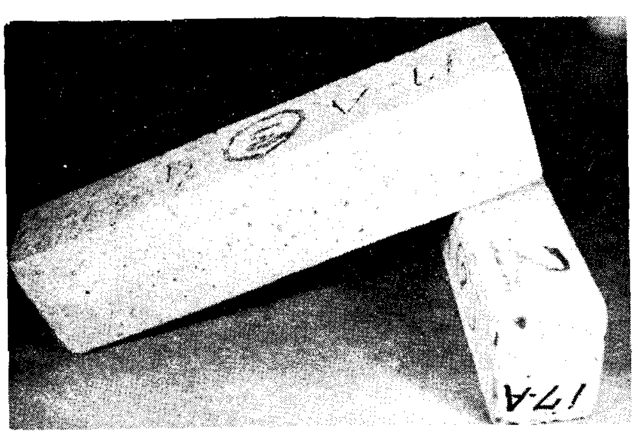
Mix No. 9 - A, 10 - A, and 11 - A - 300 Cycles of Wetting and Drying



Mix No. 12 - A, 13 - A, and 14 - A - 300 Cycles of Wetting and Drying



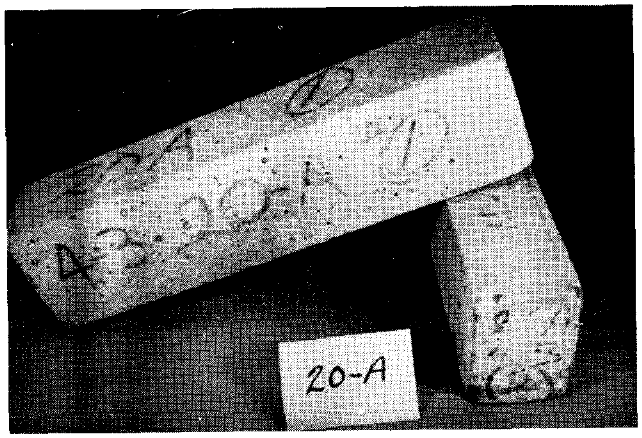
Mix No. 15 - A and 16 - A - 300 Cycles of Wetting and Drying



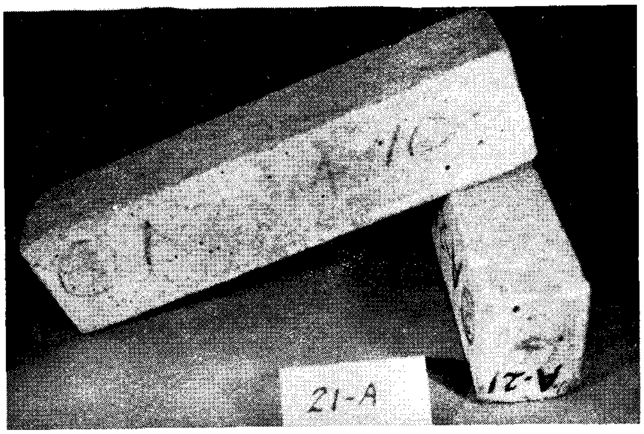
Mix No. 17 - A - 300 Cycles of Wetting and Drying

Mix No. 18 - A - 300 Cycles of Wetting and Drying

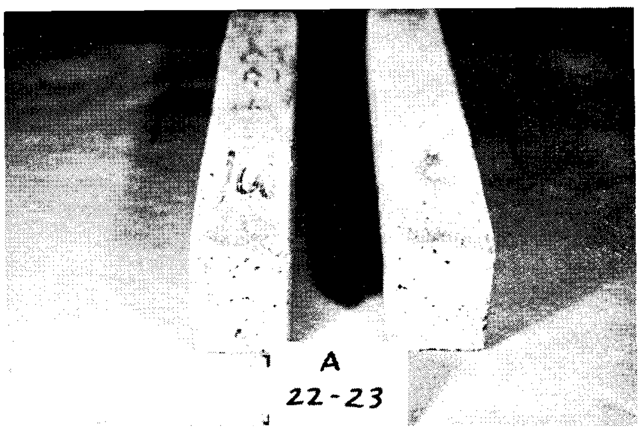
Mix No. 19 - A - 300 Cycles of Wetting and Drying



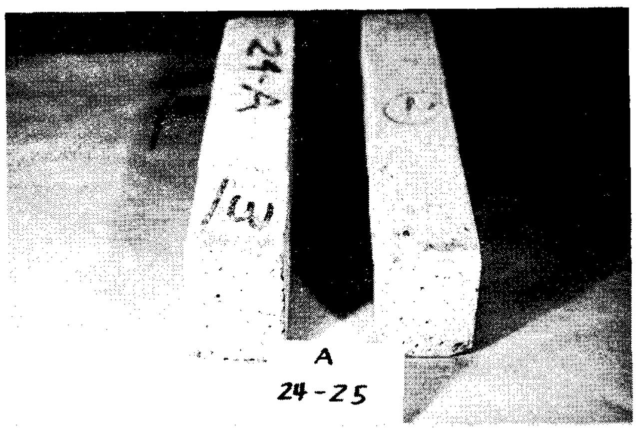
Mix No. 20 - A - 300 Cycles of Wetting and Drying



Mix No. 21 - A - 300 Cycles of Wetting and Drying

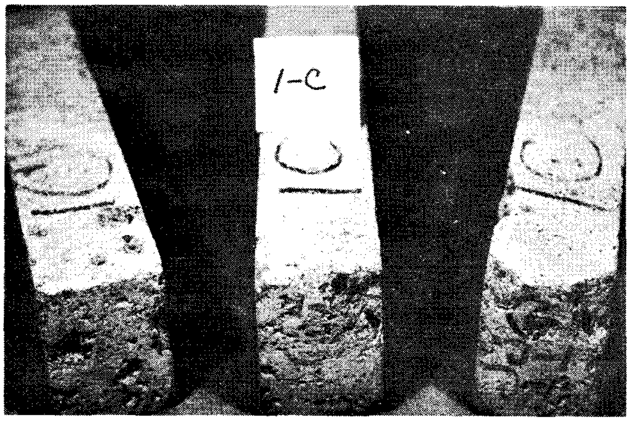


Mix No. 22 - A and 23 - A 160 and 300 Cycles, Respectively, of Wetting and Drying

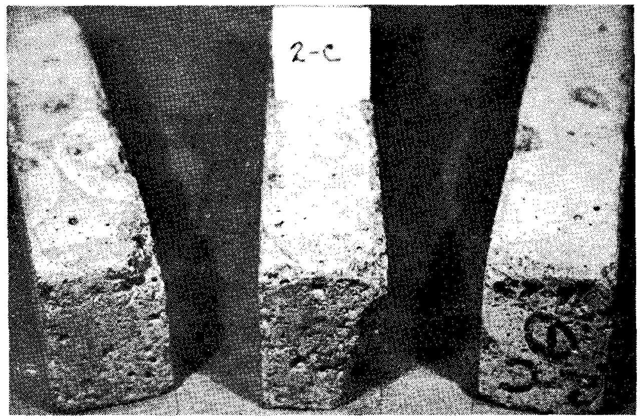


Mix No. 24 - A and 25 - A - 300 and 195 Cycles, Respectively, of Wetting and Drying

