Technical Report Documentation Page

1. REPORT No.

2. GOVERNMENT ACCESSION No.

3. RECIPIENT'S CATALOG No.

4. TITLE AND SUBTITLE

Effects of Air-Entraining Agents on Concrete Properties

5. REPORT DATE

August 1965

6. PERFORMING ORGANIZATION

7. AUTHOR(S)

B.F. Neal

8. PERFORMING ORGANIZATION REPORT No.

Work Order 250918

9. PERFORMING ORGANIZATION NAME AND ADDRESS

State of California
Highway Transportation Agency
Department of Public Works
Division of Highways
Materials and Research Department

10. WORK UNIT No.

11. CONTRACT OR GRANT No.

12. SPONSORING AGENCY NAME AND ADDRESS

13. TYPE OF REPORT & PERIOD COVERED

14. SPONSORING AGENCY CODE

15. SUPPLEMENTARY NOTES

A study made by the California Division of Highways in cooperation with the U.S. Department of Commerce bureau of public roads

16. ABSTRACT

The use of entrained air in concrete has been considered to be one of the greatest advances in concrete technology in the past 50 years. Concrete engineers are not only aware of the improved frost resistance imparted by air entrainment, but of other beneficial effects as well. Air-entrained concrete is generally less permeable and thereby retards the entry of destructive elements such as sulfates. Air entrainment reduces water demand for a given slump, improves the workability (especially for lean or harsh mixes), and reduces bleeding. Excessive bleeding sometimes causes delays and difficulties in finishing concrete surfaces. The protection that is provided against freezing and thawing is, of course, the principal purpose and benefit of using entrained air.

Not all effects of air entrainment can be considered beneficial however. For example, both flexural and compressive strengths are usually reduced, and drying shrinkage is usually increased. Bond to steel has been assumed to be reduced also, since studies show that bond strength in non-air entrained concrete is proportional to compressive strength. Whether or not these detrimental effects are significant, depends on other factors.

In testing a well-known air-entraining agent according to Section 2(d) of ASTM C 233-58 T, it was found that the agent did not meet the requirement that compressive strength of the air-entrained concrete be not less than 85% of a similar non-air-entrained concrete. Repeat tests on this and other agents confirmed these findings. To further explore the effects of air-entraining agents on concrete properties, the Materials and Research Department initiated a project which was financed in part by the U.S. Department of Commerce, Bureau of Public Roads.

17. KEYWORDS

Laboratory Project Work Order 250918

18. No. OF PAGES:

25

19. DRI WEBSITE LINK

http://www.dot.ca.gov/hq/research/researchreports/1964-1965/65-02.pdf

20. FILE NAME

65-02.pdf

STATE OF CALIFORNIA
HIGHWAY TRANSPORTATION AGENCY
DEPARTMENT OF PUBLIC WORKS
DIVISION OF HIGHWAYS

EFFECTS OF AIR-ENTRAINING AGENTS ON CONCRETE PROPERTIES

A STUDY MADE BY THE
CALIFORNIA DIVISION OF HIGHWAYS
IN COOPERATION WITH THE
U.S. DEPT. OF COMMERCE
BUREAU OF PUBLIC ROADS

August 1965

65-02

MATERIALS & RESEARCH DEPARTMENT

State of California
Highway Transportation Agency
Department of Public Works
Division of Highways

MATERIALS AND RESEARCH DEPARTMENT

August, 1965

Laboratory Project
Work Order 250918

Mr. J. C. Womack
State Highway Engineer
Division of Highways
Sacramento, California

Dear Mr. Womack:

Submitted for your consideration is a report on a study made by the California Division of Highways in cooperation with the U. S. Department of Commerce, Bureau of Public Roads, entitled:

Effects of

Air-entraining Agents on Concrete Properties

Project conducted by . . . . Concrete Section
Under direction of . . . . D. L. Spellman
Work supervised by . . . . J. H. Woodstrom
Report prepared by . . . . B. F. Neal

Very truly yours,

JOHN L. BEATON
Materials and Research Engineer

cc:LRGillis
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Research Files

Table of Contents

EFFECTS OF AIR-ENTRAINING AGENTS ON CONCRETE PROPERTIES

INTRODUCTION

The use of entrained air in concrete has been considered to be one of the greatest advances in concrete technology in the past 50 years. Concrete engineers are not only aware of the improved frost resistance imparted by air entrainment, but of other beneficial effects as well. Air-entrained concrete is generally less permeable and thereby retards the entry of destructive elements such as sulfates. Air entrainment reduces water demand for a given slump, improves the workability (especially for lean or harsh mixes), and reduces bleeding. Excessive bleeding sometimes causes delays and difficulties in finishing concrete surfaces. The protection that is provided against freezing and thawing is, of course, the principal purpose and benefit of using entrained air.

Not all effects of air entrainment can be considered beneficial however. For example, both flexural and compressive strengths are usually reduced, and drying shrinkage is usually increased. Bond to steel has been assumed to be reduced also, since studies show that bond strength in non-air entrained concrete is proportional to compressive strength. Whether or not these detrimental effects are significant, depends on other factors.

