Deterioration of Concrete Sidewalks and Curbs

ALAN D. BUCK and BRYANT MATHER, U. S. Army Engineer Waterways Experiment Station

Twenty-four 4-in. diameter concrete cores, three 6 by 12-in. concrete cylinders, and samples of fine and coarse aggregates were examined to determine the cause of heavy surface scaling that occurred in some of the concrete. Eighteen of the cores came from six locations in the affected area. The locations from which they were taken had been selected in pairs separated by expansion joints to represent concrete in relatively better and relatively worse conditions. The other six cores represented new concrete from another nearby area and from a second nearby area that was in good condition after one winter. The three cylinders represented interior concrete from the fourth floor of a new building in the area.

Air content and cement content determinations and petrographic examinations were made on the cores from the affected area. Air content determinations were made on the cores and cylinders from the other areas. These examinations yielded evidence that supported the hypothesis that the deterioration of the affected concrete was caused by freezing and thawing, which produced damage because the concrete was not sufficiently air-entrained, and that future damage to similar concrete that was still intact could be expected.

•SCALING AND DETERIORATION of concrete in sidewalks and curbs were noticed after the winter of 1962-1963 (Figs. 1 and 2). The concrete had been placed in 1960 and 1961, and no such deterioration or scaling was expected. A representative of the Concrete Division, U. S. Army Engineer Waterways Experiment Station (WES), met with representatives of other agencies in April 1963 and an inspection of the concrete in question was made. As a result of this inspection and of the discussions that followed, samples of deteriorated and undeteriorated concrete and of the aggregates used in some of the concrete were sent to WES for laboratory investigation.

The concrete was subjected to petrographic examination and air and cement content determinations. The purpose of the laboratory work was to determine the reason or reasons for the deterioration, and whether additional deterioration could be expected of the unaffected concrete already in place. In addition, recommendations to prevent similar damage in the future were to be made if possible.

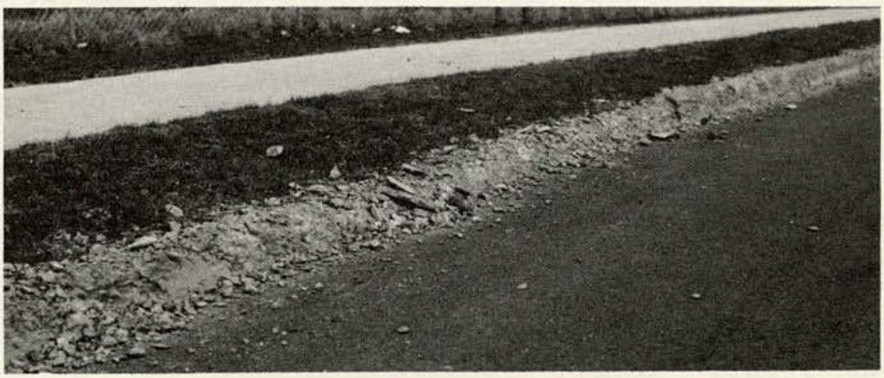

Figure 1. Close-up of section of a deteriorated concrete curb, affected area.

Identification and description of the samples (24 concrete cores, 3 concrete cylinders, and 50 lb each of coarse and fine aggregate) are given in Table 1 and are summarized in the following tabulation:

Serial No.	Sample
CON-1 to -3 -4 to -6	4-in. diameter concrete cores from two locations in sidewalks in the affected area, Contract A
CON-13 to -15 -16 to -18 -19 to -21 -22 to -24	4-in. diameter concrete cores from four locations in curbs in affected area, Contract A
CON-7 to -9	4-in. diameter concrete cores from one location in sidewalk at another area, Contract B
CON-10 to -12	4-in. diameter concrete cores from exterior slab at a third area, Contract C
CON-25 (A, B, C)	Three 6 by 12 in. jobsite concrete cylinders from a fourth area, Contract D
G-1, S-1	50 lb each of coarse and fine aggregate representative of that used in the concrete of the cores of Contract A

