AIR VOID SYSTEMS IN READY MIXED CONCRETE

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Air Entrainment in Concrete

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ABSTRACT

Concrete produced at a commercial batch plant in truck mixers was subjected to extensive testing for the properties of the entrained air system, frost resistance and compressive strength. Sixty, 6-yard batches of siliceous aggregate concrete were included in the program. The variations in the properties under investigation could be attributed to different chemical types of air-entraining agents and retarders and to different mixing methods.

The following indicators of the quality of the entrained air system were used for comparison.

1. Powers' spacing factor.
2. Philleo spacing factor.
3. Spacing factor from the VSI (Void Spacing Indicator).
4. Specific Surface.

The VSI is a new test for the quality of the entrained air system in *plastic* concrete. It is shown to be a valuable indicator of the frost resistance of concrete.

A second series of concrete batches was mixed in the laboratory. These batches were proportioned using the same aggregates, cement and admixtures as the Ready Mix concrete. The main differences were the size of batch (1.5 cf batches), the mixer (Lancaster, vertical drum mixer), and the batch temperatures (laboratory batches averaged 74°F while the Ready Mix batches averaged 89°F).

A field survey of bridge decks and concrete pours in various parts of the State of Texas is included in Appendix C. Where appropriate, data from this survey are included in the main body of the report.

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ACKNOWLEDGMENTS

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The opinions, findings and conclusions expressed in this report are those of the authors and not necessarily those of the Texas Highway Department or the Bureau of Public Roads.

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Introduction

The achievement of an adequate entrained air system in concrete is a continuing problem in concrete construction. Because of this, many concrete structures are built each year without the protection against freeze-thaw deterioration that could be provided by an adequate entrained air system.

This study was undertaken to provide additional knowledge of some of the many parameters affecting the entrained air system and to provide some way of indicating the geometric characteristics of the system in plastic concrete. The geometric characteristics such as bubble size distribution and bubble spacing reflect the quality of the entrained air system. There was no such method in existence at the time this study was begun; the only methods available being the Rosiwal Linear Traverse or the Point Count Method, both of which involve microscopic determination of the air void system on *hardened* concrete.

As the study progressed, the following reports were written covering different phases.

1. Review of Literature on Air Entrained Concrete,[1]* Research Report 103-1.

2. Influence of Chemical Admixtures and Mixing Methods on the Air Void Systems in Portland Cement Mortars,[2] Research Report 103-2.

3. Preliminary Report on the Void Spacing Indicator,[3] Research Report 103-3.

Research Report 103-2[2] presented findings which showed that mixing procedure, air-entraining agents, and retarders affected the air void systems in cement mortars.

The primary objective of this final report is to determine the effects of these same factors on laboratory and ready mixed concrete. The two major testing programs were designed as three factor factorial experiments (two mixing procedures; two air-entraining agents; three retarder conditions, two retarders and no retarder) with three batch replications of each possible combination. These testing programs are designated the "Ready Mix"* program and the "Laboratory"* program. An additional study designated "Field Survey" is presented in the appendix, and is of minor importance in the main body of this report.

This final phase of the study also provided additional data for the evaluation of the Void Spacing Indicator (VSI),[3] which was developed to provide a check on the *quality* of the entrained air system.

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*Superscripts refer to corresponding number in Selected References.

*Whenever the words Ready Mix, Laboratory, or Field Survey are capitalized in this report they refer specifically to the appropriate testing program, differentiating, for example, from the words ready mix, which refer only to that specific way of producing concrete.

Testing Program (Ready Mix)

Batch Plant and Truck Mixer

The batch plant at which this program was conducted is shown in Figure 1. It is a 400-ton punch card automatic with automatic rehandling equipment and a batching capacity of eight yards. This plant was completed in October of 1967. The control room is shown in Figure 2. Aggregate, cement and water gages were graduated to 30, 5 and 3 lbs respectively. The batching of all concrete in this study was controlled manually.

A single truck mixer was used for all batches reported. This was a Challenge, Simplimatic seven-yard mixer mounted on a 67 Mac Diesel, DM607S.

Concrete Batches

All concrete reported in this study contained 5½ sacks of cement per cubic yard. Natural siliceous sand and gravel from a Brazos river deposit were used. The cement was a widely used type 1 cement produced in Texas. The mill analysis of this cement is given in Appendix A. The commercially produced air-entraining agents were vinsol resin and a synthetic detergent, designated V and D respectively. The retarders were an organic acid (O) and a lignosulfonate (L). Properties of plastic and hardened concrete are given in Tables 1 and 2.

Batching Procedures

Two batching procedures were used and are described as follows:

Mix Method 1

a. The required amounts of coarse and fine aggregate were weighed.

b. The required cement was weighed.

c. The required water was weighed.

d. Both retarder and AEA were poured by hand into the batch water (Figure 3).

e. All of the aggregates and 2/3's of the mix water were released into the truck mixer which was turning at mixing speed (10 rpm).

f. The cement was added.

g. Ten revolutions after addition of the cement, the remaining ⅓ of the mix water was added.

h. The truck was then moved approximately 50 ft with the drum at agitating speed (2 rpm).

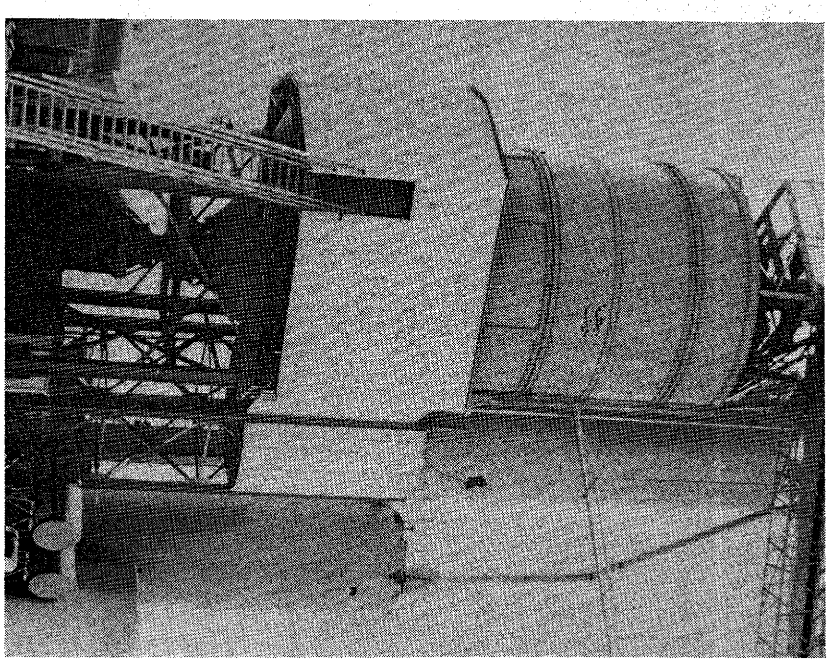

Figure 1. Batch plant.

i. The drum was turned at mixing speed for an additional 50 revolutions. Mixing was stopped and slump was determined.

j. Additional mix water was added as indicated by the slump and the concrete was mixed another 20 revolutions. Mixing was stopped and the slump was again determined.

k. Final adjustment of mix water was made and the concrete was mixed another thirty revolutions, after

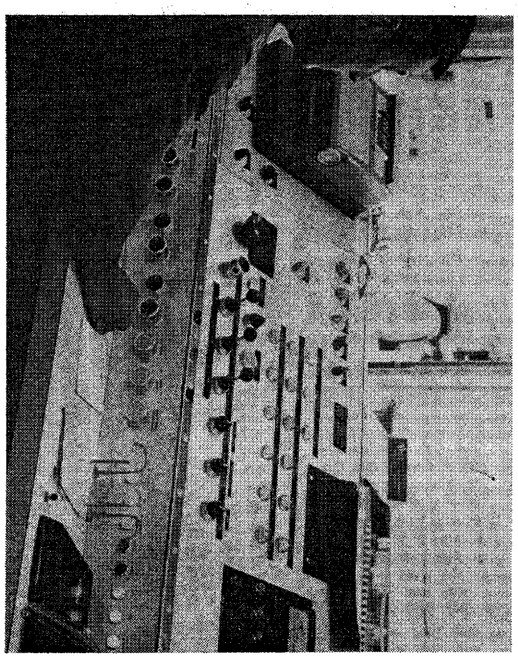

Figure 2. Control room.

TABLE 1. PROPERTIES OF PLASTIC CONCRETE (READY MIX)

		Admixtures				Aggregate		Air Properties					
Batch Type	Batch Numbers	AEA cc/cy	Retarder cc/cy	Cement sks/cy	Total Water lbs/cy	Coarse lbs/cy	Fine lbs/cy	Pressure Meter %	VSI sq. in.	VSI Spacing Factor (inches)	Slump in.	Unit Weight Wet lbs/cf	Batch Temperature
1D	(12,15,10)**	119	None	5.527	263*	1778	1332	5.57	1.55	.0142	3.6	144.1	86.0°
2D	(33,09,13)	145	None	5.517	263	1772	1335	5.30	1.34	.0155	3.3	144.0	87.3°
1V	(27,24,44)	167	None	5.477	277	1752	1340	5.37	1.52	.0148	3.3	143.9	91.7°
2V	(41,53,58)	124	None	5.493	270	1760	1342	5.37	1.29	.0167	2.8	144.0	90.0°
1DL*	(05,14,34)	141	809	5.480	261	1770	1366	5.43	1.14	.0189	2.3	144.8	89.7°
2DL	(35,17,36)	158	802	5.443	269	1756	1353	5.63	1.46	.0154	4.1	144.1	91.0°
1DO	(38,39,37)	191	486	5.503	276	1746	1360	5.20	1.41	.0149	3.8	144.4	90.0°
2DO	(18,45,46)	189	482	5.463	259	1749	1354	5.73	1.50	.0147	3.7	143.6	91.7°
1VL	(11,57,59)	66	810	5.530	255	1773	1344	5.60	1.49	.0146	3.2	144.1	88.3°
2VL	(28,29,54)	80	813	5.513	267	1773	1353	5.47	1.52	.0141	3.1	144.8	92.0°
1VO	(08,20,21)	105	485	5.497	267	1775	1346	5.33	1.24	.0171	2.9	144.7	87.3°
2VO	(22,19,56)	96	485	5.497	264	1768	1341	5.60	1.48	.0148	3.6	144.1	89.0°

*First numeral (1 or 2) designates mixing method, first letter designates AEA (V—vinsol resin and D—synthetic detergent), second letter designates retarder (O—organic acid and L—lignosulfonate). The values given for each batch designation are the average values for the three batch replications (for example, 5.57 is the average air content for batches 12, 15 and 10 each of which is a replication of Batch Type 1D).

**Batch data for each individual batch is given in Table 1-A in Appendix A.

TABLE 2. PROPERTIES OF HARDENED CONCRETE (READY MIX)

Batch Designation	Batch Numbers	Volume of Air by ASTM C-457 %	Powers $\bar{L}$ inches	Philleo $\bar{S}$ inches	Durability ASTM C-290 %	Compressive Strength 28 day-psi
1D	(12,15,10)	3.81	.0186	.00582	39.4	3192.6
2D	(33,09,13)	3.33	.0178	.00597	53.0	3132.2
1V	(27,24,44)	3.44	.0150	.00959	25.6	3181.0
2V	(41,53,58)	3.31	.0165	.00735	45.6	3633.1
1DL	(05,14,34)	3.99	.0164	.00537	14.4	3783.3
2DL	(35,17,36)	3.07	.0162	.00634	20.7	3230.7
1DO	(38,39,27)	3.24	.0159	.00709	37.4	3516.0
2DO	(18,45,46)	3.48	.0168	.00654	51.8	3512.9
1VL	(11,57,59)	3.29	.0173	.00580	23.6	3889.4
2VL	(28,29,54)	2.86	.0163	.00534	29.4	3870.9
1VO	(08,20,21)	3.70	.0152	.00675	34.9	3104.0
2VO	(22,19,56)	3.21	.0163	.00766	52.5	4191.4

which the drum speed was reduced to agitating speed and the truck driven approximately 100 yards to the sampling site.

Mix Method 2

This batching procedure differs from Procedure 1 in the following ways:

a. In step c of Mix Method 2 only 2/3's of the required water was weighed, and to this was added the AEA.

b. In step g of Mix Method 2 the remaining ⅓ of the mix water was weighed and the retarder was added at this point.

Sampling Procedure

After discharging several cubic ft of the load, a two cubic ft sample was obtained by placing a sampling pan under the discharge chute. Another sample was taken from the middle of the load and a third sample from the back of the load. Figure 4 shows one sample being taken.

Testing Procedures

On each of the three samples obtained from each batch, the following tests were run:

1. Slump (ASTM C-143). (1)*
2. Unit Weight (ASTM C-138). (1)
3. Air Content, Pressure Meter (ASTM C-231). (1)
4. Void Spacing Indicator.** (3)

Figures 5, 6, 7 and 8 illustrate these tests.

Three 6″ × 12″ cylinders were taken from each sample for 28-day compressive strength determinations (ASTM C-39). From the middle sample of each batch one 3- × 3- × 16-inch prism was cast for freeze-thaw testing (ASTM C-290) and one 3- × 4- × 16-inch prism was cast for microscopic determination of air void parameters (ASTM C-457).

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*Indicates the number of tests run on each sample.

**Procedure given in Research Report 103-3 and in Appendix D of this report.

Figure 3. Adding admixtures to batch water.

Figure 4. Obtaining a sample from the mixer.

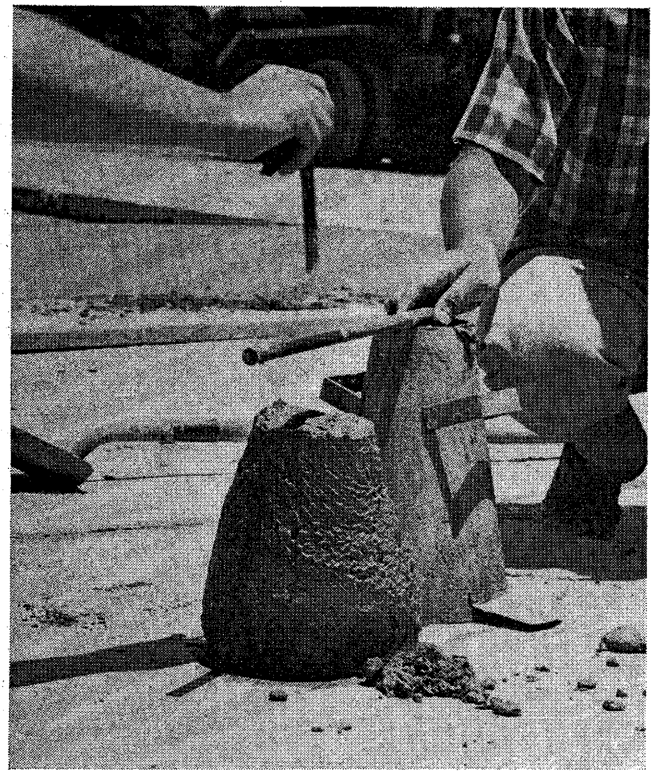

Figure 5. Slump test.

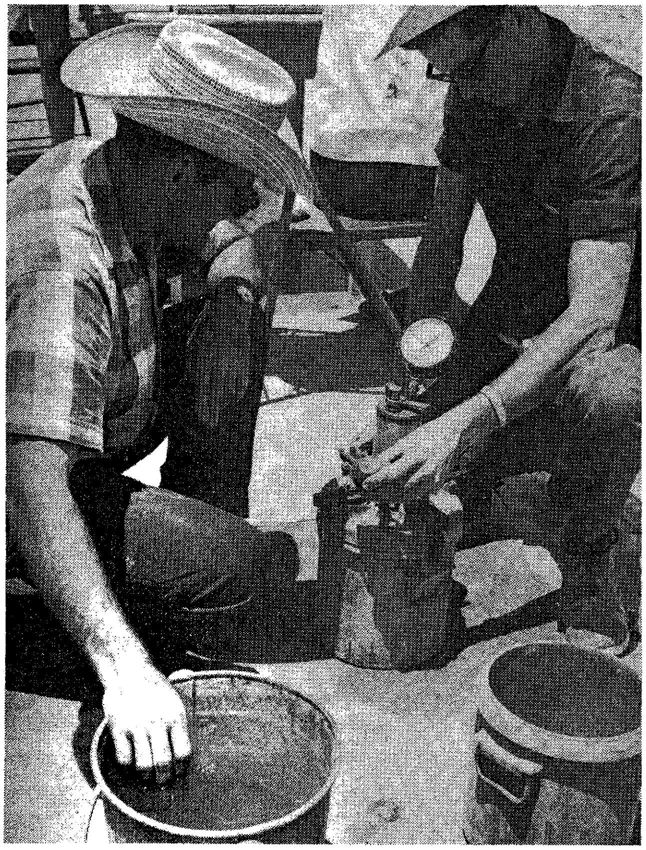

Figure 7. Pressure meter air content.

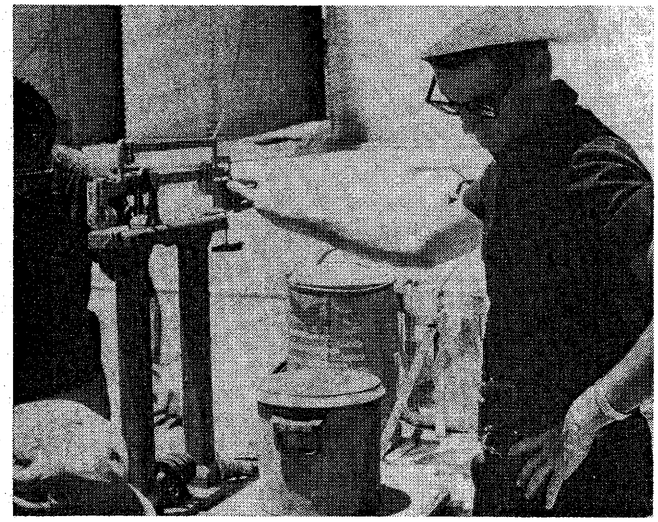

Figure 6. Unit weight.

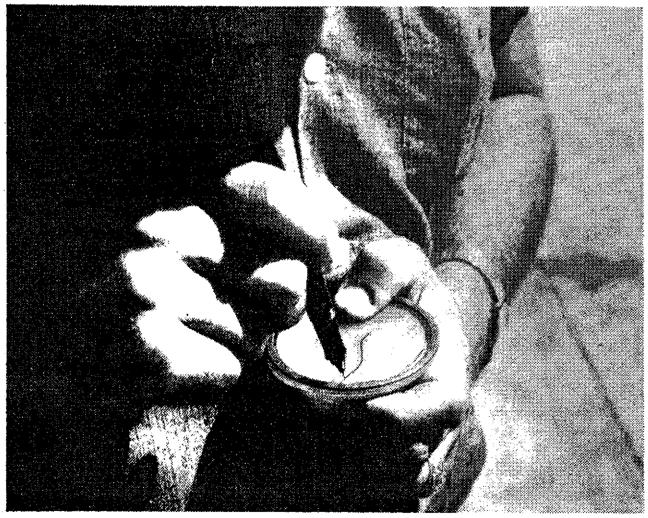

Figure 8. Void spacing indicator (VSI).