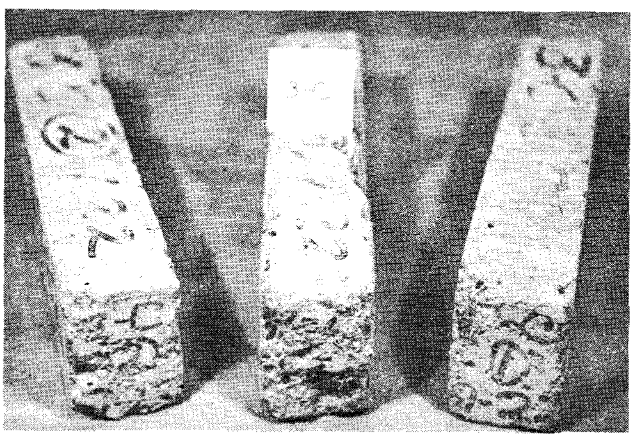
APPENDIX B



Mix No. 1-C - 504 Cycles of Freezing and Thawing

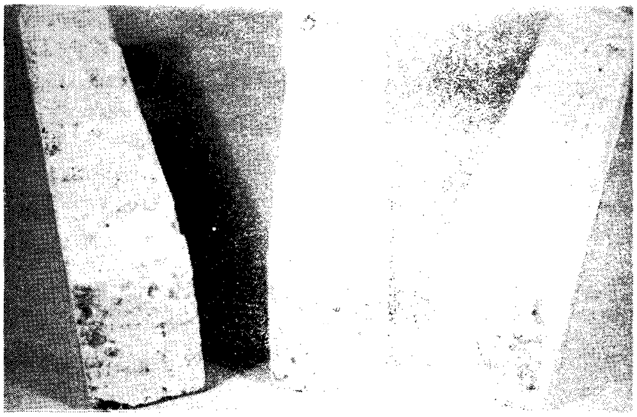


Mix No. 2-C - 504 Cycles of Freezing and Thawing

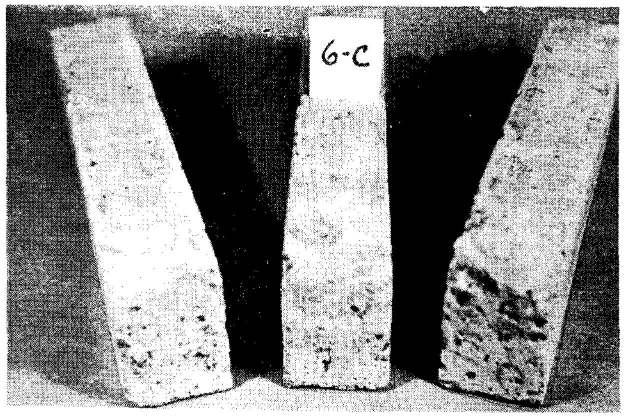


Mix No. 3-C - 503 Cycles of Freezing and Thawing

Mix No. 4-C - 503 Cycles of Freezing and Thawing

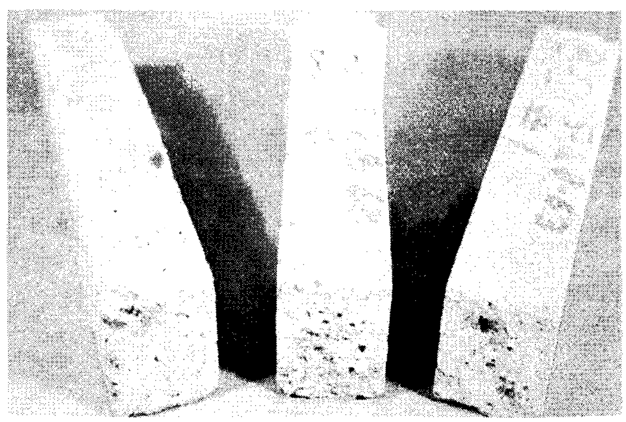


Mix No. 5-C - 502 C[illegible]*awing*

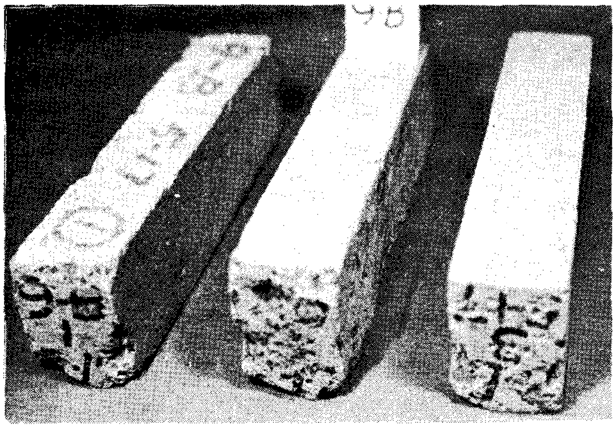


Mix No. 6-C - 502 Cycles of Freezing and Thawing

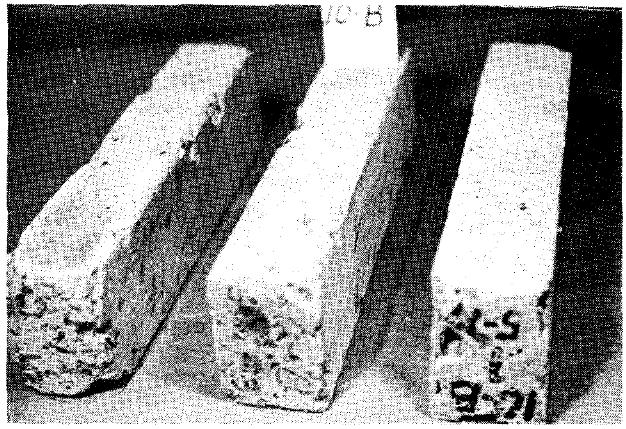
Mix No. 7-C - 502 Cy[illegible]*awing*



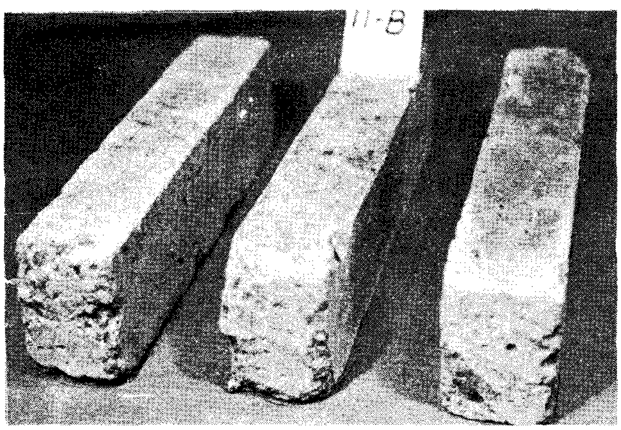
Mix No. 8-C - 502 Cycles of Freezing and Thawing



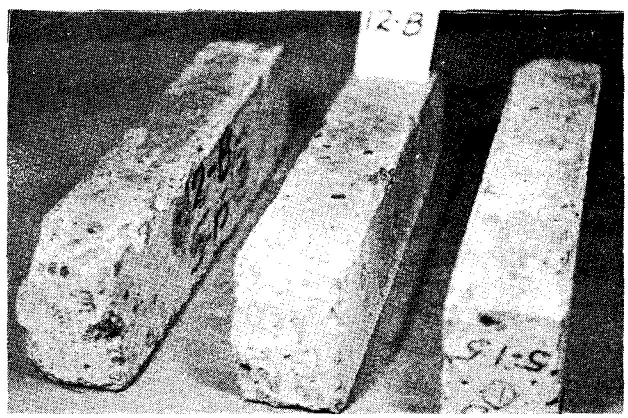
Mix No. 9-B - 504 Cycles of Freezing and Thawing



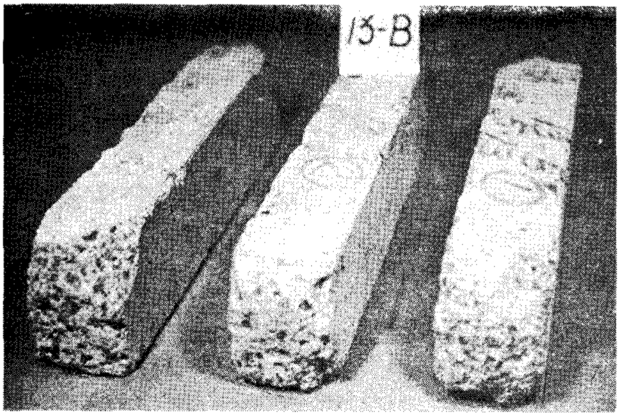
Mix No. 10-B - 504 Cycles of Freezing and Thawing



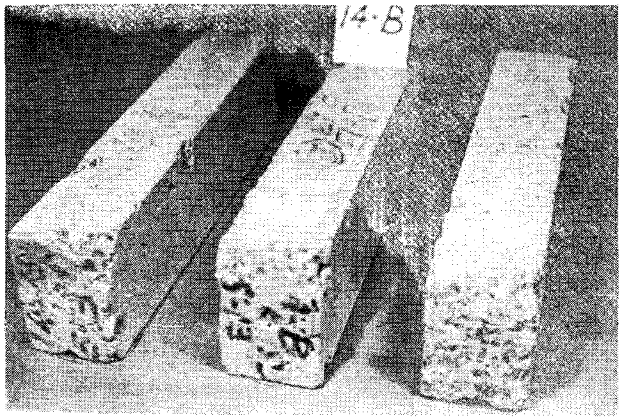
Mix No. 11-B - 504 Cycles of Freezing and Thawing



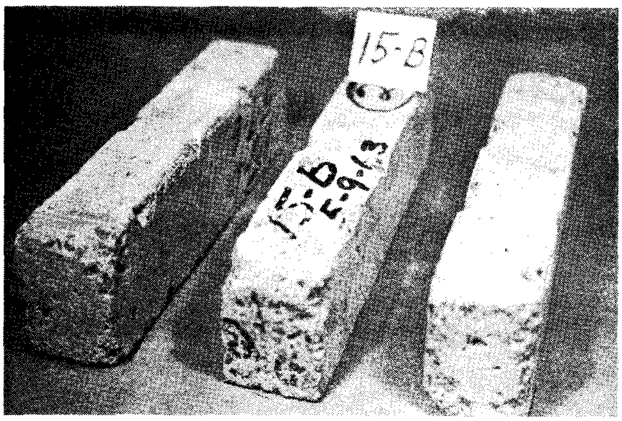
Mix No. 12-B - 504 Cycles of Freezing and Thawing



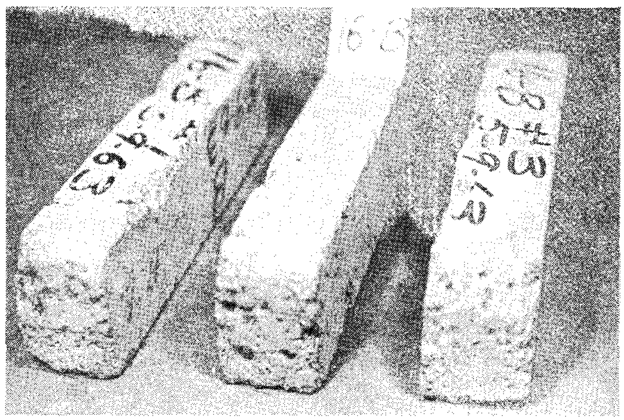
Mix No. 13-B - 502 Cycles of Freezing and Thawing



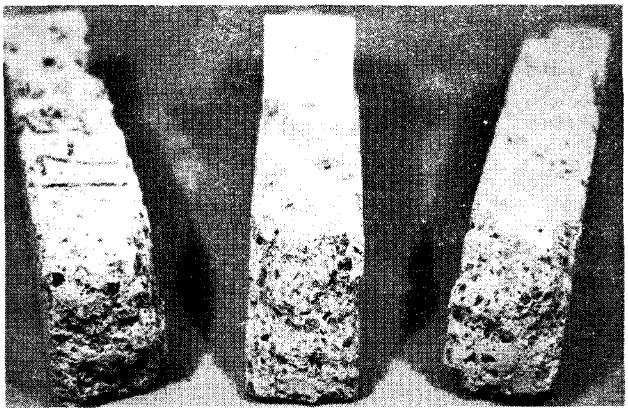
Mix No. 14-B - 502 Cycles of Freezing and Thawing



Mix No. 15-B - 500 Cycles of Freezing and Thawing

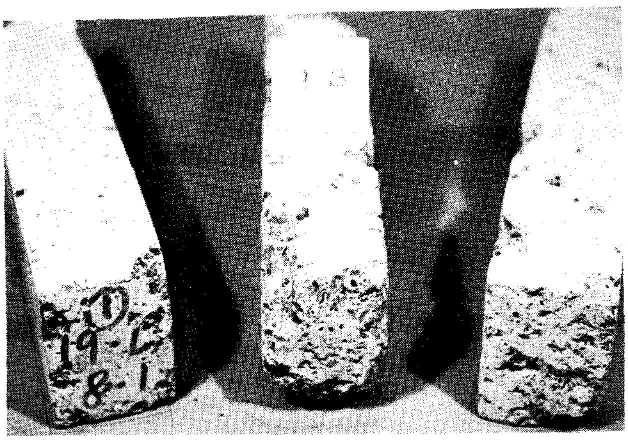


Mix No. 16-B - 500 Cycles of Freezing and Thawing

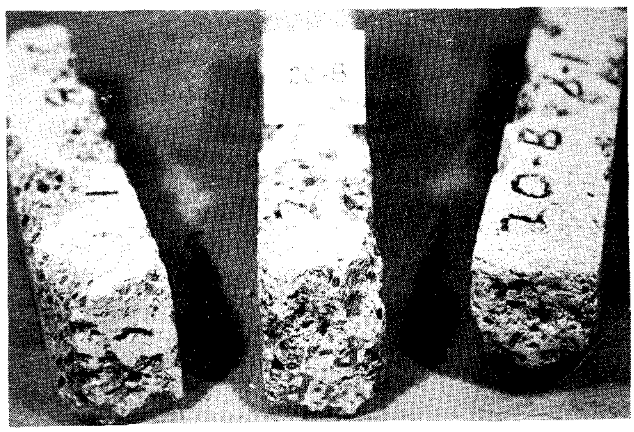


Mix No. 17-B - 250 Cycles of Freezing and Thawing

Mix No. 18-B - 494 Cycles of Freezing and Thawing



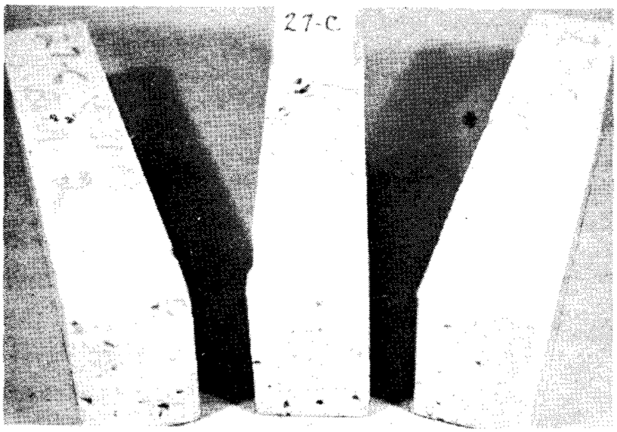
Mix No. 19-B - 463 Cycles of Freezing and Thawing