MATERIALS AND MIXTURES

Information on materials and mixtures intended or required to have been used in the work represented by the samples and on placing dates and the nature of subsequent exposure was received from the resident engineer. Sidewalks constructed in the affected area (Contract A) were specified to be made using class B-A (air-entrained) concrete having a minimum allowable compressive strength of 2,500 psi at 28 days. By addendum to the specification, curbs were added to the work on which concrete of this class was to be used. It was required that trial batches of concrete be made by the contractor to establish a curve, based on at least three points, for the relation of water content to 28-day compressive strength, with each point representing the average values from at least four test specimens. The maximum allowable water content was then required to be selected as that quantity giving a compressive strength 15 percent greater than the minimum specified.

Figure 2. Deteriorated concrete sidewalk, affected area.

In June 1960, the contractor was advised of approval of mixtures covered by a report from a commercial testing laboratory to the contractor, based on tests of concrete made by the supplier of ready-mixed concrete. The only data contained in the referenced report were results of 28-day compressive strength tests, measured in psi, of trial mixtures 1, 2, and 3 as follows:

	Mixture 1	Mixture 2	Mixture 3
	2,334	3,714	5,129
	2,476	3,555	5,306
	2,299	3,484	5,483
	2,423	3,643	5,235
Average	2,383	3,599	5,288

The testing laboratory made a second recommendation for class B air-entrained concrete to be proportioned as follows:

Measure	Cement	Sand	1 in. Gravel	Water
Volume proportions (1 bag)	1.00	2.30	3.86	6.70 gal
Volume proportions (1 cu yd)	5.08	11.67	19.59	34.00 gal
Absolute volume (1 cu yd)	2.43	7.61	11.45	4.53 cu ft
Dry weight (1 cu yd)	478	1,249	1,900	34.00 gal

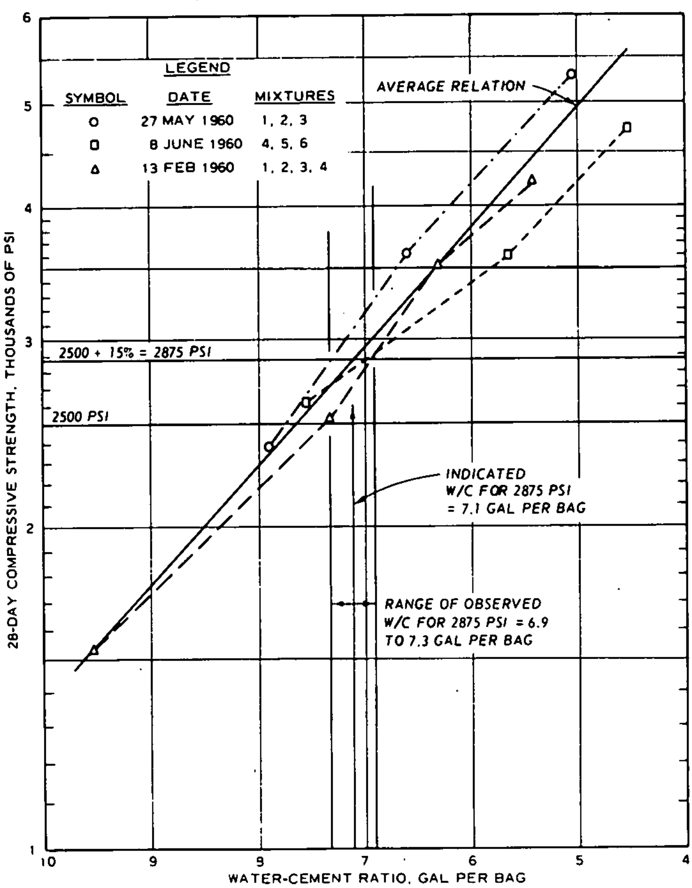

Figure 3. Relationship of water-cement ratio to compressive strength based on data submitted for Contracts A, B, C, and D.