In testing a well-known air-entraining agent according to Section 2(d) of ASTM C 233-58 T, it was found that the agent did not meet the requirement that compressive strength of the air-entrained concrete be not less than 85% of a similar non-air-entrained concrete. Repeat tests on this and other agents confirmed these findings. To further explore the effects of air-entraining agents on concrete properties, the Materials and Research Department initiated a project which was financed in part by the U. S. Department of Commerce, Bureau of Public Roads.

The variables considered in this program were compressive strength, flexural strength, bond of concrete to reinforcing steel, surface bleeding, length change, and void system analysis by the linear traverse method. Variations in cement factor and aggregate combinations were also included. Pertinent data from previous laboratory findings are incorporated into this report. Freeze-thaw tests were not part of this program.

Since this testing program began, the ASTM specifications for air-entraining agents and the methods for testing have been revised. In the tests reported here, however, the procedures were based on the 1958 ASTM specifications and methods.

CONCLUSIONS

Based on the findings from this limited test program using mixes containing 6 to 8 sacks per cubic yard, and certain materials available in California, the following conclusions seem warranted:

1. The compressive strength of concrete decreases with an increase in air content. The flexural strength is also decreased, though to a lesser degree.

2. The specification requiring a relative compressive strength of 85% of a non-air-entrained control concrete cannot be met under some of the test conditions allowed by ASTM C 233-58 T.

3. For concrete with 1-1/2-inch maximum size aggregate and containing 4% air, the addition of approximately one extra sack of cement per cubic yard is generally needed to obtain a relative strength of at least 85% of control concrete without air.

4. The maximum size of the aggregate is a major factor in compressive strength reduction of air-entrained concrete, with 1-1/2-inch maximum size showing more strength loss than 1-inch maximum for equivalent air contents.

5. The influence of air entrainment on compressive strength is dependent on the cement factor level and aggregate properties.

6. The effect of air entrainment on the bond of concrete to steel appears to be insignificant.

7. The reproducibility of both bond tests and bleeding tests were poor and the results of such tests are questionable.

8. The drying shrinkage of concrete containing 4-1/2% air is approximately 10% greater than non-air-entrained concrete when tested in conformance with Test Method No. Calif. 530, modified.

9. Portions of past and current requirements of air-entraining agents as set forth in ASTM C-260 have limited effectiveness in controlling and evaluating the use of such agents.

TEST PROGRAM

Part A - Description of Tests

A comprehensive testing program was outlined, but it became apparent as work progressed that it would not be necessary to perform all the planned work. Six series of tests were carried out under this program and, in addition, pertinent data obtained in conjunction with other work is reported herein as Test Series 7 and 8.

The admixtures selected for evaluation in this study were chosen primarily for their use or proposed use in concrete on State work. Following is a list of the agents tested and a brief description of the eight test series:

Agent	Description
A	A neutralized Vinsol resin
B	An organic salt of sulfonated hydrocarbon
C	A composition of several organic and mineral-organic compounds which are polymerized and carried in an aromatic solvent. (Not sold as an air-entraining agent.)
D	A neutral liquid containing chemically modified protein derivatives which have marked colloidal and dispersing properties. (Not sold as an air-entraining agent.)
E	A neutralized Vinsol resin.
F	A neutralized Vinsol resin.

Test Series No. 1

The purpose of this series of tests was to determine the reduction in compressive strength of concrete due to air entrainment. A total of 6 mixes were tested with cement contents ranging from 6 to 7 sacks per cubic yard and air contents varying up to 6% (Agent A). Aggregates were of 1-1/2-inch maximum size from the American River, taken from laboratory stock. The cement was Type II modified (as per 1964 California Standard Specifications), from a local mill. Three rounds of concrete were mixed on three different days for each of the 6 mixes tested. Two 6x12-inch test cylinders were made from each batch for 7 and 14-day compressive strengths. For results of these tests, see Table 1.

Test Series No. 2

These tests were made to compare the compressive strength of a 7-sack concrete with 4-1/2% air, to a 6-sack, non-air-entrained mix. Two rounds of concrete were made on different days for each of the two mixes. Three 6x12-inch cylinders were made from each batch for 14-day compressive strengths. The same air-entraining agent (Agent A), cement, aggregates and gradings were used as in Test Series No. 1. See Table 2 for test results.

Test Series No. 3

The purpose of these tests was to verify results obtained from Test Series Nos. 1 and 2. Using data collected from the first two series, cement factors were predicted by interpolation to yield a certain range of strengths with the various air contents. The cement factor was increased to partially offset strength loss due to air entrainment and produce at least 85% of the control concrete strength as required in ASTM Designation: C 260-58 T. The following amounts of cement were used for each of the levels of entrained air selected.

Air Content, %	Cement Factor Lbs./Cubic Yard	Cement Factor Sacks/Cu. Yd.
Non-air-entrained (1.2)	564	6.00
3.0	589	6.27
3.5	614	6.53
4.5	658	7.00
5.5	739	7.85

Three rounds of concrete were made on different days for each mix. Two standard test cylinders were made from each batch for 14-day compressive strength determinations. The air-entraining agent (Agent A), cement, and aggregates were the same as used in Series Nos. 1 and 2. For results of these tests, see Table 3.

