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MISCELLANEOUS PAPER C-75-6

INVESTIGATION OF HIGH-STRENGTH FROST-RESISTANT CONCRETE

by

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Final Report

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Miscellaneous Paper C-75-6

INVESTIGATION OF HIGH-STRENGTH FROST-RESISTANT CONCRETE

KEY

Manufacturer	Symbol	Product
Lone Star Cement Co. Spocari, Alabama	RC-635 RC-602	Portland cement, type II
Vulcan Materials Co. Hermitage Limestone Quarry Nashville, Tennessee	CRD MS-17(9)	Manufactured limestone fine aggregate
Vulcan Materials Co. Hermitage Limestone Quarry Nashville, Tennessee	CRD G-31(14)	Manufactured limestone coarse aggregate, No. 4 to 3/4 in.
Hunt Process Corp-Southern Ridgeland, Mississippi	AEA-896	Air-entraining admixture (Air-In)

Unclassified

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This study was conducted to determine if reduction in air content by vibration of a well proportioned concrete mixture of relatively high cement content reduces the frost resistance of the hardened concrete and also to determine the effect of such reduction in air content on compressive strength. One 3/4-in. (19.0-mm) maximum-size crushed limestone aggregate concrete mixture was proportioned to have a compressive strength of approximately 5500 psi (37.92 MPa) at 28 days age. The mixture had an air content of 8 ± 1 percent. Various vibration times were used to reduce the air content until the samples had (Continued)

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20. ABSTRACT (Continued)

an air content as low as could be practically obtained. Specimens were cast for determining compressive strength, resistance to freezing and thawing, and air void parameters to evaluate the effect of reduction in air content of the concrete on strength and frost resistance. Strength test results indicate that the strength did increase as the air content decreased. The results of the tests for determining resistance to freezing and thawing indicate that frost resistance decreased as air content decreased. However, it appears that even though the durability decreased as the air content was reduced, the concrete still had adequate frost resistance with nominal air contents of 1.5 percent. Even though this is a low air content percentage, the air void spacing factor was 0.0068 in. (0.1727 mm), which is below the value that is considered adequate, i.e. 0.0080 in. (0.2032 mm).

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PREFACE

The investigation reported herein was authorized by first indorsement dated 28 October 1968 from the Office, Chief of Engineers, U. S. Army, to a U. S. Army Engineer Waterways Experiment Station (WES) letter dated 3 October 1968, subject: "Project Plan for Frost-Resistant Concrete of High Strength," a part of ES Item 601.

The investigation was conducted from 1969 to 1973 at the Concrete Laboratory, WES, under the direction of Mr. Bryant Mather, Chief, Concrete Laboratory. Members of the Concrete Laboratory staff actively concerned with the investigation included Messrs. James M. Polatty, William O. Tynes, Alan D. Buck, and Willard B. Lee, and Mrs. Katharine Mather. This report was prepared by Mr. Tynes.

Directors of WES during the conduct of the investigation and the preparation and publication of this report were BG E. D. Peixotto, CE, and COL G. H. Hilt, CE. Technical Director was Mr. F. R. Brown.

CONTENTS

CONVERSION FACTORS, U. S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

U. S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

Multiply	By	To Obtain
inches	25.4	millimetres
cubic feet	0.02831685	cubic metres
pounds (mass)	0.4535924	kilograms
pounds (mass) per cubic foot	16.01846	kilograms per cubic metre
pounds (mass) per cubic yard	0.5933	kilograms per cubic metre
pounds (force) per square inch	0.006894757	megapascals

INVESTIGATION OF HIGH-STRENGTH FROST-RESISTANT CONCRETE

PART I: INTRODUCTION

Background

1. Entrainment of air in a concrete mixture improves the subsequent frost resistance of the hardened concrete, but it also reduces the compressive strength. A need exists for the increased frost resistance achieved by proper air-entrainment, but without the concomitant reduction in compressive strength. Mielenz et al.[1] have shown that air-entrained concrete will retain its characteristic frost resistance even after expulsion, by extended vibration, of a large proportion of its air content. This is generally true if the mixture is well proportioned and if the air content is initially as high as is desirable to ensure frost resistance. In view of this, it has been suggested that frost resistance can be obtained, with significantly less loss in strength as compared with that of nonair-entrained concrete, in mixtures of relatively high cement content by the use of extended vibration to lower the air content. ACI Committee 212 stated[2] that:

> resistance of concrete to laboratory freezing and thawing has not been found to be affected adversely by loss of air as a result of vibration, provided that the concrete originally contained an adequate void system.

Mielenz et al. stated[1] that a satisfactory entrained air void system in job concrete is assured if "Recommended Practice for Selecting Proportions for Concrete (ACI 613-54)" is followed, provided the air-entraining admixture meets the requirements of ASTM C 260, "Specifications for Air-Entraining Admixtures for Concrete." It appears that if the air content is greatly reduced by the process of consolidation, the spacing factor will remain adequate because the lower air content will be compensated for by the high specific surface of the voids.

Purpose

2. The purpose of this investigation was to determine if reduction in air content by vibration of a well proportioned mixture of relatively high cement content also reduces its frost resistance and to determine what effects such a reduction in air content would have on the strength of the concrete.

Scope

3. One basic concrete mixture containing 3/4-in. (19.0-mm)* maximum size limestone aggregate was proportioned to have a slump of 1-1/2 ± 1/2 in. (38.1 ± 12.7 mm) and a compressive strength of approximately 5500 psi (37.92 MPa) at 28 days age. The air content of the hardened concrete was to be 8 ± 1 percent. Various vibration times were used to provide different reductions in air content until the samples had as low an air content as could be practically obtained. Specimens were cast and tests conducted to evaluate the concrete for strength and resistance to freezing and thawing and to determine microscopically air void parameters. All specimens were tested for specific gravity by displacement, and this parameter was the basic index of actual air content employed for correlation with strength and the durability factor. Two other concrete mixtures and one mortar mixture were also made.

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* A table of factors for converting U. S. customary units of measurement to metric (SI) units is presented on page 4.

PART II: MATERIALS, MIXTURES, SPECIMENS, AND TESTS

Materials

Portland cement

4. Type II portland cement (RC-635 and RC-602) from Alabama was used for all concrete made during this investigation. The chemical and physical properties of the cement are presented in Table 1. RC-602 was used in batches 1-5 of mixture 1, and RC-635 was used in all other concrete used in this investigation.

Aggregates

5. The fine (CRD MS-17(9)) and coarse (CRD G-31(14)) limestone aggregates were obtained from Tennessee. The aggregates were graded to meet the requirements of CE-1401.01.[3] The gradings and physical properties of the aggregates are presented in Table 2.

Air-entraining admixture

6. The air-entraining admixture (AEA-896) used in the investigation was a solution of neutralized vinsol resin.

Mixtures

7. Three concrete mixtures, two air-entrained and one nonair-entrained, were proportioned with 3/4-in. (19.0-mm) maximum-size limestone aggregate to have a slump of 1-1/2 ± 1/2 in. (38.1 ± 12.7 mm). These mixtures were designated mixtures 1, 2, and 3. The air-entrained mixtures were proportioned to have 8 ± 1 percent air. One of the air-entrained mixtures (mixture 1) was proportioned to have a compressive strength of approximately 5500 psi (37.92 MPa) at 28 days age. The other air-entrained mixture (mixture 2) was proportioned to have a higher water content to provide a mixture with excessive bleeding characteristics. The nonair-entrained mixture (mixture 3) was proportioned to have the same amount of cement and workability as mixture 1. Mixture data for all three mixtures are presented in Table 3.

8. One mortar mixture, designated mixture 4, was proportioned

with 564 lb of cement per cu yd (334.6 kg/m^3), a water-cement ratio by weight of 0.580, and an air content of 8 ± 1 percent. Data for this mixture are also presented in Table 3.

Specimens

9. Ten batches of concrete were made from mixture 1, and one batch of concrete was made from each of the other two concrete mixtures (mixtures 2 and 3). Six batches of mortar were made from the mortar mixture (mixture 4). From each of the first five batches of concrete made from mixture 1, three 6- by 12-in. (152- by 305-mm) cylinders and four 3-1/2- by 4-1/2- by 16-in. (89- by 114- by 406-mm) beams were made. Two additional cylinders were made from batch 3 and one from batch 4. Seven 6- by 12-in. (152- by 305-mm) cylinders were made from batch 6, 23 from batch 7, 30 from batch 8, and 15 from batch 9 of mixture 1. Only air content determinations were made on specimens from batch 10 of mixture 1.

10. Six 0.2-ft^3 (0.005663-m^3) batches of mortar were made using mixture 4 and one 6- by 12-in. (152- by 305-mm) cylinder was molded from each batch.

11. The rodding method was used to consolidate specimens from batch 2 of mixture 1, and the internal vibration method was used to consolidate specimens from batches 1, 3, 4, and 5 (see Table 4). Different vibration times were used for each of batches 1, 3, 4, and 5 in order to produce air contents varying from 8 to as close to 0 percent as practical. The normal vibration time for casting specimens (6 sec) was used for batch 1, and the vibration time was increased for each of batches 3, 4, and 5 at the project leader's discretion in an attempt to provide air contents between 6 and 0 percent.

Tests

12. The specimens were tested for compressive strength, resistance to freezing and thawing, and air content of hardened concrete by

the high-pressure method, and air void parameters were determined using microscope techniques. These tests were conducted in accordance with methods CRD-C 14, 20, 83, and 42, respectively, of the <u>Handbook for Concrete and Cement.</u>[4] Micrometric air content determinations were made on one beam from each of batches 1-5 of mixture 1. Micrometric air content determinations were also made on either the core or rim portions of the specimen used in the normal pressure air content determinations (CRD-C 41)[4] that were allowed to harden for batches 1, 2, 3, and 5 of mixture 1. Air void spacing factor determinations were made on one beam from each of batches 2-5 of mixture 1. Air void spacing factor determinations were also made on either the core or rim portions of the hardened air pot sample. The high-pressure method (CRD-C 83)[4] was used to determine the air content on the core specimen from batches 1, 2, 3, and 5 of mixture 1. All compressive strength and freezing and thawing specimens for the air-entrained mixtures were tested for unit weight by displacement at 48 ± 4 hr (weighed in air and in water). Some of the hardened air content tests were made when the specimens were 1, 2, and 28 days old. The air pot specimens were weighed in air and water at 1 day.

PART III: DISCUSSION OF TEST RESULTS

13. The results of each individual test for compressive strength, resistance to freezing and thawing, air content of hardened concrete, and air void spacing factor for batches 1-5 of mixture 1 are presented in Table 4. Specimens from batch 1 were vibrated in accordance with normal procedures. Specimens from batch 2 were treated the same as specimens from batch 1 except that the specimens were rodded instead of vibrated. An attempt was made to leave about 4 percent air in batch 3 and about 2 percent air in batch 4. An effort was made to vibrate batch 5 until as much air was removed as practical. These exact percentages of air were not attained, as shown by the results given below. Instead, the average air contents of batches 1, 3, 4, and 5 were 5.0, 4.6, 3.1, and 0 percent, respectively, as shown in the tabulation below. However, these air content values did provide a satisfactory

	Air Content Hardened Concrete Percent Calculated**			
Specimen* No.	Batch 1	Batch 3	Batch 4	Batch 5
1	5.9	5.1	3.0	0
2	5.9	4.7	2.9	0
3	4.9	4.7	3.3	0
4	5.3	5.2	3.1	0
5	4.4	3.8	3.9	0
6	4.5	4.3	2.3	0
7	4.4	4.5	3.5	0
Avg	5.0	4.6	3.1	0

* Specimens 1-4 were beams, and specimens 5-7 were cylinders.

** Calculated from theoretical and actual unit weights of concrete; actual unit weight calculated from specific gravity by displacement.

range to allow interpretation of the effect of reduction of air content on the compressive strength and frost resistance of the concrete.