TABLE 1

IDENTIFICATION AND DESCRIPTION OF CONCRETE CORES AND CYLINDERS

Serial No.	Location	Diameter (in.)	Length (in.)	Concrete Condition	Date Placed	Class of Concrete	Contract
CON-1	Sidewalk, 20 ft from cores 4, 5, 6	4	4½	Good	Sept. 28, 1961	B-A	A
-2		4	4⅜	Good	Sept. 28, 1961	B-A	
-3		4	3⅝	Good	Sept. 28, 1961	B-A	
-4	Sidewalk	4	5	¼ in. spalled	Sept. 28, 1961	B-A	A
-5		4	3¾	¾ in. spalled	Sept. 28, 1961	B-A	
-6		4	5½	¾ in. spalled	Sept. 28, 1961	B-A	
-13	Curbing, 15 ft from cores 16, 17, 18	4	12½	Good	July 12, 1961	B-A	A
-14		4	9¾	Good	July 12, 1961	B-A	
-15		4	12	Good	July 12, 1961	B-A	
-16	Curbing	4	12	¾ in. spalled	July 12, 1961	B-A	A
-17		4	11⅞	¾ in. spalled	July 12, 1961	B-A	
-18		4	12	¾ in. spalled	July 12, 1961	B-A	
-19	Curbing	4	8¾	¾ to 1 in. spalled	Oct. 1, 1960 to Dec. 12, 1960[a]	B-A	A
-20		4	11¼	¾ to 1 in. spalled		B-A	
-21		4	8½	¾ to 1 in. spalled		B-A	
-22	Curbing, 10 ft from cores 19, 20, 21	4	10½	Good	Oct. 1, 1960 to Dec. 12, 1960[a]	B-A	A
-23		4	5¼	Good		B-A	
-24		4	11	Good		B-A	
-10	Area 2	4	8¾	Good	Aug. 3, 1962	A(A)	C
-11		4	8¼	Good	Aug. 3, 1962	A(A)	
-12		4	8¼	Good	Aug. 3, 1962	A(A)	
-7	Area 3	4	7⅝	Good	Aug. 10, 1962	A(A)	B
-8		4	7⅝	Good	Aug. 10, 1962	A(A)	
-9		4	7⅝	Good	Aug. 10, 1962	A(A)	
-25A	Area 4	6	12	Good	Oct. 16, 1962	B	D
-25B		6	12	Good	Oct. 16, 1962	B	
-25C		6	12	Good	Oct. 16, 1962	B	

[a]Concrete in certain sections was replaced May 1 and June 6, 1961.

This recommendation stated that the slump range was 2 to 3 in., the air content was 3 to 6 percent, and that ¾ oz of air-entraining agent was to be added per sack of cement.

It will be noted that this mixture requires 6.7 gal of water per bag of cement and 5.1 bags of cement per cubic yard of concrete. The water-cement ratio of 6.7 gal per bag is lower than that indicated to be required by the strength test results, which would appear to justify a water-cement ratio of at least 6.9 gal and possibly as high as 7.3 gal per bag. The first recommendation suggested a water-cement ratio of 7.2 gal per bag and a cement content of 5.35 bags per cu yd. Presumably the approval of the first recommendation was rescinded by the second recommendation.

All 28-day cylinder test data included in the laboratory mixture proportioning reports furnished WES are shown in Figure 3. Because the relation of water-cement ratio to concrete strength is a straight line on a semilogarithmic plot, the data have been so plotted rather than in arithmetic plots such as were included in the data submitted.

From the information reviewed in the preceding paragraphs, it is assumed that the maximum allowable water content of the concrete in the sidewalks and curbs of the affected area was 6.7 gal per bag with a corresponding cement content of 5.1 bags per cu yd. Test reports 60, 61, 65, and 67 cover 28-day tests of field-made cylinders of class B air-entrained concrete used in porches and curbs in the affected area in October 1960. The reported strengths for nine cylinders ranged from 2,550 to 4,420 psi and averaged 3,335 psi. The average curve in Figure 3 predicts a strength of 3,175 psi for a water-cement ratio of 6.7 gal per bag.