Testing Program (Laboratory)

The concrete batches mixed and tested in the laboratory were similar to the concrete batches in the Ready Mix program. They were proportioned using the same aggregates, cement and admixtures as the Ready Mix concrete. The main differences in the laboratory testing program and the Ready Mix testing program are shown by Table 3.

The same thirty-six batches composing the three factor factorial experiment for the Ready Mix work were repeated in the laboratory. In addition to this, six batches containing calcium chloride were mixed and tested. The properties of the plastic and hardened concrete are given in Tables 4 and 5.

TABLE 3. DIFFERENCES IN LABORATORY CONCRETE AND READY MIX CONCRETE

	Laboratory Batches	Ready Mix Batches
Batch Size	1.5 cf	6.0 cy
Mixer	Lancaster, Vertical Drum, 2 cf Mixer	7 yard Truck
Average Batch Temperature	74°	89°

TABLE 4. PROPERTIES OF PLASTIC CONCRETE (LABORATORY)

		Admixtures				Aggregate		Air Properties					
Batch Type	Batch Numbers	AEA cc/cy	Retarder cc/cy	Cement sks/cy	Total Water lbs/cy	Coarse lbs/cy	Fine lbs/cy	Pressure Meter %	VSI sq. in.	VSI Spacing Factor (inches)	Slump in.	Unit Weight Wet lbs/cf	Batch Temperature
1V	(040,330,300)	100	None	5.53	259	1760	1332	5.47	1.301	.0168	3.67	143.3	75°
1D	(170,210,140)	127	None	5.52	262	1772	1319	5.10	0.987	.0215	3.25	143.2	74°
1VO	(110,260,270)	110	488	5.53	244	1747	1346	5.53	1.202	.0174	3.42	142.7	73°
1VL	(160,090,220)	79	785	5.50	260	1757	1323	5.60	1.168	.0189	3.68	142.8	74°
1VCC*	(130,150,100)	111		5.51	260	1749	1329	5.57	1.262	.0198	3.33	142.8	75°
1DO	(360,370,030)	117	488	5.51	250	1752	1362	5.67	1.644	.0129	3.25	143.7	75°
1DL	(070,200,400)	129	785	5.51	243	1760	1328	5.87	1.251	.0177	3.08	142.4	75°
2V	(310,320,020)	109	None	5.49	251	1751	1356	5.47	1.018	.0212	3.42	143.0	75°
2D	(390,120,180)	119	None	5.53	260	1755	1322	5.10	1.011	.0203	3.75	142.7	75°
2VO	(280,350,380)	109	488	5.53	240	1748	1366	5.50	1.120	.0184	5.50	143.3	72°
2VL	(080,340,350)	86	785	5.50	243	1745	1351	5.83	1.497	.0142	3.25	142.6	76°
2VCC*	(050,190,060)	109		5.51	265	1751	1317	5.50	0.895	.0248	5.50	142.2	76°
2DO	(010,290,240)	106	488	5.49	238	1797	1356	5.53	1.188	.0179	3.33	143.6	70°
2DL	(410,230,420)	120	785	5.54	243	1771	1324	5.90	1.361	.0162	3.25	143.2	73°

Admixture Dosages:
(1) 785 cc/cy Retarder L = ⅛ lb/sk cement.
(2) 488 cc/cy Retarder O = 3 oz/sk cement.
(3) 163 cc/cy AEA V = 1 oz/sk cement.
(4) 146 cc/cy AEA D = 1 oz/sk cement.
*2 lbs $CaCl_2$ per 100 lbs cement.

TABLE 5. PROPERTIES OF HARDENED CONCRETE (LABORATORY)

Batch Designation	Batch Numbers	Volume of Air by ASTM C-457 %	Powers $\overline{L}$ inches	Philleo $\overline{S}$ inches	Durability ASTM C-290 %
1V	(040,330,300)	5.59	.00851	.00396	85.1
1D	(170,210,140)	4.98	.00835	.00363	82.7
1VO	(110,260,270)	5.25	.00780	.00348	86.2
1VL	(160,090,220)	5.90	.00798	.00337	89.8
1VCC	(130,150,100)	5.61	.00858	.00379	26.9
1DO	(360,370,030)	5.46	.00829	.00404	85.2
1DL	(070,200,400)	5.59	.00685	.00332	82.4
2V	(310,320,020)	5.26	.00962	.00409	85.1
2D	(390,120,180)	4.58	.00852	.00397	85.0
2VO	(280,250,380)	5.14	.00777	.00386	82.3
2VL	(080,340,350)	6.01	.00885	.00370	79.6
2VCC	(050,190,060)	5.50	.00921	.00394	23.3
2DO	(010,290,240)	5.09	.00801	.00359	83.6
2DL	(410,230,420)	5.98	.00722	.00361	82.4

Test Results and Discussion

A standard analysis of variance was performed on the Ready Mix and Laboratory concrete programs. The differences indicated by the mixing methods, air-entraining agents and retarders will be discussed in this section with reference to statistical significance. The results of these statistical analyses are summarized by Tables 6 and 7. It was found that there were no significant third order interactions. This implies that all significant effects can be explained in terms of two-factor interactions and single factors. For example, the third order interaction of mixing method, air-entraining agent and retarder is not statistically significant for any of the parameters tested, but there is a significant interaction effect on compressive strength shown in Table 6 between mixing method and retarder.

The following sections will discuss the differences in concrete properties due to mixing methods, air-entraining agent and retarder. The findings of the Ready Mix program, the Laboratory program and the previously published Mortar program[2] will be compared.

Effect of Different Mixing Methods

The effect of the two different mixing methods on the Powers spacing factor ($\overline{L}$) for the Ready Mix batches is given by Figure 9. The statistical treatment showed no significant difference in any of the air void parameters due to mixing method in either the Ready Mix or the Laboratory concrete programs. In the comparison of mixing methods given in the Mortar study,[2] the pro-

TABLE 6. SUMMARY OF STATISTICAL SIGNIFICANCE (READY MIX)

Air Void System Parameters, Durability Factor & Compressive Strength	Significance of Single Factor Effects			Significance of Two Factor Effects		
	Air-Entraining Agent	Retarder	Mix Procedure	Mixing Procedure by Air-Entraining Agent	Mixing Procedure by Retarder	Air-Entraining Agent by Retarder
$\overline{L}$ (Powers' Spacing Factor)						
$\overline{S}$ (Philleo Spacing Factor)	90%					
α (Specific Surface Area)	90%				85%	
Compressive Strength	95%	95%		99%	95%	
Durability Factor		95%	85%	85%		

Note: Although 60 batches of concrete were produced in the Ready Mix program only the 36 batches with acceptable air contents, slump and cement factors were included in this statistical analysis. All batches are reported in Appendix A.

TABLE 7. SUMMARY OF STATISTICAL SIGNIFICANCE (LABORATORY)

Air Void System Parameters and Durability Factor	Significance of Single Factor Effects			Significance of Two Factor Effects		
	Air-Entraining Agent	Retarder	Mix Procedure	Mixing Procedure by Air-Entraining Agent	Mixing Procedure by Retarder	Air-Entraining Agent by Retarder
$\overline{L}$ (Powers' Spacing Factor)		90%				
$\overline{S}$ (Philleo Spacing Factor)						
α (Specific Surface Area)	90%					
No./cc concrete (0-400μ) by Lord & Willis		85%				
No./cc concrete (0-400μ) by Pennsylvania Univ.						
Durability Factor						

cedure which would be most like Method 1 in the concrete studies gave a significantly higher value of $\overline{L}$. This is the method whereby the AEA and retarder are mixed in the same water phase.

The effect of mixing method on concrete frost resistance as indicated by the freeze-thaw durability factor (DF) is shown by Figure 10 for the Ready Mix batches. This figure shows little difference in concrete durability due to mixing methods for concretes using AEA D, but a significant difference for concretes containing AEA V. For each corresponding batch type (i.e., 1V to 2V, 1VL to 2VL and 1VO to 2VO) there is an increase in DF when the change is made from Mix Method 1 to Mix Method 2. This difference was significant at the 85% level.

Differences in DF due to mixing method were not significant in the laboratory batches. These concretes all had average DF's above 79.6%, with the exception of the three batches containing $CaCl_2$, which showed a significant reduction in frost resistance. In the Mortar program,[2] the mixing method corresponding closely to Mix Method 2 gave the lowest value of freeze-thaw weight loss, thus agreeing with the Ready Mix concrete findings.

Effect of Different Air-Entraining Agents

Both Ready Mix and Laboratory concretes showed a difference at the 90% level in the specific surface (α) of the air void system due to the type of AEA used. In the Ready Mix concrete program AEA V gave the larger average value of α which corresponds to the lower average value of Powers' spacing factor shown in Figure 11 for concrete without a retarder and with Retarder O. AEA V also gave the lower average value of Powers' spacing factor in the Mortar study, thus reinforcing the findings of the Ready Mix program.

Comparing air-entraining agents on the basis of durability factors did not yield statistically significant

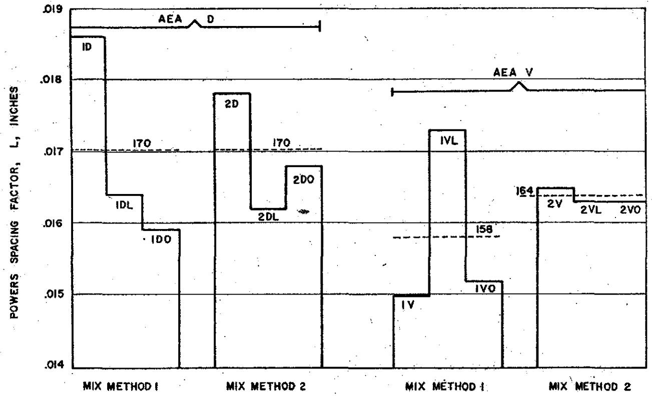

Figure 9. Mixing methods compared by Powers' spacing factor (ready mix).

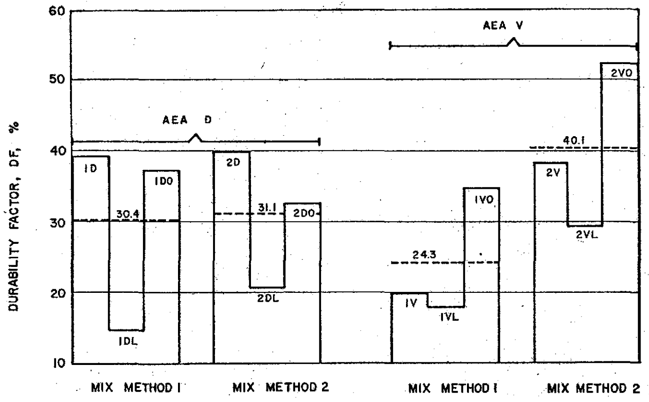

Figure 10. Mix methods compared by durability factor (ready mix).

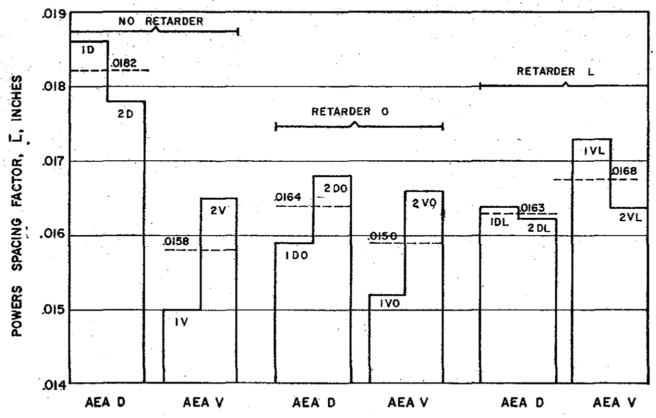

Figure 11. Air-entraining agents compared by Powers' spacing factor (ready mix).

results. This comparison is given by Figure 12 for the Ready Mix concrete. There appears to be some trend toward AEA V yielding concretes of higher frost resistance when combined with a retarder (three out of four cases; 2DO < 2VO, 1DL < 1VL and 2DL < 2VL). This trend is not apparent in the batches without a retarder or in the Laboratory concrete program, but is reinforced by the Mortar program which shows a trend toward higher freeze-thaw weight loss in the AEA D mortars.

There is an interaction effect of Mixing Method and AEA shown by Figure 13. AEA D gives the larger value of DF under Mix Method 1 while AEA V gives an improved DF under Mix Method 2. This interaction is of low statistical significance (85% level). The primary cause of this interaction seems to be the effect of the different mixing methods on the AEA V concretes. The AEA D concretes are apparently affected very little by these mixing methods.

Effect of Different Retarders

The effect of the three different retarder conditions was of statistical significance in both the Laboratory program (90% level for Powers' spacing factor, $\bar{L}$) and in the Ready Mix program (95% level for durability factor, DF). The differences in $\bar{L}$ for the two programs are given in Figure 14. In the case of the Laboratory

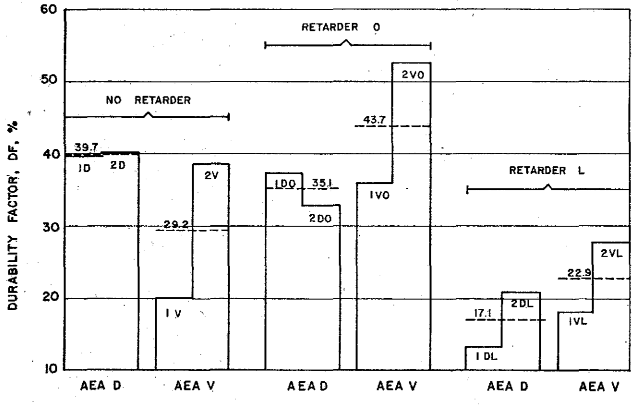

Figure 12. Air-entraining agents compared by durability factor (ready mix).

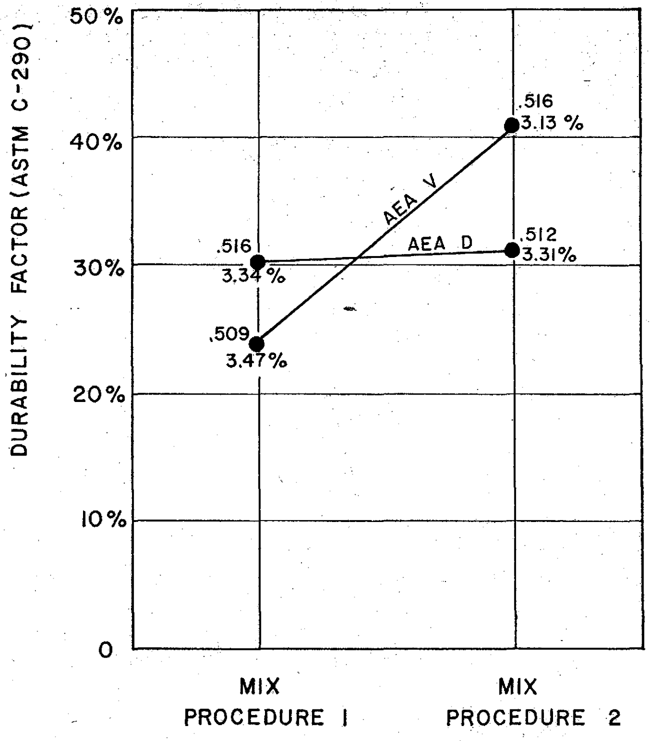

Figure 13. Interaction effects of mixing procedure and air-entraining agent (ready mix).

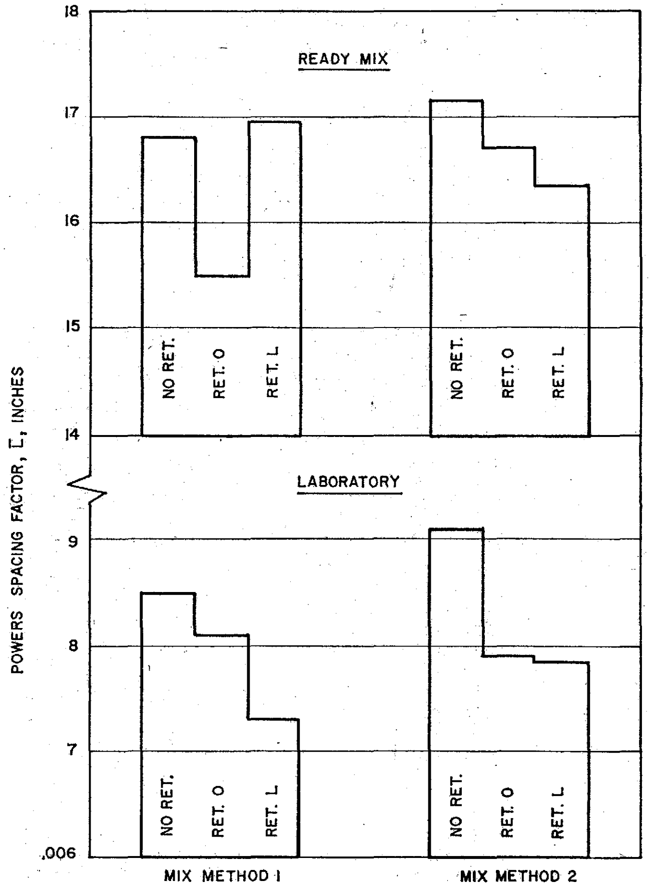

Figure 14. Retarders compared by Powers' spacing factor.

batches, the concretes without retarders show the highest value of $\bar{L}$, Retarder O an intermediate value and Retarder L the smaller value. This trend is repeated in the Mix Method 2 section for the Ready Mix concrete, but is not repeated for Mix Method 1. In Figure 15 it is seen that there is little difference in the average values of the Powers spacing factors, all of them in the Ready Mix program being extremely large.

A definite trend in DF for the Ready Mix batches (significant at the 95% level) is shown by Figure 16. This figure shows Retarder O consistently yielding the most frost resistant concrete and Retarder L yielding concrete having the least frost resistance. This is substantiated by the results of the Mortar program[2] and also by Research Report 70-3 (Final).[4] The opinion of the authors is that once the $\bar{L}$ values have substantially exceeded the values necessary for good durability, other factors are more important to concrete frost resistance than small variations in $\bar{L}$.

Compressive Strength

Compressive strength data were obtained from the Ready Mix concrete as an item of secondary importance. The statistical analysis of these data revealed significant differences in the compressive strength due to both AEA and retarder (95% level), and a significant interaction effect between the mixing procedure and both AEA and retarder. The variation of compressive strengths for the different types of batches is given by Figure 17. Figure 18 illustrates the interaction of retarders and AEA's with mix method. Figure 18 shows that both retarders improve compressive strength. Retarder L produced higher strength concrete under Mix Method 1 while Retarder O produced the higher compressive strength under Mix Method 2. These interactions are significant at the 99% and 95% level respectively. These increases are from 3300 to 3830 (530 psi) and from 3550 to 3850 (300 psi) for Mix Methods 1 and 2 respectively.

