# Field and Laboratory Air-Content Studies of Salt-Damaged Concrete Structures

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A paper dealing with the first phase of "A Survey of Air-Entrained Structures in Illinois" was published in HRB Bulletin 323. Data obtained during the second phase of that survey are presented. To determine the uniformity and effectiveness of air entrainment, and the extent of damage to air-entrained concrete bridges attributable to the action of salt, an investigation of all structures constructed in Illinois with air-entrained concrete was started in 1960.

Of the 879 bridges surveyed, 503 were studied in some detail and 67 were given a thorough investigation, including drilling of cores for air-content studies. The adequacy of the entrained air and preventative measures and treatments are discussed.

•DURING 1960 an investigation was undertaken in Illinois to determine the extent of concrete disintegration on structures that was caused by salt and to determine the air content of the concrete in these structures. The physical survey of these structures included not only the concrete deterioration attributable to the application of chloride salts for ice removal but also all cracks, popouts, and pitting, even though air entrainment might have no direct bearing on these. The use of air entrainment became mandatory in Illinois in 1947. Inasmuch as this survey was primarily to learn how effective air entrainment has been, the structures studied were those built between 1947 to 1959.

This study of surface disintegration on structures due to salt had three main objectives: (a) to ascertain whether air entrainment does not impart adequate resistance to scaling, (b) to determine whether concrete placed in structures always contains adequate entrained air, and (c) to determine the need for other preventive measures or treatments.

The field survey of the structures included all types of distress. The scope of this paper, however, is limited to an analysis of the apparent damage resulting from salt applications and how this is influenced by the air content of the concrete.

## FIELD OBSERVATIONS

### Original Survey

During the fall, winter, and early spring of 1960 and 1961 a complete physical survey was made on 879 concrete structures. The data included ratings as to the degree of scaling, aggregate popouts, surface pitting, hairline cracks, larger cracks and leaching. The study was done separately for deck, gutter, hubguard, and sidewalk. Also included were certain construction information and sources of materials.

Of the 879 bridges reported, 376 had undergone since original construction some sort of modification, including widening and the addition of a bituminous surface. These structures are referred to as modified bridges, whereas the remaining 503 structures are designated as original bridges. Only this latter group is considered herein.

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As an example of the degree of scaling in the deck, 5 percent had light scaling, 3 percent had medium scaling, 4 percent had heavy scaling, and 1 percent was classified as threatening structural failure. The degree of scaling in the gutter, hubguard, and sidewalk was similar to that in the deck.

### Second Survey

During the early part of 1962 a second survey of 67 of the original structures was made by a team of engineers from the Illinois Bureaus of Construction, Design, Maintenance, Materials, and Research and Planning. The structures selected were distributed throughout the State with approximately seven structures to each of the ten highway districts.

On each of these structures, locations were pinpointed for the drilling of 2-in. diam cores for air-content determinations. The cores, approximately 4 in. long, were drilled from scaled and unscaled areas of the deck, gutter area, and sidewalk.

## LABORATORY TESTS

### Method of Air Determination

A high-pressure air meter was used to determine the air content of the cores. This meter operates on the same principle as that used for determining the air content of concrete in the plastic state. The major difference is that 15 psi pressure is used for the test of concrete in the plastic state, whereas 5,000 psi pressure is utilized when determining the air content of hardened concrete. The accuracy of this meter has been verified several times since it was built in 1953.

### Pavement Cores

The high-pressure meter has been used in approximately one-third of the 8,094 routine air tests made on 4-in. diam pavement cores between 1954 and 1961. The average air content of these cores is 3.7 percent, whereas 62,107 air tests in the field on the plastic concrete from the same jobs gave an average air content of 4.3 percent. Most of the 0.6 percent differential is probably due to loss of air during surface vibration of the concrete. Various field tests have shown approximately 0.5 percent loss by tests of the plastic concrete before and after such surface vibration.

### Structure Cores

From the 67 structures, 604 2-in. diam cores were drilled and tested in a high-pressure meter of the same design as, but smaller than, that used for the 4-in. pavement cores. A summary of these data is given in Table 1.