Test Series No. 4

Except for the following modifications, Series 4 was the same as Series 3. Agent E, also a neutralized Vinsol resin, was substituted for Agent A. In addition to compressive strength tests, flexural strength and drying shrinkage were evaluated.

Three rounds of concrete were made on different days for each mix. One 6x12-inch cylinder, one 6x6x20-inch beam, and one 4x5x18-inch shrinkage specimen was made from each batch. For results of these tests, see Table 4.

Test Series No. 5

In this series, two different types of air-entraining agents were compared (Agents A and B), and a third admixture (Agent C) which is not sold as an air-entraining agent, was also tested to determine its effect on bond and bleeding. Three rounds were made on different days for each of the four mixes tested and the following specimens were fabricated from each batch:

For Bond Tests:

1 - 6x6x6-inch bond specimen with a No. 6 steel reinforcing bar placed in a vertical position

1 - 6x6x12-inch double bond specimen containing two No. 6 reinforcing bars placed in horizontal positions

For Agent C, no other specimens were fabricated. From the other mixes (Agents A and B), in addition to the bond specimens, two 6x12-inch cylinders for compressive strengths at 7 and 28 days, and three 3x3x11-1/4-inch bars for determining drying shrinkage were fabricated. Bleeding tests were also made from the first and third rounds of each mix tested.

The cement and aggregates were from the same sources as those used in the earlier series. However, the cement content of all mixes was 6 sacks, and the aggregates were of 1-inch maximum size instead of 1-1/2-inch. For results of these tests, see Table 5.

Test Series No. 6

The principle purpose of this series was to evaluate the reproducibility of the bond test. The agents tested were A, B, and D. In addition to bond tests, compressive strengths and bleeding characteristics were compared.

Three rounds of concrete were made on different days for each condition of concrete. Bond specimens as described in Series 5 and two 6x12-inch cylinders for 7 and 28-day compressive strengths were fabricated from each batch.

The cement and aggregates were from the same source as used in Series 1, but aggregates were of 1-inch maximum size. For results of these tests, see Table 6.

Test Series No. 7

The purpose of these tests was to determine the amount of drying shrinkage that could be attributed to the use of air-entraining admixtures when tested in accordance with Test Method

No. Calif. 530, modified. In addition, air void characteristics were determined by the linear traverse method. Agents D and F were used in this series.

Three rounds of concrete were made on different days for each mix tested, and three 3x3x11-1/4-inch specimens were fabricated from each batch.

Aggregates were of 1-inch maximum size from the same source as used in the other tests. A blend of Type II cements from five different mills was used for this series. For results of these tests, see Table 7.

Test Series No. 8

In this series, tests were made to determine the amount of flexural and compressive strength loss caused by air entrainment at a nominal level of 4-1/2%. The agents used were A and E. Tests were made using 1-1/2-inch maximum size aggregates from various sources throughout the State. The cement was Type II modified from a local mill, and used at both 5 and 6-sacks per cubic yard.

Five rounds of concrete were made for each aggregate under test. One 6x12-inch cylinder and one 6x6x20-inch beam was made from each batch for 14-day strengths. For results of these tests, see Figures 1 and 2.

Part B - Test Methods

Following are brief descriptions and details of the various tests performed to evaluate the different agents.

1. Compressive Strength

Compressive strength tests on 6x12-inch cylindrical specimens were performed according to ASTM Designation C 39-56. Test ages varied but were either 7, 14, or 28 days. Representative cylinders were cast from each batch of the air-entrained concrete and also from each batch of non-air-entrained concrete. The number of cylinders for each variable tested ranged from 3 to 6. All specimens were stripped from their molds at 24 hours and placed in the fog room at 73°F for curing until capped and tested. Testing was done on a 300,000-lb. capacity Baldwin press at a constant loading rate of about 40 psi per second. The compressive strengths were calculated to the nearest 10 psi.

2. Flexural Strength

Flexural tests were performed on 6x6x20-inch beam specimens according to ASTM Designation C 78-59, "Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading)." The number of beams tested for each condition varied from 3 to 5. All beams were stripped from their molds at 24 hours and placed in the fog room at 73°F for curing until the test age of 14 days. The beams were broken in flexure using third-point loading on a 300,000-lb. capacity Baldwin testing machine. The flexural strength, or modulus of rupture, was calculated to the nearest 5 psi.

3. Bond Strength

Bond strength tests were performed according to ASTM Designation C 234-57 T, "Comparing Concretes on the Basis of the Bond Developed with Reinforcing Steel." One 6x6x6-inch specimen with a No. 6 steel reinforcing bar placed in the vertical position and one 6x6x12-inch double specimen containing two No. 6 reinforcing bars placed in a horizontal position, were cast from each batch of concrete. Sets of three specimens were fabricated for each variable tested. The specimens were stripped from their molds at 24 hours and placed in the fog room. At age 7 days, the 6x6x12-inch double specimens were separated in flexure using a special jig placed in the Baldwin press. The resulting cubes were then returned to the fog room for an additional 21 days of curing. Specimens with the vertically positioned steel were capped, when necessary, with a neat cement paste at least 24 hours before testing. Bond tests were performed on all 6-inch cubes at the age of 28 days, using a special test apparatus on a 60,000-lb. capacity tensile testing machine. The average rate of loading was about 1000-lbs. per minute. The strength of the bond between the steel and the concrete was evaluated in terms of the nominal average bond stress as measured at five equal points on the stress-slip curves.