Another effect of lesser statistical significance is the interaction of air-entraining agent and mix method shown in Figure 18. AEA D gives a slight improvement in compressive strength under Mix Method 1 (3400 to 3500, 100 psi) while AEA V gives a more significant improvement in compressive strength under Mix Method 2 (3300 to 3900, 600 psi).

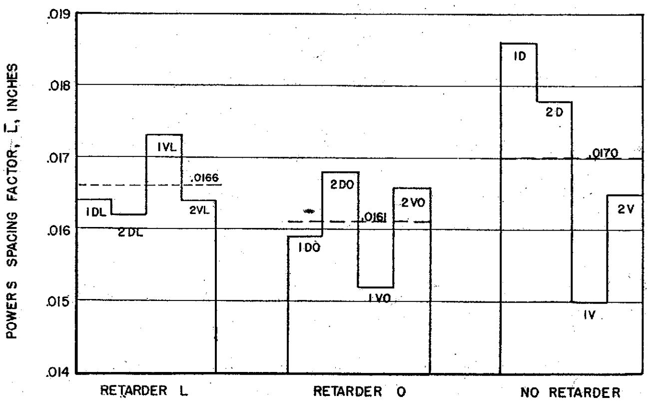

Figure 15. Retarders compared by spacing factor (ready mix).

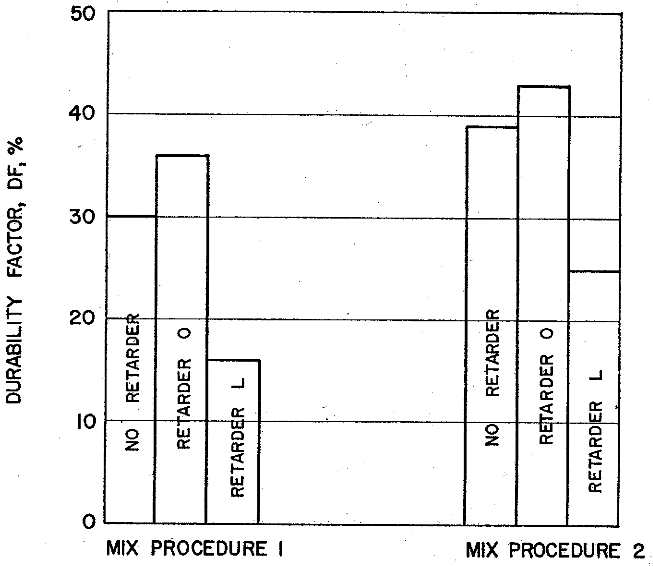

Figure 16. Retarders compared by durability factor (ready mix).

Comparison of Spacing Factors with Freeze-Thaw Durability

The development of both the Powers and Philleo spacing factors was an attempt to provide a measurement of the quality of a concrete air void system. If one concrete with one set of constituents is made with varying air contents, a fairly good relationship between concrete durability and either of the spacing factors can be achieved. In the case of concretes containing different constituents, especially different chemical admixtures, the relationship between frost resistance and spacing factor becomes increasingly tenuous. Figure 19, durability factor (DF) vs Powers' spacing factor ($\bar{L}$), shows the Laboratory concretes closely grouped with high durability factors and low values of $\bar{L}$, and the Ready Mix concrete showing considerably more scatter with low durability factors and large values of $\bar{L}$. One reason for this is shown by a comparison of the coefficients of variation between the Laboratory and Ready Mix programs. The average batch to batch CV for each 3 batch series in the Laboratory was 12.6% for $\bar{L}$ and 6.9% for DF, while in the Ready Mix program the corresponding numbers were 15.7% and 38.4%.

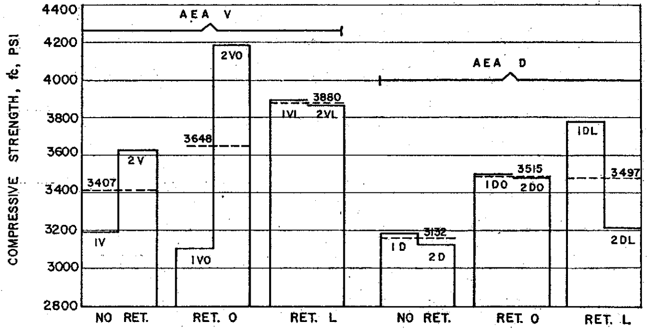

Figure 17. Retarders compared by compressive strength (ready mix).

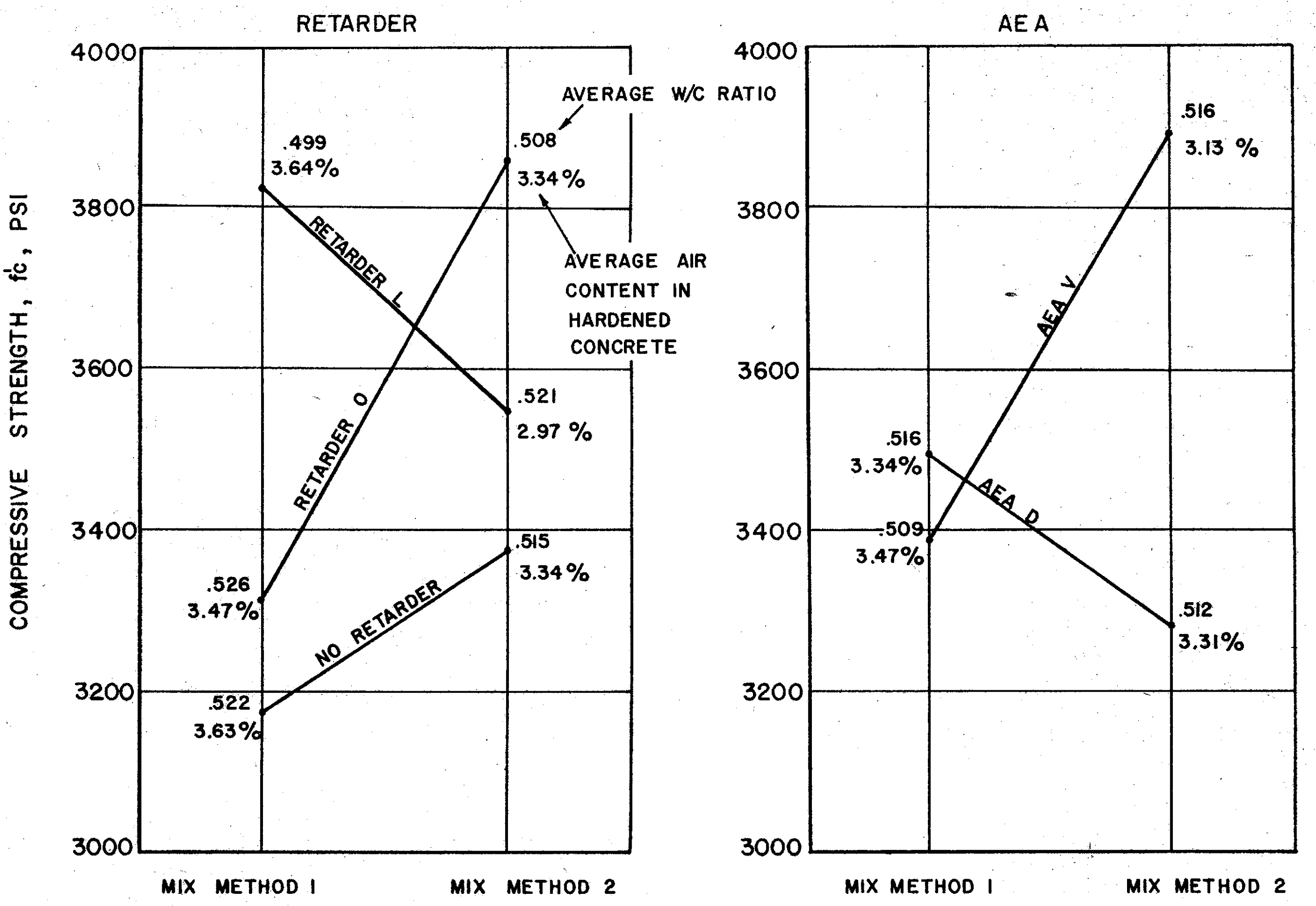

Figure 18. Compressive strength interaction diagrams.

There are two notable exceptions to the close grouping of the Laboratory concrete. The six batches of mix containing $CaCl_2$ (the two points with DF's about 25%) produced concretes having relatively good values of $\bar{L}$, but an extremely poor resistance to freeze-thaw cycles.

The other batches shown on Figure 19 are from the Field Survey data in Appendix C. These batches provide a transition in freeze-thaw durability between the high DF Laboratory concrete and the low DF Ready Mix concrete.

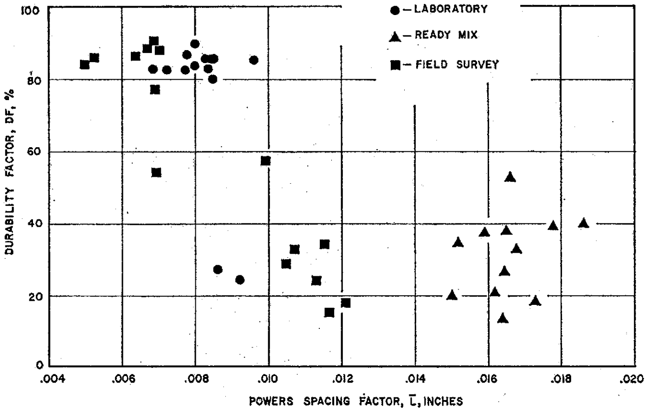

Figure 19. Durability factor vs Powers' spacing factor.

These field data were developed from concrete produced by ready mix trucks. However, the concrete was produced in the spring when the batch temperatures were considerably lower. The concrete temperature is apparently the prime difference between the lower spacing factors found in the Field Survey data and the high values determined in the Ready Mix program. These differences will be discussed in more detail on pages 10 through 12. As reported by other researchers[5,6] the transition between durable and nondurable concrete seems to be somewhere between an $\bar{L}$ of .008 in. and .010 in.

Figure 20 shows the Laboratory and Ready Mix concretes plotted in terms of DF and Philleo spacing factor, $\bar{S}$. The same basic relationship shown by the DF vs $\bar{L}$ plot is shown by the plot of durability factor and Philleo spacing factor. The transition from frost resistant to non-frost resistant concrete occurs at a value of $\bar{S}$ of approximately .004 inches.

Comparison of the Air Void Systems in Ready Mix Concrete, Laboratory Concrete and Mortar

The average distribution of bubble sizes for the Laboratory concrete, Ready Mix concrete and Mortar batches is shown by Figure 21. Comparing Diagram A with Diagrams B and C, it is seen that considerably less air and fewer bubbles remained in the Ready Mix

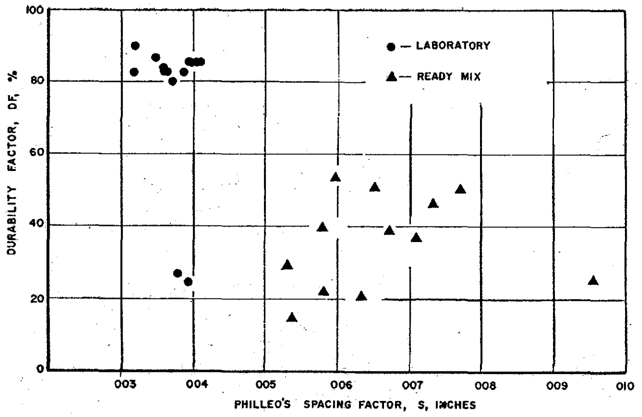

Figure 20. Durability factor vs Philleo spacing factor.

concrete after hardening than in either the Mortar or the Laboratory concrete.

Noting the conditions under which the Laboratory and Ready Mix concretes were prepared, three major differences are observed. These are: (1) mixing or agitation of the concrete batches, (2) size of the batches, and (3) temperature of the batches.

Concrete prepared in the laboratory was mixed in a pan-type mixer as compared to the drum type for the ready mixed concrete. Concerning the formation of bubbles in air-entrained concrete, Powers[7] states that,

> "In a drum-type concrete mixer, stirring is produced as the fluid material follows a tortuous path around the baffles, and as it cascades from elevating buckets. The same action produces kneading when the material is too stiff to behave like a fluid. In a pan-type mixer (Eirich-type) used mostly in laboratories and factories, stirring is done by rotating blades on a vertical shaft mounted eccentrically with respect to the center of the pan; material is carried to the blades, and away, by rotation of the pan. In some of these mixers, particularly those used in laboratories, perhaps half the batch is within the effective radius of the stirrer, and thus at a given instant only part of the batch is being stirred. When mixtures are too stiff for stirring, kneading is produced as the stirrers squeeze material against the vertical wall of the pan. This action, as well as that of stirring, is aided by a scraper that cleans the walls and deflects material toward the center."

He further states that,

> "Even though a drum-type concrete mixer is a relatively low speed device, its load of aggregate makes it a relatively high speed device for cement paste in concrete. It is probably more efficient than a laboratory stirrer such as that used by Bruere,[8] and undoubtedly much more efficient than the pan-type (Eirich) mixer used by Danielsson and Wastesson[9] as applied to stirrable neat cement paste."

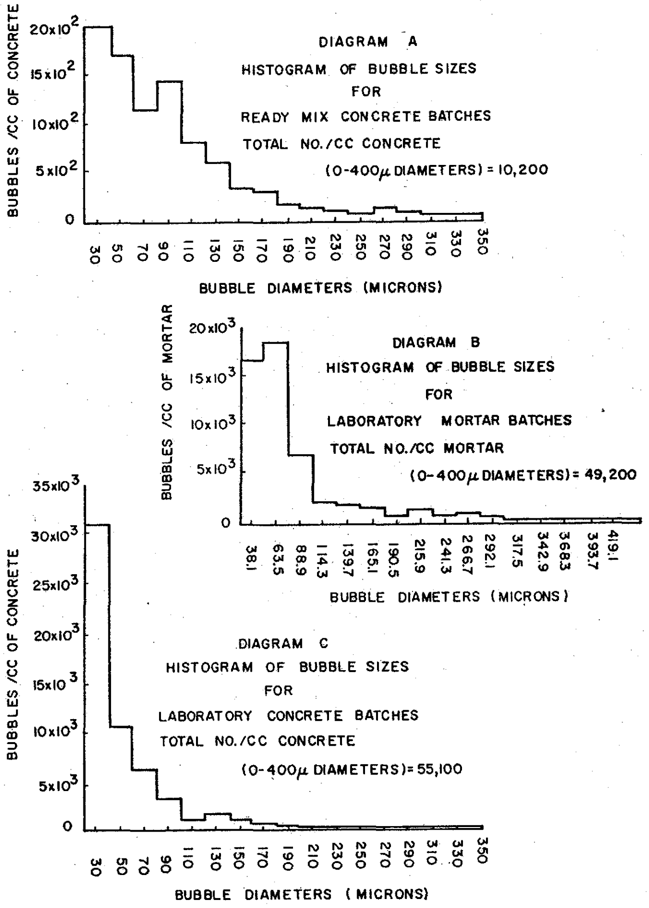

Figure 21. Comparison of air void systems between test programs.

Some specimens of ready mixed concrete have been obtained in the Field Survey portion of this study and found to possess a very desirable air void system. Although this would seem to show that the drum-type mixer is effective in entraining air in concrete, variations in the mixing characteristics of the Field Survey truck mixers and the truck mixer used for the Ready Mix concrete could account for some of the differences shown by Figure 21. Furthermore, batch size could account for some of these differences. While it is generally felt that the rate of air accumulation is lower the larger the batch,[7] Table 8 shows that the desired *amount* of air was initially entrained in the ready mixed concrete as well as in the laboratory concrete.

TABLE 8. COMPARISON OF AIR VOID PARAMETERS BETWEEN CONCRETE TEST PROGRAMS

Concrete Batches	Batch Temp (°F)	% Air in Hardened Concrete	% Air in Fresh Concrete	Specific Surface (in.)	Mean $\overline{r}_A$	Bubble $\overline{r}_S$	Radii $\overline{r}_V$
Laboratory	74°	5.3	5.4	550	34	44	66
Ready Mix	89.5°	3.6	5.6	340	59	76	110

The remaining factor which might account for these differences in the air void systems is that of batch temperature. In the case of the ready mixed concrete, it is seen that the air content of the hardened concrete is considerably less than the fresh concrete. Both Kliegler[10] and Larson[11] have observed this same anomaly. The question that arises from this observation is whether this reduced amount of air resulted from the loss of predominantly large or small bubbles, or a general loss of all bubble sizes. Powers[7] states that,

> "It seems temperature has little effect on the specific surface of the fine component of the bubbles, but at a higher temperature a smaller quantity of the fine component is added to the original quantity of coarse bubbles, and thus the composite system shows a relatively low specific surface area."

As shown in Table 8, the findings of this work are in agreement with Powers' statement, and it appears that the higher temperature may have caused the formation of an air void system with a significantly reduced number of small bubbles. If relatively few small bubbles were present when the air content was determined on the plastic concrete, it would follow that the reduction of air content from the plastic to the hardened state should be attributed to the loss of predominantly large bubbles.

The authors believe that high batch temperature was the principal cause of the rather poor air void systems developed in the Ready Mix program as compared to the more desirable systems achieved in the Laboratory program.

The Void Spacing Indicator (VSI)

One of the prime objectives of this study was the development of a field test which would indicate the quality of an air void system. The test which was developed is described in detail in Research Report 103[3] and the procedure is given in Appendix D. By knowing the batch proportions, a spacing factor can be calculated using the results of the VSI, which is almost as easy to operate as a Chace Air Indicator.