TABLE 1

AVERAGE RESULTS[a] OF AIR CONTENT DETERMINATIONS

| District | Average Air Content of Cores (%) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Deck | | Gutter | | Sidewalk | | Over-All Average | |
| | Scaled | Unscaled | Scaled | Unscaled | Scaled | Unscaled | Scaled | Unscaled |
| 1 | 1.7(20) | 3.5(33) | 1.5(5) | 4.2(11) | 2.2(5) | 3.5(13) | 1.8(30) | 3.6(57) |
| 2 | 1.7(11) | 1.6(20) | 1.0(12) | 3.2(11) | 0.1(10) | 0.8(14) | 1.0(33) | 1.7(45) |
| 3 | 1.4(5) | 2.1(25) | 1.1(15) | 1.8(5) | 0.6(8) | 1.7(11) | 1.0(28) | 2.0(41) |
| 4 | 3.9(14) | 3.8(26) | 2.2(2) | 3.3(3) | 1.0(6) | 2.8(11) | 2.9(22) | 3.5(40) |
| 5 | 0.4(4) | 2.9(18) | - | 2.2(1) | 1.4(7) | 2.6(2) | 1.0(11) | 2.8(21) |
| 6 | 1.1(7) | 2.0(11) | 0.0(3) | 1.5(2) | 1.3(6) | 1.5(7) | 1.0(16) | 1.7(20) |
| 7 | 2.4(6) | 2.8(15) | 1.7(2) | 2.1(4) | 2.7(5) | 2.9(17) | 2.4(13) | 2.8(36) |
| 8 | 1.9(8) | 2.8(24) | 4.8(6) | 2.3(4) | 3.2(11) | 3.2(16) | 3.2(25) | 2.9(44) |
| 9 | 2.6(7) | 2.7(24) | 2.0(9) | 3.4(4) | 2.4(4) | - | 2.3(20) | 2.8(28) |
| 10 | 1.7(27) | 2.1(28) | 0.2(2) | 1.9(8) | 1.2(4) | 1.5(5) | 1.5(33) | 2.0(41) |
| Avg. | 2.0(109) | 2.7(224) | 1.6(56) | 2.9(53) | 1.6(66) | 2.3(96) | 1.8(231) | 2.6(373) |

[a] Figures in parentheses are number of cores tested.

To verify test procedures, laboratory control specimens were tested with the field cores. Five batches each of crushed stone concrete and gravel concrete were mixed and 6- by 6- by 30-in. test beams were cast. The air contents were varied from 0.2 to 6.5 percent. Two-inch and 4-in. cores were drilled from the beams and air contents were determined by the high-pressure meter. The average of ten determinations on the concrete in plastic state was 2.8 percent. Seventy-eight tests on 2-in. cores gave an average air content of 2.6 percent and 40 tests on 4-in. cores gave an average air content of 2.8 percent. Inasmuch as these tests were intermingled with the 604 tests made on the structure cores, it is believed that the results of the air tests on the structure cores are fairly accurate. There is a slight indication that the 2-in. cores may give results a couple of tenths or so less than the 4-in. cores. The results of these tests are given in Table 2.

The over-all average air contents of 1.8 and 2.6 percent (Table 1) for the scaled and unscaled areas of the structures are entirely too low to provide the adequate protection against salt damage expected of air-entrained concrete. The large proportion of cores with low air contents indicates inadequate control of truck loads of concrete. There is no doubt that a considerable number of truck loads of non-air-entrained concrete were placed in these structures. Also, a considerable loss of entrained air may have taken place at certain locations due to excessive internal vibration.

One disconcerting part of the data was that some cores that were drilled from scaled areas showed adequate air entrainment. This condition is quite different that that found in pavement concrete where practically no scaling is found on pavements containing adequate entrained air. Due to various conditions it is impossible to establish an exact percentage of entrained air below which protection will always be inadequate and above which protection will always be sufficient. The percentage may be somewhere between 2.5 and 3.0. For adequate protection, however, the percentage of remaining entrained air should be greater than 4 percent.