Compressive Strength and Air Content

Mixture 1, batches 1-5

14. The compressive strengths of the specimens with the lowest air contents (batch 5 of mixture 1) were slightly lower than those of the specimens from the other four batches (1-4) with higher air contents. One extra 6- by 12-in. (152- by 305-mm) cylinder was made and tested from batches 3 and 4 from which 1 in. (25.4 mm) of the top of the specimen was removed by sawing prior to testing. It was believed that possibly there was enough segregation of low-strength mortar in the upper inch of the specimen due to the long time of vibration to affect the strength. The results of tests of these specimens are also presented in Table 4. The strength of one specimen was slightly lower and that of the other was slightly higher than strengths of comparable specimens tested without the top 1 in. (25.4 mm) sawed off. From these limited data, it would appear that the properties of the upper 1 in. (25.4 mm) of the specimens did not cause the low-air-content specimens to have slightly lower compressive strengths than specimens with higher air contents. Normally, it would be expected that the unit weight would increase with decreasing air content. Hence, an increase in strength would also be expected. In this study, the unit weight did increase with a decrease in air content, but the anticipated strength increase did not occur. The strengths were essentially the same for all air contents obtained. A statistical evaluation using an F test and then a t test[5] showed that there was no significant difference between the variances and means of the strength data regardless of air content of the specimen. The average compressive strength for each vibration time is plotted in Plate 1.

15. One additional 6- by 12-in. (152- by 305-mm) cylinder was cast from batch 3 of mixture 1 to determine if the air was evenly distributed. Air contents of the top, middle, and bottom thirds of the specimen were determined in accordance with test method CRD-C 42.[4] The results are shown in Figure 1. The air contents of the top, middle, and bottom thirds of the specimen were 6.27, 4.15, and 5.63 percent, respectively,

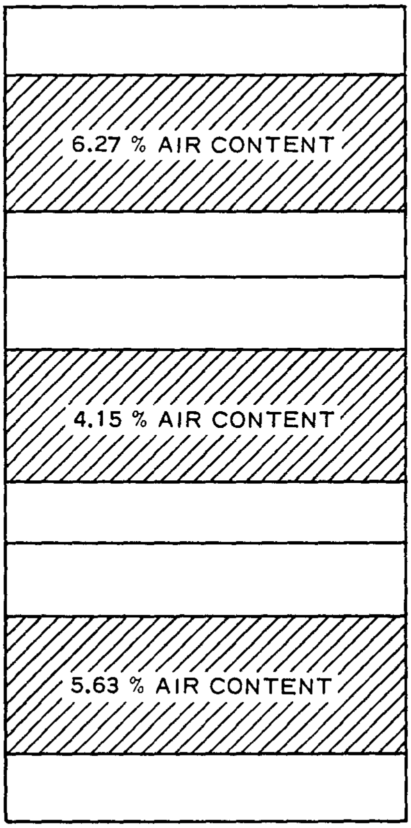

Figure 1. Specimen sectioned for determination of air contents of top, middle, and bottom thirds

yielding an average air content of 5.35 percent. The specimen was sectioned as shown, and air contents were determined for 1- to 3-in. (25.4- to 76.2-mm), 5- to 7-in. (127- to 178-mm), and 9- to 11-in. (229- to 279-mm) portions. The maximum difference of 2.12 percent air occurred between the middle and top thirds of the specimen. The compressive strength results may have been influenced somewhat if this difference in air content existed in all the specimens. This may have contributed to the general lack of increase in compressive strength as the air content decreased and the unit weight increased. This variation in the air content could possibly be attributed to segregation caused by the vibration.

Additional batches of mortar and concrete

16. In order to try to determine why the strengths of the specimens from batches 1-5 of mixture 1 did not increase as the air content was reduced by longer periods of vibration, several additional batches of concrete and some batches of mortar were made and tested. The results of the individual compressive strength tests for the various methods of consolidation, vibration times, test ages, and unit weights for the mortar batches are presented in Table 5, and those for the concrete batches are presented in Tables 6-10.

17. Mortar. Compressive strength increased and air content decreased as the vibration time increased for the internal vibration method. However, there was a slight decrease in strength as the vibrating time increased for the external vibration method. Excluding the method of consolidation, the individual compressive strength test results plotted in Plate 2 indicate a considerable increase in the strength as the air content decreased.

18. Concrete. The results of the individual compressive strength tests for the various vibration times, test ages, and unit weights for batches 6 and 7 of mixture 1 are presented in Table 6. In general, the compressive strengths of the specimens from batch 6 increased as the vibrating time increased. The average strengths of specimens from batch 7 are plotted in Plate 3. There is no significant difference between the variances and means of the strength data at 28 days age regardless of time of vibration.

19. Compressive strength test results for batch 8 of mixture 1 are presented in Table 7. The average compressive strength for each vibration time is plotted in Plate 3. There appears to be a slight trend in these data (3 and 7 days age) for compressive strength to increase as vibration time increases and air content decreases. This was not the case for specimens from batch 7 at 28 days age.

20. Compressive strength test results for batch 9 of mixture 1 are presented in Table 8. The average compressive strength for each vibration time is plotted in Plate 4. In general, the data indicate a trend for compressive strength to increase as vibration time increases. In Plate 5, where the individual strength tests are plotted versus the individual air contents, the data indicate a definite trend for compressive strength to increase as the air content decreases.

21. Compressive strength test results for batch 1 of mixture 3 (nonair-entrained) are presented in Table 9. The average compressive strength for each vibration time is plotted in Plate 6. There appears to be a slight increase in strength at both 3 and 7 days age for the longest vibration time (90 sec) but not at 28 days age.

22. One batch of concrete was made from each of mixtures 1 and 2. Pressure meter tests were conducted on specimens from these batches in accordance with CRD-C 41.[4] Also, gravimetric tests were conducted on the concrete using the pressure meter bowl as unit weight measure. Mixture 2 had a sufficiently high water-cement ratio to produce a mixture that bleeds and mixture 1 had a water content sufficiently low to produce a mixture that does not bleed. In one test of each mixture, after air content had been determined, water was kept on top of the specimen

and the other test specimen was kept free of surface water. The specimens were then allowed to harden in air pot containers. After 24 to 48 hr, the specimens were removed from the containers and weighed in air and water. Then the air content of the hardened concrete sample was calculated. The specimens were then wiped off, wrapped in plastic, sealed, and moist-cured for 28 days. After 28 days, the specimens were weighed in air and water, and the air content was again calculated. Micrometric air content determinations (CRD-C 42)[4] were then made on each specimen. The weights and air contents are presented in Table 10. These tests were made to determine if there were any discrepancies in the pressure and gravimetric air determinations. Results of the tests revealed no such discrepancies. The strength data indicate no significant difference in the average compressive strength when vibration time was increased and air content reduced.

23. Examination of some of the strength data shows a definite trend for the strength to increase as vibration time increases or air content decreases, while examination of other data does not. This phenomenon of some data not showing a strength increase as air content decreased may partially be due to factors such as limited test data, segregation caused by vibration techniques, and possibly a lack of a more precise method of measuring differences in mass. A small change in mass will influence air content considerably. It is possible that if more tests had been conducted, there would be a trend in the data showing an increase in all compressive strengths with decreasing air contents. The specimens foamed and bled after the longer vibration times. However, it appears that the extended vibration times used to reduce the air content are not detrimental to the compressive strength.

Resistance to Accelerated Freezing and Thawing

24. The results of tests for resistance to freezing and thawing, presented in Table 4 and Plate 7, show generally that resistance to freezing and thawing decreased as vibration time increased and air content decreased. All tests for resistance to freezing and thawing were

made when the specimens were 14 days old and tested according to CRD-C 20.[4] Generally, concrete yielding a durability (DFE) value of 60 at 14 days or more is considered highly resistant to freezing and thawing.[6] Even though DFE of the concrete tested in this study generally decreased as the air content was reduced to 1.5 percent as determined by the micrometric procedure and to 0 percent as determined by the unit weight water displacement procedure, the concrete still had adequate frost resistance, i.e., the lowest average DFE value was 74. The air void spacing factor of 0.0068 in. (0.1727 mm) for the lowest air content was also satisfactory, i.e., the value is somewhat lower than the 0.0080-in. (0.2-mm) value that is considered adequate.[1,7,8] The spacing factors for all other air contents were satisfactory, i.e., they were below 0.0068 in. (0.1727 mm). Backstrom et al. reported[9] that

> With a given proportion of air-entraining admixture, if other factors are held essentially constant, concrete develops a void system such that the spacing factor ($\overline{L}$) varies only slightly, regardless of manipulation of the fresh concrete, within practical limits, and in spite of large changes in surface area and air content.

The air void spacing factors of this study varied only slightly, which indicates that the statement above is true. With all the manipulation of the concrete, the air void spacing factors ranged only from 0.0038 to 0.0068 in. (0.0965 to 0.1727 mm). These factors agree closely with those reported by Backstrom et al.[9] (0.0040 to 0.0071 in. (0.1016 to 0.1803 mm)). This indicates that concrete from well proportioned mixtures is difficult to overvibrate, i.e., the concrete can withstand a much longer time of vibration than is normally used and still be frost resistant. It has been reported[10] that

> Vibration has little effect on the smaller bubbles, and therefore, does not materially change the spacing factor, and such concrete would therefore have good durability in spite of a lower air content than is normally thought proper.

PART IV: SUMMARY OF RESULTS

25. In this study, resistance to freezing and thawing generally decreased as air content decreased. Even though DFE decreased as air content was reduced to 1.5 percent as determined by the micrometric procedure and 0 percent as determined by the unit weight displacement procedure, the concrete still had adequate frost resistance, i.e., the lowest average DFE value was 74.

26. The air void spacing factor was also satisfactory for the concrete with reduced air contents, i.e., the values were lower than 0.0080 in. (0.2032 mm), which is considered satisfactory.

27. There was a definite trend indicating that compressive strength increased as air content decreased as a result of increased vibration time.

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Table 1

Chemical and Physical Properties of Type II Portland Cement

Tests	Type II RC-635	Type II RC-602
	Chemical Properties	
SiO_2, %	21.5	21.6
Al_2O_3, %	5.3	5.7
Fe_2O_3, %	4.7	4.5
CaO, %	63.1	--
MgO, %	0.9	0.7
SO_3, %	2.0	2.0
Loss on ignition, %	1.3	1.8
Insoluble residue, %	0.37	0.14
Na_2O, %	0.08	--
K_2O, %	0.40	--
Total alkalies, Na_2O, %	0.34	0.34
C_3S, %	45.4	--
C_2S, %	27.4	--
C_3A, %	6.2	7.4
C_4AF, %	14.2	--
	Physical Properties	
Specific gravity	3.15	3.15
Fineness, air permeability, cm^2/g	3610	3255
Initial setting time, Gillmore, hr:min	3:05	3:30
Final setting time, Gillmore, hr:min	6:05	5:35
Autoclave expansion, %	0.01	0.02
Air content, %	7.8	6.3
Compressive strength, psi (MPa)		
3 days age	2340 (16.13)	1920 (13.24)
7 days age	3060 (21.10)	2585 (17.82)

Table 2

Gradings and Physical Properties of Fine and Coarse Aggregates

Sieve Size in. (mm, μm)	Percent Passing Coarse Aggregate CRD G-31(14)	Fine Aggregate (Sand) CRD MS-17(9)
	Gradings	
1 in. (25.0 mm)	100	--
3/4 in. (19.0 mm)	96	--
1/2 in. (12.5 mm)	66	--
3/8 in. (9.5 mm)	40	--
No. 4 (4.75 mm)	4	100
No. 8 (2.36 mm)	--	86
No. 16 (1.18 mm)	--	58
No. 30 (600 μm)	--	35
No. 50 (300 μm)	--	21
No. 100 (150 μm)	--	11
No. 200 (75 μm)	--	6.9
Passing No. 200	--	0
	Physical Properties	
Absorption, %	0.4	1.6
Specific gravity	2.73	2.66
Fineness modulus	6.60	2.89

Table 3

Concrete and Mortar Mixture Data

Mixture No.	Maximum Size Aggregate in. (mm)	Cement Content lb/yd^3	Cement Content (kg/m^3)	Water Content lb/yd^3	Water Content (kg/m^3)	Water-Cement Ratio by Weight	Slump in. (mm)	Air Content %
1	3/4 (19.0)	611.0	(362.5)	249.3	(147.9)	0.408	1-1/2 (38.1)	7.5
2	3/4 (19.0)	305.5	(181.3)	229.1	(135.9)	0.750	1-1/2 (38.1)	7.6
3	3/4 (19.0)	611.0	(362.5)	293.3	(174.0)	0.480	1-1/2 (38.1)	1.8
4	No. 4 (4.75)	564.0	(334.6)	327.1	(194.1)	0.580	*	8.0

* Mortar mixture (slump not determined).