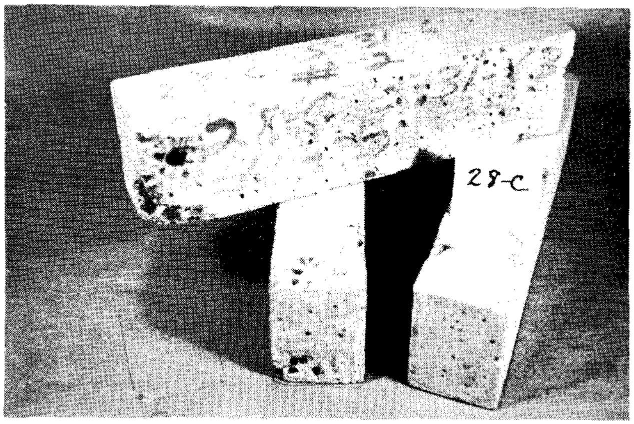
Mix No. 20-B - 466 Cycles of Freezing and Thawing

Mix No. 25-C - 501 Cycles of Freezing and Thawing

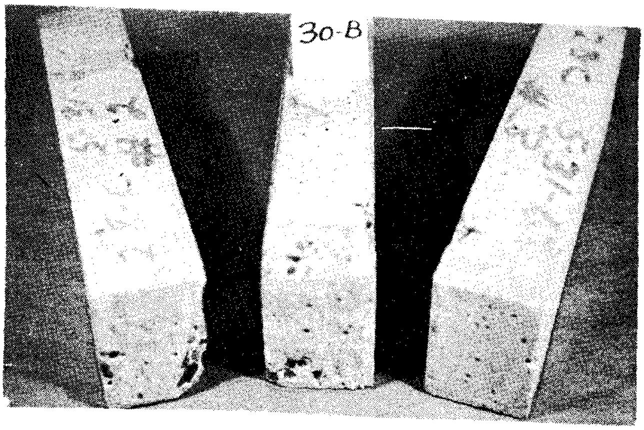
Mix No. 26-C - 501 Cycles of Freezing and Thawing



Mix No. 27-C - 502 Cycles of Freezing and Thawing



Mix No. 28-C - 502 Cycles of Freezing and Thawing



Mix No. 30-B - 85 Cycles of Freezing and Thawing

Mix No. 31-B - 83 Cycles of Freezing and Thawing

Louisiana Highway Research

DURABILITY OF LIGHTWEIGHT CONCRETE
PHASE III
FREEZING AND THAWING TESTS
OF LIGHTWEIGHT CONCRETE

Louisiana Department of Highways-Research Unit

DURABILITY OF LIGHTWEIGHT CONCRETE

PHASE III

FREEZING AND THAWING TESTS
of
LIGHTWEIGHT CONCRETE

by

HOLLIS B. RUSHING
Concrete Research Engineer

Research Report No. 18

Research Project No. 61-8C
Louisiana HPR 1(3)

Conducted by
LOUISIANA DEPARTMENT OF HIGHWAYS
Research & Development Section
in Cooperation with
U. S. Department of Commerce
BUREAU OF PUBLIC ROADS

August 1965

SYNOPSIS

This report is primarily concerned with developing a criterion to be used in evaluating lightweight aggregates for use in structural concrete. It covers Phase III, Freeze and Thaw Resistance, of a three phase project dealing with Durability of Lightweight Concrete.

Phases I and II are described in the introduction of the report and the findings of these studies will be reported as soon as the work is completed.

The testing program covered three sources of lightweight aggregate and one source of gravel and sand. The tests consisted of subjecting specimens made from concrete mixes containing various cement contents and aggregate gradations with the moisture condition of the aggregates varied, to rapid freezing and thawing in air. In addition, complete physical tests were run on the aggregates such as, gradation, unit weight, abrasion and soundness loss.

The results of this study indicate that lightweight concrete is more resistant to freezing than sand and gravel concrete. In addition, a criterion of 500 cycles of freezing and thawing in air with a loss of original modulus not to exceed 10 per cent, should be used for accepting lightweight aggregates for use in structural concrete.

FREEZING AND THAWING TESTS OF LIGHTWEIGHT AGGREGATE CONCRETE

INTRODUCTION

The Louisiana Department of Highways has undertaken an extensive program to study the properties of lightweight concrete. This program was started in 1961 with the awarding of a contract to Louisiana State University to study the shrinkage properties of various lightweight concrete mixes. The next study was conducted by the Research & Development Section of the Department and consisted of two projects. The first being determination of the abrasion characteristics of lightweight aggregates and the development of a more comprehensive method of performing the abrasion test. The second was established to study the durability characteristics of lightweight concrete. This study was divided into three phases. Phase I consisted of installing a recording thermometer in both lightweight concrete and sand and gravel concrete bridge decks to determine the range of temperature encountered during a one year period. Phase II of the study consisted of studing various lightweight mixes when subjected to 300 cycles of wetting and drying. Phase III consisted of studying the effects of freezing and thawing on lightweight concrete mixes. The next step in this program was the awarding of a contract to Louisiana State University to make a field evaluation of all lightweight bridges built in the State.

As of this writing, the project on shrinkage conducted by Louisiana State University and the abrasion study performed by the Department have been completed and reports published. Phase I and II of the Durability Study are in progress and reports will be published as soon as possible. Phase III is complete and is covered by this report. The bridge study is approximately 95 per cent complete and a report will be forthcoming during the summer of 1965.

It is hoped that a much better understanding and knowledge of lightweight concrete will evolve when the results of these studies are evaluated and analyzed.

SCOPE

The use of lightweight aggregate in concrete is increasing rapidly, this is particularly true in structural application. Because of this, as much information as possible needs to be gathered concerning this material. Although several studies have been made by other agencies of freeze and thaw characteristics of lightweight concrete, it has become apparent that every source of lightweight aggregate will have to be studied for its particular properties. Because it is a manufactured product, results from one source cannot be used for another source.

The principal objective of this study was not to determine the number of cycles of freezing and thawing that lightweight concrete could endure, but to determine a test criteria for acceptance of a source of lightweight aggregate.

Three lightweight aggregates and one normal weight sand and gravel aggregate were used in this study. One lightweight coarse aggregate was also used in conbination with sand in concrete mixes.

Cement contents of 5.5 and 6.0 bags per cubic yard were studied for each parameter. Two lightweight fine aggregate gradations were used, (1) approximately 15 per cent passing the No. 100 sieve, and (2) approximately 25 per cent passing the No. 100 sieve. The lightweight aggregates were used at two different moisture conditions, (1) at approximately 50% saturation (2) after 24 hours of immersion in water. The moisture content that approximated 50 per cent saturation, was found by immersing samples of the lightweight aggregates in water for various periods of time. The moisture content was then plotted versus the immersed time. From the curve, a value was selected which most nearly represented 50 per cent saturation. The moisture content was in the range of 15-18 per cent by weight. It was also found that the largest per cent of absorption occurred during the first 24 hours. After 24 hours, the rate of absorption is very slow and very little change in moisture content occurs. An air entraining agent and a water reducing agent were used in all lightweight mixes, and in one sand and gravel mix. The air content was maintained between 6 to 9 per cent in the lightweight concrete and 3 to 6 per cent in the sand and gravel mix.

MATERIALS

The cement used in all the concrete mixes was Type I produced in Baton Rouge, Louisiana.

The three lightweight aggregates and the sand and gravel used in this study are briefly described as follows:

Aggregate 1 - An expanded clay produced in a rotary kiln. The raw material is passed through a 3 inch screen prior to introduction into the 160 foot long kiln in which the maximum temperature is near 2000°F. Some crushing is necessary to produce fine aggregate.

Aggregate 2 - An expanded clay produced in a rotary kiln. The raw material is passed through a 5 inch screen prior to introduction into a 40 foot long kiln in which the maximum temperature is near 2000°F. Some crushing is necessary to produce fine aggregate.

Aggregate 3 - An expanded clay produced by the sintering process. The raw material is compressed into small briquettes approximately one inch in diameter and eight inches long. The briquettes are then placed on a continously moving sintering grate and screeded off to a depth of approximately 8 inches before entering the kiln where the temperature is maintained at approximately 2000°F. All aggregates, both coarse and fine are produced by crushing the briquettes.

Aggregate 4 - The sand and gravel aggregates are natural uncrushed material obtained from the Amite River in Louisiana. They are both predominantly siliceous materials. These aggregates have a good service record in this area.

The admixtures used in the study consisted of a water reducing, set retarding agent (calcium lignosulfonate) and an air entraining agent (neutralized vinsol resin). The water reducing, set retarding admixture was used at a rate of 0.25 lb. per sack of cement, while the air entraining agent was used at a rate necessary to produce the required amount of air. This rate varied from 0.75 oz. to 1.25 ozs. per sack of cement, depending on the mix being used.

TEST PROCEDURES FOR AGGREGATES

The aggregates were prepared and tested in accordance with the methods listed below:

AASHO T 27-60 Method of Test for Sieve Analysis of Fine and Coarse Aggregate.

AASHO T 19-56 Method of Test for Unit Weight of Aggregate.

AASHO T 96-60 Method of Test for Abrasion of Coarse Aggregate by Use of the Los Angeles Machine

AASHO T 104-57 Method of Test for Soundness of Aggregates by Use of Sodium Sulfate or Magnesium Sulfate

LDH TR 103-63 Method of Test for Sand Equivalent

TEST RESULTS FOR AGGREGATES

The gradations and the unit weights of the aggregates are shown in Table I.

The results of all other tests performed on the aggregates are given in Table II. The sand equivalent test was run on all the fine aggregates in an effort to determine the amount of colloids that may be present.

TABLE II

LOS ANGELES ABRASION, SOUNDNESS AND SAND EQUIVALENT RESULTS

	Los Angeles Abrasion Grade B-Per Cent Loss	Magnesium Sulfate Soundness	Sand Equivalent
Aggregate 1			
Coarse	26.3	3.0	
Fine 1A		10.3	76
Fine 1B		11.8	67
Aggregate 2			
Coarse	41.1	6.4	
Fine 2A		4.0	87
Fine 2B		4.4	79
Aggregate 3			
Coarse	37.0	17.5	
Fine 3A		32.3	56
Aggregate 4			
Gravel	21.7	6.7	
Sand		2.3	92

Concrete

As stated before, cement contents of 5.5 and 6.0 sacks per cubic yard were used for all variables tested. The concrete was mixed in a 3.5 cu ft revolving drum mixer. The aggregate and approximately two-thirds of the water including the admixtures when required were added and mixed for 1 minute. The cement and remaining water were then added and mixing continued for 4 additional minutes.

The lightweight mixes were designed by trial and error based on the unit weight of concrete. An estimated fresh unit weight was predicted and the mix designed from this figure. A trial mix was then made and the fresh unit weight determined. If the measured unit weight varied from the estimated unit weight, then the mix was redesigned using the measured unit weight. This procedure was followed for all lightweight mixes. No attempt was made to determine specific gravities of the lightweight aggregates. It was felt that since lightweight aggregates are manufactured products their gravities would change from day to day and hence could not be used as a basis for design. In addition, it is almost impossible to obtain a saturated surface dry condition because of the highly absorptive characteristic of the lightweight aggregates. The sand and gravel mixes were designed by absolute volume.

The consistency of the concrete was generally held in a range of 2 to 4 inches in slump. Air content was determined by AASHO T152-57.