## Sprinkling of Concrete Surface

One factor that might make spots of scaling on air-entrained concrete more prevalent on structures is the greater use of water sprinkled on the surface of the concrete to facilitate finishing operations. To study the effect that this practice has on the surface of the concrete, an investigation of the problem was made on slabs cast outside the laboratory. A truck load of ready-mixed concrete that was going to a structure was diverted past the laboratory so that four 24- by 48- by 4-in. slabs could be cast. The concrete was given internal vibration and was struck off by a vibrating screed. The slabs were finished similar to a bridge deck, except that one slab had no water sprinkled on it, whereas the other three had various amounts sprinkled on them with a calcimine brush. This sprinkling took place after the initial strike off and before the final surface finishing. If the water penetrates the concrete to a depth of ⅛-in., which is a reasonable assumption, the surface concrete would have the water-cement ratio increased 1¼ gal/bag of cement by one light swish of the brush. The three slabs were treated so that each unit area had the equivalent of one light stroke of the brush, three light strokes of the brush, and two heavier strokes, respectively. Therefore, the first treated slab had 1¼ gal of water added, the second had 3¾, and the third about 5 gal/bag of cement. There is no doubt but that some of this water evaporated.

TABLE 2

RESULTS OF AIR CONTENT DETERMINATIONS ON LABORATORY CONCRETE IN PLASTIC AND HARDENED STATE

| Core Size (in.) | Average Air Content (%) | | | |
|---|---|---|---|---|
| | Gravel Aggregate | | Crushed Stone Aggregate | |
| | Hardened Concrete | Plastic Concrete | Hardened Concrete | Plastic Concrete |
| 2 × 6 | 0.2 | 0.2 | 0.4 | 0.4 |
| 4 × 6 | 0.2 | | 0.6 | |
| 2 × 6 | 1.4 | 1.4 | 1.8 | 1.3 |
| 4 × 6 | 1.4 | | 1.4 | |
| 2 × 6 | 1.8 | 2.3 | 2.8 | 2.7 |
| 4 × 6 | 1.8 | | 2.8 | |
| 2 × 6 | 3.0 | 3.6 | 4.4 | 4.4 |
| 4 × 6 | 3.3 | | 4.6 | |
| 2 × 6 | 4.2 | 5.0 | 6.4 | 6.5 |
| 4 × 6 | 5.2 | | 6.9 | |

After curing for 14 days, surface tension tests were made to determine strengths. This was accomplished by gluing 2-in. diam pipe caps to the surface of the concrete with an epoxy and then pulling the caps from the surface. The load, determined by a dynamometer, was converted to pounds per square inch tension to indicate the strength of the concrete surface. There were 14 or more tension tests made on each of the four slabs. The control surface, where no water was sprinkled, gave a strength of 280 psi. The surface of the second slab, where water was sprinkled with one light stroke of the brush, also gave the same 280 psi strength. The third slab, where water was sprinkled with three light strokes of the brush, gave a strength of 210 psi. The fourth slab, which had the water sprinkled on with two heavy strokes of the brush, gave a strength of 200 psi. The slabs were turned over and about six tension tests were made on each of the four slabs. All gave a tensile strength of 285 psi or about the same as the top unsprinkled surface. The tension test apparatus is shown in Figure 1. A curve of the resulting strengths is shown in Figure 2. The loss in surface strength between the unsprinkled concrete surface and the two heavier sprinkled surfaces was about 25 percent. This weaker surface no doubt was more porous, although there is no test to prove it. It was noted that when water was placed on the nonsprinkled surface and the heavier sprinkled surface, there was visually much more rapid absorption in the latter slab. It would, therefore, be more susceptible to the absorption of salt brines. Perhaps some of the entrained air in the surface of the concrete may have floated out or was worked out of the surface during finishing. All of these conditions lead to less durable air-entrained concrete which would be less resistant to scaling due to salt brines.