Table 4

Vibration Time, Strength, and Air Content Data of Concrete (Mixture 1, Batches 1-5)

Batch No.	Specimen No.	Vibration Time, sec: Air Content Specimens	Beams	Cylinders	Weight of Beams, lb (kg): In Air	In Water	Weight of Cylinders, lb (kg): In Air	In Water	Weight of Air Pot Specimens, lb (kg): In Air	In Water	Weight of Cores, lb (kg): In Air	In Water	Difference in weight air vs water lb (kg)
1	9103	--	6	--	22.00 (9.98)	12.60 (5.72)	--	--	--	--	--	--	9.40 (4.26)
	9104	--	6	--	22.00 (9.98)	12.60 (5.72)	--	--	--	--	--	--	9.40 (4.26)
	9105	--	6	--	21.75 (9.87)	12.55 (5.70)	--	--	--	--	--	--	9.20 (4.17)
	FS-1B	--	6	--	21.82 (9.90)	12.55 (5.70)	--	--	--	--	--	--	9.27 (4.20)
	FS-1C	--	--	6	--	--	29.00 (13.15)	16.80 (7.62)	--	--	--	--	12.20 (5.53)
	FS-2C	--	--	6	--	--	28.85 (13.09)	16.70 (7.57)	--	--	--	--	12.15 (5.51)
	FS-3C	--	--	6	--	--	28.75 (13.04)	16.65 (7.55)	--	--	--	--	12.10 (5.49)
	Air pot	8	--	--	--	--	--	--	34.70 (15.74)	19.60 (8.89)	--	--	15.10 (6.85)
	Core	--	--	--	--	--	--	--	--	--	19.65 (8.91)	11.30 (5.13)	8.35 (3.68)
	Core rim	--	--	--	--	--	--	--	--	--	--	--	--
2	9106	--	Rodded	--	21.88 (9.93)	12.65 (5.74)	--	--	--	--	--	--	9.23 (4.19)
	9107	--	Rodded	--	21.88 (9.93)	12.55 (5.70)	--	--	--	--	--	--	9.33 (4.23)
	9108	--	Rodded	--	21.72 (9.85)	12.45 (5.65)	--	--	--	--	--	--	9.27 (4.20)
	FS-2B	--	Rodded	--	21.51 (9.76)	12.35 (5.60)	--	--	--	--	--	--	9.16 (4.15)
	FS-4C	--	--	Rodded	--	--	28.80 (13.06)	16.70 (7.57)	--	--	--	--	12.10 (5.49)
	FS-5C	--	--	Rodded	--	--	28.82 (13.07)	16.75 (7.60)	--	--	--	--	12.07 (5.47)
	FS-6C	--	--	Rodded	--	--	28.85 (13.09)	16.70 (7.57)	--	--	--	--	12.15 (5.51)
	Air pot	8	--	--	--	--	--	--	34.60 (15.69)	19.75 (8.96)	--	--	14.55 (6.60)
	Core	--	--	--	--	--	--	--	--	--	19.43 (8.81)	11.15 (5.06)	8.28 (3.75)
	Core rim	--	--	--	--	--	--	--	--	--	--	--	--
3	9118	--	40	--	21.70 (9.84)	12.50 (5.67)	--	--	--	--	--	--	9.20 (4.17)
	9119	--	40	--	21.80 (9.89)	12.60 (5.72)	--	--	--	--	--	--	9.20 (4.17)
	9120	--	40	--	21.80 (9.89)	12.60 (5.72)	--	--	--	--	--	--	9.20 (4.17)
	FS-7B	--	40	--	21.45 (9.73)	12.35 (5.60)	--	--	--	--	--	--	9.10 (4.13)
	FS-18C	--	--	60	--	--	29.30 (13.29)	17.05 (7.73)	--	--	--	--	12.25 (5.56)
	FS-19C	--	--	60	--	--	29.15 (13.22)	16.90 (7.67)	--	--	--	--	12.25 (5.56)
	FS-20C	--	--	60	--	--	28.95 (13.13)	16.75 (7.60)	--	--	--	--	12.20 (5.53)
	Air Pot	960	--	--	--	--	--	--	34.90 (15.83)	20.65 (9.37)	--	--	14.25 (6.46)
	Core	--	--	--	--	--	--	--	--	--	19.59 (8.89)	11.80 (5.32)	7.79 (3.57)
	Core Rim	--	--	--	--	--	--	--	--	--	--	--	--
4	9121	--	90	--	22.00 (9.98)	12.88 (5.84)	--	--	--	--	--	--	9.12 (4.14)
	9122	--	90	--	22.19 (10.07)	13.00 (5.90)	--	--	--	--	--	--	9.19 (4.17)
	9123	--	90	--	22.25 (10.09)	13.00 (5.90)	--	--	--	--	--	--	9.25 (4.20)
	FS-8B	--	90	--	22.12 (10.03)	12.94 (5.87)	--	--	--	--	--	--	9.18 (4.16)
	FS-21	--	--	100	--	--	29.56 (13.41)	17.19 (7.80)	--	--	--	--	12.37 (5.61)
	FS-22	--	--	110	--	--	29.75 (13.49)	17.50 (7.94)	--	--	--	--	12.25 (5.56)
	FS-23	--	--	80	--	--	29.69 (13.47)	17.31 (7.85)	--	--	--	--	12.38 (5.62)
	Air Pot	1080	--	--	--	--	--	--	37.45 (16.99)	22.10 (10.02)	--	--	15.35 (6.96)
	Core	--	--	--	--	--	--	--	--	--	21.25 (9.64)	12.62 (5.72)	8.63 (3.91)
	Core Rim	--	--	--	--	--	--	--	--	--	--	--	--
5	9112	--	1200	--	22.80 (10.34)	13.75 (6.24)	--	--	--	--	--	--	9.05 (4.11)
	9113	--	1200	--	23.20 (10.52)	14.00 (6.35)	--	--	--	--	--	--	9.20 (4.17)
	9114	--	1200	--	22.98 (10.42)	13.90 (6.30)	--	--	--	--	--	--	9.08 (4.12)
	FS-4B	--	1200	--	22.95 (10.41)	13.85 (6.28)	--	--	--	--	--	--	9.10 (4.13)
	FS-10C	--	--	1200	--	--	30.80 (13.97)	18.70 (8.48)	--	--	--	--	12.10 (5.49)
	FS-11C	--	--	1200	--	--	30.05 (13.63)	18.05 (8.19)	--	--	--	--	12.00 (5.44)
	FS-12C	--	--	1200	--	--	30.35 (13.77)	18.25 (8.28)	--	--	--	--	12.10 (5.49)
	Air Pot	1200	--	--	--	--	--	--	38.00 (17.24)	22.90 (10.39)	--	--	15.10 (6.85)
	Core	--	--	--	--	--	--	--	--	--	21.25 (9.64)	12.80 (5.80)	8.45 (3.83)
	Core Rim	--	--	--	--	--	--	--	--	--	--	--	--

(Continued)

Note: Mixture 1 was made using limestone fine and coarse aggregates, a cement content of 611 lb/yd^3 (362.5 kg/m^3), a water-cement ratio by weight of 0.41, and a slump of 1-1/4 in. (31.75 mm).

Table 4 (Concluded)

Batch No.	Specimen No.	Specific Gravity	Air Content, %: Calculated	Air Content, %: Original Batch Pressure Method	Air Content, %: After Vibration	Air Content, %: Micrometric Method	Air Content, %: Hardened Concrete High-Pressure Method	Air Void Spacing Factor in. (mm)	28-Day Compressive Strength psi (MPa)	28-Day Compressive Strength psi (MPa)*	DFE (300 Cycles)
1	9103	2.340	5.9	--	--	--	--	--	--	--	92
	9104	2.340	5.9	--	--	--	--	--	--	--	90
	9105	2.364	4.9	--	--	--	--	--	--	--	92
	FS-1B	2.354	5.3	--	--	5.4	--	--	--	--	--
	FS-1C	2.377	4.4	--	--	--	--	--	5480 (37.78)	--	--
	FS-2C	2.374	4.5	--	--	--	--	--	5390 (37.16)	--	--
	FS-3C	2.376	4.4	--	--	--	--	--	5390 (37.16)	--	--
								Avg	5420 (37.37)		
	Air Pot	2.980	7.6	7.5	7.5	--	--	--	--	--	--
	Core	2.353	5.4	--	--	--	7.9	--	--	--	--
	Core Rim	--	--	--	--	6.8	--	--	--	--	--
2	9106	2.371	4.6	--	--	--	--	--	--	--	92
	9107	2.345	5.7	--	--	--	--	--	--	--	92
	9108	2.343	5.8	--	--	--	--	--	--	--	92
	FS-2B	2.348	5.6	--	--	5.2	--	0.0066 (0.1676)	--	--	--
	FS-4C	2.380	4.3	--	--	--	--	--	5540 (38.20)	--	--
	FS-5C	2.388	3.9	--	--	--	--	--	5630 (38.82)	--	--
	FS-6C	2.374	4.5	--	--	--	--	--	5640 (38.89)	--	--
								Avg	5600 (38.61)		
	Air Pot	2.330	6.3	7.7	7.7	--	--	--	--	--	--
	Core	2.347	5.6	--	--	--	9.3	--	--	--	--
	Core Rim	--	--	--	--	6.4	--	0.0050 (0.1270)	--	--	--
3	9118	2.359	5.1	--	--	--	--	--	--	--	85
	9119	2.370	4.7	--	--	--	--	--	--	--	75
	9120	2.370	4.7	--	--	--	--	--	--	--	88
	FS-7B	2.357	5.2	--	--	6.5	--	0.0038 (0.0965)	--	--	--
	FS-18C	2.392	3.8	--	--	--	--	--	5250 (36.20)	--	--
	FS-19C	2.380	4.3	--	--	--	--	--	5480 (37.78)	--	--
	FS-20C	2.373	4.5	--	--	--	--	--	5230 (36.06)	--	--
								Avg	5320 (36.68)		
	Air Pot	2.449	1.5	7.8	3.5	--	--	--	--	5070 (34.96)	--
	Core	2.463	0.9	--	--	2.7	4.9	0.0056 (0.1422)	--	--	--
	Core Rim	--	--	--	--	--	--	--	--	--	--
4	9121	2.412	3.0	--	--	--	--	--	--	--	90
	9122	2.415	2.9	--	--	--	--	--	--	--	88
	9123	2.405	3.3	--	--	--	--	--	--	--	86
	FS-8B	2.410	3.1	--	--	4.9	--	0.0066 (0.1676)	--	--	--
	FS-21	2.390	3.9	--	--	--	--	--	5380 (37.10)	--	--
	FS-22	2.429	2.3	--	--	--	--	--	5090 (35.10)	--	--
	FS-23	2.390	3.5	--	--	--	--	--	5610 (38.68)	--	--
								Avg	5360 (36.96)		
	Air Pot	2.440	1.9	8.0	2.5	--	--	--	--	5620 (38.75)	--
	Core	2.462	1.0	--	--	--	--	--	--	--	--
	Core Rim	--	--	--	--	--	--	--	--	--	--
5	9112	2.519	--	--	--	--	--	--	--	--	73
	9113	2.522	--	--	--	--	--	--	--	--	73
	9114	2.531	--	--	--	--	--	--	--	--	76
	FS-4B	2.522	--	--	--	1.5	--	0.0068 (0.1727)	--	--	--
	FS-10C	2.545	--	--	--	--	--	--	5070 (34.96)	--	--
	FS-11C	2.504	--	--	--	--	--	--	5250 (36.20)	--	--
	FS-12C	2.508	--	--	--	--	--	--	5390 (37.16)	--	--
								Avg	5240 (36.13)		
	Air Pot	2.517	--	8.5	2.0	--	--	--	--	--	--
	Core	2.515	--	--	--	--	6.0	--	--	--	--
	Core Rim	--	--	--	--	3.0	--	0.0068 (0.1727)	--	--	--

* One in. sawed off top of specimen.