The specimens for freeze and thaw testing were 3 x 4 x 16 inch concrete prisms. Cylinders used for determining compressive strength were 6 in. x 12 in. All specimens were made and cured in accordance with AASHO T 126 - 60 except as otherwise noted.

Table III shows the data for all of the concrete mixtures. The condition of the aggregate is shown either by (1) 50%, which means approximately 50 per cent saturated, or (2) saturated meaning immersed for 24 hours prior to use. The compressive strength results shown are an average of 3 cylinders tested at 28 days age.

Freeze and Thaw Tests

The specimens for freeze and thaw testing were cured for 7 days in a moist room at 73.4± 2°F. and 100 per cent relative humidity. They were then placed in a curing room maintained at 73.4± 2°F. and 50 per cent relative humidity for 14 days. The specimens were then moved to the moist room for 7 additional days. At the completion of this curing procedure, which took 28 days, the freeze and thaw tests were started. This curing procedure is the one recommended by the Bureau of Public Roads for freeze and thaw specimens.

The test procedure used for the freeze and thaw tests was ASTM Designation C 291-57T, Test for Resistance of Concrete Specimens to Rapid Freezing in Air and Thawing in Water.

TABLE III
CONCRETE MIX DATA

Aggregate No.	Aggregate Cond.	Fine Agg. No.	Mix No.	Quantities Per Sack of Cement: Cem. Lbs.	Aggregate Fine Lbs.	Aggregate Coarse Lbs.	Total Water Lbs.	Admixtures: Air Entraining Ozs.	Admixtures: Water Reducer Lbs.	Slumps In.	Air Content Per Cent	Unit Wt. of Plastic Concrete lbs./cu.ft.	Actual Cement Content Bags/Yard	Comp. Strength 28 days p.s.i.
							5.5 Sack Mix							
1	50%	1A	1-C	94	131.0	85.6	95.0	1.25	.25	2 3/4	7.8	87.2	5.54	4581
1	50%	1B	3-C	94	133.0	109.5	95.0	1.25	.25	2 3/4	8.4	87.6	5.47	5150
1	Sat.	1A	5-C	94	131.0	107.0	105.0	1.00	.25	3 1/2	9.0	88.0	5.45	3704
1	Sat.	1B	7-C	94	140.5	115.0	107.0	1.00	.25	3	7.5	92.8	5.47	4528
1	50%	Sand	25-C	94	233.0	125.5	68.0	1.25	.25	2 3/4	8.0	106.0	5.50	4170
1	Sat.	Sand	27-C	94	231.5	125.0	75.0	0.75	.25	3 3/4	8.0	106.8	5.50	4005
2	50%	2A	9-B	94	163.5	133.5	105.0	1.00	.25	2 3/4	8.0	100.8	5.51	3233
2	50%	2B	11-B	94	160.5	131.5	105.0	1.00	.25	2 3/4	7.5	100.8	5.54	3922
2	Sat.	2A	13-B	94	160.5	131.5	110.0	1.00	.25	2 1/4	8.0	101.2	5.50	2901
2	Sat.	2B	15-B	94	159.0	130.0	100.0	1.00	.25	2 3/4	8.0	100.8	5.58	3599
3	50%	3A	17-B	94	166.0	135.5	110.0	2.00	.25	3 3/4	6.5	104.0	5.55	3649
3	Sat.	3B	19-B	94	168.5	138.0	115.0	2.00	.25	3 1/2	7.5	104.0	5.47	3414
4	-	-	30-B	94	204	357	43.0	1.00	.25	3	4.9	140.8	5.46	4178
4	-	-	31-B	94	217	357	50.0	-	-	3	1.5	145.2	5.46	4337
							6.0 Sack Mix							
1	50%	1A	2-C	94	119.5	97.5	85.0	1.25	.25	3	8.0	88.0	6.00	4734
1	57%	1B	4-C	94	119.5	97.5	85.0	1.25	.25	3	7.8	89.6	6.07	4864
1	Sat.	1A	6-C	94	121.5	99.5	97.0	1.00	.25	3	8.0	91.2	6.00	4652
1	Sat.	1B	8-C	94	127.0	104.0	98.0	1.00	.25	3	7.0	94.4	6.00	5076
1	50%	Sand	26-C	94	211.0	113.5	63.0	1.25	.25	3	7.5	106.4	5.97	4399
1	Sat.	Sand	28-C	94	210.5	113.5	68.0	0.75	.25	3 1/2	7.5	108.0	6.01	4641
2	50%	2A	10-B	94	163.5	133.5	105.0	1.00	.25	2 3/4	8.0	100.8	6.00	3900
2	50%	2B	12-B	94	143.0	117.0	95.0	1.00	.25	3	7.0	102.0	6.13	4576
2	Sat.	2A	14-B	94	143.5	117.0	100.0	1.00	.25	2 1/2	7.8	101.6	6.02	3463
2	Sat.	2B	16-B	94	146.0	119.5	95.0	1.00	.25	2 1/2	7.5	101.2	5.99	3909
3	50%	3A	18-B	94	150.5	123.5	100.0	2.00	.25	3 1/4	6.0	105.2	6.09	4170
3	Sat.	3B	20-B	94	148.0	121.0	105.0	2.00	.25	3 1/4	7.0	104.0	6.03	3816

The freeze and thaw cabinet used in this study is capable of producing from one cycle of freezing and thawing in 48 hours to eight cycles of freezing and thawing in 24 hours. Sixty specimens can be tested at one time. The temperature range is from 0°F. to 40°F. at the center of the specimens. The cycle consists of approximately two hours freezing and one hour thawing, when eight cycles are performed per day. Figures 1 and 2 show the freeze and thaw cabinet used in this study.

Drying Shrinkage Tests

The measurement of drying shrinkage of concrete specimens was included in study in order to gain as much information as possible about lightweight concrete mixes.

Two shrinkage tests were performed. The first was the procedure described in ASTM C-330 60 T Lightweight Aggregates for Structural Concrete and the second was the procedure described in AASHO M 195 - 62T, Interim Specification for Lightweight Aggregates for Structural Concrete.

In each case the mix was composed of one part of Portland Cement to six parts of aggregate by dry rodded volume. Two specimens were made for each mix. The average shrinkage of the two specimens are given in Table IV.

TABLE IV

DRYING SHRINKAGE DATA

Aggreate		Shrinkage ASTM-C 330 Per Cent	Shrinkage AASHO-M 195 Per Cent
Coarse Aggregate Number	Fine Aggregate Number		
1	1A	0.060	0.053
1	1B	0.065	0.059
1	Sand	0.039	0.032
2	2A	0.076	0.051
2	2B	0.085	0.063
3	3A	0.141	0.099
4	Sand	0.040	-

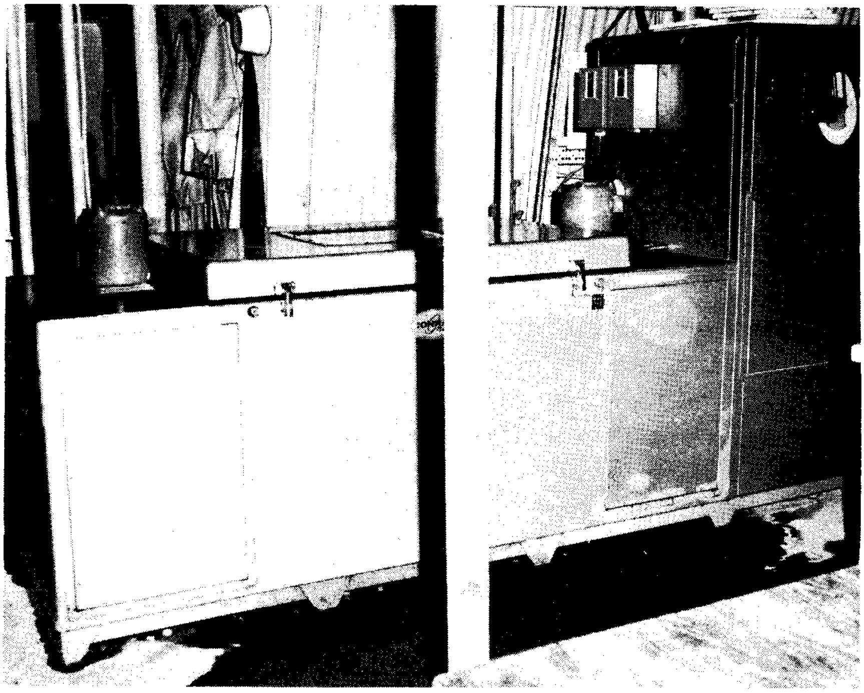


Fig. 1 Freeze and Thaw Machine Used in This Study

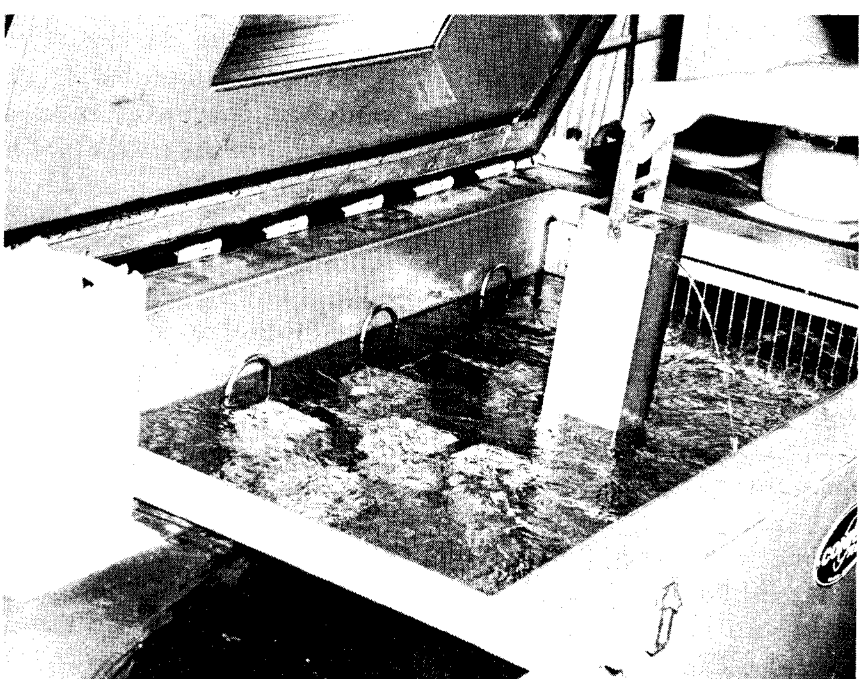


Fig. 2 Inside View of Freeze and Thaw Machine

DISCUSSION OF RESULTS

Freeze and Thaw Test

The criteria used for comparing the durability of the concrete specimens was dynamic modulus of elasticity. The dynamic modulus of elasticity was determined in accordance with ASTM C 215 - 60, Method of Test for Fundamental, Transverse Longitudinal, and Torsional Frequencies of Concrete Specimens. The transverse frequencies method was used for this study. The equipment for determining the dynamic modulus is shown in Figure 3.