## PREVENTIVE AND PRECAUTIONARY MEASURES

### Number of Tests on Plastic Concrete

At about the same time that the field study was decided on, further steps were taken

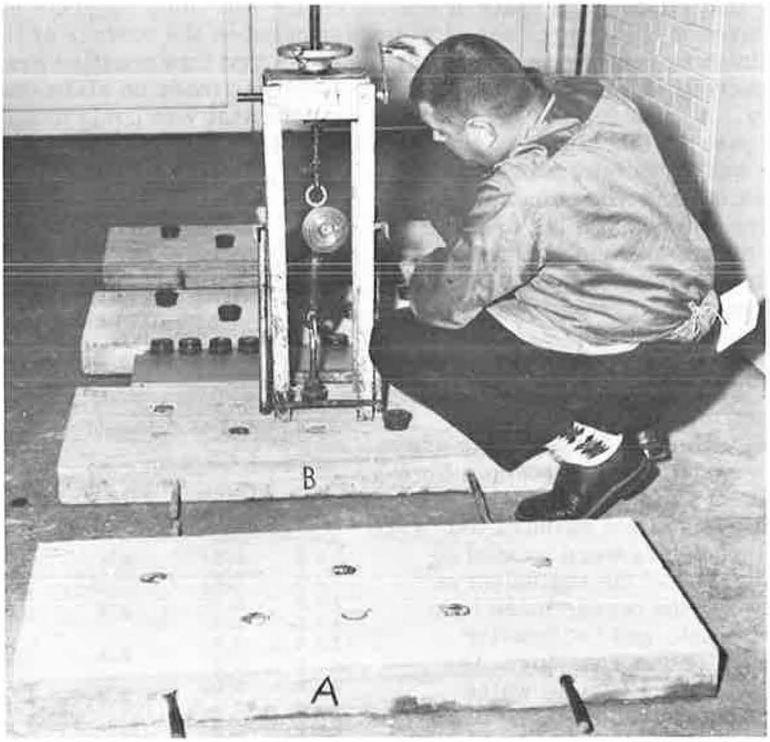

Figure 1. Surface tension test.

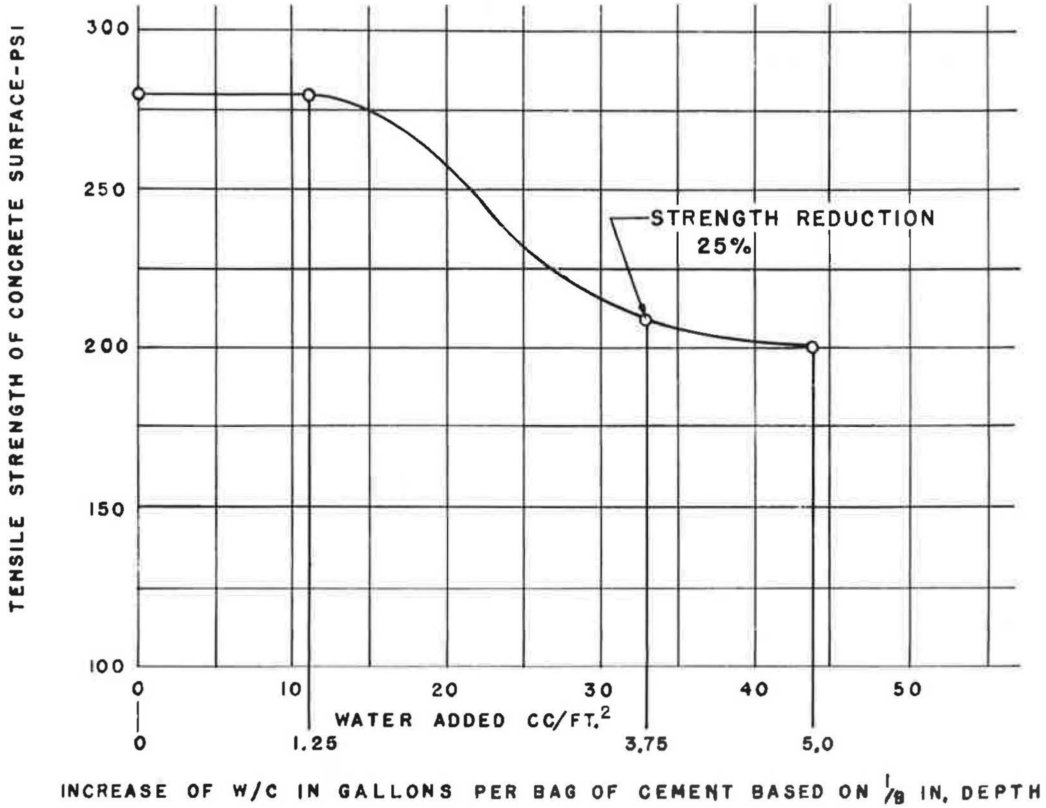

Figure 2. Tensile strength of concrete surface vs quantity of water sprinkled during finishing.