Table 5

Vibration Time, Strength, and Air Content Data of Mortar (Mixture 4)

Batch No.	Cylinder No.	Type of Consolidation	Vibration Time sec	Weight, lb (kg) In Air	Weight, lb (kg) In Water	Weight, lb (kg) Difference	Specific Gravity	Length in. (mm)	Length Correction Factor	Air Content, % Calculated	7-Day Compressive Strength psi (MPa)
1	1	Rodded	--	24.125 (10.943)	11.750 (5.330)	12.375 (5.613)	1.95	12.0 (304.8)	1.0	17.6	1480 (10.20)
2	2	Internal vibration	12.5	26.125 (11.850)	14.000 (6.350)	12.125 (5.499)	2.15	12.0 (304.8)	1.0	9.1	2400 (16.55)
3	3	External	150.0	23.9375 (10.8579)	11.500 (5.816)	12.4375 (5.6416)	1.92	12.0 (304.8)	1.0	18.8	1470 (10.14)
4	4	External	330.0	24.500 (11.113)	12.125 (5.499)	12.375 (5.613)	1.98	12.0 (304.8)	1.0	16.3	1370 (9.45)
5	5	Internal vibration	60.0	25.6875 (11.6517)	14.750 (6.690)	10.9375 (4.9612)	2.35	11.3 (287.0)	0.99	1.1	3550 (24.48)
6	6	Internal vibration	180.0	25.6875 (11.6517)	14.8125 (6.7188)	10.875 (4.933)	2.36	11.0 (279.4)	0.99	0.2	3710 (25.58)

Note: Six batches of mortar (0.2 cu ft) each mixed 3-1/2 min by hand were used to cast one 6- by 12-in. cylinder per batch.

Table 6

Vibration Time, Strength, and Air Content Data (Mixture 1, Batches 6 and 7)

Mixture No.	Batch No.	Cylinder No.	Weight, lb (kg): In Air		In Water		Difference		Specific Gravity	Length of Cylinder in. (mm)	Length Correction Factor	Compressive Strength psi (MPa): 7 Days	28 Days	Vibration Time sec	Unit Weight, lb/ft^3 (kg/m^3): Theoretical	Actual	Difference	Air Content, %: Calculated	Pressure Method
1	6	1	29.062	(13.182)	16.750	(7.598)	12.312	(5.585)	2.360	12.25 (311.15)	--	4040 (27.86)	--	6	154.88 (2480.94)	147.03 (2355.19)	7.85 (125.74)	5.1	7.5
		2	27.938	(12.672)	16.438	(7.456)	11.500	(5.216)	2.429	12.00 (304.80)	--	3500 (24.13)*	--	16	154.88 (2480.94)	151.33 (2425.03)	3.55 (56.87)	2.3	
		3	27.562	(12.502)	16.312	(7.399)	11.250	(5.103)	2.450	11.75 (298.45)	--	4620 (31.85)	--	26	154.88 (2480.94)	152.64 (2445.06)	2.24 (35.88)	1.4	
		4	27.562	(12.502)	16.250	(7.371)	11.312	(5.131)	2.436	11.50 (292.10)	0.993	4920 (33.92)	--	36	154.88 (2480.94)	152.76 (2446.98)	2.12 (33.96)	1.0	
		5	27.312	(12.389)	16.250	(7.371)	11.062	(5.018)	2.469	11.38 (289.05)	0.990	5460 (37.65)	--	46	154.88 (2480.94)	153.82 (2463.96)	1.06 (16.98)	0.7	
		6	27.500	(12.474)	16.312	(7.399)	11.188	(5.075)	2.458	11.38 (289.05)	0.990	5190 (35.79)	--	66	154.88 (2480.94)	153.13 (2452.91)	1.75 (28.03)	1.0	
		7	27.625	(12.530)	16.438	(7.456)	11.187	(5.074)	2.469	11.38 (289.05)	0.990	5400 (37.23)	--	86	154.88 (2480.94)	153.82 (2463.96)	1.06 (16.98)	0.7	
	7	5-1	29.438	(13.353)	17.125	(7.768)	12.313	(5.585)	2.391	12.23 (310.64)	--	--	6440 (44.40)	5	154.88 (2480.94)	148.96 (2386.11)	5.92 (94.83)	3.8	7.2
		5-2	29.125	(13.211)	16.938	(7.683)	12.187	(5.528)	2.390	12.21 (310.13)	--	--	6070 (41.85)	5	154.88 (2480.94)	148.90 (2385.15)	5.98 (95.79)	3.9	
		5-3	29.875	(13.551)	17.438	(7.910)	12.437	(5.641)	2.402	12.20 (309.88)	--	--	6450 (44.47)	5	154.88 (2480.94)	149.64 (2397.15)	5.24 (83.94)	3.4	
		5-4	29.312	(13.296)	17.125	(7.768)	12.187	(5.528)	2.405	12.20 (309.88)	--	--	6210 (42.82)	5	154.88 (2480.94)	149.83 (2400.05)	5.05 (80.89)	3.3	
		5-5	29.375	(13.324)	17.062	(7.739)	12.313	(5.585)	2.386	12.25 (311.15)	--	--	6460 (44.54)	5	154.88 (2480.94)	148.65 (2381.14)	6.23 (99.80)	4.0	
												Avg	6330 (43.65)						
		12-1	28.688	(13.012)	16.938	(7.683)	11.750	(5.330)	2.442	11.82 (300.23)	--	--	6610 (45.58)	12	154.88 (2480.94)	152.14 (2437.05)	2.74 (43.89)	1.8	
		12-2	28.562	(12.956)	16.812	(7.626)	11.750	(5.330)	2.431	11.88 (301.95)	--	--	6110 (42.13)	12	154.88 (2480.94)	151.45 (2426.00)	3.43 (54.94)	2.2	
		12-3	28.500	(12.927)	16.812	(7.626)	11.688	(5.301)	2.438	11.78 (299.21)	--	--	6140 (42.34)	12	154.88 (2480.94)	151.89 (2433.04)	2.99 (47.90)	1.9	
		12-4	28.625	(12.984)	16.938	(7.683)	11.687	(5.301)	2.449	11.82 (300.23)	--	--	6590 (45.44)	12	154.88 (2480.94)	152.57 (2443.94)	2.31 (37.00)	1.5	
		12-5	28.875	(13.098)	17.062	(7.739)	11.813	(5.358)	2.444	11.80 (299.72)	--	--	6450 (44.47)	12	154.88 (2480.94)	152.26 (2438.97)	2.62 (41.97)	1.7	
												Avg	6380 (43.99)						
		30-1	28.438	(12.899)	16.875	(7.654)	11.563	(5.245)	2.459	11.70 (297.18)	--	--	6250 (43.09)	30	154.88 (2480.94)	153.20 (2454.03)	1.68 (26.91)	1.1	
		30-2	28.000	(12.701)	16.625	(7.541)	11.375	(5.160)	2.462	11.50 (292.10)	0.993	--	6350 (43.78)	30	154.88 (2480.94)	153.38 (2456.91)	1.50 (24.03)	1.0	
		30-3	28.750	(13.041)	17.125	(7.768)	11.625	(5.273)	2.473	11.70 (297.18)	--	--	6210 (42.82)	30	154.88 (2480.94)	154.07 (2467.96)	0.81 (12.97)	0.5	
		30-4	28.750	(13.041)	17.062	(7.739)	11.688	(5.301)	2.460	11.65 (295.91)	--	--	6290 (43.37)	30	154.88 (2480.94)	153.26 (2454.99)	1.62 (25.95)	1.0	
		30-5	28.375	(12.871)	16.875	(7.654)	11.500	(5.216)	2.467	11.68 (296.67)	--	--	6140 (42.34)	30	154.88 (2480.94)	153.69 (2461.88)	1.19 (19.06)	0.1	
												Avg	6250 (43.09)						
		50-1	27.938	(12.672)	16.688	(7.569)	11.250	(5.103)	2.483	11.68 (296.67)	--	--	6290 (43.37)	50	154.88 (2480.94)	154.69 (2477.85)	0.19 (3.09)	0.1	
		50-2	28.250	(12.814)	16.938	(7.683)	11.312	(5.131)	2.497	11.70 (297.18)	--	--	6640 (45.78)	50	154.88 (2480.94)	155.56 (2491.83)	-0.68 (-10.89)	-0.4	
		50-3	28.688	(13.012)	17.125	(7.768)	11.563	(5.245)	2.481	11.65 (295.91)	--	--	6000 (41.37)	50	154.88 (2480.94)	154.57 (2475.97)	0.31 (4.97)	0.2	
		50-4	28.500	(12.927)	17.000	(7.711)	11.500	(5.216)	2.478	11.65 (295.91)	--	--	6360 (43.85)	50	154.88 (2480.94)	154.38 (2472.93)	0.50 (8.01)	0.3	
		50-5	28.250	(12.814)	16.875	(7.654)	11.375	(5.160)	2.484	11.68 (296.67)	--	--	5320 (36.68)	50	154.88 (2480.94)	154.75 (2478.86)	0.13 (2.08)	0.1	
												Avg	6320 (43.58)						
		90-1	29.562	(13.409)	17.750	(8.051)	11.812	(5.358)	2.503	11.70 (297.18)	--	--	6250 (43.09)	90	154.88 (2480.94)	155.94 (2497.02)	-1.06 (-16.08)	-0.7	
		90-2	29.125	(13.211)	17.500	(7.938)	11.625	(5.273)	2.505	11.70 (297.18)	--	--	6460 (44.54)	90	154.88 (2480.94)	156.06 (2499.84)	-1.78 (-18.90)	-0.8	
		90-3	29.438	(13.353)	17.625	(7.995)	11.813	(5.358)	2.492	11.68 (296.67)	--	--	6290 (43.37)	90	154.88 (2480.94)	155.26 (2487.03)	-0.38 (-6.09)	-0.2	
												Avg	6330 (43.65)						

Note: Slump for batches was 1-1/2 in. (38.1 mm).
* This cylinder when tested had about 1/2 in. more mortar on top than other cylinders from batch 6.