At the completion of the curing period, the specimens were removed from the moist room, surface dried with cloth, weighed and then the dynamic modulus value was determined. After this step was completed, the specimens were placed in the freeze and thaw machine. Subsequent modulus readings were taken approximately every twenty cycles of freezing and thawing. This was changed to allow readings to be taken more often as the loss in modulus became greater and the specimens approached a failing condition. A specimen was considered to have failed when the original modulus was reduced by 40 per cent. However, since the machine performs 8 cycles of freeze and thaw per day, it was impossible to get a reading every time exactly when the specimens had lost 40 per cent of the originial modulus. Table V shows the results of the freeze and thaw test. The durability factors were calculated in accordance with ASTM C 291-57 T. In the cases where the dynamic modulus readings were not taken at exactly 300 cycles it was assumed that no change would have been evident at 300 cycles and, therefore, 300 cycles was used in determining the durability factors. The relative durability factor was determined by using the durability factor of the gravel and sand mix, containing no admixtures, as the reference and assuming this to be 100 per cent and then determining the other durability factors as based on a percentage of this value.

It became apparent after 300 cycles of freezing and thawing the lightweight concrete mixes, that very little loss in modulus was being obtained. Even the mixes made from the lightweight aggregate which had shown a poor service record had only lost approximately 6 per cent. Therefore, it was decided to continue the tests until 500 cycles were completed. This was done in all cases where possible. Photographs were taken of all specimens at the completion of the test. These photographs are given in the Appendix.

The reference concrete used in the study failed after 85 cycles of freezing and thawing. As seen in Table V, all lightweight mixes were in excess of five times better as far as resistance to freeze and thaw cycles is concerned as was the gravel and sand mixes.

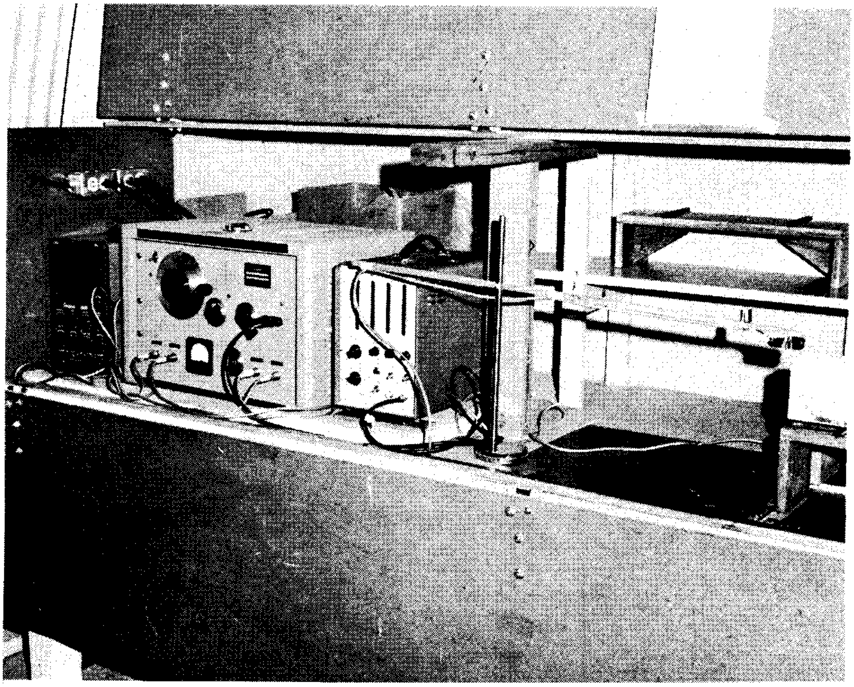


Fig. 3 Daynamic Modulus Equipment used in This Study

TABLE V

RESULTS OF FREEZING AND THAWING TESTS

Aggregate No.	Aggregate Cond.	Aggregate Agg.	Mix No.	Per Cent of Original E at Approximately 300 Cycles	Durability Factor at 300 Cycles	Relative Durability Factor at Approximately 300 Cycles	Per Cent of Original E at Completion of Test
				5.5 Sack Mix			
1	50%	1A	1-C	99.6 (301)	99.6	588	98.7 (504)
1	50%	1B	3-C	97.4 (305)	97.4	573	98.1 (503)
1	Sat.	1A	5-C	99.8 (318)	99.8	587	97.0 (502)
1	Sat.	1B	7-C	99.9 (318)	99.9	588	98.0 (502)
1	50%	Sand	25-C	99.4 (302)	99.4	585	98.0 (501)
1	Sat.	Sand	27-C	100.0 (373)	100.0	588	98.7 (502)
2	50%	2A	9-B	99.3 (304)	99.3	584	96.0 (504)
2	50%	2B	11-B	97.2 (297)	97.2	572	96.0 (504)
2	Sat.	2A	13-B	96.3 (302)	96.3	566	95.0 (502)
2	Sat.	2B	15-B	95.4 (308)	95.4	561	93.9 (500)
3	50%	3A	17-B	94.4 (250)	-	-	-
3	Sat.	3A	19-B	93.6 (299)	93.6	551	79.9 (463)
4	-	-	30-B	60.0 (85)	17.0	100	-
4	-	-	31-B	60.0 (83)	16.6	97.6	-

Numbers in parentheses refer to cycles of freezing and thawing.

TABLE V.(Continued)

RESULTS OF FREEZING AND THAWING TESTS

Aggregate No.	Aggregate Cond.	Aggregate Agg.	Mix No.	Per Cent of Original E at Approximately 300 Cycles	Durability Factor at 300 Cycles	Relative Durability Factor at Approximately 300 Cycles	Per Cent of Original E at Completion of Test
				6.0 Sack Mix			
1	50%	1A	2-C	97.6 (301)	97.6	574	97.6 (504)
1	50%	1B	4-C	97.7 (306)	97.7	575	97.3 (503)
1	Sat.	1A	6-C	97.7 (318)	97.7	575	95.1 (502)
1	Sat.	1B	8-C	98.7 (318)	98.7	581	96.9 (502)
1	50%	Sand	26-C	97.7 (302)	97.7	575	97.6 (501)
1	Sat.	Sand	28-C	99.7 (313)	99.7	586	97.7 (502)
2	50%	2A	10-B	98.6 (304)	98.6	580	96.6 (504)
2	50%	2B	12-B	98.1 (297)	98.1	577	95.7 (504)
2	Sat.	2A	14-B	99.1 (302)	99.1	583	99.0 (502)
2	Sat.	2B	16-B	95.4 (308)	95.4	561	93.8 (500)
3	50%	3A	18-B	91.8 (298)	91.8	540	84.4 (494)
3	Sat.	3A	20-B	91.5 (296)	91.5	538	88.2 (466)

Numbers in parentheses refer to cycles of freezing and thawing.

Influence of Fine Aggregate Gradation on Durability

Figure 4 shows the durability factors compared for mixes which were identical except for the percentage of fine aggregate passing a 100 sieve. Of the mixes containing 5.5 sacks of cement per cubic yard, only one showed better results with approximately 25 per cent of the fine aggregate passing a 100 sieve. The other three comparative mixes showed better results with approximately 15 per cent of the fine aggregates passing a 100 sieve.

The mixes containing 6.0 sacks of cement per cubic yard had two mixes which gave better results with 25 per cent of the fine aggregate passing a No. 100 sieve and two mixes which gave better results with approximately 15 per cent of the fine aggregate passing a No. 100 sieve.

The loss in modulus at 500 cycles is not shown graphically, however, the trend was the same as that observed at 300 cycles.

Analyzing all the results, it appears that the larger percentage of material passing the 100 sieve is detremental to the lightweight concrete. The loss in durability was greater than the slight increase which occurred in some cases.

Influence of Moisture Content of Aggregates on Durability

Figure 5 shows the durability factors arranged to compare similar mixes with only the moisture condition of the aggregate as the variable. The two moisture conditions were (1) aggregate at approximately 50 per cent saturation and (2) aggregate that had been immersed in water for 24 hours prior to use.

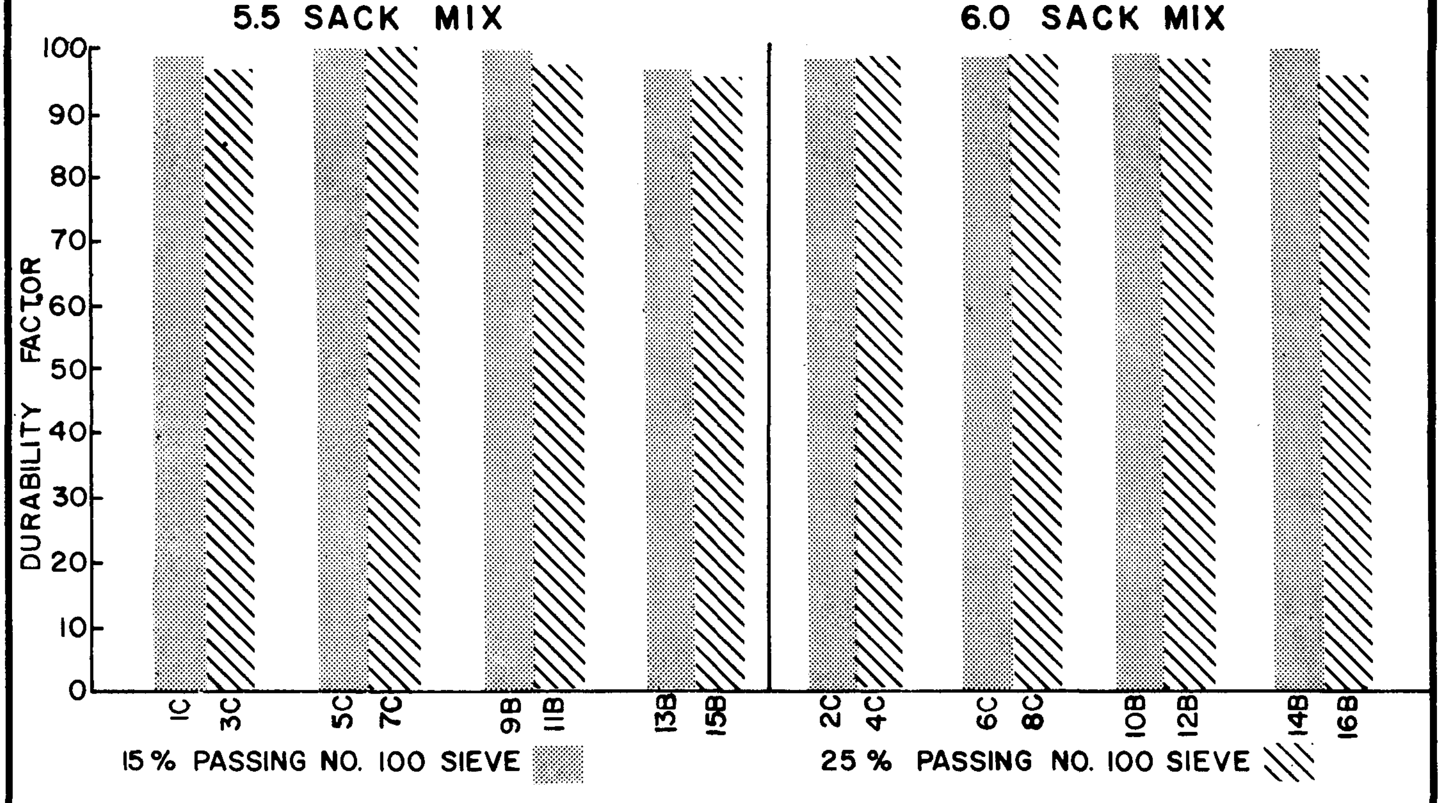
The results of this phase of the study gave no conclusive results. Aggregate 1 gave better results with a saturated aggregate. Aggregate 2 gave better results with the aggregate at approximately 50 per cent saturation, and Aggregate 3 gave almost identical results for both conditions.