in the field control of the plastic concrete to insure initially that all concrete had the proper amount of entrained air when it was placed in the structure. In 1960 it was required that an air test be conducted on each load of ready-mixed concrete delivered for placement in decks, hubguards, sidewalks, handrails, and other parts of the structures that would be exposed to salt or splashes of brine. To check the effectiveness of this requirement, 32 cores were drilled for air content tests from three structures built during 1962. Results of these tests, shown in Table 3, indicate a 0.8 percent loss of air or slightly more than was shown for pavement concrete.

## Amount of Entrained Air

The second measure taken to provide greater protection to the concrete was to raise the specifications of air content limits of 3 to 5 percent to 4 to 6 percent in 1961. At the present time the specifications are being changed to 4 to 7 percent. These changes are for pavement concrete, as well as for structure concrete. The increased air content seems entirely warranted, especially in highway structure concrete.

## Linseed Oil Treatment

The third measure taken may be considered as temporary assistance to the air-entrained concrete. On July 1, 1962, the treatment of all new structure decks with a mixture of 50 percent boiled linseed oil and 50 percent mineral spirits was made effective. Whereas it is known that concrete with adequate entrained air is very resistant to salt damage, it is also known that if air-entrained concrete has not aged somewhat and dried out, it has not developed this high resistance to salt action. Laboratory tests have shown that linseed oil treatment will not prevent salt damage, but it is hoped that the treatment will act as a retardant during the early age of the concrete and until the air-entrained concrete has developed its full potential for resistance to salt action.

TABLE 3

RESULTS OF FIELD STUDIES ON AIR CONTENT OF HARDENED AND PLASTIC CONCRETE

| Tests | Air Content (%) | | |
|---|---|---|---|
| | Bridge A | Bridge B | Bridge C |
| Hardened concrete[a] | 5.8 | 6.3 | 9.2 |
| | 5.5 | 5.7 | 8.4 |
| | 5.4 | 4.8 | 8.1 |
| | 5.2 | 4.4 | 7.6 |
| | 4.9 | 4.1 | 7.5 |
| | 4.8 | 3.9 | 6.1 |
| | 4.1 | 3.8 | 5.4 |
| | 3.5 | 2.4 | 5.0 |
| | 3.4 | 2.2 | 3.2 |
| | 3.4 | 1.8 | 3.0 |
| | 2.6 | - | 2.1 |
| Average | 4.4 | 3.9 | 6.0 |
| Plastic concrete[b] | | | |
| High | 7.1 | 6.4 | 8.4 |
| Low | 4.0 | 3.4 | 5.5 |
| Average | 5.6 | 4.7 | 6.5 |

[a] Using 2-in. cores.
[b] Number of loads of concrete tested for Bridges A, B, and C were 45, 30, and 15, respectively.

## CONCLUSIONS

From the data presented, the following conclusions can be made:

1. From 6 to 13 percent of the original air-entrained bridges showed scaling in varying degrees in the deck, gutter, hubguard and sidewalk.
2. Between 1947 and 1959, the control and number of air tests made were inadequate to assure that the proper amount of entrained air was always incorportated in the concrete.
3. On the average, the 1.8 percent entrained air obtained from the cores drilled from scaled areas is too low for adequate protection.
4. The average air content of 2.6 percent for the cores drilled from unscaled areas is too low for assurance that scaling will not develop.
5. A loss of 0.5 to 1.0 percent of entrained air may be expected in the concrete between the plastic and hardened state, probably 0.5 percent for pavement concrete and about 1.0 percent for structural concrete.
6. The need for more rigid control of air content by increase in the required number of air tests and increase in the specified air content is borne out by the data.
7. Sprinkling of air-entrained concrete surface may cause a reduction of 25 percent in surface strength and will result in a surface more permeable to salt brines.