Table 7

Vibration Time, Strength, and Air Content Data (Mixture 1, Batch 8)

Cylinder No.	Weight, lb (kg) In Air	Weight, lb (kg) In Water	Weight, lb (kg) Difference	Specific Gravity	Length of Cylinder in. (mm)	Length Correction Factor	Compressive Strength psi (MPa) 3 Days	Compressive Strength psi (MPa) 7 Days	Vibration Time sec	Unit Weight, lb/ft^3 (kg/m^3) Theoretical	Unit Weight Actual	Unit Weight Difference	Air Content, % Calculated	Air Content, % Pressure Method
5-1	29.125 (13.211)	16.812 (7.626)	12.313 (5.585)	2.365	12.1 (307)	--	3250 (22.41)	--	5	154.88 (2480.94)	147.34 (2360.16)	7.54 (120.78)	4.9	8.0
5-2	29.188 (13.239)	16.688 (7.569)	12.500 (5.670)	2.335	12.1 (307)	--	3110 (21.44)	--	5	154.88 (2480.94)	145.47 (2330.21)	9.41 (150.73)	6.1	
5-3	29.062 (13.182)	16.812 (7.626)	12.250 (5.556)	2.372	12.0 (305)	--	3500 (24.13)	--	5	154.88 (2480.94)	147.78 (2367.21)	7.10 (113.73)	4.6	
						Avg	3290 (22.60)							
5-4	29.438 (12.899)	17.062 (7.739)	11.376 (5.614)	2.379	12.0 (305)	--	--	4790 (33.03)	5	154.88 (2480.94)	148.21 (2374.10)	6.67 (106.84)	4.3	
5-5	28.750 (13.041)	16.500 (7.484)	12.250 (5.556)	2.347	12.0 (305)	--	--	4200 (28.96)	5	154.88 (2480.94)	146.22 (2342.22)	8.66 (138.72)	5.6	
5-6	29.438 (13.353)	16.938 (7.683)	12.500 (5.670)	2.355	12.1 (307)	--	--	4140 (28.55)	5	154.88 (2480.94)	146.72 (2350.23)	8.16 (130.71)	5.3	
							Avg	4380 (30.18)						
12-1	27.875 (12.644)	16.250 (7.371)	11.625 (5.273)	2.398	11.5 (292)	0.993	3240 (22.34)	--	12	154.88 (2480.94)	149.40 (2393.16)	5.48 (87.78)	3.5	
12-2	28.312 (12.842)	16.562 (7.513)	11.750 (5.330)	2.410	11.4 (290)	0.992	3510 (24.20)	--	12	154.88 (2480.94)	150.14 (2405.01)	4.74 (75.93)	3.1	
12-3	27.875 (12.644)	16.312 (7.399)	11.563 (5.245)	2.411	11.3 (287)	0.990	3550 (24.48)	--	12	154.88 (2480.94)	150.21 (2406.13)	4.67 (74.81)	3.0	
						Avg	3430 (23.67)							
12-4	27.938 (12.672)	16.312 (7.399)	11.626 (5.273)	2.403	11.3 (287)	0.990	--	4480 (30.89)	12	154.88 (2480.94)	149.71 (2398.12)	5.17 (82.82)	3.3	
12-5	27.812 (12.616)	16.250 (7.371)	11.562 (5.245)	2.406	11.3 (287)	0.990	--	3410 (23.51)	12	154.88 (2480.94)	149.89 (2401.01)	4.99 (79.93)	3.2	
12-6	28.438 (12.899)	16.625 (7.541)	11.813 (5.358)	2.407	11.5 (292)	0.993	--	4240 (29.23)	12	154.88 (2480.94)	149.86 (2400.53)	5.02 (80.41)	3.2	
							Avg	4040 (27.88)						
30-1	28.125 (12.757)	16.500 (7.484)	11.625 (5.273)	2.419	11.4 (290)	0.992	3820 (26.34)	--	30	154.88 (2480.94)	150.70 (2413.98)	4.18 (66.96)	2.7	
30-2	28.312 (12.842)	16.750 (7.598)	11.562 (5.245)	2.449	11.5 (292)	0.993	4170 (28.75)	--	30	154.88 (2480.94)	152.57 (2443.94)	2.31 (37.00)	1.5	
30-3	27.938 (12.672)	16.625 (7.541)	11.313 (5.131)	2.470	11.4 (290)	0.992	4080 (28.13)	--	30	154.88 (2480.94)	153.88 (2464.92)	1.00 (16.02)	0.6	
						Avg	4020 (27.44)							
30-4	28.125 (12.757)	16.562 (7.513)	11.563 (5.245)	2.432	11.4 (290)	0.992	--	4540 (31.30)	30	154.88 (2480.94)	151.51 (2426.96)	3.37 (58.98)	2.2	
30-5	28.312 (12.842)	16.812 (7.626)	11.500 (5.216)	2.462	11.3 (287)	0.990	--	5490 (37.85)	30	154.88 (2480.94)	153.38 (2456.91)	1.50 (24.03)	1.0	
30-6	28.188 (12.786)	16.625 (7.541)	11.563 (5.245)	2.438	11.3 (287)	0.990	--	4420 (30.48)	30	154.88 (2480.94)	151.89 (2433.04)	2.99 (47.90)	1.9	
							Avg	4820 (33.21)						
50-1	28.562 (12.956)	16.937 (7.683)	11.625 (5.273)	2.457	11.3 (287)	0.990	3890 (26.82)	--	50	154.88 (2480.94)	153.07 (2451.95)	1.81 (28.99)	1.2	
50-2	28.438 (12.899)	16.875 (7.654)	11.563 (5.245)	2.459	11.1 (282)	0.990	3820 (26.34)	--	50	154.88 (2480.94)	153.20 (2454.03)	1.68 (26.91)	1.1	
50-3	28.750 (13.041)	17.062 (7.739)	11.688 (5.301)	2.460	11.2 (285)	0.990	3970 (27.37)	--	50	154.88 (2480.94)	153.26 (2454.99)	1.62 (25.95)	1.0	
						Avg	3890 (26.84)							
50-4	28.250 (12.874)	16.812 (7.626)	11.438 (5.188)	2.470	11.1 (282)	0.990	--	5130 (35.37)	50	154.88 (2480.94)	153.88 (2464.92)	1.00 (12.01)	0.6	
50-5	28.000 (12.701)	16.625 (7.683)	11.375 (5.160)	2.462	11.1 (282)	0.990	--	4660 (32.13)	50	154.88 (2480.94)	153.88 (2464.92)	1.00 (22.11)	0.6	
50-6	28.250 (12.814)	16.812 (7.626)	11.438 (5.188)	2.470	11.1 (282)	0.990	--	5360 (36.96)	50	154.88 (2480.94)	153.88 (2464.92)	1.00 (12.01)	0.6	
							Avg	5050 (34.82)						
90-1	28.188 (12.786)	16.812 (7.626)	11.376 (5.160)	2.478	11.1 (282)	0.990	3850 (26.55)	--	90	154.88 (2480.94)	154.38 (2472.93)	0.50 (2.08)	0.3	
90-2	28.062 (12.729)	16.750 (7.598)	11.312 (5.131)	2.481	11.1 (282)	0.990	4050 (27.92)	--	90	154.88 (2480.94)	154.57 (2475.97)	0.31 (2.08)	0.2	
90-3	28.500 (12.927)	17.000 (7.711)	11.500 (5.216)	2.478	11.2 (285)	0.990	3870 (26.68)	--	90	154.88 (2480.94)	154.38 (2472.93)	0.50 (2.08)	0.3	
						Avg	3920 (27.05)							
90-4	28.312 (12.842)	16.938 (7.683)	11.375 (5.160)	2.489	11.1 (282)	0.990	--	4990 (34.41)	90	154.88 (2480.94)	155.06 (2483.82)	-0.18 (-8.01)	-0.1	
90-5	27.625 (12.530)	16.438 (7.456)	11.187 (5.075)	2.469	11.0 (280)	0.990	--	4950 (34.13)	90	154.88 (2480.94)	153.82 (2463.96)	1.06 (12.01)	0.7	
90-6	28.312 (12.842)	16.875 (7.654)	11.437 (5.188)	2.476	11.0 (280)	0.990	--	3920 (27.03)	90	154.88 (2480.94)	154.25 (2470.85)	0.63 (2.08)	0.4	
							Avg	4620 (31.86)						

Note: Slump for batch 8 was 1-1/2 in. (38.1 mm).

Table 8

Vibration Time, Strength, and Air Content Data (Mixture 1, Batch 9)

Cylinder No.	Type of Consolidation	Weight, lb (kg) In Air	Weight, lb (kg) In Water	Weight, lb (kg) Difference	Specific Gravity	Length of Cylinder in. (mm)	Length Correction Factor	28-Day Compressive Strength psi (MPa)	Unit Weight, lb/ft^3 (kg/m^3) Theoretical	Unit Weight, lb/ft^3 (kg/m^3) Actual	Unit Weight, lb/ft^3 (kg/m^3) Difference	Air Content, % Calculated	Air Content, % Pressure Method	Vibration Time sec
5-1	Internal	28.562 (12.956)	16.312 (7.399)	12.250 (5.557)	2.332	12.34 (313.44)	1.00	5550 (38.27)	154.88 (2480.94)	145.28 (2327.16)	9.60 (153.78)	6.2	8.2	5
5-2	Internal	27.875 (12.644)	15.750 (7.144)	12.125 (5.499)	2.299	12.43 (315.72)	1.00	4630 (31.92)	154.88 (2480.94)	143.23 (2294.32)	11.65 (186.62)	7.5		5
5-3	Internal	28.312 (12.842)	16.062 (7.286)	12.250 (5.557)	2.311	12.35 (313.69)	1.00	5150 (35.50)	154.88 (2480.94)	143.98 (2306.34)	10.90 (174.60)	7.0		5
							Avg	5110 (35.23)						
12-1	Internal	27.500 (12.474)	15.812 (7.172)	11.688 (5.302)	2.353	11.80 (299.72)	1.00	5020 (34.61)	154.88 (2480.94)	146.59 (2348.15)	8.29 (132.79)	5.4		12
12-2	Internal	27.750 (12.587)	16.000 (7.257)	11.750 (5.323)	2.362	11.89 (302.01)	1.00	5460 (37.65)	154.88 (2480.94)	147.15 (2357.12)	7.73 (123.82)	5.0		12
12-3	Internal	27.938 (12.672)	16.125 (7.314)	11.813 (5.358)	2.365	12.00 (304.80)	1.00	5790 (39.92)	154.88 (2480.94)	147.34 (2360.16)	7.54 (120.78)	4.9		12
							Avg	5420 (37.37)						
30-1	Internal	27.812 (12.615)	16.188 (7.343)	11.624 (5.273)	2.393	11.79 (299.47)	1.00	4860 (33.51)	154.88 (2480.94)	149.08 (2388.03)	5.80 (92.91)	3.7		30
30-2	Internal	27.812 (12.615)	16.188 (7.343)	11.625 (5.273)	2.393	11.79 (299.47)	1.00	5880 (40.54)	154.88 (2480.94)	149.08 (2388.03)	5.80 (92.91)	3.7		30
30-3	Internal	27.875 (12.644)	16.250 (7.371)	11.625 (5.273)	2.398	11.80 (299.72)	1.00	5760 (39.72)	154.88 (2480.94)	149.40 (2393.16)	5.48 (87.78)	3.5		30
							Avg	5500 (37.92)						
50-1	Internal	28.438 (12.899)	16.812 (7.626)	11.626 (5.273)	2.446	11.61 (294.89)	1.00	6340 (43.71)	154.88 (2480.94)	152.39 (2441.05)	2.49 (39.89)	1.6		50
50-2	Internal	28.000 (12.701)	16.500 (7.484)	11.500 (5.216)	2.435	11.53 (292.86)	1.00	6650 (45.85)	154.88 (2480.94)	151.70 (2430.00)	3.18 (50.94)	2.1		50
50-3	Internal	27.625 (12.530)	16.375 (7.428)	11.250 (5.103)	2.456	11.52 (292.61)	1.00	6430 (44.33)	154.88 (2480.94)	153.01 (2450.98)	1.87 (29.95)	1.2		50
							Avg	6470 (44.61)						
90-1	Internal	27.938 (12.672)	16.562 (7.512)	11.376 (5.160)	2.456	11.48 (291.59)	0.993	6430 (44.33)	154.88 (2480.94)	153.01 (2450.98)	1.87 (29.95)	1.2		90
90-2	Internal	27.688 (12.559)	16.438 (7.456)	11.250 (5.103)	2.461	11.41 (289.81)	0.991	6350 (43.78)	154.88 (2480.94)	153.32 (2455.95)	1.56 (24.99)	1.0		90
90-3	Internal	27.562 (12.502)	16.375 (7.428)	11.187 (5.074)	2.464	11.35 (288.29)	0.989	5390 (37.16)	154.88 (2480.94)	153.51 (2458.99)	1.37 (21.95)	0.9		90
							Avg	6060 (41.78)						

Note: Batch 9 was subjected to internal vibration; slump was 1-1/2 in. (38.1 mm).