Figure 22 shows the VSI spacing factor ($\bar{V}$) compared to freeze-thaw durability for all concretes mixed in ready mix trucks. This includes both the Ready Mix program and the Field Survey concrete data. For VSI spacing factors below .012 high durability factors are shown while above .012 low durability factors are found. There is some indication that coalescence of bubbles might be a problem in the VSI test at the higher temperatures. It is recommended that a single VSI reading not be used as an indication of spacing factor. The test shows considerable variability (Average CV for within batch tests on Ready Mix concrete was 21%),

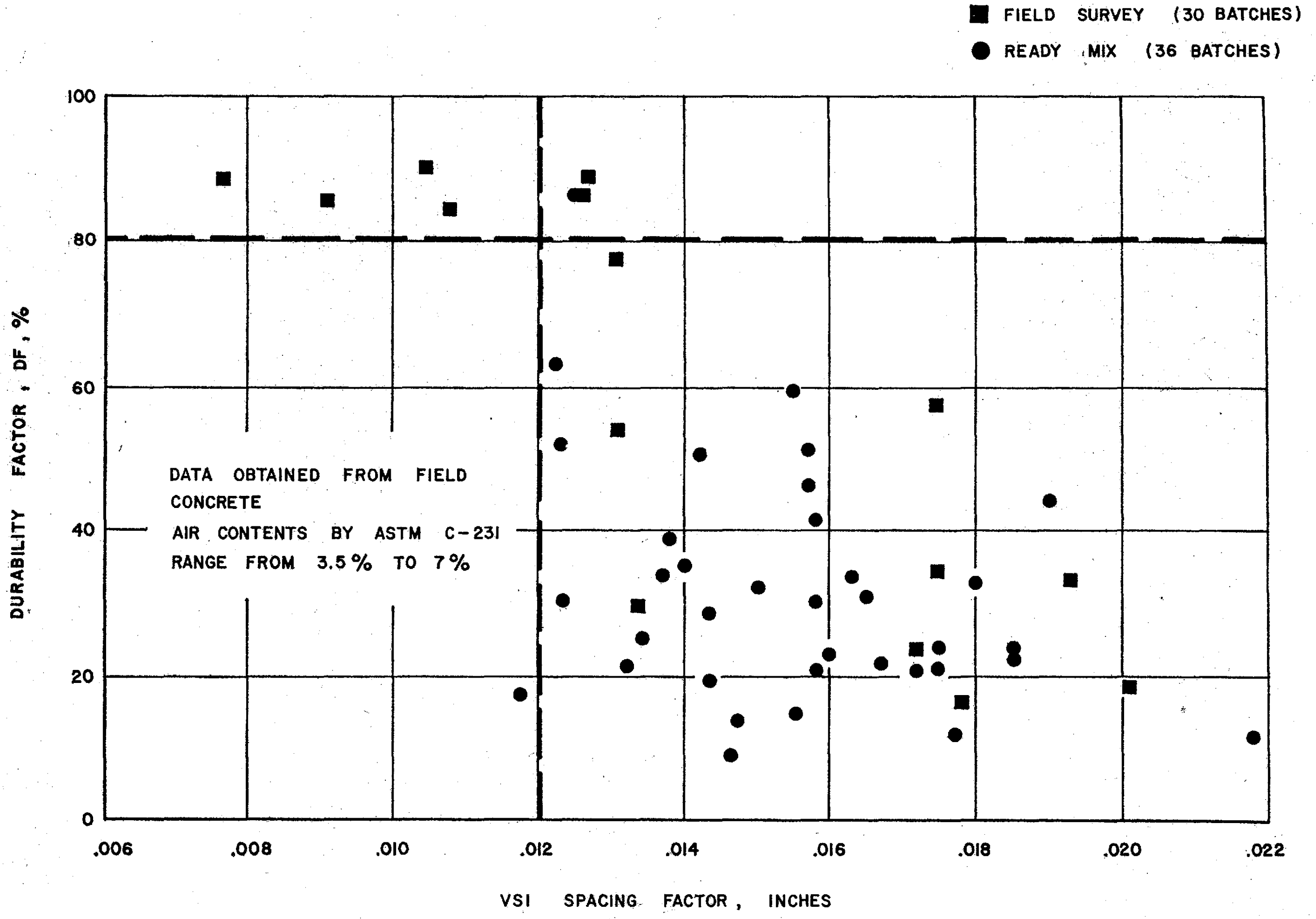

Figure 22. Comparison of VSI with frost resistance.

thus indicating that multiple tests be used to indicate the VSI spacing factor. This does not mean that a series of single tests is not a useful indicator for quality control purposes, but that repeated tests must be run for a reliable estimate of the VSI spacing factor.

For running quality control checks on concrete with constant proportions, an experienced inspector should be able to pick up changes in the quality of the air system by visual examination of the VSI view plate.

A significant difference was encountered in the ratio of the VSI spacing factor ($\overline{V}$) to Powers' spacing factor between the Laboratory concrete batches and the Ready Mix and Field Survey concrete batches. When the Laboratory batches are considered, the values of $\overline{V}$ determined were considerably above the values determined for $\overline{L}$. The average ratio of $\overline{V}/\overline{L}$ was 2.18 for these concretes. In this case there was an almost negligible reduction of air content from the plastic to the hardened state (5.55% to 5.40%).

Among the Field Survey batches, the average ratio of VSI spacing factor to Powers' spacing factor, $\overline{V}/\overline{L}$, was 1.66. In the case of the Ready Mix batches this average ratio decreased to a value of 0.94. The reason for this becomes obvious when the decrease of air content from the plastic to the hardened concrete is considered (see Tables 1 and 2). In the Ready Mix batches $\overline{V}$ was determined on the plastic concrete which had an average air content of 5.47%. $\overline{L}$ was then determined on the hardened concrete which had an average air content of only 3.48% (an average reduction of 1.99%). This decrease of air content causes a higher value of $\overline{L}$, resulting in a reduced ratio of $\overline{V}/\overline{L}$. This reduction in air content also must have influenced the values of $\overline{V}/\overline{L}$ determined in the Field Survey, where the average air content of the plastic concretes was 5.40% as compared to the average air content of 3.94% after hardening (an average reduction of 1.46%). This variation in the ratio of $\overline{V}$ to $\overline{L}$ is shown in Figure 23 as a function of the ratio of pressure meter air content to hardened air content (A_p/A_H). If further investigation shows that Figure 23 accurately describes this relationship, it may be possible to calibrate the VSI for a given project with a series of determinations of air content on both the plastic and hardened concrete.

Such a calibration could be applied as a modifying coefficient in the $\overline{V}$ equation. The data that are pres-

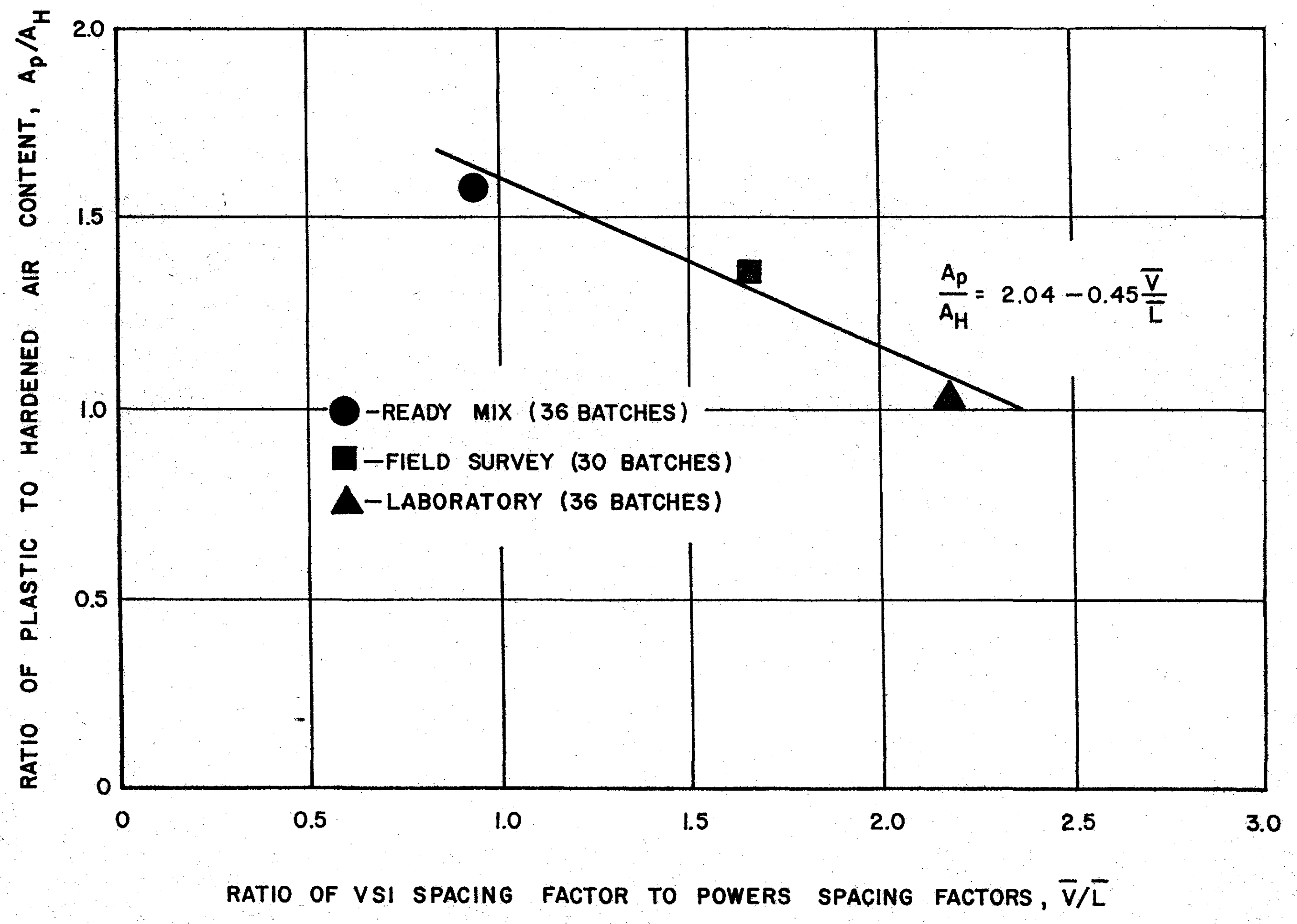

Figure 23. Variation of $\overline{V}/\overline{L}$ with A_p/A_H.

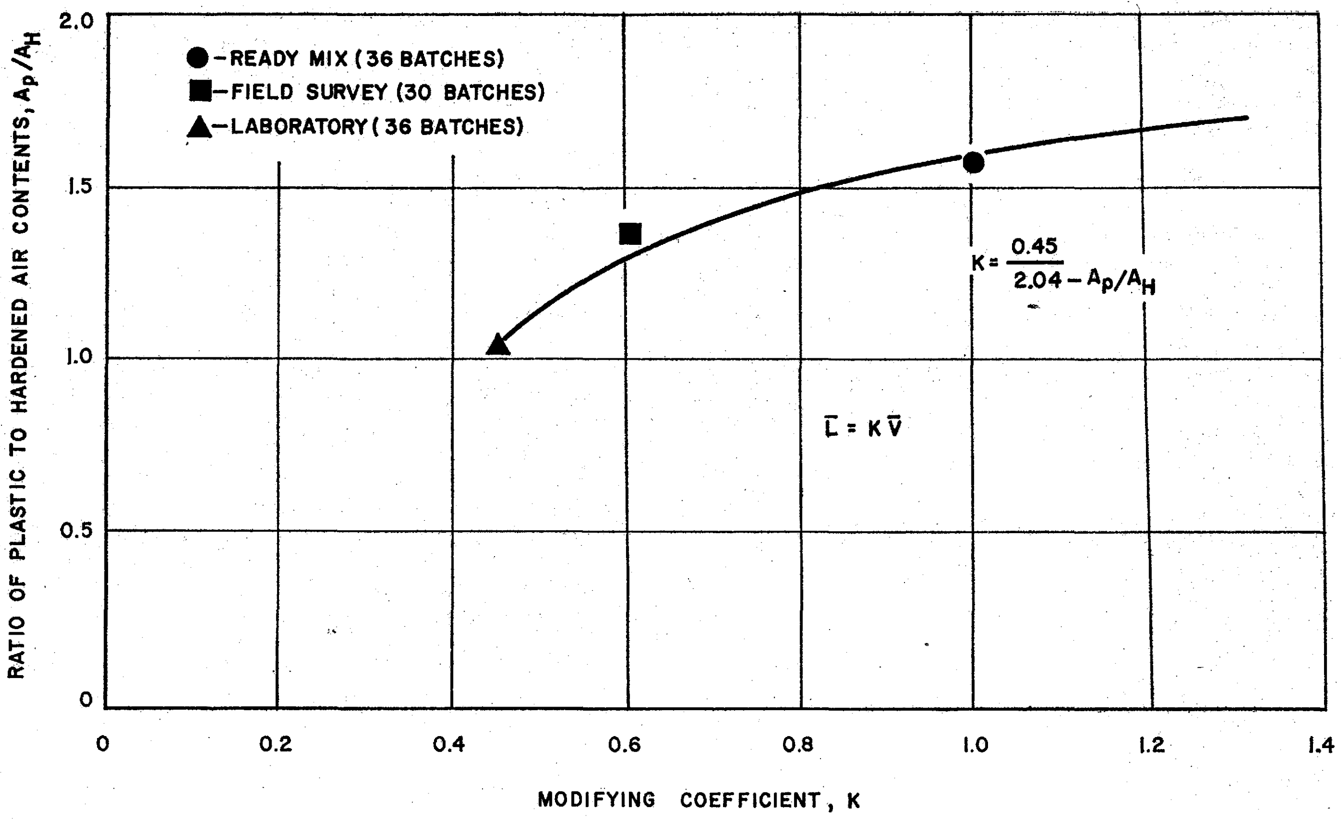

Figure 24. Variation of K with A_p/A_H.

ently available indicate that this coefficient has a fairly linear variation with the A_p/A_H ratio. Using the method of least squares to fit a line to the points shown in Figure 18, this modifying coefficient, K, can be related to the A_p/A_H ratio. This relationship is shown in Figure 24.

The data which have been developed in this study are not sufficient to fully evaluate the Void Spacing Indicator. It is recommended that if the test is to be used to determine actual values, as opposed to relative values of void spacing factor, it should first be correlated with determinations of Powers' spacing factor for the particular concrete involved.

Within Batch Variations, Ready Mix

Since samples were taken from the front, middle and back of each batch, data were acquired that give an indication of within batch variations in air content, slump and compressive strength for this particular truck mixer.

The variations in concrete properties within the same batch are given by Table 9. Comparing the air content, compressive strength and slump from front to middle and from middle to back of the load, it is seen that the differences are highly significant (99% probability level) in all cases except the VSI determinations (no significance front to middle and 90% significance

TABLE 9. WITHIN BATCH VARIATIONS (60 BATCHES)

Test	Point of Determination in Load				
	Front	Difference and Significance	Middle	Difference and Significance	Back
Air Content-Pressure Meter (%)	5.81	t = 9.35 0.22 99 %	5.59	t = 3.08 0.11 99 %	5.48
Bubble Area-VSI (in.^{2})	1.58	t = .013 0.01 None	1.59	t = 1.86 0.06 90 %	1.53
Compressive Strength (psi)	3371	t = 3.38 185 99 %	3556	t = .362 33 None	3589
Slump (inches)	3.75	t = 4.46 0.18 99 %	3.57	t = 3.96 0.23 99%	3.34

middle to back) and the compressive strength (no significance middle to back).

There is some doubt that these variations represent real differences within the concrete batch when the truck starts to discharge. The samples were tested in the order of front, middle and back, with approximately 15 minutes elapsing between each pressure meter test. It is possible that this time lag caused some, if not all, of the differences in pressure meter air content. Hanna et al.,[12] found a time dependency "as samples were tested in the field for air content by the pressure meter." The tests Hanna reports give the differences shown in Table 10 for three consecutive pressure meter determinations on the same sample of concrete.

TABLE 10. VARIATIONS IN PRESSURE METER READINGS

Position of Readings	Difference in Pressure Meter Air Content
	% %
First to Second	.136 to .256
Second to Third	.024 to .142
After Hanna[12] et al.	
(First) (Second) Front to Middle	0.22
(Second) (Third) Middle to Back	0.11
TTI Data	

The TTI data is seen to fall within the range indicated by Hanna. This change in air content with time could also account for a part of the differences found in VSI, compressive strength and slump.

While the differences found in these properties may be highly significant from a statistical point of view, they are seen to be relatively insignificant considering their effect on the properties of mature concrete. Neglecting time effects, the maximum differences are 0.33% in pressure meter air content, 0.06 square inches in the VSI, 218 psi in compressive strength and 0.41 inches in slump.

As indicated by these tests, the truck mixer produced a very uniform batch.

Summary and Conclusions

1. Differences in the entrained air systems and in frost resistance of concrete are influenced by mixing method, type of air-entraining agent and type of retarder. These differences can be summarized as follows.

a. *Mixing Method*—In the Mortar study a significant improvement in the air void system is achieved by adding the air-entraining agent and retarder to the concrete in *separate* water phases (Mix Method 2). Although statistically significant differences in the air systems were not shown in the concrete studies, improvements in concrete frost resistance due to Mix Method 2 are indicated.

b. *Air-Entraining Agents*—In both the Ready Mix and Mortar programs, the vinsol resin air-entraining agent, AEA V, showed the most desirable air void system. This finding was complimented by an improvement in the frost resistance of concrete containing a retarder in combination with the vinsol resin.

c. *Retarders*—In the Laboratory concrete and Mortar programs the use of the organic acid retarder (Retarder O) gave a significant improvement in the air void system. Although a corresponding improvement was not shown by the Ready Mix program, a significant improvement in frost resistance was shown. This agreed with the Mortar study in which the mortar containing the organic acid showed a reduction of freeze-thaw weight loss.

d. *Interaction Effects*—A significant interaction effect between mixing method and frost resistance was shown in the Ready Mix program. The combination of vinsol resin and Mix Method 2 gave the most frost resistant concrete.

2. The three major variables (Mixing Method, Air-Entraining Agent and Retarder) have shown a considerable effect on concrete strength. The most significant of these effects is that the lignosulfonate (Retarder L) gives higher compressive strengths under Mix Method 1 (3300 to 3810 psi) while the organic acid (Retarder O) gives the higher compressive strength under Mix Method 2 (3550 to 3850 psi). The basic difference in the mix methods is that in Mix Method 1 both retarder and air-entraining agent are mixed in the same water phase whereas in Mix Method 2 they are added to the concrete in separate water phases. Both retarders improved compressive strength above that of concrete without a retarder.

Another effect of lesser statistical significance is the interaction of air-entraining agent and mix method. The synthetic detergent (AEA D) gives a slight improvement in compressive strength under Mix Method 1 (3400 to 3500 psi) while the vinsol resin (AEA V) gives a more significant improvement in compressive strength under Mix Method 2 (3300 to 3900 psi).

3. The comparison of the various void spacing factors with freeze-thaw durability shows, in general, poorly defined relationships. Differences in other properties of the concrete appear to be such that variation in frost resistance occurs at basically equal void spacing factors.

a. *Powers and Philleo Spacing Factors*—The comparison of the Powers spacing factor ($\bar{L}$) with frost resistance shows a reasonably well defined break point between frost resistant and non-frost resistant concrete at a value of about .008 inches. This break point for the Philleo spacing factor is about .004 inches.

b. *VSI Spacing Factor*—The comparison of the VSI spacing factor with frost resistance shows that the

VSI (Void Spacing Indicator) can be a significant aid in differentiating between frost resistant and non-frost resistant concrete. A well defined break point between these two conditions occurs at a VSI spacing factor of .012 inches. This test procedure is given in Appendix D.

c. *Effects of Temperature on the Air Void System and Frost Resistance*—Elevated batch temperatures averaging 89°F are suspected as one cause of the undesirable air void systems and correspondingly low frost resistances of the concretes from the Ready Mix program. It should be emphasized that these poor air void systems occurred in concrete that had an adequate amount of entrained air in the plastic state. Most of the concretes from the Laboratory program and the Field Survey program which had fundamentally the same *amount* of entrained air had an adequate air void system. This would indicate that the control of batch temperature may be of importance to the achievement of frost resistant concrete.