4. Surface Bleeding

Bleeding tests were performed on the fresh concrete according to ASTM Designation C 232-58, "Test for Bleeding of Concrete." Specimens consisted of approximately 0.6 cubic foot of concrete placed in a 5-gallon container to a depth of 10 inches. In some series, only two of three rounds were tested for bleeding. Results were calculated as bleeding water per unit area of surface, and also as a percent of the net mixing water in the test specimens.

5. Length Change (Shrinkage)

In Series 4, 5, and 7, drying shrinkage tests were conducted using modified Test Method No. Calif. 530, "Method of Test for Determining the Effect of Water-Reducing and Set-Retarding Admixtures on the Drying Shrinkage of Concrete." The tests were used to compare concretes containing various air-entraining agents to a non-air-entrained control concrete. Shrinkage specimens were 4x5x18-inch when 1-1/2-inch maximum size aggregates were used, but when 1-inch maximum size aggregates were used, the specimen size was 3x3x11-1/4-inches.

Basic differences between Test Method No. Calif. 530 and ASTM Designation C 157-64 T, are as follows:

	ASTM C 157	Calif. 530
Soaking in water before initial measurement	30 minutes	None
Age at initial measurement	24 ± 1/2 hour	7 days
Cure	28 days in lime saturated water	7 days in fog room

6. Void System in Hardened Concrete

The investigation of the air void systems was done in accordance with ASTM Designation C 457-60 T, "Microscopical Determination of Air-Void Content, Specific Surface, and Spacing Factor of the Air-Void System in Hardened Concrete." Only two samples of concrete containing entrained air were investigated during this testing program.

DISCUSSION

Compressive Strength

The compressive strength data reported herein demonstrate the fact that as the amount of entrained air increases, strength decreases. Starting with a 6-sack, non-air-entrained concrete made with 1-1/2-inch maximum size American River aggregate as a control, the cement factor would have to be increased to about 8 sacks per cubic yard or more to completely regain the compressive strength lost as a result of entraining 4% air. For most of the agents tested, the cement factor of air-entrained concrete would have to be increased from 6 sacks to 7 sacks in order to obtain at least 85% of the strength of comparable 6-sack, non-air-entrained concrete.

The effects of air entrainment on concrete strength may vary considerably due to certain characteristics of the aggregate particles. Whether or not a particular agent would meet the strength requirements of ASTM might depend upon what aggregate is used as well as its maximum size.

Figure 1 compares compressive strengths of concrete made with various types of aggregates from throughout the State. When 5-sack non-air-entrained concrete is used as a control, 6-sack concrete with 4-1/2% air results in relative compressive strengths of 89% to 106%, or an average of about 95%. This finding when compared with that discussed in the above paragraphs, supports other published data which show that loss of strength is less in the leaner mixes. The entrainment of 4-1/2% air in 6-sack mixes gave results similar to those obtained in the other test series; that is, a reduction in compressive strength of 16% to 25%. Using the approximate figure of 3.3% as the air actually added by use of the agent, the average compressive strength loss for each percent of added air is about 6-1/2%.

The data shown in Tables 5 and 6 indicate that agents tested in concrete made with 1-inch maximum size aggregates generally will meet the relative compressive strength requirement of 85% of a control concrete without air. Earlier tests, though not reported here, also indicated that the grading of the aggregate had a significant effect on results. These tests, made with Agents A and B and following ASTM Designation C 233-58, produced relative compressive strengths of 85% to 92% of a control concrete without air.

The fact that the compressive strength requirement can be met when smaller size aggregates are used, appears meaningful only when 1-inch or smaller maximum size aggregates are specified for the actual concrete work involved. To indicate that the relative strength is over 85% might be misleading if 1-1/2-inch maximum size aggregates were actually to be used on the job. For most highway work in California, 1-1/2-inch maximum size aggregates are used and specifications now require the use of additional cement when the concrete is air-entrained. The amounts of cement required by the 1964 Standard Specifications to partially offset the strength lost due to entrained air are as follows:

Total Air Content, %	Additional Cement, Lbs. per Cu. Yd.
Less than 3	None
3 to less than 4	50
4 to less than 5	94
5 to 6	175

It should be noted that air-entrained concrete even at reduced strength, is superior to non-air-entrained concrete under some conditions. In areas where freezing and thawing is a factor, California specifications require the use of air entrainment, and any cost of additional cement is included in the bid price for the concrete. If the Contractor elects to use air entrainment for his own benefit, he must pay for any additional cement required.

From the foregoing observations, it can be seen that the specification which requires a relative compressive strength of at least 85% of control concrete without air, cannot be met under some of the test conditions allowed by ASTM C 233-58. ASTM requirements and methods have since been revised and now compare the strength of air-entrained concrete made with the test admixture to that of a similar air-entrained concrete made with a reference admixture. This arrangement, in effect, allows relative strengths to be substantially less than under the old specification. Theoretically, an agent would be acceptable if its use resulted in a compressive strength of only 77% of a similar non-air-entrained mix. California specifications require that air-entrained concrete made with the agent under test have a relative compressive strength of at least 75% of comparable non-air-entrained concrete.