TESTS

Air Content

A slice about 1 in. thick was cut parallel to the axis from the central portion of each of the 24 concrete cores and 3 concrete cylinders. Such slices representing each set of cores or cylinders (slices from cores 1 through 7, 10, 13, 16, 20, and 24, and from cylinder 25C) were chosen to provide sufficient surface area to represent the mortar, allowing for the maximum size of the coarse aggregate used in the concrete. These surfaces were ground with abrasive and water to develop a smooth plane surface. The air content of the hardened concrete was determined micrometrically by the point-count method at a magnification of 40 diameters, in accordance with ASTM Designation C 457-60 T. The following criteria were used in classifying the types of air voids encountered:

1. Large voids of irregular shape attributable to incomplete consolidation were ignored on the premise that such air-filled space would not have been present in the concrete contained in a sample that had been properly prepared for test in the freshly mixed condition in accordance with ASTM Designation C 231-62.
2. Entrained air voids were differentiated as those voids having essentially a spherical shape and represented in the polished surfaces as circles having a diameter of 1.25 mm or less.
3. Entrapped air voids were considered to be those having an irregular (nonspherical) shape and represented by sections having a diameter greater than 1.25 mm.

Cement Content

Portions of the 18 cores taken to represent the concrete from six locations in the affected area (Contract A) that were not used in the examination for air content were used to determine cement contents by chemical analysis in accordance with ASTM Designation C 85-54. Representative samples of aggregate similar to those used in this concrete were analyzed chemically for soluble silica and soluble calcium oxide. The results of the aggregate analyses and the SiO_2 value obtained from National Bureau of Standards analyses of portland cements used in the construction, or the CaO value determined by means of ASTM C 85-54, were used to calculate the cement contents of the cores analyzed. The specific gravities of the cores were determined using a modification of Method CRD-C 23-58 (U. S. Corps of Engineers Handbook for Concrete and Cement). The cement contents of the cores in terms of bags of cement per cubic yard of concrete were calculated from the cement content and specific gravity data.

Petrographic Examination

The 18 cores from the affected area and the slices taken from them were examined visually and with a stereomicroscope for signs of deleterious chemical reactions.

TEST RESULTS

Air Content

Table 2 gives a compilation of the air content data on the concrete from the affected area (Contract A). It shows location and condition of the cores and amount of entrained,

TABLE 2

AIR CONTENT OF CORES FROM AFFECTED AREA, CONTRACT A

Concrete[a]		Core No.[b]	Air Content, percent[c]		
Location	Condition		Entrained	Entrapped	Total
Sidewalk	Good	CON-1	3.0	2.6	2.9
		-2	0.4	1.0	1.4
		-3	0.2	1.3	1.5
		Average	0.3	1.6	1.9
Sidewalk	Poor	-4	0.5	1.9	2.4
		-5	0.5	1.4	1.9
		-6	0.6	3.0	3.6
		Average	0.5	2.1	2.6
Curb (road No. 2)	Good	-13A	2.3	2.1	4.4
		-13B	1.3	2.3	3.6
		Average	1.8	2.2	4.0
Curb (road No. 2)	Poor	-16A	0.7	0.5	1.2
		-16B	0.8	1.5	2.3
		Average	0.8	1.0	1.8
Curb (road No. 1)	Good	-24A	5.4	0.7	6.1
		-24B	4.9	0.6	5.5
		Average	5.2	0.6	5.8
Curb (road No. 1)	Poor	-20A	0.4	0.4	0.8
		-20B	0.5	1.0	1.5
		Average	0.5	0.7	1.2

[a]Air-entrained concrete is represented by cores 13 and 24; other cores are of non-air-entrained concrete.
[b]"A" and "B" designate top and bottom portions, respectively, of cores 11 to 12 in. long.
[c]Averages are computed as percentage of total number of points observed in all specimens examined that were found to lie in voids of each type.

entrapped, and total air in typical cores. Table 3 gives similar data for concrete from the sidewalk at another area (Contract B), the exterior slab at a third area (Contract C), and a fourth area (Contract D).