4. The truck mixer used in the Ready Mix program produced very uniform batches.

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Appendix A

Ready Mix Concrete Data

TABLE 1-A. PROPERTIES OF PLASTIC CONCRETE, INDIVIDUAL BATCHES (READY MIX)

Batch Number	Admixtures		Cement sks/cy	Total Water lbs/cy	Aggregate		Air Properties			Slump in.	Unit Weight Wet lbs/CF	Batch Temperature
	AEA cc/cy	Retarder cc/cy			Coarse lbs/cy	Fine lbs/cy	Pressure Meter %	VSI sq. in.	VSI Spacing Factor (inches)			
1	104.7 (D)	475.6 (O)	5.38	253	1756	1328	5.9	1.496	.0231	5.0	142.4	86°
2	114.4 (V)	None	5.80	276	1721	1326	6.0	1.698	.0213	4.2	145.2	70°
3	113.8 (D)	481.1 (O)	5.45	267	1730	1336	6.4	1.750	.0127	5.9	142.4	84°
4	100.0 (V)	None	5.50	245	1754	1364	5.1	2.522	.0081	5.7	143.6	89°
5	128.9 (D)	805.5 (L)	5.46	257	1762	1380	5.3	0.960	.0218	1.1	144.8	89°
6	85.1 (V)	801.5 (L)	5.43	251	1754	1342	7.0	1.865	.0115	3.0	142.8	88°
7	78.9 (V)	801.5 (L)	5.44	261	1750	1304	7.2	2.207	.0099	5.2	141.6	84°
8	109.2 (V)	486.7 (O)	5.51	252	1787	1354	5.8	1.138	.0190	2.5	144.8	84°
9	119.7 (D)	None	5.53	259	1779	1330	5.4	1.346	.0155	3.3	144.0	84°
10	119.7 (D)	None	5.53	262	1779	1330	5.6	1.299	.0167	3.2	144.0	86°
11	78.9 (V)	802.8 (L)	5.55	256	1783	1336	4.8	1.132	.0175	3.0	144.4	85°
12	110.3 (D)	None	5.51	260	1773	1325	5.7	1.777	.0122	4.3	143.6	85°
13	117.3 (D)	None	5.54	254	1782	1332	5.4	1.339	.0157	3.5	144.0	87°
14	130.4 (D)	814.9 (L)	5.52	257	1783	1364	5.8	1.238	.0172	2.3	145.2	88°
15	117.9 (D)	None	5.54	267	1782	1340	5.4	1.562	.0137	3.3	144.8	87°
16	81.1 (V)	824.5 (L)	5.59	259	1797	1348	4.7	1.056	.0187	2.2	145.6	87°
17	116.5 (D)	812.2 (L)	5.50	260	1777	1363	5.4	1.323	.0160	3.5	145.2	87°
18	106.8 (D)	485.0 (O)	5.50	259	1791	1351	4.8	1.066	.0185	3.2	145.2	87°
19	108.1 (V)	481.8 (O)	5.46	261	1769	1341	6.1	1.592	.0138	3.3	144.0	88°
20	99.2 (V)	482.6 (O)	5.47	277	1772	1344	4.8	1.224	.0165	3.1	144.8	89°
21	105.0 (V)	486.7 (O)	5.51	273	1767	1340	5.4	1.361	.0158	3.2	144.4	89°
22	105.2 (V)	487.5 (O)	5.52	276	1770	1342	4.8	1.118	.0180	4.2	144.8	89°
23	104.1 (V)	482.6 (O)	5.47	269	1769	1344	4.5	0.969	.0205	3.3	144.4	90°
24	105.2 (V)	None	5.52	275	1778	1347	4.9	1.171	.0175	2.2	145.2	90°
25	107.8 (V)	None	5.47	289	1752	1334	4.5	1.093	.0182	4.3	144.0	92°
26	132.2 (V)	None	5.47	289	1752	1334	4.9	1.354	.0146	3.0	144.0	92°
27	149.5 (V)	None	5.50	285	1744	1340	5.2	1.543	.0146	3.8	144.0	91°
28	85.5 (V)	805.5 (L)	5.46	277	1766	1342	5.3	1.422	.0150	3.0	144.4	91°
29	86.9 (V)	819.0 (L)	5.55	268	1779	1365	5.1	1.477	.0140	3.2	145.6	96°
30	115.9 (D)	489.9 (O)	5.55	285	1762	1365	3.7	0.949	.0187	4.7	145.6	93°
31	115.9 (D)	489.9 (O)	5.55	271	1762	1365	4.4	1.119	.0172	4.3	145.2	89°
32	109.9 (D)	489.9 (O)	5.55	262	1779	1371	4.3	0.894	.0212	3.2	145.6	90°

TABLE 1A. PROPERTIES OF PLASTIC CONCRETE, INDIVIDUAL BATCHES (CONTINUED)

	Admixtures				Aggregate		Air Properties					
Batch Number	AEA cc/cy	Retarder cc/cy	Cement sks/cy	Total Water lbs/cy	Coarse lbs/cy	Fine lbs/cy	Pressure Meter %	VSI sq. in.	VSI Spacing Factor (inches)	Slump in.	Unit Weight Wet lbs/CF	Batch Temperature
33	198.7 (D)	None	5.48	276	1755	1342	5.1	1.348	.0155	3.2	144.0	91°
34	165.0 (D)	805.5 (L)	5.46	268	1766	1355	5.2	1.191	.0177	3.5	144.4	92°
35	179.4 (D)	796.3 (L)	5.40	271	1746	1340	5.9	1.548	.0143	5.0	143.2	93°
36	179.4 (D)	796.3 (L)	5.43	277	1746	1355	5.6	1.394	.0158	3.7	144.0	93°
37	142.1 (D)	488.3 (O)	5.53	277	1756	1367	4.6	1.370	.0143	3.8	145.2	88°
38	199.0 (D)	484.2 (O)	5.49	275	1741	1355	5.4	1.320	.0163	3.9	144.0	91°
39	232.2 (D)	484.2 (O)	5.49	275	1741	1358	5.6	1.551	.0142	3.6	144.0	91°
40	157.3 (V)	None	5.48	287	1755	1340	4.9	1.180	.0175	3.5	144.4	93°
41	198.7	None	5.48	275	1755	1341	5.2	1.140	.0185	2.7	144.0	93°
42	197.4 (D)	802.8 (L)	5.44	275	1760	1351	5.0	1.410	.0147	4.0	144.4	96°
43	292.7 (V)	None	5.38	261	1724	1321	7.1	2.238	.0097	3.6	141.2	92°
44	245.5 (V)	None	5.41	272	1735	1332	6.0	1.843	.0123	3.8	142.4	94°
45	246.3 (D)	479.5 (O)	5.43	256	1724	1352	6.4	1.771	.0123	4.0	142.4	94°
46	214.5 (D)	481.8 (O)	5.46	261	1733	1359	6.0	1.647	.0134	4.0	143.2	94°
47	187.8 (D)	457.0 (O)	5.24	238	1690	1285	11.0	4.103	.0049	5.7	137.2	90°
48	198.7 (V)	483.4 (O)	5.48	237	1755	1328	7.9	3.368	.0060	3.3	142.0	90°
49	106.2 (V)	477.1 (O)	5.41	247	1732	1304	8.3	2.988	.0070	4.0	140.4	91°
50	57.9 (V)	808.1 (L)	5.48	248	1755	1337	7.0	2.439	.0087	2.3	142.8	90°
51	None	None	5.41	280	1748	1351	2.3	0.192	.0723	2.8	144.0	92°
52	66.8 (V)	None	5.52	272	1770	1347	4.9	1.121	.0182	3.4	144.8	87°
53	83.6 (V)	None	5.53	269	1773	1349	5.3	1.338	.0158	2.5	144.8	87°
54	66.9 (V)	816.2 (L)	5.53	256	1773	1351	6.0	1.660	.0132	3.2	144.4	89°
55	74.6 (V)	746.3 (L)	5.49	255	1758	1339	6.4	1.884	.0115	3.3	143.2	89°
56	74.9 (V)	485.9 (O)	5.51	256	1764	1340	5.9	1.730	.0125	3.4	143.6	90°
57	63.2 (V)	812.2 (L)	5.51	255	1764	1344	6.2	1.860	.0117	3.4	143.6	91°
58	90.9 (V)	None	5.47	267	1752	1335	5.6	1.390	.0157	3.1	143.2	90°
59	55.2 (V)	816.2 (L)	5.53	253	1773	1351	5.8	1.480	.0147	3.1	144.4	89°
60	194.8 (D)	474.0 (O)	5.37	256	1705	1327	8.1	2.980	.0072	5.7	140.4	90°

Admixture Dosages:

(1) 785 cc/cy Retarder L = ⅛ lb/sk cement.
(2) 488 cc/cy Retarder O = 3 oz/sk cement.
(3) 163 cc/cy AEA V = 1 oz/sk cement.
(4) 146 cc/cy AEA D = 1 oz/sk cement.

TABLE 2-A. PROPERTIES OF HARDENED CONCRETE (READY MIX)

Batch Number	Batch Designation	Volume of Air by ASTM C-457 %	Powers L inches	Philleo S inches	Durability ASTM C-290 %	Compressive Strength 28 day-psi
01						4071
02						3686
03						3766
04						3304
05	1DL	3.85	.0160	.00641	11.2	4160
06						3340
07						3177
08	1VO	4.46	.0119	.00464	44.0	3711
09	2D	3.01	.0157	.00660	59.0	3216
10	1D	4.32	.0163	.00347	21.6	3428
11	1VL	3.41	.0197	.00870	23.6	3699
12	1D	3.80	.0194	.00785	63.0	3029
13	2D	4.10	.0172	.00559	46.0	3210
14	1DL	5.11	.0174	.00569	20.4	3727
15	1D	3.32	.0201	.00614	33.6	3121
16						3568
17	2DL	3.33	.0153	.00406	22.4	3093
18	2DO	2.68	.0199	.00763	22.0	3768
19	2VO	3.33	.0145	.00617	38.7	4289
20	1VO	3.10	.0163	.00573	30.8	2732
21	1VO	3.54	.0173	.00988	30.0	2869
22	2VO	2.84	.0189	.00915	32.8	4102
23						3049
24	1V	2.53	.0205	.01123	20.4	3709
25						3221
26						3212
27	1V	3.84	.0144	.01048	8.8	3160
28	2VL	2.93	.0164	.00452	32.0	3634
29	2VL	2.52	.0184	.00566	35.2	4120
30	1DO					3595
31						4645
32	2VO					4069
33	2D	3.02	.0204	.00573	14.8	2972
34	1DL	3.01	.0158	.00402	11.6	3464
35	2DL	2.91	.0137	.00880	19.2	3164
36	2DL	2.98	.0197	.00615	20.4	3436
37	1DO	3.08	.0174	.00452	28.4	3854
38	1DO	3.34	.0159	.00896	33.6	3176
39	1DO	3.28	.0145	.00779	50.2	3520
40						2897
41	2V	2.37	.0157	.00790	23.6	3192
42						3181
43						2663
44	1V	3.96	.0102	.00705	30.8	2674
45	2DO	3.72	.0140	.00714	51.8	3579
46	2DO	4.05	.0166	.00485	24.4	3524
47	2VO					2875
48	2VO					3853
49						3023
50	2VL					3782
51						3332
52						3579
53	2V	3.84	.0170	.00557	41.2	3477
54	2VL	3.13	.0141	.00585	21.0	3859
55	1VL					3074
56	2VO	3.45	.0163	.00766	86.0	4183
57	1VL	3.24	.0187	.00341	17.0	3471
58	2V	3.73	.0168	.00859	50.4	4230
59	1VL	3.22	.0136	.00529	13.6	4498
60	1DO	3.73	.0168	.00859		4183

Universal Atlas Cement
Division of United States Steel Corporation

Laboratory Test Report

Date Shipped May 22, 1968

Cement T-I

Shipped From Waco, Texas

To: Bryco, Inc.
Attn: Mr. Moore
Box 73
Bryan, Texas 77801

Consigned To Bryco, Inc.

Car/Truck No.	SSW77171	SSW77056
Bbl.	401.22	407.98

The data given below is average of bin from which cement was shipped.

CHEMICAL

	%
SiO_2	20.8
Al_2O_3	6.08
Fe_2O_3	2.63
CaO	65.2
MgO	1.0
SO_3	2.7
Loss On Ignition	0.7
Insoluble Residue	0.14
C_3S	55.2
C_3A	11.7

PHYSICAL

Fineness
Specific Surface — Sq. Cm./g

Wagner	1780
Blaine	3190
Soundness, Autoclave Exp. %	0.07
Time Of Setting, Hr.: Min. — Initial	3:35
Final	6:30
Air Content — %	9.9
Compressive Strength, psi — 1 Day	
3 Day	3290
7 Day	4270

This cement complies with applicable ASTM and Federal Specifications.

UAC 529 R-9-65

By C G Schank
C. G. SCHANK, CHIEF CHEMIST

Appendix B

Laboratory Concrete Data

TABLE 1-B. PROPERTIES OF PLASTIC CONCRETE, INDIVIDUAL BATCHES, (LABORATORY)

	Admixtures				Aggregate		Air Properties					
Batch Number	AEA cc/cy	Retarder cc/cy	Cement sks/cy	Total Water lbs/cy	Coarse lbs/cy	Fine lbs/cy	Pressure Meter %	VSI sq. in.	VSI Spacing Factor (inches)	Slump in.	Unit Weight lbs/CF	Batch Temperature
010	106 (D)	488 (O)	5.48	251	1794	1354	5.6	1.456	.0146	3.75	141.9	70°
020	109 (V)	None	5.44	244	1782	1346	5.3	1.172	.0176	3.0	143.0	79°
030	120 (D)	488 (O)	5.47	258	1755	1352	5.3	1.411	.0146	3.0	143.5	76°
040	100 (V)	None	5.49	259	1748	1322	6.0	1.306	.0168	3.5	142.3	78°
050	109 (V)	2 lbs/100 lbs cement (cc)	5.49	270	1763	1312	5.5	1.062	.0203	3.75	141.9	77°
060	109 (V)	2 lbs/100 lbs cement (cc)	5.50	263	1740	1315	5.4	0.929	.0228	3.0	141.9	77°
070	145 (D)	785 (L)	5.47	231	1747	1343	5.9	1.634	.0125	3.0	141.9	79°
080	106 (V)	785 (L)	5.45	246	1742	1324	6.0	1.666	.0127	3.0	141.4	77°
090	81 (V)	785 (L)	5.49	261	1754	1303	5.7	1.449	.0150	3.25	142.0	75°
100	117 (V)	2 lbs/100 lbs cement (cc)	5.52	251	1745	1318	5.8	1.673	.0129	3.5	142.0	75°
110	110 (V)	488 (O)	5.53	232	1749	1322	5.8	1.367	.0150	4.0	141.5	78°
120	119 (D)	None	5.50	266	1738	1313	5.1	1.016	.0203	3.75	142.0	77°
130	108 (V)	2 lbs/100 lbs cement (cc)	5.50	261	1740	1315	5.5	0.681	.0315	3.5	142.0	76°
140	127 (D)	None	5.53	261	1748	1321	5.1	0.778	.0264	3.0	142.4	74°
150	108 (V)	2 lbs/100 lbs cement (cc)	5.51	265	1761	1354	5.4	1.432	.0149	3.0	144.4	74°
160	81 (V)	785 (L)	5.51	258	1759	1361	5.8	0.999	.0219	4.0	142.3	75°
170	127 (D)	None	5.52	251	1808	1320	5.0	1.198	.0168	3.0	144.1	73°
180	119 (D)	None	5.55	253	1755	1326	5.2	1.016	.0203	3.5	142.5	75°
190	109 (V)	2 lbs/100 lbs cement (cc)	5.53	261	1750	1323	5.6	0.694	.0312	3.0	142.8	75°
200	115 (D)	785 (L)	5.53	259	1766	1321	6.0	1.030	.0214	3.0	143.0	74°
210	127 (D)	None	5.51	274	1759	1316	5.2	0.985	.0214	3.75	143.2	74°
220	74 (V)	785 (L)	5.50	261	1758	1351	5.3	1.057	.0199	3.75	144.0	72°
230	139 (D)	785 (L)	5.53	246	1767	1322	6.0	1.654	.0129	3.5	143.2	72°
240	106 (D)	488 (O)	5.50	236	1799	1358	5.5	1.100	.0188	3.25	144.8	70°
250	109 (V)	488 (O)	5.53	242	1748	1366	5.1	1.175	.0172	3.5	143.5	70°
260	110 (V)	488 (O)	5.51	276	1742	1353	5.3	1.069	.0200	3.0	144.0	70°
270	110 (V)	488 (O)	5.54	225	1750	1359	5.5	1.171	.0173	3.25	142.6	70°
280	109 (V)	488 (O)	5.53	248	1750	1368	5.4	1.165	.0180	3.0	144.0	70°
290	106 (D)	488 (O)	5.49	228	1798	1357	5.4	1.008	.0202	3.0	144.2	71°
300	100 (V)	None	5.54	261	1763	1334	5.2	1.028	.0203	4.0	143.5	73°
310	109 (V)	None	5.50	254	1733	1359	5.5	1.033	.0206	3.75	143.0	73°
320	109 (V)	None	5.52	256	1739	1364	5.6	0.850	.0254	3.5	143.0	74°
330	100 (V)	None	5.55	257	1770	1339	5.2	1.568	.0132	3.5	144.0	73°
340	72 (V)	785 (L)	5.53	241	1749	1367	5.7	1.514	.0139	3.25	143.4	75°
350	81 (V)	785 (L)	5.51	242	1743	1363	5.8	1.310	.0161	3.5	143.1	75°
360	120 (D)	488 (O)	5.54	234	1753	1370	5.9	1.663	.0124	3.5	143.5	74°
370	110 (D)	488 (O)	5.52	257	1747	1365	5.8	1.858	.0117	3.25	144.0	75°
380	109 (V)	488 (O)	5.52	229	1745	1364	6.0	1.02	.0200	3.75	142.5	75°
390	119 (D)	None	5.55	260	1772	1326	5.0	1.000	.0203	4.0	143.5	73°
400	127 (D)	785 (L)	5.53	239	1766	1321	5.7	1.089	.0192	3.25	142.4	73°
410	108 (D)	785 (L)	5.55	240	1776	1328	5.8	1.408	.0149	3.0	143.2	74°
420	112 (D)	785 (L)	5.54	243	1769	1323	5.9	1.021	.0207	3.25	143.2	74°

TABLE 2-B. PROPERTIES OF HARDENED CONCRETE (LABORATORY)