Table 9

Vibration Time, Strength, and Air Content Data (Mixture 3, Batch 1)

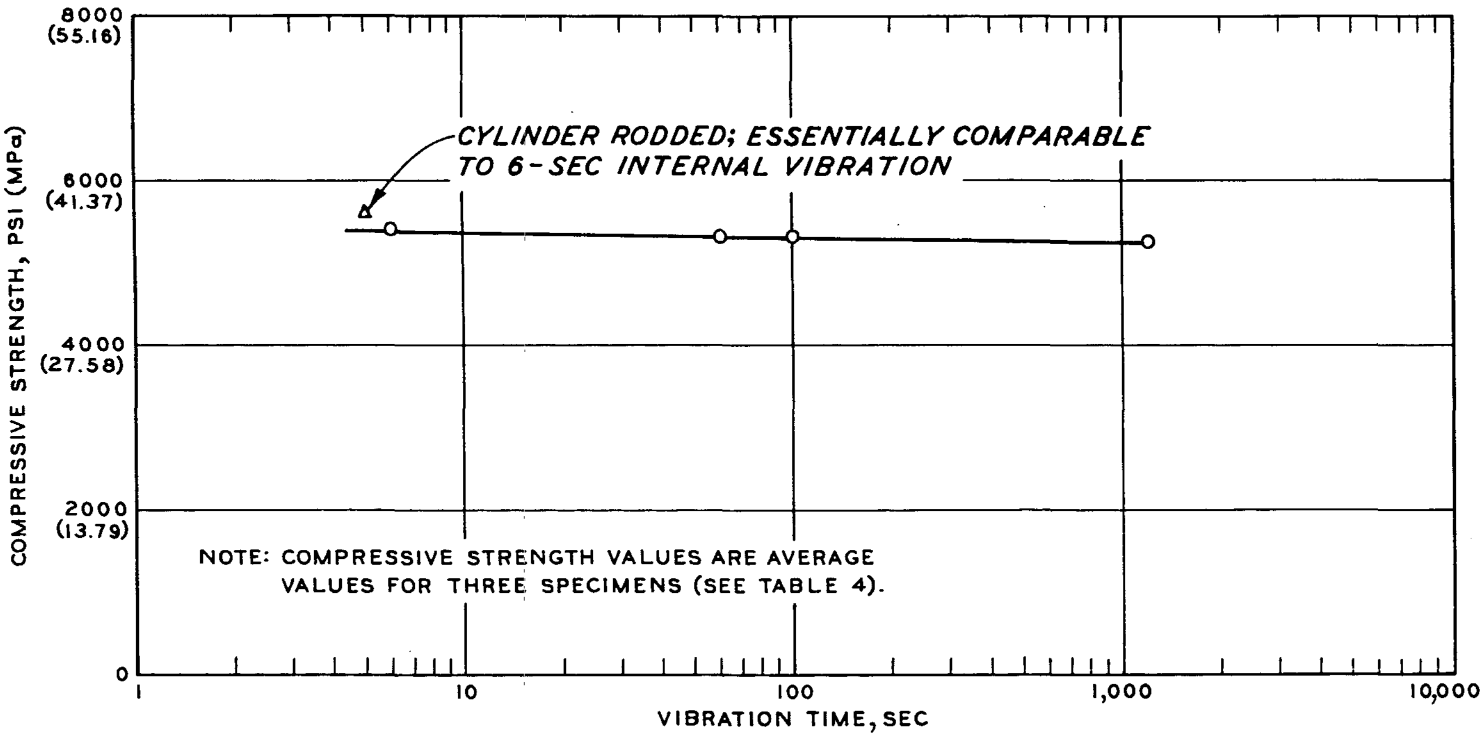
Cylinder No.	Vibration Time, sec	Compressive Strength, psi (MPa)			Air Content, % Pressure Method
		3 Days	7 Days	28 Days	
N5-1	5	3360 (23.17)	--	--	1.8
N5-2	5	3180 (21.93)	--	--	
N5-3	5	3220 (22.20)	--	--	
		Avg 3250 (22.41)			
N5-4	5	--	4410 (30.41)	--	
N5-5	5	--	4460 (30.75)	--	
N5-6	5	--	4410 (30.41)	--	
			Avg 4430 (30.54)		
N5-7	5	--	--	6730 (46.40)	
N5-8	5	--	--	6480 (44.67)	
N5-9	5	--	--	6610 (45.58)	
				Avg 6610 (45.58)	
N12-1	12	3270 (22.55)	--	--	
N12-2	12	3230 (22.27)	--	--	
N12-3	12	3340 (23.03)	--	--	
		Avg 3280 (22.62)			
N12-4	12	--	4360 (30.06)	--	
N12-5	12	--	4180 (28.82)	--	
N12-6	12	--	4550 (31.37)	--	
			Avg 4360 (30.06)		
N12-7	12	--	--	6450 (44.47)	
N12-8	12	--	--	6360 (43.85)	
N12-9	12	--	--	6610 (45.58)	
				Avg 6470 (44.61)	
N30-1	30	3380 (23.31)	--	--	
N30-2	30	3540 (24.41)	--	--	
N30-3	30	3400 (23.44)	--	--	
		Avg 3440 (23.72)			
N30-4	30	--	4520 (31.17)	--	
N30-5	30	--	4230 (29.17)	--	
N30-6	30	--	--	--	
			Avg 4370 (30.13)		
N30-7	30	--	--	6540 (45.09)	
N30-8	30	--	--	--	
N30-9	30	--	--	6460 (44.54)	
				Avg 6500 (44.82)	
N50-1	50	3430 (23.65)	--	--	
N50-2	50	3410 (23.51)	--	--	
N50-3	50	3630 (25.03)	--	--	
		Avg 3490 (24.06)			
N50-4	50	--	4170 (28.75)	--	
N50-5	50	--	4340 (29.92)	--	
N50-6	50	--	4180 (28.82)	--	
			Avg 4230 (29.17)		
N50-7	50	--	--	--	
N50-8	50	--	--	6210 (42.82)	
N50-9	50	--	--	6070 (41.85)	
				Avg 6140 (42.34)	
N90-1	90	3700 (25.51)	--	--	
N90-2	90	3660 (25.24)	--	--	
N90-3	90	3570 (24.62)	--	--	
		Avg 3640 (25.10)			
N90-4	90	--	4750 (32.75)	--	
N90-5	90	--	4890 (33.72)	--	
N90-6	90	--	5000 (34.48)	--	
			Avg 4880 (33.65)		
N90-7	90	--	--	6610 (45.58)	
N90-8	90	--	--	6500 (44.82)	
N90-9	90	--	--	6710 (46.27)	
				Avg 6610 (45.58)	

Note: Batch 1 was subjected to internal vibration; slump was 1-1/2 in. (38.1 mm).

Table 10

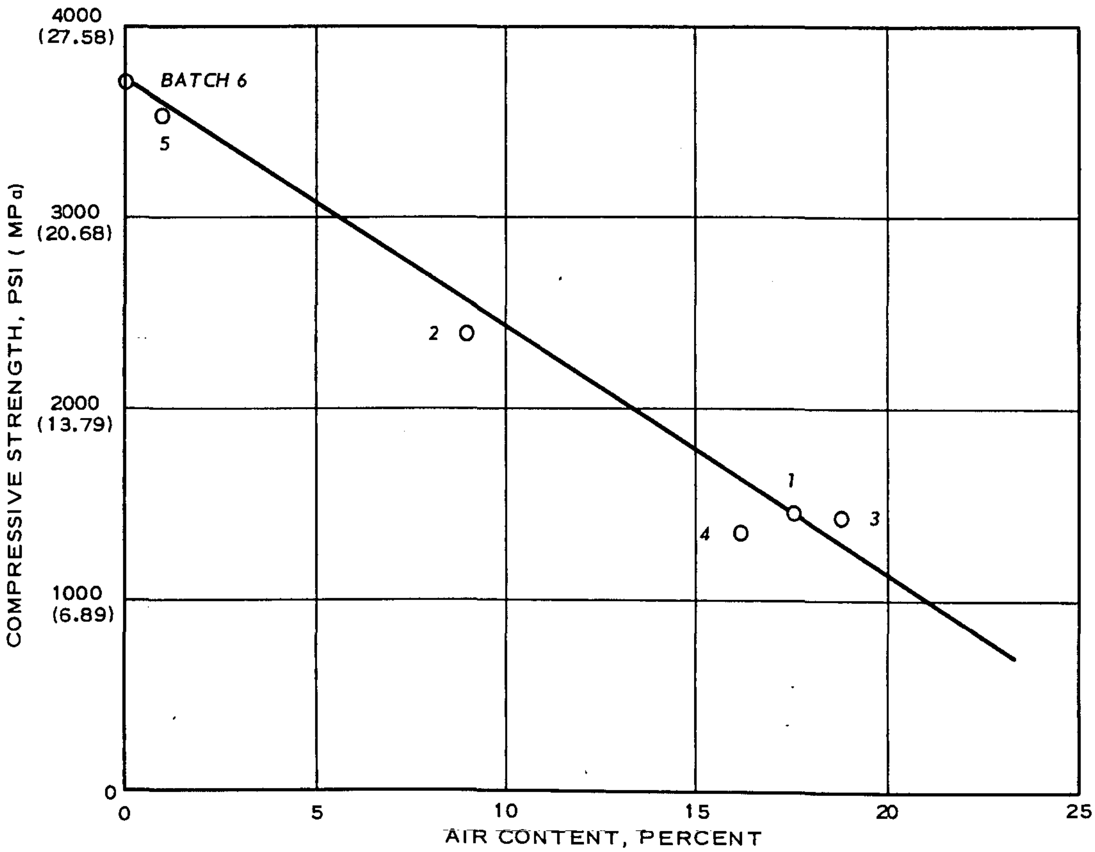
Slump and Air Content Data (Mixture 1, Batch 10; Mixture 2, Batch 1)