Portions of the prepared surfaces of two of the cores used for air content determinations were photographed. Figures 4 and 5 show the appearance of non-air-entrained concrete (core CON-20) from which about 1 in. of the top surface had been spalled, and Figures 6 and 7 illustrate air-entrained concrete (core CON-24) in good condition. Comparison of Figures 5 and 7 demonstrates that the concrete in the former is not air-entrained.

TABLE 3

AIR CONTENT OF CORES AND CYLINDERS FROM OTHER AREAS

Concrete		Core or Cylinder No.	Air Content, percent		
Location	Condition		Entrained	Entrapped	Total
Sidewalk, Area 2	Good	CON-7[a]	3.8	2.0	5.8
Exterior slab, Area 3	Good	-10[b]	2.8	1.1	3.9
Area 4	Good	-25C[c]			
		Top	0.3	0.3	0.6
		Bottom	0.5	0.5	1.0
		Average[d]	0.4	0.4	0.8

[a]Air-entrained concrete from Contract B.
[b]Air-entrained concrete from Contract C.
[c]Non-air-entrained concrete from Contract D.
[d]Averages computed as percentage of total number of points observed in all specimens examined that were found to lie in voids of each type.

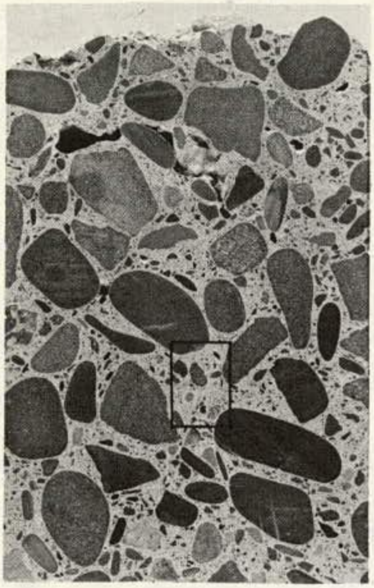

Figure 4. Sawed surface of top half of core CON-20, ½ natural size. From ¾ to 1 in. of top surface has scaled off. The section outlined is magnified in Figure 5.

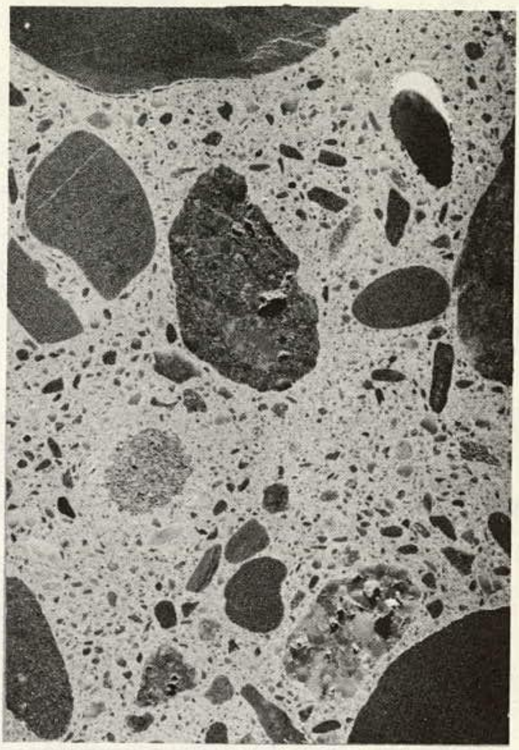

Figure 5. Sawed surface of core CON-20. This is the area outlined in Figure 4. The actual magnification is 4.4 times natural size.