Influence of Cement Content on Durability

Figure 6 shows the durability factors arranged to compare similar mixes with varying cement contents. The two cement contents used were 5.5 and 6.0 sacks of cement per cubic yard.

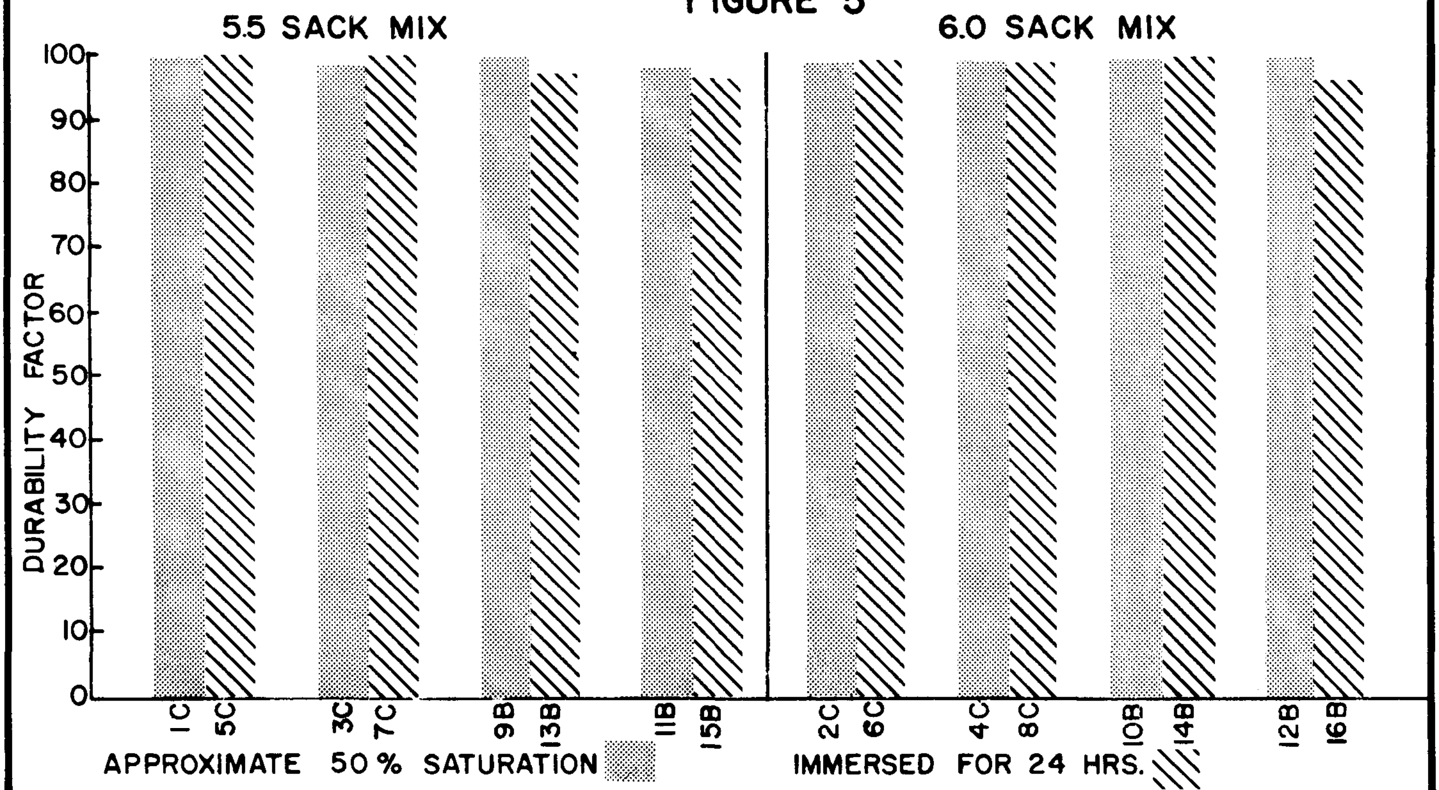
The mixes containing 5.5 sacks of cement per cubic yard performed better than did the mixes containing 6.0 sacks of cement per cubic yard for all but four mixes. This was a very interesting development which will be pursued further at a later date.

FIGURE 4



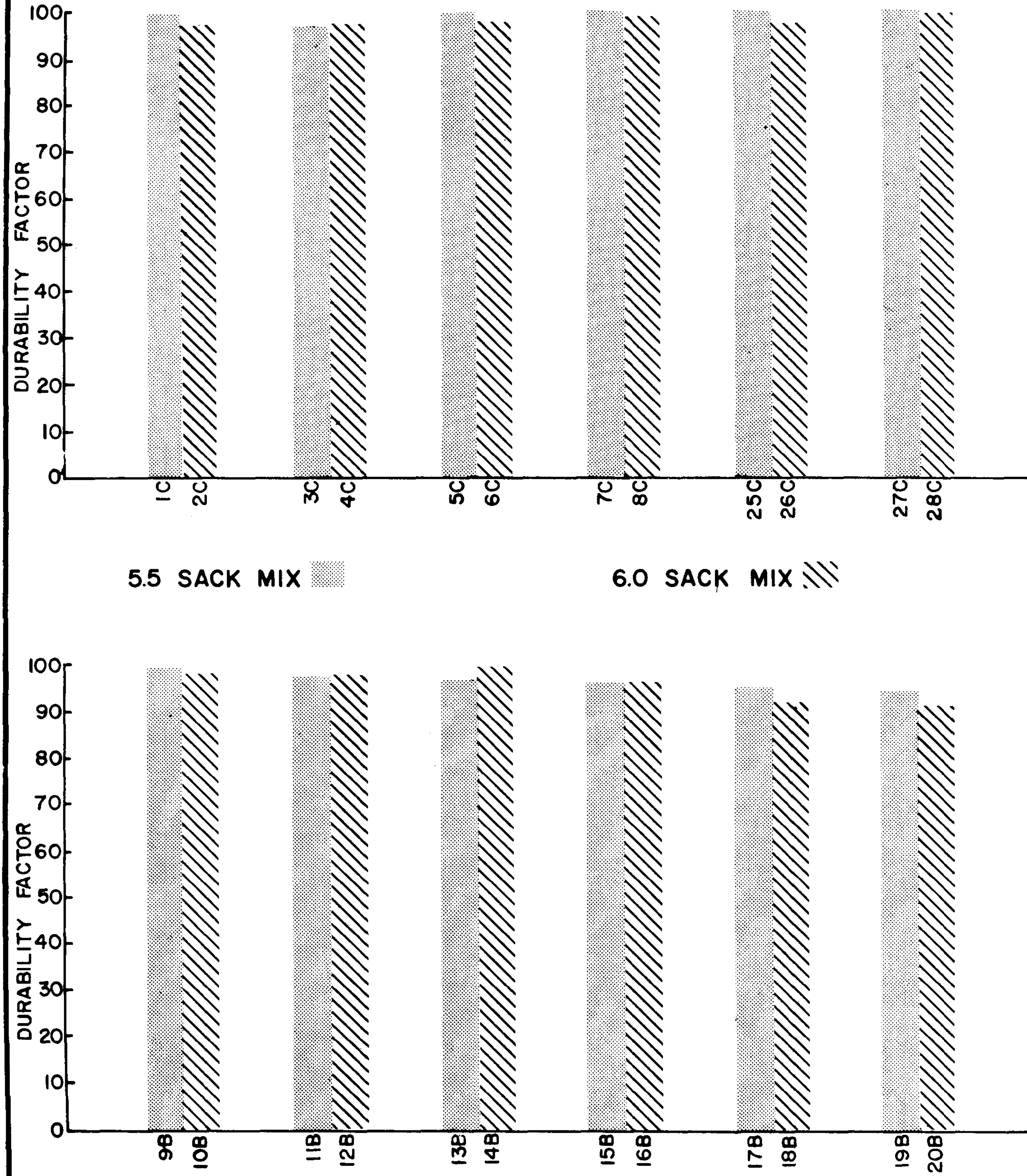
Influence of Fine Aggregate Gradation on Durability

FIGURE 5



Influence of Moisture Content of Aggregate on Durability

FIGURE 6



Influence of Cement Content on Durability

Influence of Sand Used to Replace Lightweight Fines on Durability

Figure 7 shows a comparison of the durability factors for mixes made with lightweight coarse and fine aggregate and lightweight coarse aggregate and sand. The coarse aggregate in all mixes was the same.

The results indicated that the replacement of fine lightweight aggregate with concrete sand had very little effect on the durability of the concrete. The most significant improvement was obtained on the 6.0 sack mix with the aggregate saturated.

Drying Shrinkage Test

The results of this phase of the study are shown graphically in Figure 8. Because of the test procedure called for in ASTM C 330, it was impossible to compare the effects of moisture condition and cement content on drying shrinkage. The only comparisons that were made were the effect of the per cent of fine aggregate passing the No. 100 sieve and the effect of sand when used as the fine aggregate.

In all cases, more shrinkage occurred when the fine aggregate had approximately 25 per cent passing the No. 100 sieve. Also, the mix containing sand with lightweight coarse aggregate was comparable to a sand and gravel mix.

CONCLUSIONS

The results obtained in this study warrant the following conclusions:

1. Lightweight concrete has much greater resistance to freeze and thaw damage than does the normal sand and gravel concrete used in this area.