				Weight, lb (kg)				Unit Weight, lb/ft^3 (kg/m^3)			Air Content, %						
												Calculated			Micrometric Method		
Slump in. (mm)	Specimen No.	Age When Specimen Weighed days	Type of Curing	In Air	In Water	Difference	Specific Gravity	Theoretical	Actual	Difference	Unhardened	1 Day	28 Days	Pressure Method	Entrained	Entrapped	Total
								Low-Water-Content Mixture 1, Batch 10									
1-3/4 (44.5)	1	1	Water on top	34.562 (15.677)	19.531 (8.859)	15.031 (6.818)	2.299	154.88 (2480.94)	143.23 (2294.32)	11.65 (186.62)	8.0	7.5	--	7.5	6.73	0.88	7.61
	2	1	Dry on top	34.625 (15.706)	19.562 (8.873)	15.063 (6.832)	2.299	154.88 (2480.94)	143.23 (2294.32)	11.65 (186.62)	7.7	7.5	--	7.2	6.88	0.94	7.82
	1	28	Sealed in plastic bag	34.562 (15.677)	19.531 (8.859)	15.031 (6.818)	2.299	154.88 (2480.94)	143.23 (2294.32)	11.65 (186.62)	--	--	7.5	--	--	--	--
	2	28	Sealed in plastic bag	34.656 (15.720)	19.562 (8.873)	15.094 (6.847)	2.296	154.88 (2480.94)	143.04 (2291.28)	11.84 (189.66)	--	--	7.6	--	--	--	--
								High-Water-Content Mixture 2, Batch 1									
1-1/2 (38.1)	3	1	Water on top	34.562 (15.677)	19.531 (8.859)	15.031 (6.818)	2.299	154.46 (2474.21)	143.23 (2294.32)	11.23 (179.89)	7.8	7.3	--	7.6	6.08	0.98	7.06
	4	1	Dry on top	34.562 (15.677)	19.513 (8.851)	15.049 (6.826)	2.297	154.46 (2474.21)	143.10 (2292.24)	11.36 (181.97)	7.9	7.4	--	7.5	7.89	1.90	9.79
	3	28	Sealed in plastic bag	34.656 (15.720)	19.594 (8.888)	15.062 (6.832)	2.301	154.46 (2474.21)	143.35 (2296.25)	11.11 (177.96)	--	--	7.2	--	--	--	--
	4	28	Sealed in plastic bag	34.719 (15.748)	19.562 (8.873)	15.157 (6.875)	2.291	154.46 (2474.21)	142.73 (2286.31)	11.73 (187.90)	--	--	7.6	--	--	--	--



EFFECT OF VIBRATION TIME ON COMPRESSIVE STRENGTH OF AIR-ENTRAINED SPECIMENS

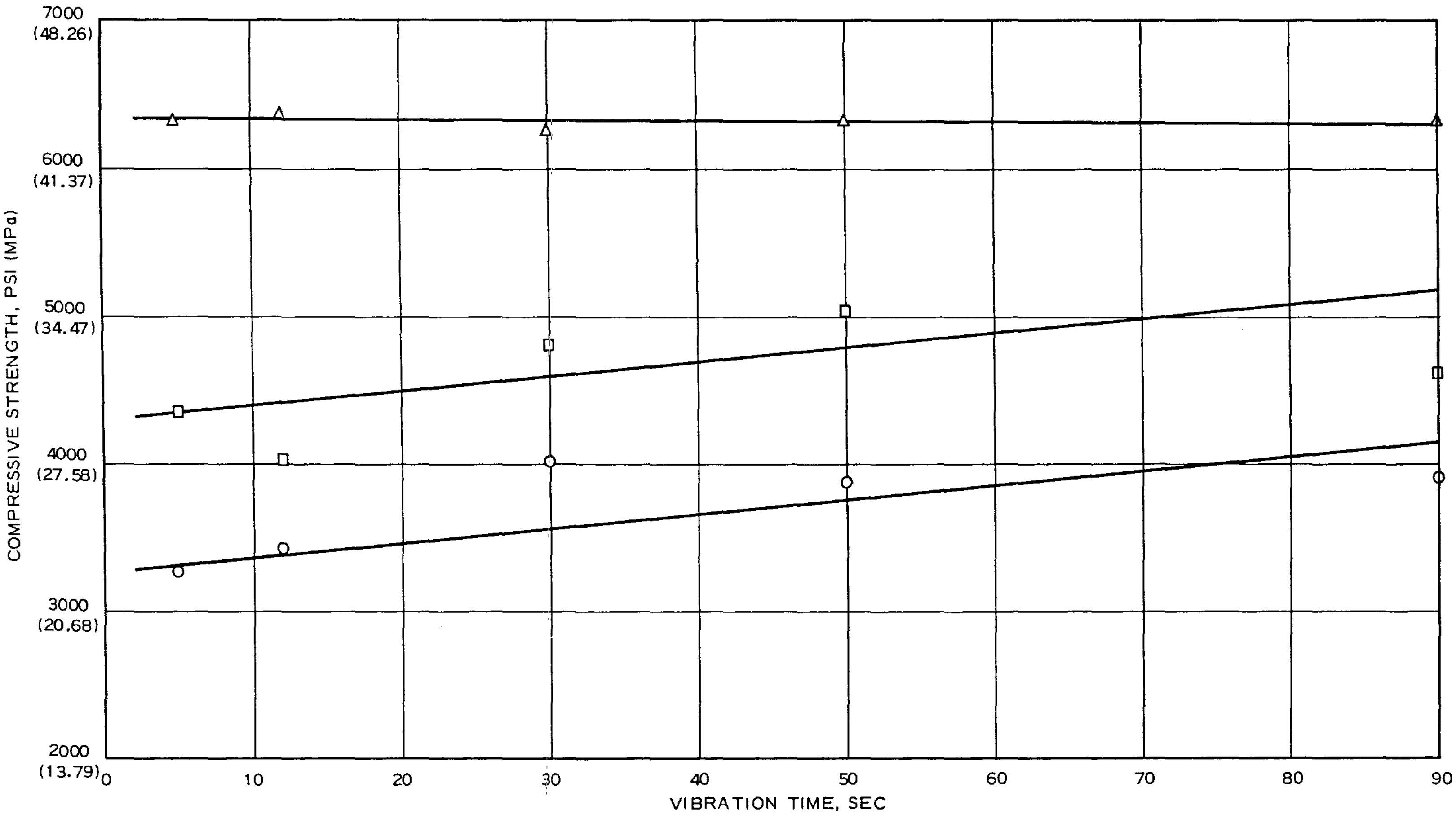
MIXTURE 1, BATCHES 1-5



NOTE: COMPRESSIVE STRENGTH VALUES ARE LISTED IN TABLE 5.

EFFECT OF AIR CONTENT ON
COMPRESSIVE STRENGTH OF
AIR-ENTRAINED SPECIMENS

MORTAR MIXTURE, BATCHES 1 - 6

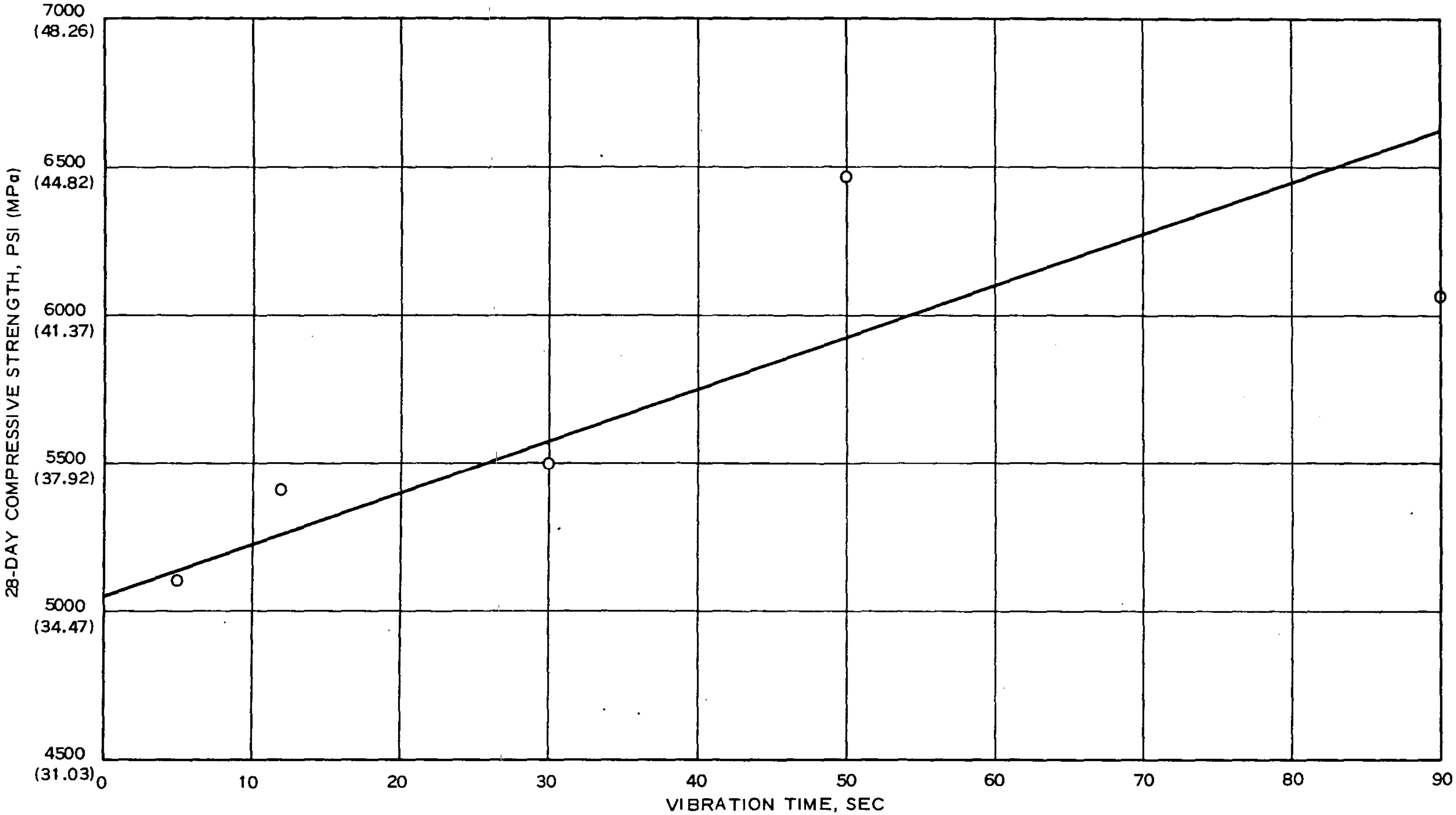


LEGEND

- O 3 DAYS (BATCH 8)
- □ 7 DAYS (BATCH 8)
- Δ 28 DAYS (BATCH 7)