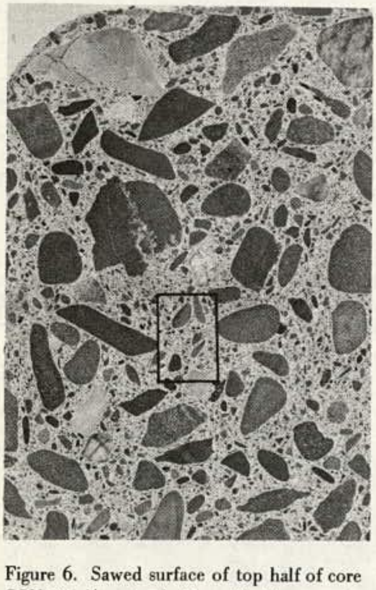

Figure 6. Sawed surface of top half of core CON-24, ½ natural size. Curbing was in good condition with formed and finished surfaces intact. The section outlined is magnified in Figure 7.

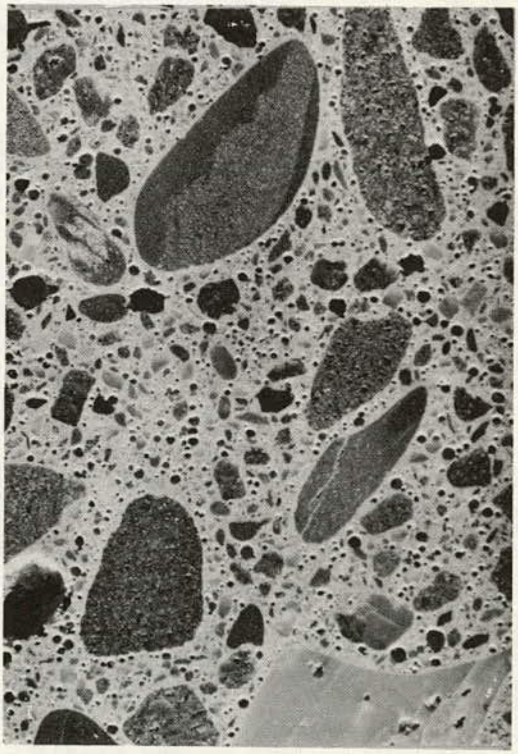

Figure 7. Sawed surface of core CON-24. This is the area outlined in Figure 6. The actual magnification is 4.4 times natural size.

TABLE 4

SPECIFIC GRAVITY OF CORES AND CEMENT CONTENT OF CONCRETE

Core No.	Specific Gravity	Cement Content Determined Chemically			Cement Content from Reported Mixture Proportions and Air Content Micrometrically Determined	
		Based on SiO_2, percent by weight	Based on CaO, percent by weight	Actual Cement Content, bags per cu yd[b]	Calculated Cement Content, bags per cu yd[c]	Actual Cement Content, bags per cu yd[d]
CON-1 to -3	2.26	11.2	12.6	4.53	5.08	5.17
-4 to -6	2.26	10.1	11.3	4.09	5.08	5.13
-13 to -15	2.26	11.5	12.3	4.64	5.08	5.06
-16 to -18	2.27	10.8	11.0	4.39	5.08	5.18
-19 to -21	2.26	12.1	16.0	4.89	5.08	5.21
-22 to -24	2.18	10.9	11.4	4.27	5.08	4.96

[a] $\frac{A}{B \cdot C}$, where A = weight of samples dried to constant weight at 105 C; B = weight of samples soaked 16 hours and surface-dried; and C = weight in water of samples after 16-hour soaking.

[b]Based on SiO_2 determination and specific gravity.

[c]Cement content of mixture described in commercial testing laboratory "second" recommendation presumably approved for use, including 3.6 percent air.

[d]Calculated from theoretical cement content using air contents in Table 2.

Cement Content

Table 4 gives cement contents of concrete from the affected area (Contract A) obtained (a) by chemical analyses and (b) from the mixture proportions by adjusting the theoretical cement content to an actual cement content using the micrometric air contents. It also gives the specific gravities determined.