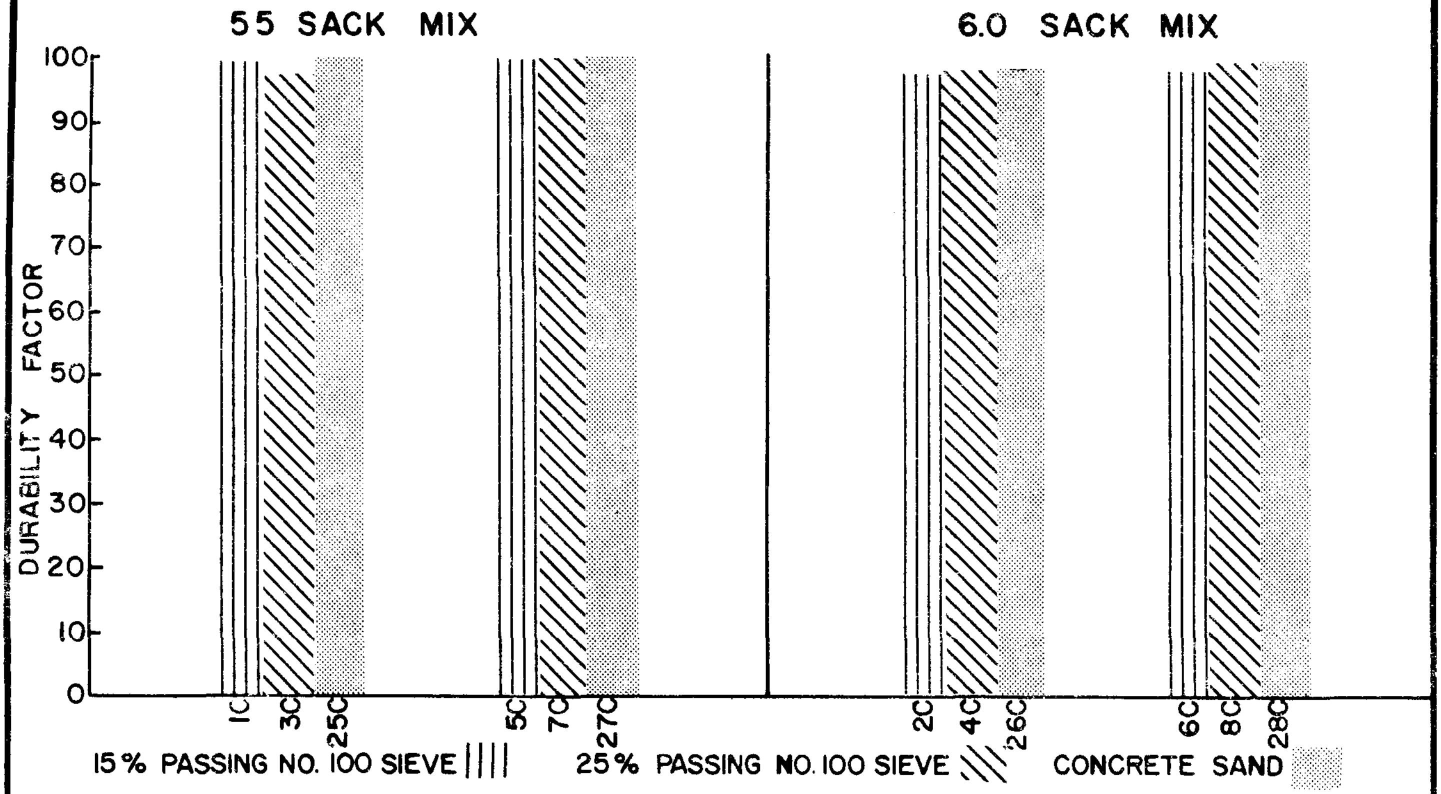
2. Lightweight fine aggregate should not have more than 20 per cent passing the No. 100 sieve.

3. The moisture condition of the aggregate has very little effect on the resistance to freeze and thaw damage, provided the concrete is properly cured before being subjected to freezing conditions.

4. The reduction in durability obtained when the cement content was increased from 5.5 to 6.0 sack per cubic yard cannot be explained at this time. However, further work will be done to try to determine the reasons.

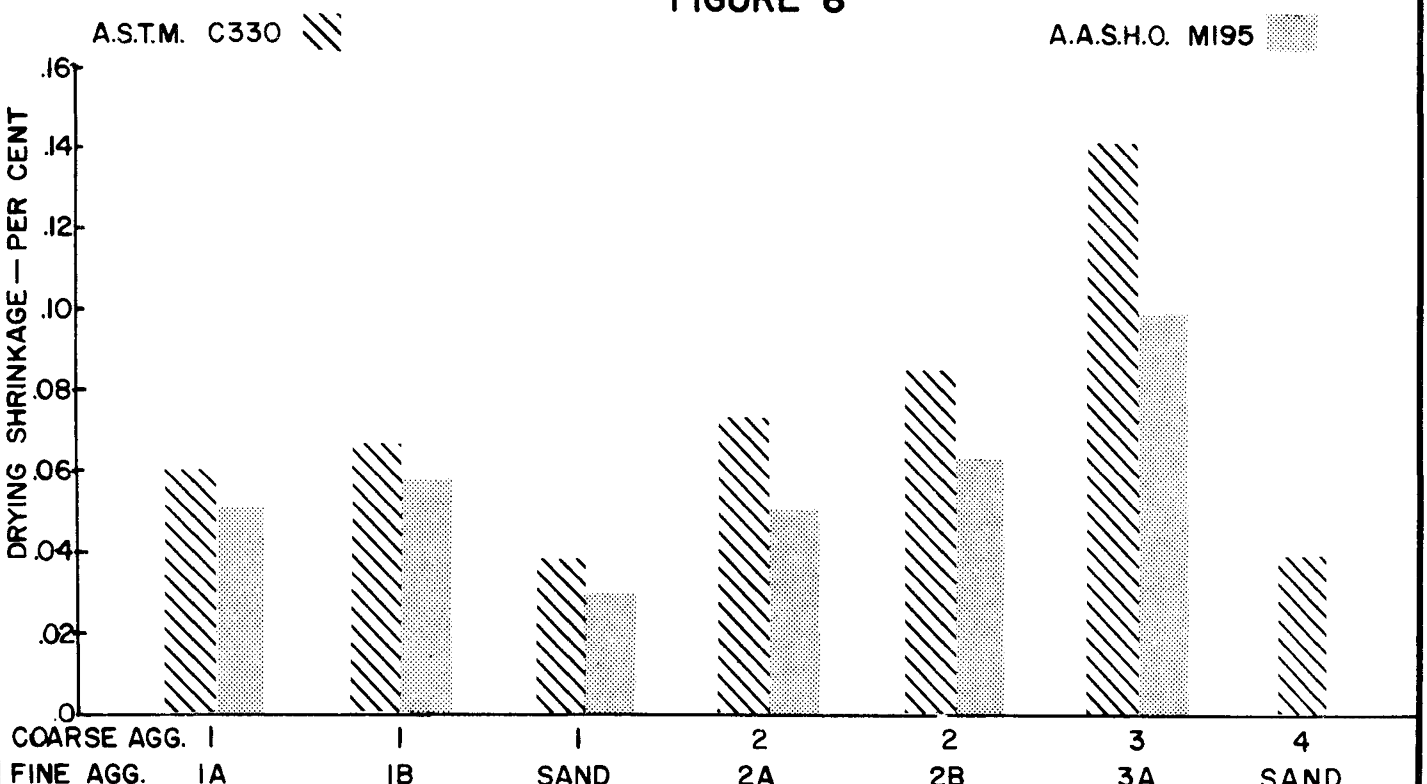
5. The use of concrete sand to replace lightweight fine aggregate had no significant effect on durability.

FIGURE 7



Influence of Sand Used to Replace Lightweight Fines on Durability

FIGURE 8

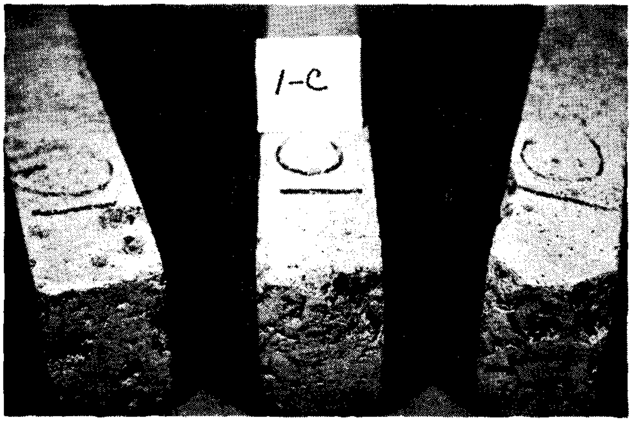


Comparison of Drying Shrinkage

6. The drying shrinkage of lightweight concrete is different for each source of aggregate. Concrete sand used to replace lightweight fines reduces the shrinkage to what is normally obtained for a sand and gravel mix.

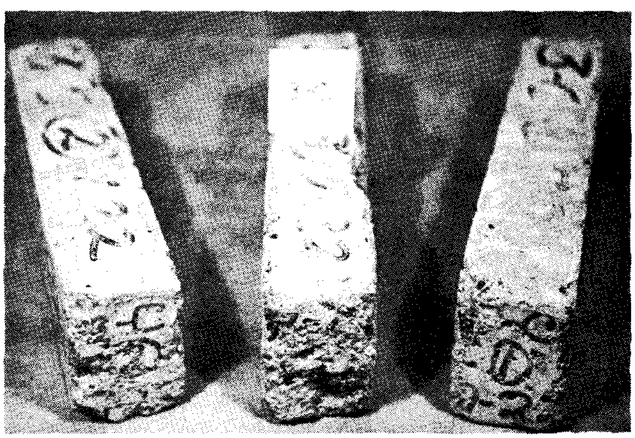
7. The test criterion for durability of lightweight concrete should be 500 cycles of freezing and thawing. An evaluation cannot be made at 300 cycles because even the lightweight aggregate which shows a poor service record was in good condition at the completion of 300 cycles. However, only the lightweight aggregates that have shown the best records endured 500 cycles of freezing and thawing with a loss in dynamic modulus of less than seven per cent.

APPENDIX



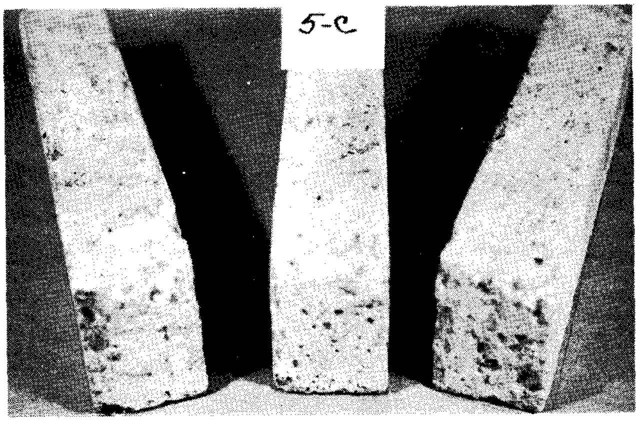
Mix No. 1-C - 504 Cycles of Freezing and Thawing

Mix No. 2-C - 504 Cycles of Freezing and Thawing

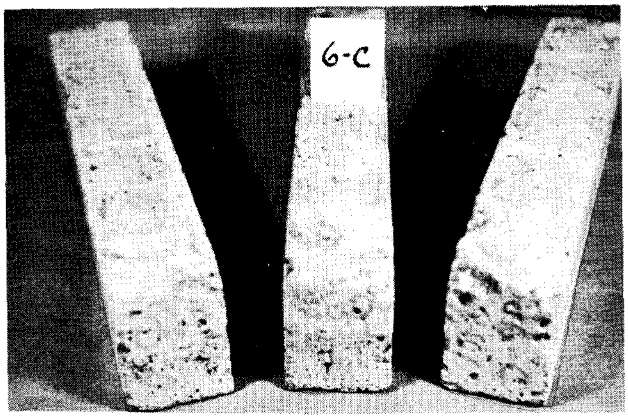


Mix No. 3-C - 503 Cycles of Freezing and Thawing

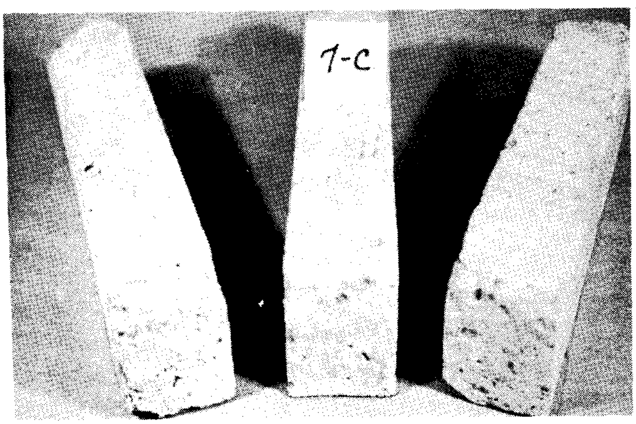
Mix No. 4-C - 503 Cycles of Freezing and Thawing