Flexural Strength

From the standpoint of percent strength loss, the effect of air entrainment on the flexural strength of concrete is approximately one-half that of its effect on compressive strength. When using American River aggregates, 7-sack concrete with 4-1/2% air will have about the same flexural strength as 6-sack, non-air-entrained concrete.

The effect of the variations introduced by different aggregate sources from throughout the State is demonstrated in Figure 2. The 6-sack concrete with a nominal air content of 4-1/2% had relative flexural strengths of from 96% to 107% when compared to 5-sack, non-air-entrained concrete. The reduction in flexural strength as a result of entraining 4-1/2% air in 6-sack mixes was 4% to 12%. Using the approximate figure of 3.3% as the air actually added by the agent, the average flexural strength loss for each percent of added air is about 3%.

Bond Strength

Test results as shown in Tables 5 and 6 indicate that the bond strength is not seriously affected by air entrainment. All of the bond tests performed show that the agents tested met the ASTM requirement that the minimum bond strength be 85% of the non-air-entrained control concrete.

Reproducibility of the bond test is not too satisfactory and the results may be questionable. The test is also quite time consuming.

Surface Bleeding

The bleeding tests were also difficult to reproduce, and the value of the results is questionable. For example, Agent A, in Test Series 5, had a relative bleeding value of 48% based on net mixing water, whereas in Test Series 6, the value was 84%. Therefore, Agent A, in Test Series 5 met the ASTM requirement that bleeding not exceed 65% of the control concrete, but failed in Test Series 6. Furthermore, the method of computing the bleeding percentage has a bearing on the test results. In Test Series 5, Agent B met specification requirements when results were based on bleeding per unit area of surface, but failed when bleeding was calculated as a percentage of net mixing water in the test specimen.

Length Change

Unless other factors have made length change properties critical, drying shrinkage of concrete does not appear to be seriously affected by air entrainment. Concrete containing 4-1/2% air indicated an increase in shrinkage of approximately 10% over non-air-entrained control concrete when measured after 14 days of drying in the case of 3x3x11-1/4-inch specimens, or 28 days for the 4x5x18-inch bars.

The expression of length change as a relative percentage of a non-air-entrained control is considered more appropriate than the ASTM requirement that the maximum allowable increase in shrinkage be an absolute number of 0.01%. For concretes with low or moderate shrinkage, this could mean that a relative increase of 30% would be acceptable. To allow such large increases for air-entraining agents seems unnecessary.

Air Voids by Linear Traverse

In these tests, only two hardened concrete specimens were examined by the linear traverse method to determine the percentage of air voids and the void spacing factor. (See Table 7.) The specimens had different dosages of Agent D and different amounts of entrained air. At the beginning of this investigation, the linear traverse device was not available so the two tests made were not part of the planned program.

Although this test is tedious and time consuming, it is considered to be a valuable tool in concrete investigations. The total amount of air determined microscopically compared quite closely with that indicated by the pressure meter test. The spacing factor, specific surface, and number of voids per cubic inch are all being studied as criteria for satisfactory void systems. However, more research is needed before conclusions can be reached as to which factor or factors would be more suitable as a control.

Table 1 - Test Series 1

Mix No.	Design Mix	Average Fresh Concrete Tests				Average Compressive Strength, Percent of Control	
		Slump, Inches	Total Air, %	Unit Wt. Lbs./CF	W/C Lbs./Sk.	7-day	14-day
1	6-sk. Control	2.8	1.2	154.6	45.8	100	100
2	6-sk. 3% Air	2.5	3.0	152.4	44.4	96	87
3	6-sk. 4-1/2% Air	2.8	4.5	149.7	42.9	85	75
4	6-sk. 6% Air	3.0	5.9	148.2	42.1	68	68
5	6.5-sk. 4-1/2% Air	3.0	4.2	150.8	42.1	88	84
6	7-sk. 4-1/2% Air	2.8	4.7	149.7	39.1	94	82

Note: Agent A used to entrain air in the concrete.

Grading as Used*	
Sieve Size	Percent Passing
1-1/2-inch	100
1-inch	80
3/4-inch	65
3/8-inch	43
No. 4	38
No. 8	30
No. 16	22
No. 30	15
No. 50	6

*Sand was reduced for the air-entrained mixes and varied from 34 to 37%.

Table 2 - Test Series 2

Mix No.	Design Mix	Average Fresh Concrete Tests: Slump, Ins.	Total Air, %	Unit Wt. Lbs./CF	W/C Lbs./Sk.	Avg. Compressive Strength, Percent of Control: 14-day	Grading as Used*: Sieve Size	Percent Passing
1	6-sk. Control	4.1	1.0	153.9	49.2	100	1-1/2-inch	100
2	7-sk. 4-1/2%	4.1	4.4	148.9	42.2	86	1-inch	80
							3/4-inch	65
							3/8-inch	43
							No. 4	38
							8	30
							16	22
							30	15
							50	6

Note: Agent A used to entrain air in the concrete.