Batch Number	Batch Designation	Volume of Air by ASTM C-457 %	Powers $\overline{L}$ inches	Philleo $\overline{S}$ inches	Durability ASTM C-290
010	2DO1	5.24	.00853	.00485	94.0
020	2V3	5.44	.00989	.00444	87.6
030	1DO3	4.52	.00748	.00302	91.3
040	1V1	6.64	.00666	.00372	89.0
050	2VCC1	5.02	.00999	.00438	24.4
060	2VCC3	5.65	.00838	.00351	25.6
070	1DL1	6.11	.00586	.00317	92.1
080	2VL1	6.22	.00717	.00346	83.8
090	1VL2	6.66	.00737	.00303	87.0
100	1VCC3	6.03	.00882	.00414	23.2
110	1VO1	6.63	.00551	.00310	91.1
120	2D2	4.42	.00927	.00438	86.5
130	1VCC1	5.46	.00844	.00405	27.8
140	1D3	4.53	.0100	.00459	81.0
150	1VCC2	5.34	.00847	.00317	29.6
160	1VL1	4.86	.00830	.00349	90.4
170	1D1	5.36	.00673	.00276	81.2
180	2D3	5.03	.00784	.00338	92.6
190	2VCC2	5.83	.00925	.00394	20.0
200	1DL2	5.53	.00727	.00310	74.1
210	1D2	5.05	.00832	.00355	86.0
220	1VL3	6.17	.00826	.00359	92.1
230	2DL2	5.33	.00516	.00230	83.6
240	2DO3	5.21	.00746	.00285	75.2
250	2VO2	3.91	.00722	.00330	77.5
260	1VO2	4.45	.00935	.00379	78.4
270	1VO3	4.66	.00854	.00355	89.2
280	2VO1	5.12	.00884	.00417	86.6
290	2DO2	4.83	.00803	.00308	81.6
300	1V3	5.39	.00887	.00418	82.0
310	2V1	4.57	.00939	.00352	85.4
320	2V2	5.76	.00959	.00431	82.4
330	1V2	4.75	.00999	.00399	84.4
340	2VL2	6.21	.00874	.00378	77.0
350	2VL3	5.59	.00974	.00387	78.0
360	1DO1	6.28	.00844	.00454	87.0
370	1DO2	5.57	.00894	.00456	77.4
380	2VO3	6.40	.00725	.00412	82.7
390	2D1	4.28	.00844	.00416	76.0
400	1DL3	5.14	.00742	.00368	81.0
410	2DL1	6.68	.00803	.00400	78.5
420	2DL3	5.92	.00846	.00453	85.0

SOUTHWESTERN LABORATORIES
FORT WORTH DALLAS HOUSTON MIDLAND BEAUMONT TEXARKANA
CONSULTING, ANALYTICAL CHEMISTS
AND TESTING ENGINEERS

Fort Worth, Texas 6-15-68 File No. 458

Report of tests on Cement

To Texas Transportation Institute; Mr. Torrans Date Rec'd. 4-22-68

Received from Same, Texas A&M College

Identification Marks None

PHYSICAL TEST:

Compressive Strength

Specimen	Age	PSI
1	3	3275
2	3	3250
3	3	3188
4	7	4150
5	7	4175
6	7	4163
7	28	5700
8	28	5600
9	28	5475

Time Set: Vicat

2 Hours & 36 Min.

Air Content

14.8%

Normal Consistancy

25.4

Blaine Fineness

3777

Autoclave Soundness

No.	% Expansion
1	0.19
2	0.23
Avg.	0.21

Con't on Page 2

SOUTHWESTERN LABORATORIES
FORT WORTH DALLAS HOUSTON MIDLAND BEAUMONT TEXARKANA
CONSULTING, ANALYTICAL CHEMISTS
AND TESTING ENGINEERS

Fort Worth, Texas 6-15-68 File No. 458

Report of tests on Cement

To Texas Transportation Institute Date Rec'd.

Received from

Identification Marks Page Two.

CHEMICAL ANALYSIS:

Silicon Dioxide ----------- 20.26%

Aluminum Oxide ------------ 5.55%

Iron Oxide ---------------- 3.45%

Calcium Oxide ------------- 62.60%

Magnesium Oxide ----------- 2.07%

Sulfur Trioxide ----------- 2.50%

Loss on Ignition ---------- 1.60%

Insoluble Residue --------- 0.75%

3cc: Texas Transportation Institute

SOUTHWESTERN LABORATORIES

Lab. No. 26411

FORM NO. 130-B

Laboratory

Universal Atlas Cement
Division of United States Steel Corporation

Laboratory Test Report

Date Shipped 10/20/67
Cement Type I
Shipped From Waco, Texas

To: Bryco, Inc.
Attn: Mr. Moore
Box 73
Bryan, Texas 77801

Consigned To Bryco, Inc.
Car/Truck No. HEX3642
Bbl. 52.5

The data given below is average of bin from which cement was shipped.

CHEMICAL

	%
SiO_2	20.8
Al_2O_3	5.91
Fe_2O_3	2.63
CaO	65.1
MgO	1.0
SO_3	2.4
Loss On Ignition	1.5
Insoluble Residue	0.13
C_3S	56.6
C_3A	11.2

PHYSICAL

Fineness
Specific Surface — Sq. Cm./g

Wagner	1890
Blaine	3710
Soundness, Autoclave Exp. %	0.07
Time Of Setting, Hr.: Min. — Initial	2:50
Final	5:50
Air Content — %	9.2
Compressive Strength, psi — 1 Day	
3 Day	3280
7 Day	4280

This cement complies with applicable ASTM and Federal Specifications.

UAC 529 R-9-65

By C. G. Shank
C. G. Shank,Chief Chemist

Appendix C

Field Surveys

Laboratory and Field Study of Air Contents in Bridge Deck Concrete

Information gathered from laboratory and field studies of air contents in bridge deck concrete is presented in three parts. Part I presents data obtained from linear traverse measurements of entrained air in bridge deck cores. In Part II, air entrainment data obtained during bridge deck construction are given. Part III is a summary of findings and recommendations based on these surveys and past research.

PART I

Laboratory Study of Air Content in Hardened Concrete Cores

A slice approximately 1-inch thick was cut from the bridge deck surface end of each core. The bridge deck surface part of the slice was then polished on a lapping wheel until a surface suitable for microscopic observation was obtained. Approximately ¼-inch of surface material was removed from these slices before achieving a satisfactory surface. In some cases, two slices were cut from a core, the second one at a greater depth from the bridge deck surface than the first slice. Air contents of the prepared slices were determined microscopically by the linear traverse method in accordance with ASTM C457-60T. These air contents are shown on the bridge deck survey sheets contained in this appendix and are summarized in Table 1-C. Concrete design factors and physical properties of the fresh concrete in the slabs from which the cores were taken are also shown on the survey sheets.

From Table 1-C it may be noted that of the 23 bridges investigated, 10 bridge decks were designed for 4% entrained air. Of these 10 bridges, three had been open to traffic for less than 60 days at the time of survey. Of the remaining seven bridges, six had experienced some degree of surface scaling.

Cores from four of these 10 bridges were reexamined microscopically for air content at a depth of approximately 2 inches. These air contents are reported in Table 2-C. It is seen that while the average air content of the cores obtained from these four bridges was 4% at a depth of 2 inches below the bridge deck surface, it was 3.2% at ¼-inch below the bridge deck surface.

TABLE 1-C. AIR CONTENTS OF BRIDGE DECK CORES

Number of Bridge Decks Investigated	Number of Cores Obtained	Design Air Content (percent)	Average Air Content of Hardened Concrete (percent) (by ASTM C-457*)
4	13	Unknown	2.1
4	21	0	.8
2	11	3	3.4
10	35	4	2.9
1	1	4.5	2.9
1	3	6	3.1
1	7	7	3.6
TOTAL 23	91		

*Air Content at an average depth of ¼ inch below finished bridge deck surface

Table 3-C gives the air contents of cores taken from different areas of the 10 slabs. In slab number 4 of structure number 23, a variation of 2.5% was noted between cores 1 and 2.

PART II

Field Study of Air Content in Fresh Concrete

Data reported in this section were obtained by sampling fresh concrete as it was being placed in the bridge deck. Four construction jobs, indicated A, B, C, and D in Table 4-C, were surveyed in this manner. For each sample, the air content was determined in accordance with ASTM C-231 and a 3- × 4- × 16-inch prism was cast and later prepared for microscopic determination of air void parameters in accordance with ASTM C-457. A limited number of 3- × 3- × 16-inch prisms were also cast and, after 14 days moist curing, were subjected to rapid freezing and thawing as described by ASTM C-291. Table 4-C summarizes the findings of this work.

Concrete placed in Job D exhibited the highest average freeze-thaw durability factor, indicating its ability to better withstand the disruptive forces of freezing. Of the four jobs, it is also noted that the Job D concrete contained the greatest amounts of entrained air, and the smallest average spacing factor.

While the entrained air system of Job C concrete was found to have relatively small spacing factors, it may be noted that the concrete experienced rapid freeze-thaw deterioration (average durability factor of 38%).

TABLE 2-C. VARIATION OF AIR CONTENT WITH DEPTH OF SLAB

(Slabs Designed for 4% Entrained Air)

Structure Designation	Slab No. / Core No.	Air Content at an average depth of ¼ inch below finished slab (percent) (by ASTM C-457)	Air Content at an average depth of 2 inches below finished slab (percent) (by ASTM C-457)
23	4/1	2.1	7.2
	4/2	4.6	3.6
	4/3	4.0	6.0
30	5/4	2.2	3.2
	5/5	2.2	3.0
	5/6	1.3	2.2
31	1/1	2.9	4.1
	1/2	3.2	2.1
	1/3	4.0	3.6
	2/4	3.1	2.7
	2/5	4.1	5.3
32	3/1	4.3	4.5
	3/2	3.3	4.7
	3/3	3.9	3.9
	Average	3.2	4.0

This is attributed to failure of the aggregate rather than to the cement paste. Figure 1-C shows several of the Job C specimens after freeze-thaw failure.

Aggregate used in Job D concrete was a crushed limestone while that used in Jobs A, B, and C was a siliceous gravel. With the exception of Job A, all mixes were 5-sack. Concrete placed in Job A was a 6-sack mix.

Comparing the air contents of the hardened and fresh concretes, it is noted that the hardened concrete contains an average of about 1.5% less entrained air than the plastic concrete. It is further noted that the average air content of the hardened concrete obtained from Job A was 3.2% while the fresh concrete contained an average of 5.4%. However, this 2% difference in air content does not seem to have been detrimental to the air void system of Job A concrete, since the spacing factor was small enough (.0069 inches) to assure relatively high frost resistance (average durability factor of 74%).

TABLE 3-C. VARIATION OF AIR CONTENT WITHIN SLABS

(Slabs Designed for 4% Entrained Air)

Structure Designation	Slab No./ Core No.	Air Contents* (percent) (by ASTM C-457)	Variation of Air Content Within the Slab (percent)
19	1/1	2.9	1.3
	1/2	1.6	
	1/3	1.7	
	6/4	2.4	0
	6/5	2.4	
	6/6	2.3	
20	5/1	2.4	1.2
	5/2	2.5	
	5/3	1.3	
23	4/1	2.1	2.5
	4/2	4.6	
	4/3	4.0	
29	4/1	2.2	.4
	4/2	1.8	
	5/3	3.1	.5
	5/4	2.6	
30	3/1	2.9	.7
	3/2	2.4	
	3/3	2.2	
	5/4	2.2	.9
	5/5	2.2	
	5/6	1.3	
31	1/1	2.9	1.1
	1/2	3.2	
	1/3	4.0	
	2/4	3.1	1
	2/5	4.1	
32	3/1	4.3	1
	3/2	3.3	
	3/3	3.9	
	1/4	2.5	.6
	1/5	1.9	

*Air Content at an average depth of ¼ inch below finished slab surface.

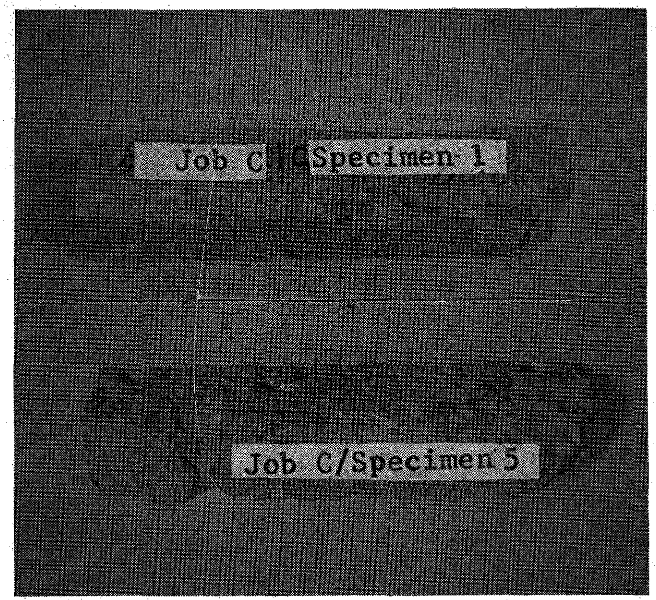

Figure 1-C. Aggregate failure in freeze-thaw specimens from Job C.

PART III

Summary of Findings and Recommendations Based on Present and Past Investigations

Findings from this study of air contents in bridge deck concrete may be summarized as follows.

1. Of the 91 core samples obtained, 67% had air contents of 3% or less at a depth of approximately ¼″ below the finished bridge deck surface. At a depth of about 2″ below the bridge deck surface, the average air content of the cores was equivalent to the designed air content of 4%.
2. Variation of air contents exist within a given slab of bridge deck concrete. The significance of this will be discussed later.
3. The fresh concrete obtained during bridge deck construction contained an average of about 30% more entrained air than the resulting hardened concrete.

Reduced air content at or near the wearing surface has been noted in several other research projects. In a study concerned with bridge deck durability, Larson[1] found that of 29 cores investigated, the air contents in the top surfaces of 18 were less than the air contents in the body of the same cores and the paste volume of the top surfaces were found to be from 16 to 126 percent higher than the paste volumes in the body of the cores. According to Larson,

> "This means that the air volume at the top surface is distributed throughout a much larger paste volume and therefore would be less effective. To demonstrate the reduction in effectiveness, the air volumes at the top of the cores were recalculated based on a paste volume equivalent to the paste volume in the main body. On this basis the air volumes determined at the top of the cores were less than those for the body in 28 of the 29 cases."

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[1] Larson, T. D., Malloy, J. J., and Prize, J. T., **Durability of Bridge Deck Concrete**, Report No. 4, Vol. I, July 1967.

TABLE 4-C. SUMMARY OF DATA OBTAINED FROM CONSTRUCTION JOB SURVEYS

Job Designation	Specimen Number	Air Content of Fresh Concrete (ASTM C-231) (%)	Air Content of Hardened Concrete (ASTM C-457) (%)	VSI Spacing Factor	Spacing Factor (ASTM C-457) (in.)	Durability Factor (ASTM C-290)
A	1	5.3	3.31	.0131	.00690	53.6
	2	5.3	2.46	.0131	.00687	77.0
	3	5.5	3.71	.0105	.00688	90.0
Average		5.4			.00688	74.0
B	1	4.4	2.98	.0193	.01067	33.0
	2	4.4	3.14	.0175	.00992	57.0
	3	3.5	2.86	.0178	.01160	16.0
	4	4.6	3.14	.0134	.01048	29.6
	5	4.3	2.89	.0175	.01153	34.0
	6	4.2	2.57	.0201	.01208	18.0
	7	4.7	3.71	.0172	.01133	23.6
Average		4.3			.0111	30.0
C	1	7.0	4.57	.0146	.00655	32.6*
	2	4.5	4.11	.0115	.00843	no specimen cast
	3	7.0	5.12	.0081	.00639	no specimen cast
	4	4.6	4.03	.0080	.00676	no specimen cast
	5	3.0	2.55	.0091	.00850	28.0*
	6	6.2	4.61	.0076	.00646	49.0*
	7	6.5	4.91	.0086	.00541	no specimen cast
	8	5.2	3.30	.0137	.00735	no specimen cast
	9	6.0	3.82	.0141	.00594	45.4*
	10	5.0	3.52	.0106	.00838	34.0*
Average		5.5			.00702	38.0
D	1	6.6	5.10	.0126	.00635	86.2
	2	6.4	3.87	.0127	.00678	88.2
	3	7.0	6.09	.0108	.00499	84.0
	4	6.2	6.72	.0091	.00523	85.0
	5	6.6	5.23	.0077	.00698	88.0
	6	6.6	6.33	.0086	.00578	no specimen cast
	7	4.5	3.35	.0141	.00909	no specimen cast
	8	6.4	4.12	.0071	.00700	no specimen cast
	9	5.5	3.68	.0110	.00649	no specimen cast
	10	5.0	2.28	.0149	.00790	no specimen cast
Average		5.27			.00666	86.1

*Aggregate failures precluded comparison of durability factors with those specimens experiencing paste failures.

Work reported by the Portland Cement Association[2] has also revealed the presence of nonuniformity in air entrainment of bridge deck slabs. The report states that

> "Nonuniformity of air entrainment was observed in two respects:
>
> a. Batch-to-batch, or possibly even within-batch, nonuniformity of air entrainment often resulted in variable resistance to scaling. Gross variations in air content from different locations on a particular deck indicate that field procedures for controlling the character of the air void system in the concrete are not yet completely satisfactory.
>
> b. An inadequate amount of entrained air at the deck surface often resulted in lowered resistance to scaling. Since the reduced amount of entrained air at the top surface of an otherwise adequately air-entrained concrete was usually associated with an increased water-cement ratio near the surface, the inference is that this condition was brought about during the finishing operation in the presence of excess water at the surface."

In an effort to eliminate a possible weak top layer of mortar, Michigan has adopted a procedure whereby structural members are built up slightly higher than the finished elevation and struck off to proper elevation when bleeding has stopped. Larson et al.,[3] feel that

> "One of the causes of overfinishing bridge decks is the requirement for smooth riding surfaces. The riding quality achieved by finishing versus the price of deterioration should be studied."

He further suggests that

"The present method of placing decks should

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[2] **Durability of Concrete Bridge Decks—A Cooperative Study—Summary, Observations and Recommendations,** Extract From Report 1, Code No. XS6514, Portland Cement Association, May 1965.

[3] **Ibid.**

> be re-evaluated. Conventional method of paving instead of the "custom" operation should be investigated to determine the feasibility of building decks in other ways."

The importance of having a sufficient quantity of entrained air in the fresh concrete is pointed out by Hilton et al.[4] Figure 2-C shows spacing factors determined from the cores of bridge deck concrete plotted as a function of the air content of the *corresponding fresh* concrete. Concerning this figure, Hilton states that

> "If concrete having a spacing factor below 0.0055 inch is accepted as unquestionably resistant, that with spacing factors between 0.0055 and 0.010 inch as borderline or variable, and that with spacing factors above 0.010 as unprotected, than an air content of 5.0 percent in the *fresh* concrete was required to insure durability. Concretes with air contents between 3.0 and 5.0 percent fall within the borderline area and those below 3.0 percent are unprotected. These field data substantiate the recent recommendation from the Portland Cement Association developed from cooperative bridge deck studies that concrete for bridge decks should contain air in the amount of 6 ± 1 percent, the lower limit being the most critical.

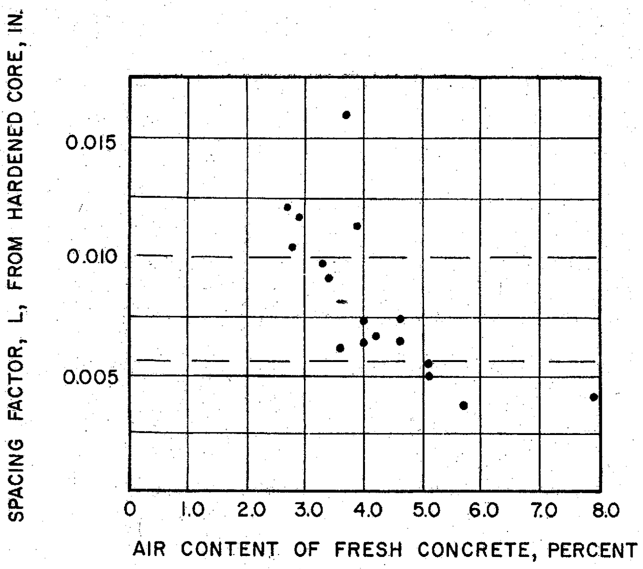

Figure 2-C. Relationship between spacing factors of hardened concrete and air contents determined on corresponding concrete.