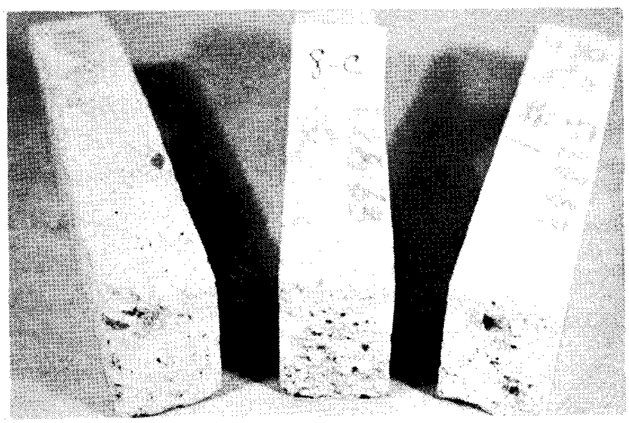
Mix No. 5-C - 502 Cycles of Freezing and Thawing



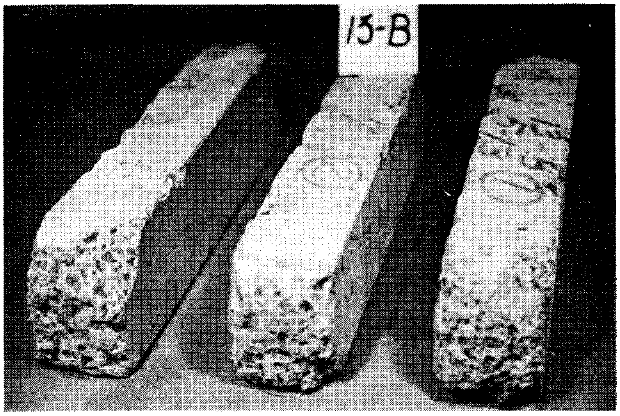
Mix No. 6-C - 502 Cycles of Freezing and Thawing



Mix No.. 7-C - 502 Cycles of Freezing and Thawing



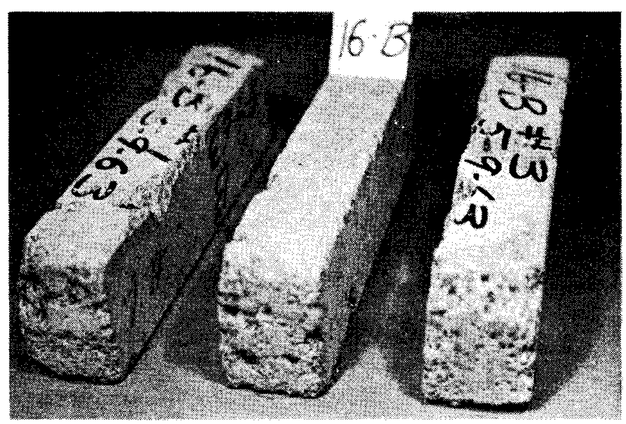
Mix No. 8-C - 502 Cycles of Freezing and Thawing



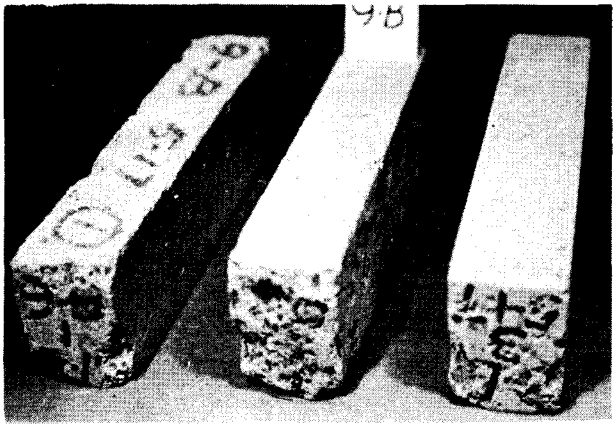
Mix No. 13-B - 502 Cycles of Freezing and Thawing

Mix No. 14-B - 502 Cycles of Freezing and Thawing

Mix No. 15-B - 500 Cycles of Freezing and Thawing

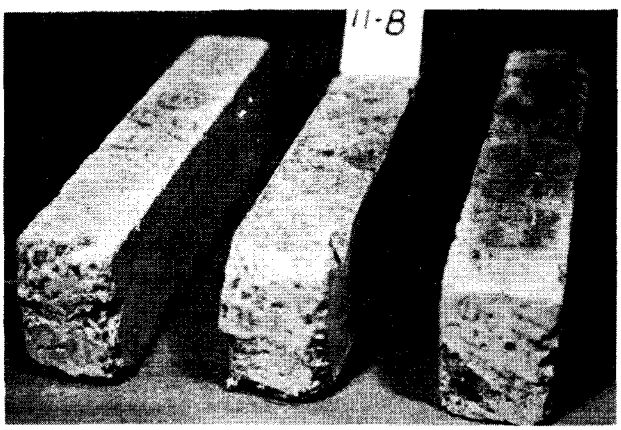


Mix No. 16-B - 500 Cycles of Freezing and Thawing



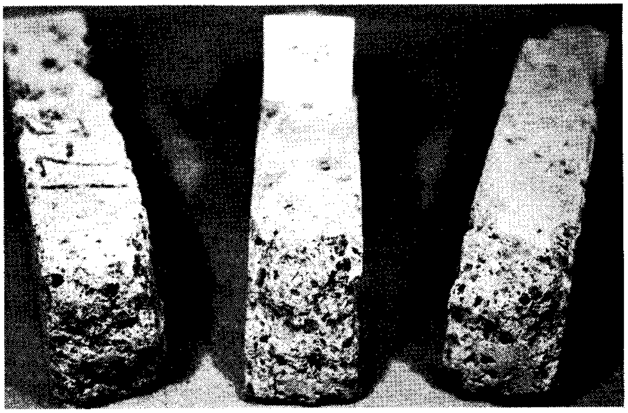
Mix No. 9-B - 504 Cycles of Freezing and Thawing

Mix No. 10-B - 504 Cycles of Freezing and Thawing



Mix No. 11-B - 504 Cycles of Freezing and Thawing

Mix No. 12-B - 504 Cycles of Freezing and Thawing



Mix No. 17-B - 250 Cycles of Freezing and Thawing

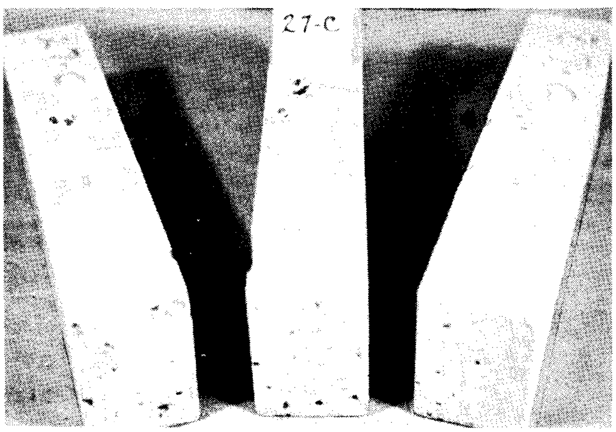
Mix No. 18-B - 494 Cycles of Freezing and Thawing

Mix No. 19-B - 463 Cycles of Freezing and Thawing

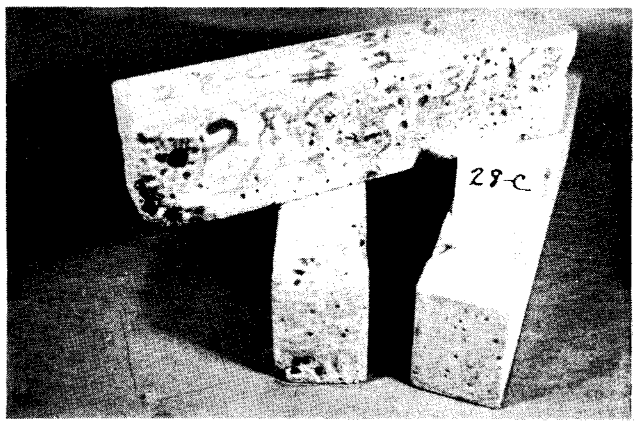
Mix No. 20-B - 466 Cycles of Freezing and Thawing

Mix No. 25-C - 501 Cycles of Freezing and Thawing

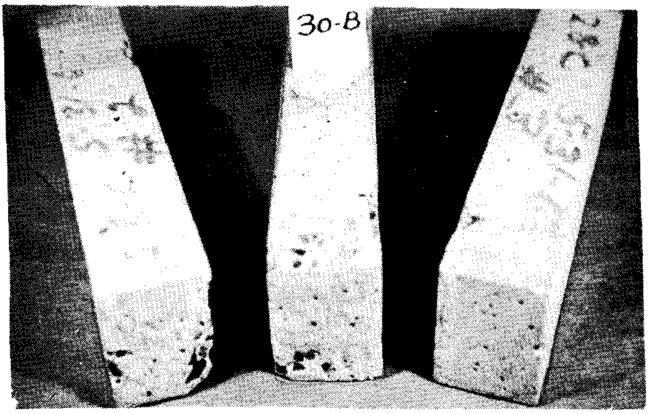
Mix No. 26-C - 501 Cycles of Freezing and Thawing



Mix No. 27-C - 502 Cycles of Freezing and Thawing



Mix No. 28-C - 502 Cycles of Freezing and Thawing



Mix No. 30-B - 85 Cycles of Freezing and Thawing

Mix No. 31-B - 83 Cycles of Freezing and Thawing

RESEARCH PUBLICATIONS

Effect of Viscosity in Bituminous Construction. Verdi Adam, 1961.

Slab Breaking and Seating on Wet Subgrades with Pneumatic Roller, J. W. Lyon, Jr., January 1963.

Lightweight Aggregate Abrasion Study. Holis B. Rushing, Research Project No. 61-7C, February 1963.

Texas Triaxial R-Value Correlation. Harry L. Roland, Jr., Research Project No. 61-1S, March 1963.

Asphaltic Concrete Pavement Survey. S. C. Shah, Research Project No. 61-1B, April 1963.

Compaction of Asphaltic Concrete Pavement with High Intensity Pneumatic Roller. Part I. Verdi Adam, S. C. Shah and P. J. Arena, Jr. Research Project No. 61-7B, July 1963.

A Rapid Method of Soil Cement Design. Harry L. Roland, Jr. Ali S. Kemahlioglu, Research Project No. 61-8S, March 1964.

Correlation of the Manual Compaction Hammer with Mechanical Hammers for the Marshall Method of Design for Asphaltic Concrete. P. J. Arena, Jr. Research Project No. 63-1B, September 1964.

Nuclear Method for Determining Soil Moisture and Density. Harry L. Roland, Jr. Research Project No. 62-1S, November 1964.

Service Temperature Study for Asphaltic Concrete. P. J. Arena, Jr., Research Project No. 61-3B, October 1964.

Quality Control Analysis. S. C. Shah, Research Project No. 63-1G, November, 1964.

Typical Moisture-Density Curves. C. M. Higgins, Research Project No. 61-11S, May 1965.

High - Pressure Lime Injection. C. M. Higgins, Research Project No. 63-7S, August 1965.

Durability of Lighteight Concrete - Phase III - Freezing and Thawing Tests of Lightweight Concrete. Hollis B. Rushing, Research Project No. 61-8C, August 1965.