*Sand was reduced to 34% for the air-entrained mix.

Table 3 - Test Series 3

Mix No.	Design Mix	Average Fresh Concrete Tests: Slump Ins.	Total Air, %	Unit Wt. Lbs./CF	W/C Lbs./Sk.	Avg. Compr. Strength, % of Control 14-day
1	6-sk. Control	3.4	1.0	155.3	45.8	100
2	6.27-sk. 2-1/2% Air	3.6	2.7	153.3	43.7	92
3	6.53-sk. 3-1/2% Air	3.6	3.7	151.0	41.4	89
4	7.00-sk. 4-1/2% Air	3.5	4.7	149.8	38.5	81
5	7.85-sk. 5-1/2% Air	3.5	5.5	148.1	35.7	79

Note: Agent A used to entrain air in the concrete

Grading as Used*: Sieve Size	Percent Passing
1-1/2-inch	100
1-inch	80
3/4-inch	65
No. 4	36
8	29
16	22
30	15
50	6

*Sand was reduced for air-entrained mixes and varied from 30% to 35%

Table 4, Test Series 4

Mix No.	Design Mix	Average Fresh Concrete Tests				Avg. Compr. Strength, % of Control	Avg. Flexural Strength, % of Control	Avg. Drying Shrinkage, 4x5x18-inch Specimens % of Control
		Slump, Ins.	Total Air, %	Unit Wt. Lbs./CF	W/C Lbs./Sk.	14-day	14-day	28-day**
1	6-sk. Control	3.1	1.1	155.8	45.8	100	100	100
2	6.27-sk. 3% Air	3.1	3.0	152.8	42.9	87	101	107
3	6.53-sk. 3-1/2% Air	2.8	3.6	152.8	40.5	85	90	110
4	7.00-sk. 4-1/2% Air	3.3	4.5	151.7	38.8	80	98	110
5	7.85-sk. 5-1/2% Air	3.1	5.4	149.8	34.9	78	97	117

Note: Agent E used to entrain air in the concrete

** 7-day wet cure, then 28 days drying at 50% RH and 73°F

Grading as Used*	
Sieve Size	Percent Passing
1-1/2-inch	100
1-inch	80
3/4-inch	65
3/8-inch	42
No. 4	36
8	29
16	22
30	15
50	6

*Sand was reduced for the air-entrained mixes and varied from 30% to 35%

Table 5 - Test Series 5

Mix No.	Design Mix	Average Fresh Concrete Tests: Agent	Slump, Ins.	Total Air, %	Unit Wt. Lbs./CF	W/C Lbs./Sk.	Surface Bleeding: As % of Net Mixing Water	% of Cont.	As Ml Water per cm^2 of Surface	% of Cont.
1	6-sk. Control	None	3.6	1.3	152.0	57.4	0.85	100	0.045	100
2	6-sk. 5% Air	A	3.5	5.2	147.3	52.1	0.41	48	0.020	44
3	6-sk. 5% Air	B	3.6	4.8	147.8	52.7	0.60	71	0.029	64
4	6-sk. 3-1/2% Air	C	3.8	3.6	148.4	54.4	1.10	129	0.052	116

Mix No.	Average Compressive Strength, % of Control: 7-day	28-day	Average Bond Stress, PSI and % of Control: Vert. Steel	% of Cont.	Horiz. Steel	% of Cont.	Avg. Drying Shrinkage 3x3x11-1/4" Specimens % of Control: 14-day**	28-day**
1	100	100	1030	100	950	100	100	100
2	92	81	940	91	940	99	111	107
3	93	84	960	93	870	92	105	100
4	---	---	1040	101	890	94	---	---

** 7-day wet cure before drying at 50% RH and 73°F

Grading as Used*: Sieve Size	Percent Passing
1-inch	100
3/4-inch	88
3/8-inch	62
No. 4	48
8	38
16	28
30	18
50	7

*Sand was reduced to 46% for Mixes 2 and 3

Table 6 - Test Series 6

Mix No.	Design Mix	Average Fresh Concrete Tests					Surface Bleeding			
		Agent	Slump, Ins.	Total Air, %	Unit Wt. Lbs./CF	W/C Lbs./Sk.	As % of Net Mixing Water	% of Cont.	As Ml Water per cm^2 of Surface	% of Cont.
1	6-sk. Control	None	3.7	1.4	152.0	50.2	1.11	100	0.061	100
2	6-sk. 5-1/2% Air	A	3.8	5.3	148.0	46.3	0.93	84	0.048	79
3	6-sk. 5-1/2% Air	B	3.8	5.1	148.0	47.2	0.87	78	0.047	77
4	6-sk. 5-1/2% Air	D	3.8	5.5	147.4	44.8	0.69	62	0.034	56

Mix No.	Average Compressive Strength, % of Control 7-day	28-day	Average Bond Stress, PSI and % of Control: Vert. Steel	% of Cont.	Horiz. Steel	% of Cont.
1	100	100	730	100	810	100
2	87	86	860	118	730	90
3	88	85	750	103	770	95
4	89	95	760	104	790	98