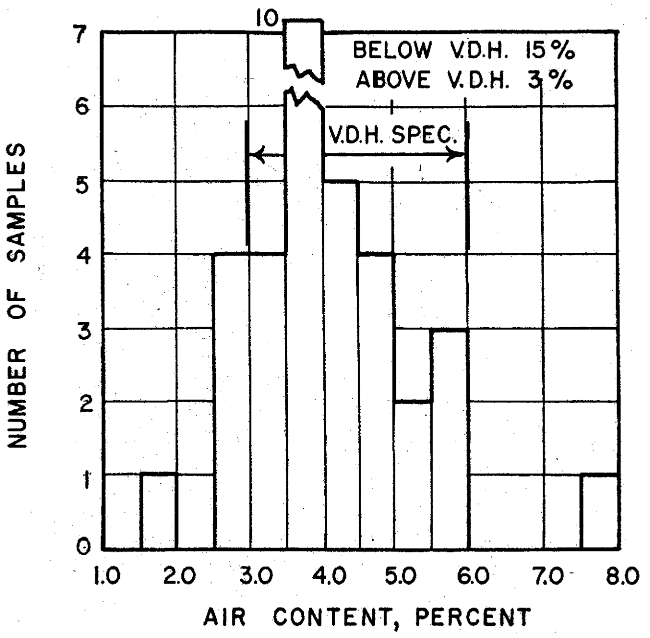

Figure 3C. Distribution of air contents measured for fresh concrete.

(Figures 2-C and 3-C taken from Reference (4).)

> In the majority of the cases studied, the poor air void characteristics are the result of a deficient amount of air entrained in the fresh concrete. Although the specification requirement existing at the time of sampling was lower than would be desirable, the problem was compounded by the tendency of the project inspectors to work to the lower limit rather than to the center or upper limit. This fact is illustrated in Figure 3-C, which presents the results of the air determination on the 34 samples from 17 projects. It will be noted that the distribution is skewed toward the low side of the range. Only one sample (3%) exceeds the upper limit while five (15%) are below the lower one. It is interesting to note that four of the five low samples were between 2.5 and 3.0 percent, reflecting the natural tendency to accept air contents which are only tenths of a percent below the required value. Twenty-four of the 34 samples (71%) are below the intended goal of the specification limits; namely 4.5 percent. Since satisfactory spacing factors were obtained for the few samples in which the air contents in the fresh concretes were above about 4.5 percent, the quality of the concrete would have been considerably improved had the goal been the middle rather than the lower limit of the specification range. The tendency to work to the lower limit is understandable when one considers the premium which is placed upon attaining high strength concrete. Things which tend to decrease the strength (such as increasing the air content) are avoided."

Data presented in Table 4-C are in agreement with Hilton's findings. It is seen that the average air content of the fresh concrete in Job B was 4.3% and the average spacing factor of the entrained air system was .0111 inches. A spacing factor this large does not provide protection against freeze-thaw deterioration. This is reflected by the average durability factor of 30% for Job B concrete.

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[4] Hilton, Marvin H., Newlon, Howard H., and Shelborne, Tilton E., "Research Relating to Bridge Decks in Virginia," Prepared for presentation to the Annual Meeting of the American Association of Highway Officials. Bridge Committee Session, October 6, 1965.

BRIDGE DECK DESIGNATION 10

DATE SLAB WAS PLACED DECEMBER 1961

Slab #	Core #	Air Content % ASTM C-457				Design Factors		Physical Properties of Fresh Concrete		General Condition of the Slabs	Comments
		depth* (in.)	% air	depth** (in.)	% air	Cement sk/cy	Air Content (%)	slump (in.)	air content (%)		
11	1	¼	.69			5	X	3	X	Severe cracking and scaling with extensive delamination.	
11	2	¼	.33			5	X	3	X		
12	3	¼	.48			5	X	3	X	Same as slab eleven.	
13	4	¼	.28			5	X	3	X		

X Information unavailable.

*Measured from the top surface of the core to the surface on which air content was determined.

**Air content determined on the surface beneath the top reinforcing steel.

BRIDGE DECK DESIGNATION 11

DATE SLAB WAS PLACED MAY 1949

Slab #	Core #	Air Content % ASTM C-457				Design Factors		Physical Properties of Fresh Concrete		General Condition of the Slabs	Comments
		depth* (in.)	% air	depth** (in.)	% air	Cement sk/cy	Air Content (%)	slump (in.)	air content (%)		
9	1	¼	3.06			5	3	2	X	Extensive cracking and scaling with moderate delamination. Leaking cracks observed on underside of bridge deck.	Weather during concrete placement was hot and dry. Air entrainment was achieved through the use of an air-entraining cement.
9	2	¼	3.63			5	3	2	X		
9	3	¼	2.79			5	3	2	X		
10	4	¼	2.04			5	3	2	X	Same as slab nine.	
10	5	¼	3.63			5	3	2	X		
10	6	¼	3.00			5	3	2	X		

X Information unavailable.

*Measured from the top surface of the core to the surface on which air content was determined.

**Air content determined on the surface beneath the top reinforcing steel.

BRIDGE DECK DESIGNATION 12

DATE SLAB WAS PLACED JUNE 1948

Slab #	Core #	Air Content % ASTM C-457				Design Factors		Physical Properties of Fresh Concrete		General Condition of the Slabs	Comments
		depth* (in.)	% air	depth** (in.)	% air	Cement sk/cy	Air Content (%)	slump (in.)	air content (%)		
2	1	¼	.85			5	0	2½	X	Minor fine cracking and shallow infrequent scaling.	Cores 1 & 2 were taken from a portion of the deck which was widened in 1956. Cores 3 & 4 were taken from the original deck. Records indicate that perhaps the concrete in the original deck contained an air-entraining cement.
1	2	¼	.70			5	0	2¼	X	Same as slab 2.	
6	3	¼	2.43			5	X	2½	X		
6	4	¼	2.25			5	X	2½	X		

X Information unavailable.

*Measured from the top surface of the core to the surface on which air content was determined.

**Air content determined on the surface beneath the top reinforcing steel.

BRIDGE DECK DESIGNATION 13

DATE SLAB WAS PLACED AUGUST 1956

Slab #	Core #	Air Content % ASTM C-457				Design Factors		Physical Properties of Fresh Concrete		General Condition of the Slabs	Comments
		depth* (in.)	% air	depth** (in.)	% air	Cement sk/cy	Air Content (%)	slump (in.)	air content (%)		
5	1	½	1.77			5	0	1¾	X	Severe cracking, scaling and delamination. Tension cracking on underside of slab was extensive.	Weather during concrete placement was warm and cloudy. Beams tested 569 psi after 6 days. Coarse aggregate used in the concrete was an uncrushed limestone and siliceous gravel.
5	2	1½	.78			5	0	1¾	X		

X Information unavailable.

*Measured from the top surface of the core to the surface on which air content was determined.

**Air content determined on the surface beneath the top reinforcing steel.

BRIDGE DECK DESIGNATION 14

DATE SLAB WAS PLACED PRIOR TO 1936

Slab #	Core #	Air Content % ASTM C-457				Design Factors		Physical Properties of Fresh Concrete		General Condition of the Slabs	Comments
		depth* (in.)	% air	depth** (in.)	% air	Cement sk/cy	Air Content (%)	slump (in.)	air content (%)		
2	1	¼	.69			X	X	X	X	There is no evidence of bridge deck deterioration.	Structure was built prior to 1936 and no construction records are available.

X Information unavailable.

*Measured from the top surface of the core to the surface on which air content was determined.

**Air content determined on the surface beneath the top reinforcing steel.

BRIDGE DECK DESIGNATION 15

DATE SLAB WAS PLACED MAY 1965

Slab #	Core #	Air Content % ASTM C-457				Design Factors		Physical Properties of Fresh Concrete		General Condition of the Slabs	Comments
		depth* (in.)	% air	depth** (in.)	% air	Cement sk/cy	Air Content (%)	slump (in.)	air content (%)		
2	1	¼	2.93			5	4.5	2	4.6	New structure open to traffic less than 60 days at time of survey.	The concrete contained Type II portland cement. An air-entrained agent and a water-reducing, set-retarding admixture were used. Air temperature was 72°.

X Information unavailable.

*Measured from the top surface of the core to the surface on which air content was determined.

**Air content determined on the surface beneath the top reinforcing steel.

BRIDGE DECK DESIGNATION 16
DATE SLAB WAS PLACED JULY 1965

Slab #	Core #	Air Content % ASTM C-457				Design Factors		Physical Properties of Fresh Concrete		General Condition of the Slabs	Comments
		depth* (in.)	% air	depth** (in.)	% air	Cement sk/cy	Air Content (%)	slump (in.)	air content (%)		
8	1	¼	4.79			5	4	3	4.5	New structure open less than 60 days at time of survey.	The concrete contained Type II portland cement, an air-entraining agent and a water-reducing, set-retarding admixture were used. Temperatures between 84-88° were recorded during placement of slab concrete. After 7 days curing, beams and cylinders tested 700 psi and 4530 psi respectively.

X Information unavailable.
*Measured from the top surface of the core to the surface on which air content was determined.
**Air content determined on the surface beneath the top reinforcing steel.

BRIDGE DECK DESIGNATION 17
DATE SLAB WAS PLACED APRIL 1965

Slab #	Core #	Air Content % ASTM C-457				Design Factors		Physical Properties of Fresh Concrete		General Condition of the Slabs	Comments
		depth* (in.)	% air	depth** (in.)	% air	Cement sk/cy	Air Content (%)	slump (in.)	air content (%)		
4	1	¼	5.83			5	4	2¾	3.6	New structure open to traffic less than 60 days.	The concrete contained a Type II portland cement. An air-entraining agent and a water-reducing, set-retarding admixture were used. Temperatures during placement of the slab concrete ranged from 53-59°. After 7 days curing, beams and cylinders tested 787 psi and 3852 psi respectively.

X Information unavailable.
*Measured from the top surface of the core to the surface on which air content was determined.
**Air content determined on the surface beneath the top reinforcing steel.

BRIDGE DECK DESIGNATION 18

DATE SLAB WAS PLACED MARCH 1965

Slab #	Core #	Air Content % ASTM C-457				Design Factors		Physical Properties of Fresh Concrete		General Condition of the Slabs	Comments
		depth* (in.)	% air	depth** (in.)	% air	Cement sk/cy	Air Content (%)	slump (in.)	air content (%)		
4	1	¼	6.07			5	4	3	3.8	New structure open to traffic less than 60 days at time of survey.	The concrete contained a Type II portland cement. An air-entraining agent and a water-reducing, set-retarding admixture were used. Temperatures during placement of slab concrete ranged from 50° - 52°. After 7 days curing, beams and cylinders tested 787 psi and 3852 psi, respectively.

X Information unavailable.

*Measured from the top surface of the core to the surface on which air content was determined.

**Air content determined on the surface beneath the top reinforcing steel.

BRIDGE DECK DESIGNATION 19

DATE SLAB WAS PLACED AUGUST 1963

Slab #	Core #	Air Content % ASTM C-457				Design Factors		Physical Properties of Fresh Concrete		General Condition of the Slabs	Comments
		depth* (in.)	% air	depth** (in.)	% air	Cement sk/cy	Air Content (%)	slump (in.)	air content (%)		
1	1	¼	2.93			5	4	2¾	4.2	Minor transverse cracking and scaling with minor map cracking.	Weather during pouring was generally hot and dry with temperatures ranging from 67° - 94° F and relative humidities from 29% to 81%. Aggregate used was a partially crushed limestone with siliceous sand and gravel. An air-entraining agent and a water-reducing, set-retarding admixture were used. Air contents on slab 1 ranged from 3.6% to 5.3% and slumps ranged from 2¼" to 3". The average air content was 4.2% and the average slump was 2¾". On slab 6, air contents and slumps ranged from 2.8% to 3.3% and 2¾" to 3" respectively. 18 sets of beams were cast during construction of the entire deck. At 7 days, 1 set tested at 480 psi. The average strength of the remaining 17 sets 622 psi.
1	2	¼	1.57			5	4	2¾	4.2		
1	3	¼	1.71			5	4	2¾	4.2		
6	4	¼	2.42			5	4	2¾	3.0	Map cracking more noticeable than on other slabs in the structure. Some minor transverse cracking.	
6	5	¼	2.41			5	4	2¾	3.0		
6	6	¼	2.25			5	4	2¾	3.0		

X Information unavailable.

*Measured from the top surface of the core to the surface on which air content was determined.

**Air content determined on the surface beneath the top reinforcing steel.

BRIDGE DECK DESIGNATION 20
DATE SLAB WAS PLACED OCTOBER 1964

Slab #	Core #	Air Content % ASTM C-457				Design Factors		Physical Properties of Fresh Concrete		General Condition of the Slabs	Comments
		depth* (in.)	% air	depth** (in.)	% air	Cement sk/cy	Air Content (%)	slump (in.)	air content (%)		
5	1	¼	2.42			5	4	3	3.6	Transverse cracking on this slab was more severe than on other slabs in the structure. All slabs had minor scaling and minor to moderate transverse cracking.	Weather during concrete placement was cool and humid. An air-entraining agent and a water-reducing, set-retarding admixture were used in the concrete. Seven day beam strength was 595 psi.
5	2	¼	2.52			5	4	3	3.6		
5	3	¼	1.27			5	4	3	3.6		

X Information unavailable.
*Measured from the top surface of the core to the surface on which air content was determined.
**Air content determined on the surface beneath the top reinforcing steel.

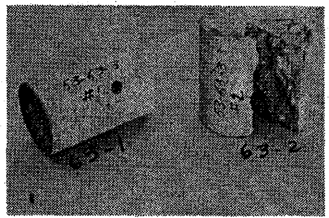
BRIDGE DECK DESIGNATION 21
DATE SLAB WAS PLACED SEPTEMBER 1950

Slab #	Core #	Air Content % ASTM C-457				Design Factors		Physical Properties of Fresh Concrete		General Condition of the Slabs	Comments
		depth* (in.)	% air	depth** (in.)	% air	Cement sk/cy	Air Content (%)	slump (in.)	air content (%)		
2	1	¼	3.59			5½	7	X	X	Minor diagonal cracking with some cracks showing leakage of salt water through the deck. Minor scaling and map cracking. 7-day beam strength for slab 2 was 544.	Air entrainment was achieved using an air-entraining cement. Because of low beam breaks, the cement factor was changed from 5 sk/cy to 5½ sk/cy and a crushed limestone aggregate was used in place of a siliceous aggregate. Low beam strength continued and the cement factor was increased to 6 sk/cy without appreciable increase in beam strength. The fine aggregate source was changed near the completion of concrete pouring, because salt began appearing on the surface as a result of washing the aggregate in salty water.
2	2	¼	2.86			5½	7	X	X		
2	3	¼	3.08			5½	7	X	X		
11	4	¼	3.99			5½	7	X	X	Minor diagonal cracking with some cracks showing leakage of salt water through the deck. Minor scaling and map cracking.	
11	5	¼	3.02			5½	7	X	X		
11	6	¼	4.01			5½	7	X	X		
23	7	¼	4.28			5	7	X	X	Minor map cracking and very minor scaling. 7-day beam strength for slab 23 was 420 psi.	

X Information unavailable.
*Measured from the top surface of the core to the surface on which air content was determined.
**Air content determined on the surface beneath the top reinforcing steel.

BRIDGE DECK DESIGNATION 22

DATE SLAB WAS PLACED MARCH 1964

Slab #	Core #	Air Content % ASTM C-457				Design Factors		Physical Properties of Fresh Concrete		General Condition of the Slabs	Comments
		depth* (in.)	% air	depth** (in.)	% air	Cement sk/cy	Air Content (%)	slump (in.)	air content (%)		
8	1	½	3.06			5½	6	2½	5.4	Minor transverse cracking with some cracks showing salt water leakage on the underside of the minor scaling.	Weather during pouring was generally cool and dry. Measured air contents of concrete ranged from 4.8% to 6.5% with average being 5.4%. A transverse crack extended across core #2. Upon removing the core, it separated into two pieces. The core is shown in Figure 1.1 and it is seen that this transverse crack penetrated the core to the bottom reinforcement of the bridge deck. 7-day beam strength was 620 psi on slab 1. 7-day beam strength was 637 psi on slab 2.  FIGURE 1.1
8	2	½	2.14			5½	6	2½	5.4		
9	3	½	4.08			5½	6	2⅓	5.4	Moderate transverse cracking with cracks showing salt water leakage on underside of deck. Isolated areas of scaling.	

X Information unavailable.

*Measured from the top surface of the core to the surface on which air content was determined.

**Air content determined on the surface beneath the top reinforcing steel.

BRIDGE DECK DESIGNATION 23

DATE SLAB WAS PLACED JULY 1965

Slab #	Core #	Air Content % ASTM C-457				Design Factors		Physical Properties of Fresh Concrete		General Condition of the Slabs	Comments
		depth* (in.)	% air	depth** (in.)	% air	Cement sk/cy	Air Content (%)	slump (in.)	air content (%)		
4	1	¼	2.08	3½	7.17	6	4	3	5	Slab showed only minor transverse cracking. There was no scaling on this slab.	Weather during concrete placement was generally hot and dry. An air-entraining agent and a set-retarding, water-reducing admixture were used in the concrete. Air content and slump of the concrete used in slab 4 ranged from 2.3% to 6.8% and 1¾″ to 3¾″, respectively. The average air content and slump was 5% and 3″, respectively.
4	2	¼	4.55	3	3.64	6	4	3	5		
4	3	¼	3.95	3	5.98	6	4	3	5		

X Information unavailable.

*Measured from the top surface of the core to the surface on which air content was determined.

**Air content determined on the surface beneath the top reinforcing steel.

BRIDGE DECK DESIGNATION 24

DATE SLAB WAS PLACED MAY 1967

Slab #	Core #	Air Content % ASTM C-457				Design Factors		Physical Properties of Fresh Concrete		General Condition of the Slabs	Comments
		depth* (in.)	% air	depth** (in.)	% air	Cement sk/cy	Air Content (%)	slump (in.)	air content (%)		
3	1	⅜	.39			5	0	X	X	Minor transverse cracking and scaling.	
3	2	⅜	2.79			5	0	X	X		
3	3	⅜	.79			5	0	X	X		
4	4	⅜	.69	2½	2.04	5	0	X	X	Extensive transverse cracking and scaling.	
4	5	⅜	.48	2½	2.66	5	0	X	X		
4	6	⅜	.71	2½	1.97	5	0	X	X		

X Information unavailable.

*Measured from the top surface of the core to the surface on which air content was determined.