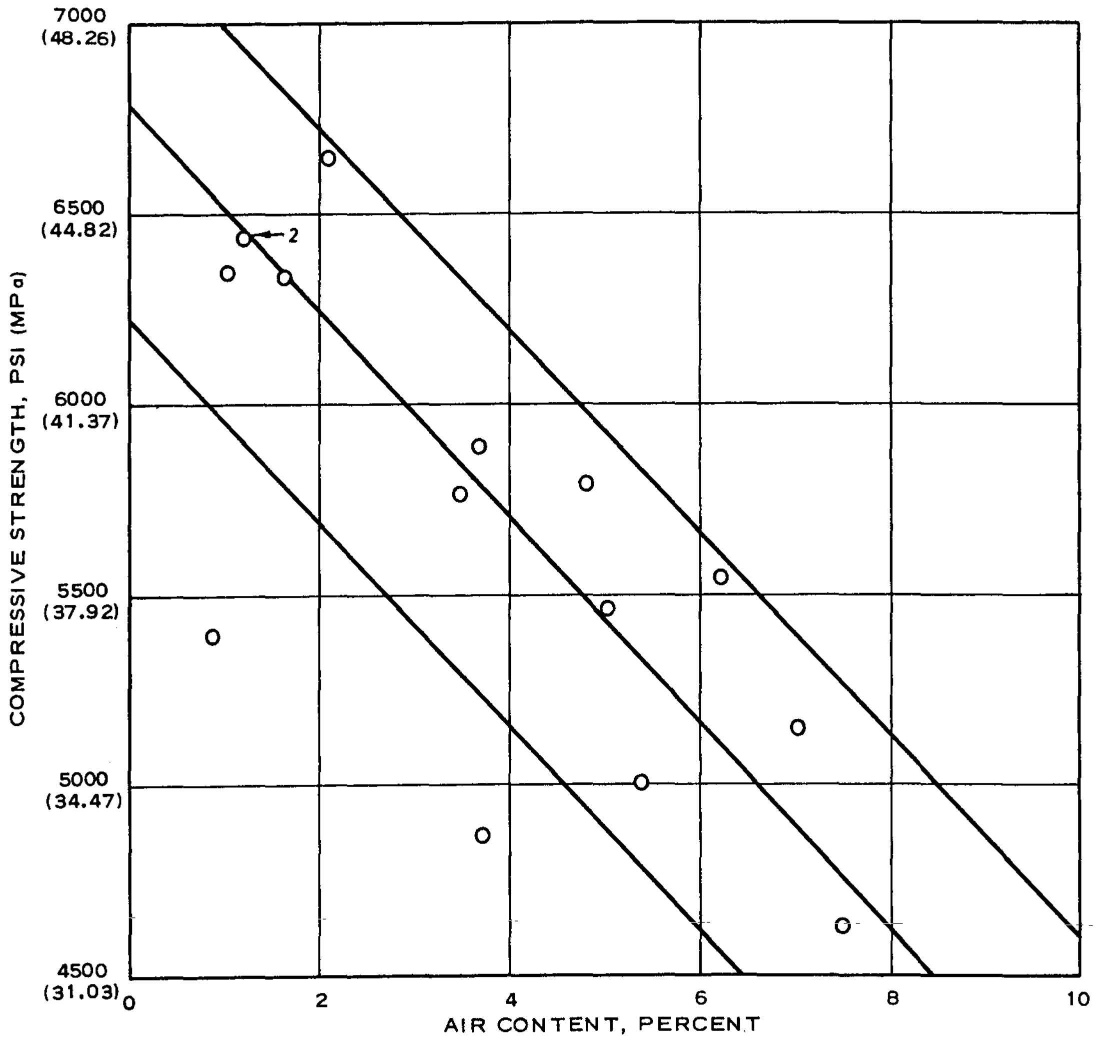
NOTE: COMPRESSIVE STRENGTH VALUES ARE AVERAGE VALUES FOR THREE OR FIVE SPECIMENS (SEE TABLES 6 AND 7).

EFFECT OF VIBRATION TIME ON COMPRESSIVE STRENGTH OF AIR-ENTRAINED SPECIMENS MIXTURE 1, BATCHES 7 AND 8



NOTE: COMPRESSIVE STRENGTH VALUES ARE AVERAGE VALUES FOR THREE SPECIMENS (SEE TABLE 8).

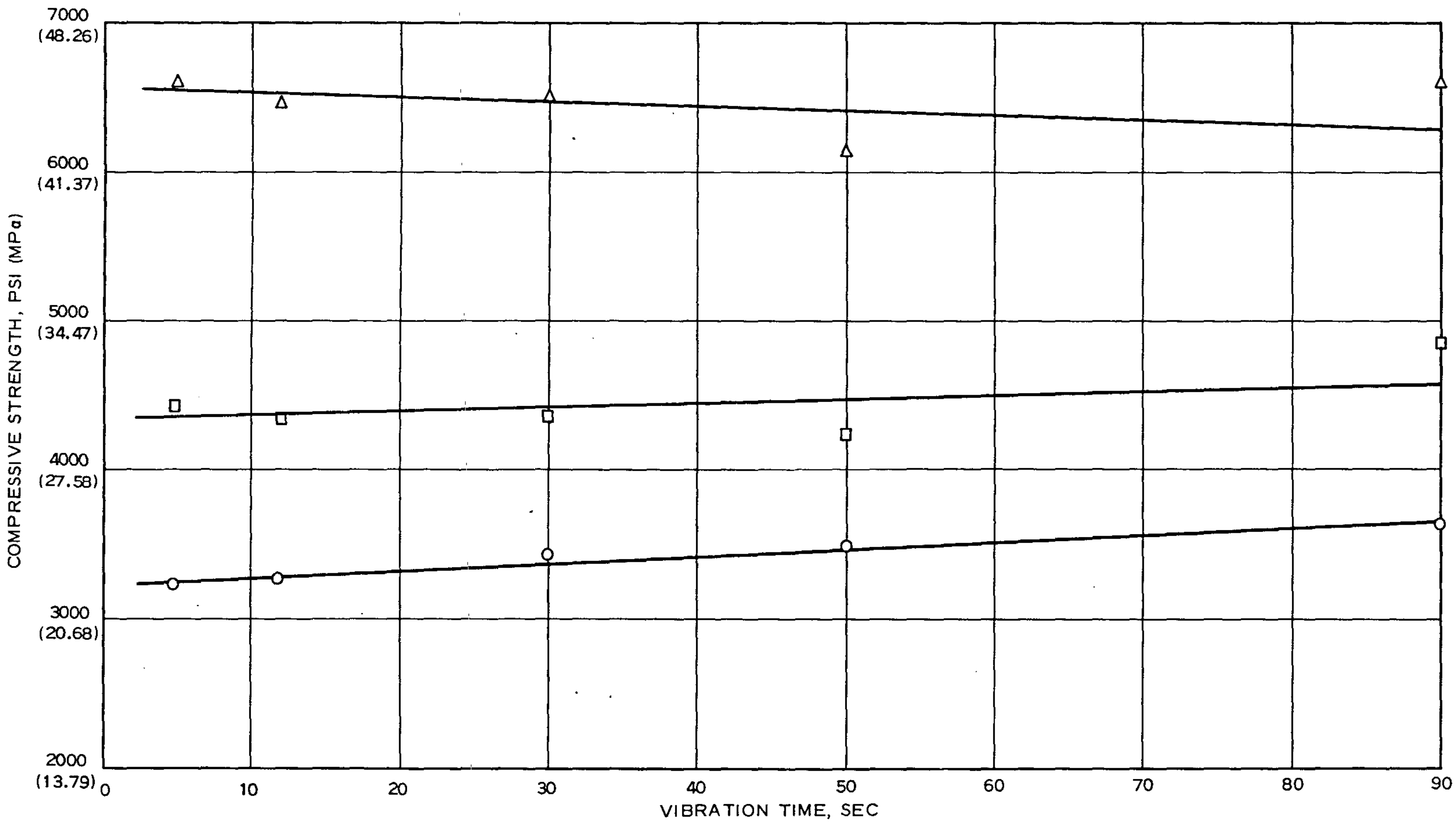
EFFECT OF VIBRATION TIME ON COMPRESSIVE STRENGTH OF AIR-ENTRAINED SPECIMENS
MIXTURE 1, BATCH 9



NOTE: COMPRESSIVE STRENGTH VALUES ARE LISTED IN TABLE 8.

EFFECT OF AIR CONTENT ON COMPRESSIVE STRENGTH OF AIR-ENTRAINED SPECIMENS

MIXTURE 1, BATCH 9

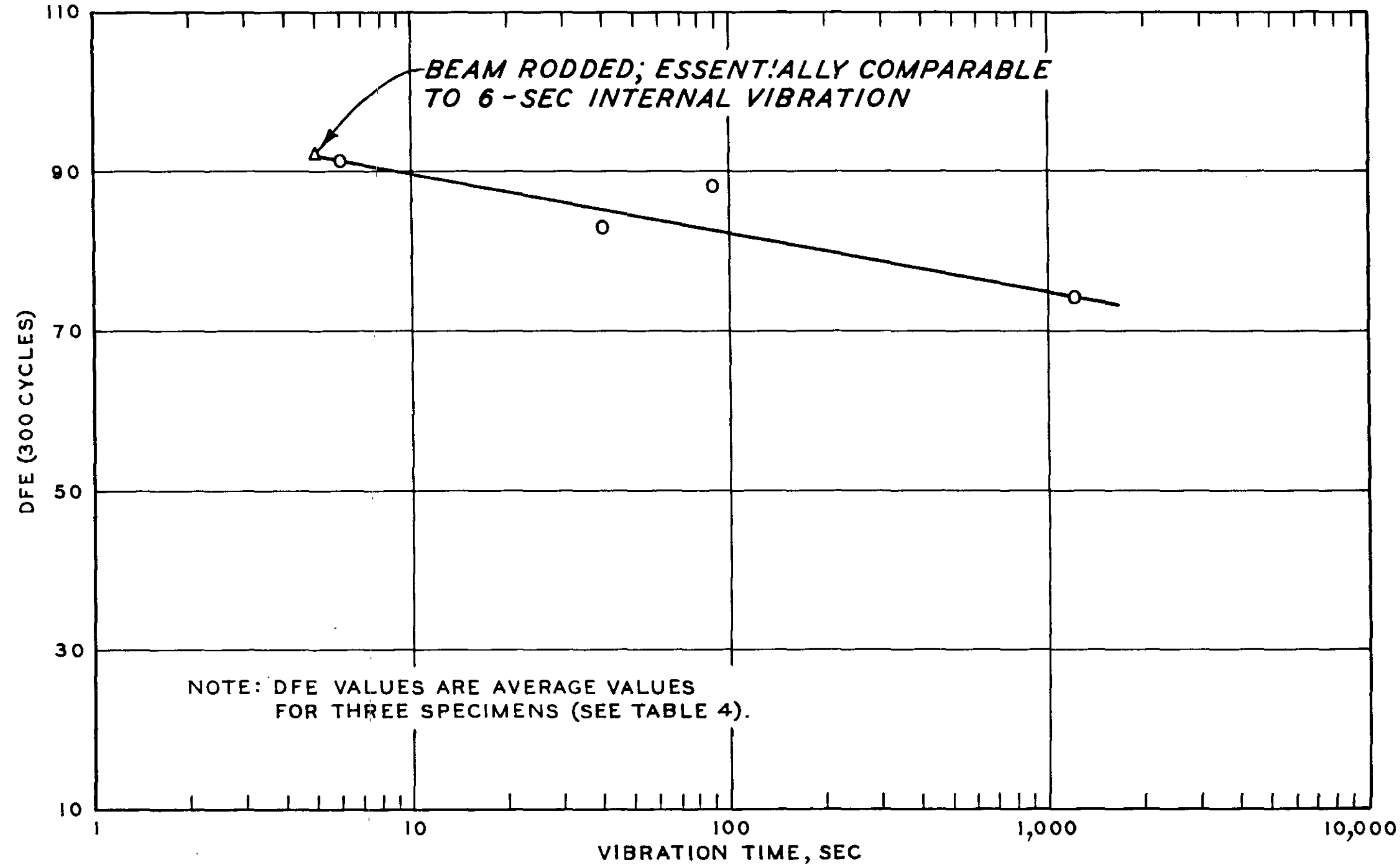


LEGEND

- ○ 3 DAYS
- □ 7 DAYS
- △ 28 DAYS

NOTE: COMPRESSIVE STRENGTH VALUES ARE AVERAGE VALUES FOR TWO OR THREE SPECIMENS (SEE TABLE 9).

EFFECT OF VIBRATION TIME ON COMPRESSIVE STRENGTH OF NONAIR-ENTRAINED SPECIMENS MIXTURE 3, BATCH 1



EFFECT OF VIBRATION TIME ON DURABILITY

MIXTURE 1, BATCHES 1-5

In accordance with ER 70-2-3, paragraph 6c(1)(b), dated 15 February 1973, a facsimile catalog card in Library of Congress format is reproduced below.

Tynes, William O

Investigation of high-strength frost-resistant concrete, by William O. Tynes. Vicksburg, U. S. Army Engineer Waterways Experiment Station, 1975.

1 v. (various pagings) illus. 27 cm. (U. S. Waterways Experiment Station. Miscellaneous paper C-75-6)

Prepared for Office, Chief of Engineers, U. S. Army, Washington, D. C.

Includes bibliography.

1. Concrete tests. 2. Frost-resistant concretes. 3. High-strength concretes. I. U. S. Army. Corps of Engineers. (Series: U. S. Waterways Experiment Station, Vicksburg, Miss. Miscellaneous paper C-75-6)

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