Grading as Used*

Sieve Size	Percent Passing
1-inch	100
3/4-inch	90
3/8-inch	63
No. 4	48
8	39
16	27
30	18
50	7

*Sand was reduced to 46% for the air-entrained mixes

Table 7 - Test Series 7

Mix No.	Design Mix	Average Fresh Concrete Tests				
		Agent	Slump, Ins.	Total Air, %	Unit Wt. Lbs./CF	W/C Lbs./sk.
1	7-sack, Control	None	3.7	1.6	151.4	47.2
2	7-sack, 4-1/2% Air	F	3.7	4.1	148.4	44.7
3	7-sack, 3% Air	D	3.3	2.8	149.9	44.4
4	7-sack, 5-1/2% Air	D	3.3	5.1	147.0	42.8

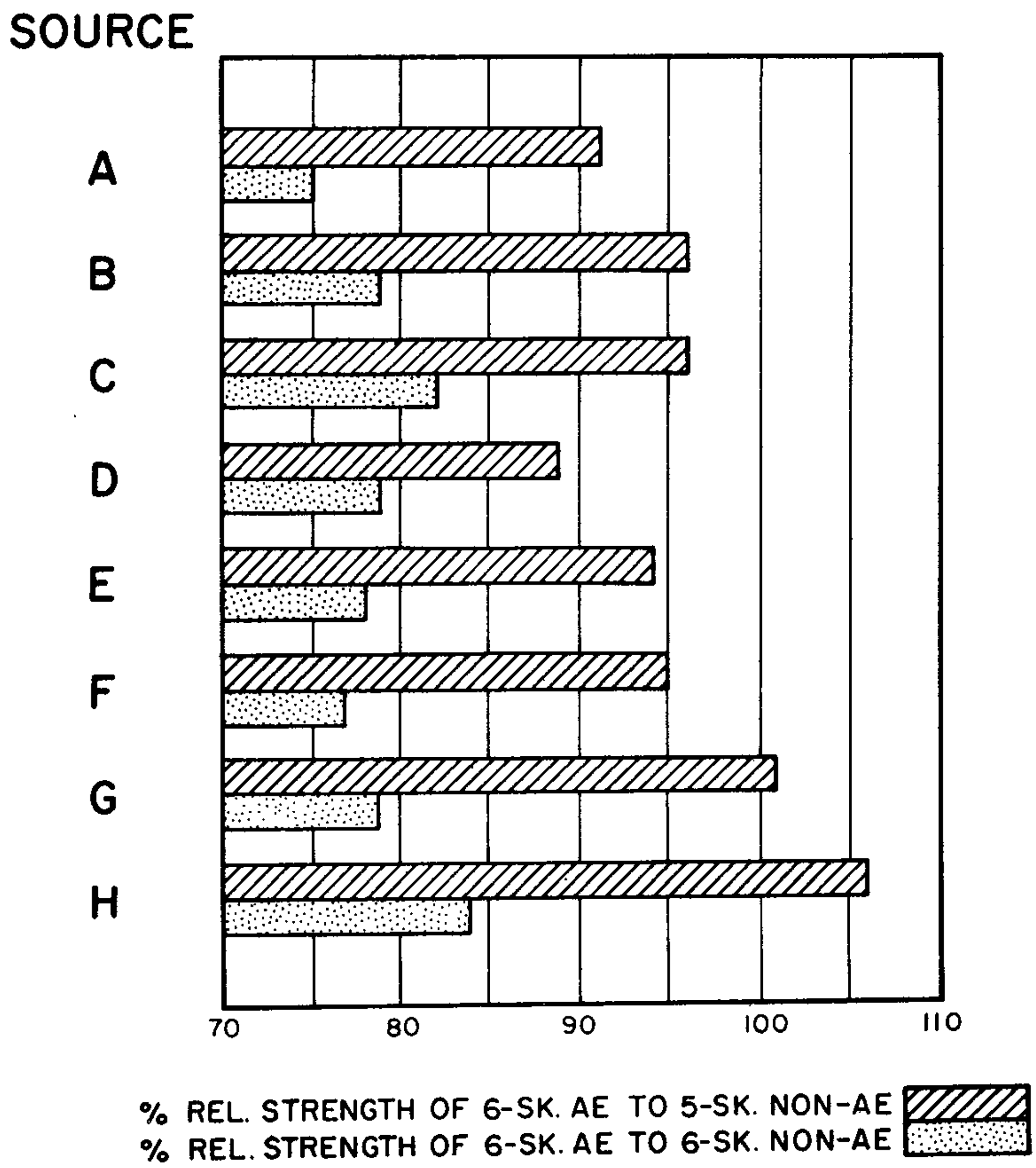
Mix No.	Agent	Avg. Drying Shrinkage 3x3x11-1/4" Specimens % of Control	Air Void Determination of Hardened Concrete by Linear Traverse				
		14-days**	% Air Voids	Avg. Chord Intercept	Avg. No. Voids per Inch of Traverse	Specific Surface	Spacing Factor
1	None	100					
2	F	107					
3	D	107	2.8	.0063"	4.44	635 $in.^{-1}$	.0107"
4	D	113	5.5	.0057"	9.64	700 $in.^{-1}$	.0071"

Grading as Used*

Sieve Size	Percent Passing
1-inch	100
3/4-inch	90
3/8-inch	63
No. 4	48
8	39
16	27
30	18
50	7

*Sand was reduced to 46% for the air-entrained mixes.