**Air content determined on the surface beneath the top reinforcing steel.

BRIDGE DECK DESIGNATION 25

DATE SLAB WAS PLACED MAY 1962

Slab #	Core #	Air Content % ASTM C-457				Design Factors		Physical Properties of Fresh Concrete		General Condition of the Slabs	Comments
		depth* (in.)	% air	depth** (in.)	% air	Cement sk/cy	Air Content (%)	slump (in.)	air content (%)		
4	1	¼	2.71			5	X	X	4.9	No evidence of deterioration on this slab. 7-day beam strength was 555 psi.	An air-entraining agent and a water-reducing, set-retarding admixture were used in the concrete placed in slabs 4 and 7. Only the air-entraining agent was used in concrete placed in slabs 8 and 9. Weather during concrete placement was generally cloudy and warm. Most of the scaling was in the wheel paths.
7	2	¼	3.71			5	X	X	4.6	Minor scaling. 7-day beam strength was 620 psi.	
8	3	¼	4.23			5	X	X	3.2	No evidence of deterioration on this slab. 7-day beam strength was 545 psi.	
9	4	¼	3.37			5	X	X	4.2	Minor scaling. 7-day beam strength was 550 psi.	
9	5	¼	2.32			5	X	X	4.2		
9	6	¼	3.18			5	X	X	4.2		

X Information unavailable.

*Measured from the top surface of the core to the surface on which air content was determined.

**Air content determined on the surface beneath the top reinforcing steel.

BRIDGE DECK DESIGNATION 26
DATE SLAB WAS PLACED MAY 1948

Slab #	Core #	Air Content % ASTM C-457				Design Factors		Physical Properties of Fresh Concrete		General Condition of the Slabs	Comments
		depth* (in.)	% air	depth** (in.)	% air	Cement sk/cy	Air Content (%)	slump (in.)	air content (%)		
2	1	¼	2.15			5	3	1¼	2.8	Minor transverse and map cracking with minor scaling. 7-day beam strength was 640 psi.	The concrete used in this bridge deck was pumped from the mixer to the deck and deposited in a shopper. It was then taken from the hopper to the pour by buggy. Considerable difficulty was encountered in maintaining proper slump and air content through the pump lines. Air contents and slumps at the mixer were 4% and 2″, respectively. The measurements after pumping the concrete to the deck were 2¾% and 1″, respectively. The length of the pump line ranged from 100 ft for slab 2 to 240 ft for slab 9. Several delays were encountered during the screening and finishing of concrete in slab 2 because of rain. The water factor was increased from 6½ gal/sk to 6¾ gal/sk for concrete placed in slab 6. This increase did not produce the desired increase in slump, and for concrete placed in slab 8 the factor was increased to 7 gal/sk and no air-entraining agent was used. This resulted in a 2¾″ slump. For concrete placed in slab 9, the water factor was 7 gal/sk and the dosage of air entraining agent previously used was doubled. This produced the desired slump of 3″ after pumping through the 240 ft line. The weather conditions during pouring were generally hot with temperatures between 85° and 95°.
3	2	¼	5.29			5	3	2	3.4	Moderate transverse and map cracking with minor scaling. 7-day beam strength was 670 psi.	
5	3	¼	5.30			5	3	1½	3.5	Minor transverse and map cracking with minor scaling. 7-day beam strength was 640 psi.	
6	4	¼	.94			5	3	2⅛	3.6	Moderate transverse and map cracking with minor scaling. 7-day beam strength was 610 psi.	
8	5	¼	.81			5	0	2¾	X	Minor transverse and map cracking with extensive scaling to a depth of ¼″. 3-day beam strength was 600 psi.	
9	6	¼	5.84			5	3	3	4.3	Minor transverse and map cracking with minor scaling. 7-day beam strength was 580 psi.	

X Information unavailable.
*Measured from the top surface of the core to the surface on which air content was determined.
**Air content determined on the surface beneath the top reinforcing steel.

BRIDGE DECK DESIGNATION 27

DATE SLAB WAS PLACED JULY 1958

Slab #	Core #	Air Content % ASTM C-457				Design Factors		Physical Properties of Fresh Concrete		General Condition of the Slabs	Comments
		depth* (in.)	% air	depth** (in.)	% air	Cement sk/cy	Air Content (%)	slump (in)	air content (%)		
3	1	¼	.66			X	0	X	X	Large areas of delamination moderately spaced. 7-day beam strength was 606 psi.	Weather during placement varied from cloudy and warm to clear and hot.
3	2	¼	.56			X	0	X	X		
4	3	¼	.74			X	0	X	X	This slab was superior to all others on the deck and only minor wear was observed. 7-day beam strength was 658 psi.	
4	4	¼	.81			X	0	X	X		

X Information unavailable.
*Measured from the top surface of the core to the surface on which air content was determined.
**Air content determined on the surface beneath the top reinforcing steel.

BRIDGE DECK DESIGNATION 28

DATE SLAB WAS PLACED JULY 1955

Slab #	Core #	Air Content % ASTM C-457				Design Factors		Physical Properties of Fresh Concrete		General Condition of the Slabs	Comments
		depth* (in.)	% air	depth** (in.)	% air	Cement sk/cy	Air Content (%)	slump (in.)	air content (%)		
10	1	¼	.78	2	1.7	5	0	X	X	The condition of this slab was superior to all others on the deck and only minor wear was observed. 7-day beam strength was 632 psi.	
10	2	¼	.25	1	4.45	5	0	X	X		
10	3	¼	.33	1	.99	5	0	X	X		
15	4	¼	.62	1	.99	5	0	X	X	Large areas of delamination closely spaced. Damaged beams tested 453 psi at 7 days.	
15	5	¼	.33	1	1.28	5	0	X	X		
15	6	¼	1.49	1	1.30	5	0	X	X		

X Information unavailable.
*Measured from the top surface of the core to the surface on which air content was determined.
**Air content determined on the surface beneath the top reinforcing steel.

BRIDGE DECK DESIGNATION 29
DATE SLAB WAS PLACED JULY 1958

Slab #	Core #	Air Content % ASTM C-457				Design Factors		Physical Properties of Fresh Concrete		General Condition of the Slabs	Comments
		depth* (in.)	% air	depth** (in.)	% air	Cement sk/cy	Air Content (%)	slump (in.)	air content (%)		
4	1	¼	2.22			5	4	2	4.2	Moderate transverse cracking with very minor scaling. 7-day beam strength was 490 psi.	Following completion of pouring operations on slab 4, rainfall during the night amounted to .4″. A membrane curing compound was used.
4	2	¼	1.84			5	4	2	4.2		
5	3	¼	3.07			5	4	2½	3.2	Moderate transverse and diagonal cracking, with extensive scaling to a depth of 1 inch. Small areas of delamination. 7-day beam strength was 550 psi.	Weather during construction was hot with a temperature of 92° being recorded during the pouring of slab 5.
5	4	¼	2.64			5	4	2½	3.2		

X Information unavailable.

*Measured from the top surface of the core to the surface on which air content was determined.

**Air content determined on the surface beneath the top reinforcing steel.

BRIDGE DECK DESIGNATION 30
DATE SLAB WAS PLACED AUGUST 1960

Slab #	Core #	Air Content % ASTM C-457				Design Factors		Physical Properties of Fresh Concrete		General Condition of the Slabs	Comments
		depth* (in.)	% air	depth** (in.)	% air	Cement sk/cy	Air Content (%)	slump (in.)	air content (%)		
3	1	½	2.91			5.5	4	X	X	Minor scaling with small areas of delamination.	With the exception of slab 3, the bridge deck showed extensive delamination and severe cracking. Delamination of the concrete in slab 5 is evident from cores shown in Figure 1.2.
3	2	½	2.41			5.5	4	X	X		
3	3	½	2.20			5.5	4	X	X		
5	4	½	2.20	1	3.23	5.5	4	X	X	Moderate transverse and map cracking with extensive scaling to a depth of 1 inch. Delamination in large, moderately spaced areas.	
5	5	½	2.19	2⅓	3.00	5.5	4	X	X		 FIGURE 1.2
5	6	½	1.25	2¼	2.24	5.5	4	X	X		

X Information unavailable.

*Measured from the top surface of the core to the surface on which air content was determined.

**Air content determined on the surface beneath the top reinforcing steel.

BRIDGE DECK DESIGNATION 31

DATE SLAB WAS PLACED MAY 1962

		% ASTM C-457 Air Content				Design Factors		Physical Properties of Fresh Concrete			
Slab #	Core #	depth* (in.)	% air	depth** (in.)	% air	Cement sk/cy	Air Content (%)	slump (in.)	air content (%)	General Condition of the Slabs	Comments
1	1	¼	2.91	1	4.13	5	4	X	4	Minor transverse cracking and scaling. Large isolated areas of delamination. 7-day beam strength was 525 psi.	Delamination of the concrete in slab 1 is evident from cores 2 and 3 shown in Figure 1.3. The reinforcing steel seen in Core 3 was corroded, apparently a result of salt water leakage along the delaminated surface.
1	2	¼	3.21	1	2.12	5	4	X	4		
1	3	¼	3.99	1¼	3.61	5	4	X	4		
2	4	¼	3.12	1	2.70	5	4	X	4	Minor transverse cracking and scaling. Moderate map cracking. 7-day beam strength was 417 psi.	 FIGURE 1.3
2	5	¼	4.07	2	5.27	5	4	X	4		

X Information unavailable.

*Measured from the top surface of the core to the surface on which air content was determined.

**Air content determined on the surface beneath the top reinforcing steel.

BRIDGE DECK DESIGNATION 32

DATE SLAB WAS PLACED OCTOBER 1961

Slab #	Core #	Air Content % ASTM C-457				Design Factors		Physical Properties of Fresh Concrete		General Condition of the Slabs	Comments
		depth* (in.)	% air	depth** (in.)	% air	Cement sk/cy	Air Content (%)	slump (in.)	air content (%)		
3	1	¼	4.28	1¾	4.54	5	4	3½	3.9	Minor transverse cracking with Moderate scaling to a depth of ¼″. Areas of delamination moderately spaced. 7-day beam strength was 519 psi.	Delamination of concrete in slab 3 is evident from Figure 1.4. Apparently, steel corrosion shown in Figure 1.4 has occurred as a result of salt water leakage along the delaminated surface.  FIGURE 1.4
3	2	¼	3.30	1¾	4.73	5	4	3½	3.9		
3	3	¼	3.92	1¾	3.89	5	4	3½	3.9		
1	4	¼	2.48			5	4	3	4.0	Some minor transverse cracking and scaling. 7-day beam strength was 517 psi.	
1	5	¼	1.89			5	4	3	4.0		

X Information unavailable.
*Measured from the top surface of the core to the surface on which air content was determined.
**Air content determined on the surface beneath the top reinforcing steel.

Appendix D

Test Procedure for the Void Spacing Indicator

VOID SPACING FACTOR OF FRESH CONCRETE

Equipment: Planimeter and equipment as shown in Figure D-1.

Procedure:

1. Using a small spatula as shown in Figure D-1, or the blade of a pocket knife, mortar is taken from the concrete and placed in the brass cup. Care should be taken to exclude aggregate particles larger than about ⅛″ in diameter.

Fill the brass cup in two layers and rod each layer 20 times with a wire rod approximately 6 inches long and .05 inch in diameter. A straightened 2-inch size paper clip is ideal for this purpose.

After the second layer is rodded, strike off excess mortar even with the top of the cup.

2. Completely fill the container with distilled water and free any air bubbles adhering to the glass surfaces. Insert the cup and stopper into the filled container taking care that no air is introduced.

3. Secure the cup and stopper in the container by advancing the screw shown in Figure D-1 until contact is made with the rubber stopper; then, advance the screw one additional turn.

4. When the cup is first inserted in the container, very few air bubbles escape from the mortar. It is possible at this time to determine if air has inadvertently been introduced by inverting the container and observing the glass plate.

5. With the container held at an angle of about 60° to horizontal, rotate it as shown in Figure D-2 until the mortar dislodges from the cup. After the mortar is dislodged, gently rotate the container from a vertical to horizontal position several times to disperse the mortar in the distilled water.

6. After the mortar is dispersed in the distilled water, invert the container allowing the air bubbles to rise and collect on the glass plate.

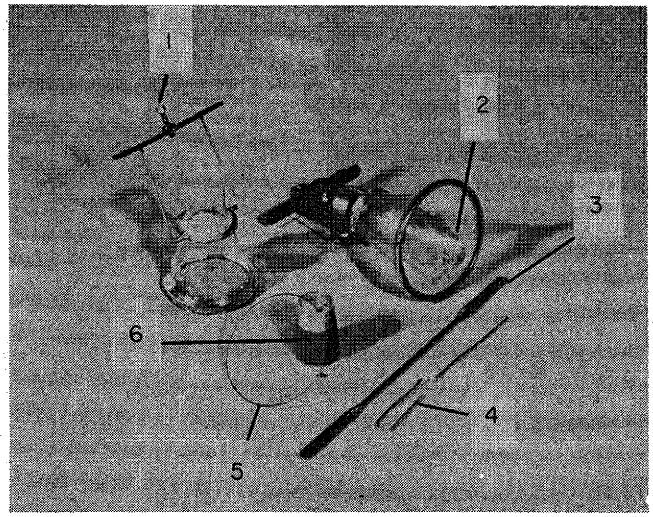


Figure D-1. Apparatus used in determining the void spacing factor in fresh concrete: (1) Screw; (2) Glass plate; (3) Spatula; (4) Paper clip; (5) Transparent disc; (6) Brass cup with rubber stopper.

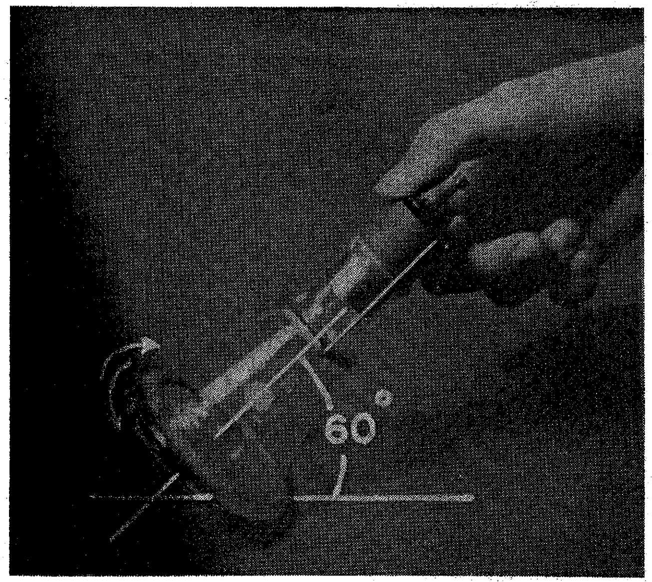
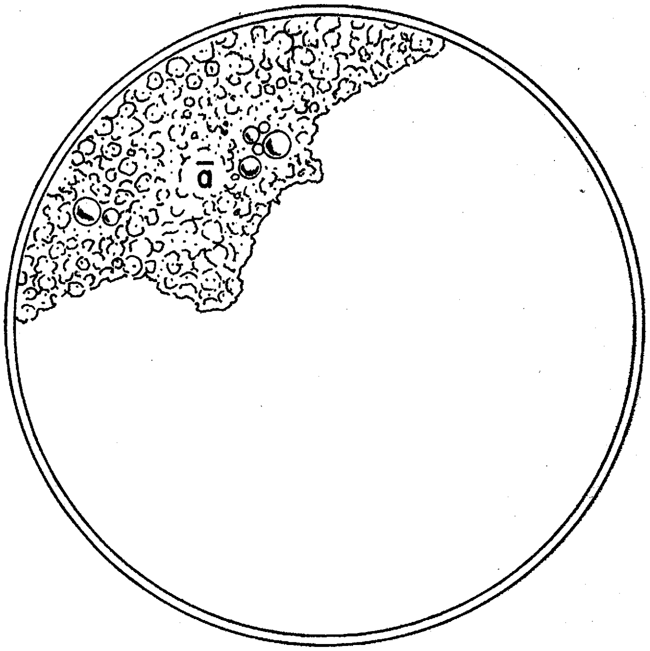


Figure D-2. Dislodging mortar from brass cup.

7. Tip the container such that the glass plate makes an angle of about 15° to the horizontal. This causes the bubbles to arrange themselves in a closely packed condition as shown diagrammatically in Figure D-3.

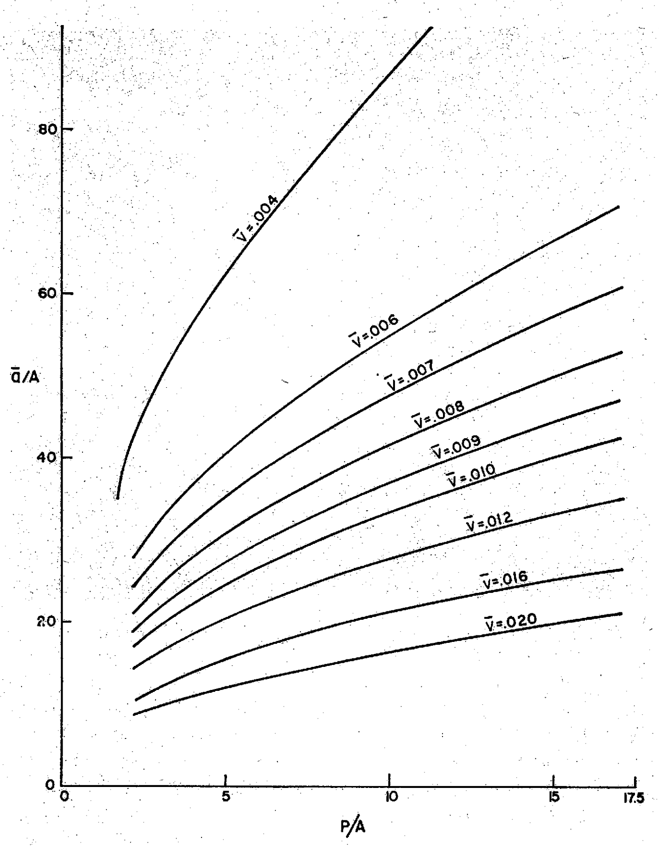
8. With the glass plate in a horizontal position, gently tap the container to arrange the bubbles in one layer against the glass plate.

9. Place the transparent disc shown in Figure D-1 on the glass plate and outline the area covered by bubbles. Trace the outlined area illustrated diagrammatically in Figure D-3 with a planimeter to determine $\bar{a}$.



DIAGRAMMATICAL SKETCH SHOWING AREA OF GLASS PLATE COVERED BY BUBBLES

Figure D-3.



GRAPHICAL DETERMINATION OF $\bar{V}$

Figure D-4.

10. Determination of V from Equation 3* can be simplified by use of Figure D-4. Locate a horizontal line at the value of $\bar{a}/A$ and a vertical line at the value of P/A. The intersection of these two lines gives the value of $\bar{V}$.

11. If the value of P/A is not given in Figure D-4, then use Equation 3* to determine $\bar{V}$.

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*As given in Report 103-3, "Preliminary Report on the Void Spacing Indicator."