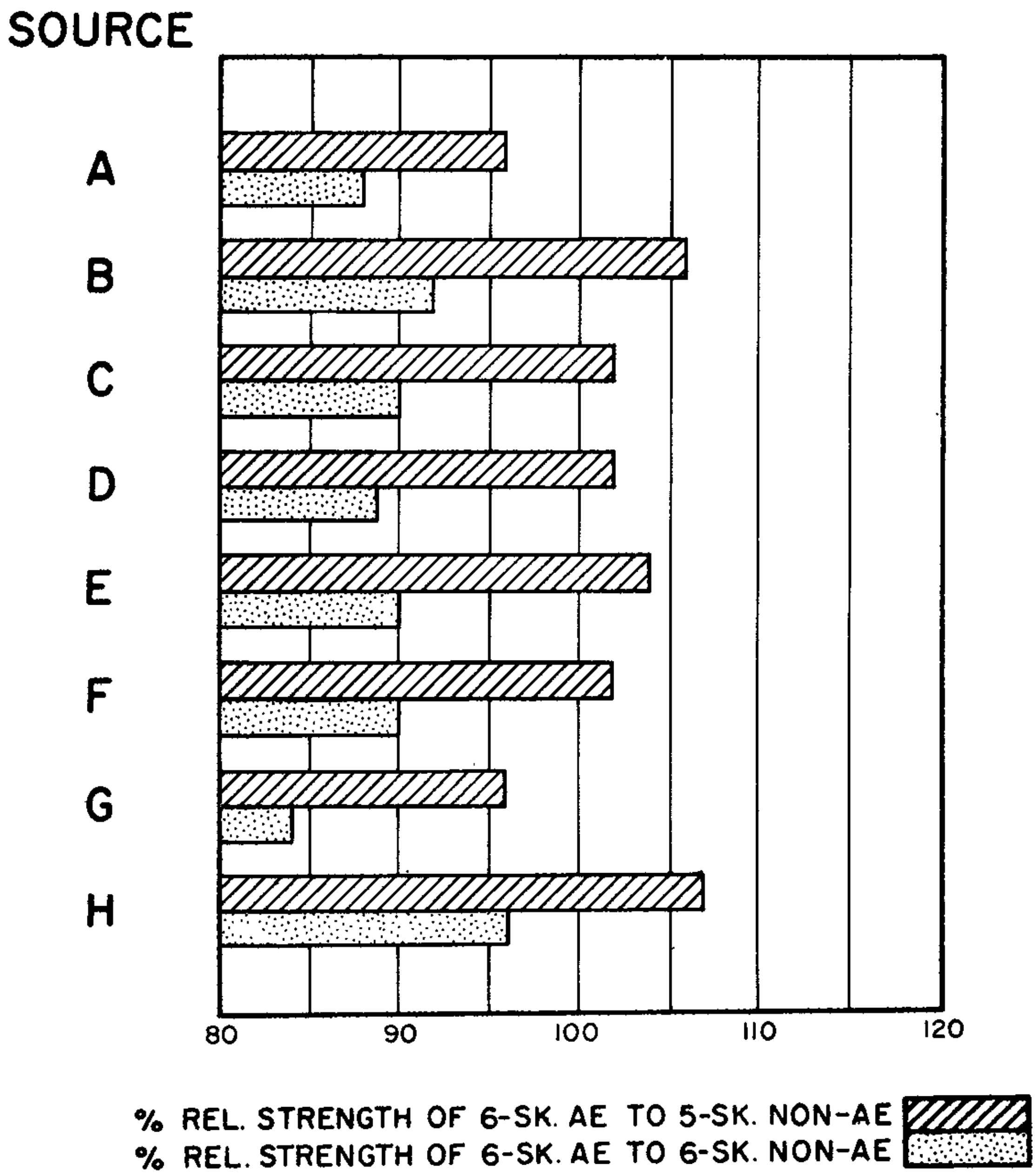
COMPARATIVE COMPRESSIVE STRENGTHS OF AIR ENTRAINED AND NON AIR ENTRAINED CONCRETE (VARIOUS AGGREGATE SOURCES)



NOTE: 4 1/2 % AIR ENTRAINED
1 1/2" MAXIMUM SIZE AGGREGATE
2" SLUMP
14 DAY STRENGTHS
DATA FROM CEMENT FACTOR TESTS
6 x 12 INCH CYLINDERS

FIGURE 2

COMPARATIVE FLEXURAL STRENGTHS OF AIR ENTRAINED AND NON AIR ENTRAINED CONCRETE (VARIOUS AGGREGATE SOURCES)



NOTE: 4 1/2 % AIR ENTRAINED
1 1/2" MAXIMUM SIZE AGGREGATE
2" SLUMP
14 DAY STRENGTHS
DATA FROM CEMENT FACTOR TESTS
6 x 6 x 20 INCH BEAMS