The 18 cores obtained from six locations in the affected area were selected to provide samples of concrete in relatively good and relatively poor condition from areas separated by expansion joints. This selection provided three sets of concrete cores for comparison. Table 5 gives this comparison and includes the data developed in this examination.

Petrographic Examination

Petrographic examination of the concrete revealed no indications of deleterious chemical reactions or premature freezing.

DISCUSSION OF TEST RESULTS

Affected Area Concrete

It was the opinion of those who inspected the deteriorated concrete in April 1963 that the damage was caused by freezing and thawing and hastened by applications of de-icing salts. The concrete was believed to have been susceptible to such damage because of inadequate air-entrainment or low cement content, or both. The informa-

TABLE 5

COMPARISON OF CEMENT CONTENT, AIR CONTENT, AND PHYSICAL CONDITION OF CONCRETE, CONTRACT A

Location	Core No.	Concrete Condition	Cement Content, bags per cu yd			Total Air Content, percent	With Air Entrainment	Without Air Entrainment
			Chemical Determination[a]	Mixture Data and Micrometric Air Content[b]	Difference			
Sidewalk	CON-1 to -3	Good	4.53	5.17	0.64	1.9		X
	-4 to -6	Poor	4.09	5.13	1.04	2.6		X
Curbing	-13 to -15	Good	4.64	5.06	0.42	4.0	X	
	-16 to -18	Poor	4.39	5.18	0.79	1.8		X
Curbing	-19 to -21	Poor	4.89	5.21	0.32	1.2		X
	-22 to -24	Good	4.27	4.96	0.69	5.8	X	

[a]ASTM Designation C85-54.

[b]Mixture assumed to have been used, adjusted by micrometric air contents.

tion developed during the laboratory examination (Tables 2 through 5 and Figures 4 through 7) appears to indicate that the primary reason for the rapid deterioration of some of the concrete was freezing-and-thawing damage that occurred because the concrete was not sufficiently air-entrained. The cement contents determined by chemical analysis were, in general, close enough to the cement contents shown in the mixture proportions believed to have been used, adjusted by the air contents determined, to suggest that low cement was not a major factor responsible for the deterioration. Petrographic examination of the concrete revealed no indications that deleterious chemical reactions or premature freezing might have contributed to the deterioration.

The sidewalk concrete represented by cores CON-1 to -6 was non-air-entrained; the concrete in cores 1 to 3 was in good condition and that in cores 4 to 6 in poor condition. The explanation for this difference is probably twofold. First, cores 4 to 6 were taken nearer the curb and had more exposure to de-icing salt solutions produced by the melting of salts applied to the streets (i.e., the salt solution accumulated near the curb and passing traffic splashed it onto the sidewalk). Second, the concrete of cores 4 to 6 does have a cement content that is significantly lower than it should have been and is considerably lower than the cement content of cores 1 to 3. The air-entrained sidewalk concrete of low air content can be expected to suffer ultimately the same type of deterioration that the air-entrained concrete curbing of low air content has already shown. Any other air-entrained concrete of low air content present can also be expected to deteriorate much more rapidly than that protected from frost damage by an adequate air-void system.

The specifications called for all of the concrete used to be air-entrained and to contain 3 to 6 percent air. However, it has been shown that some of the concrete was not sufficiently air-entrained and contained only from 1.2 to 2.6 percent air (Table 2). The air contents (Table 3) of the concrete from the other three nearby areas were within the range required by applicable specifications.

Aggregates

The aggregates used in all of the concrete represented by the samples examined are natural sand and gravel. Test data on this material indicate relatively high absorption (2.6 percent for sand, 1.7 percent for gravel), but also high resistance to freezing and thawing in concrete (durability factor DFE = 87). More recent data show relatively similar results; an absorption of 1.8 percent for sand and 2.4 percent for No. 4 to ¾-in. gravel, but a DFE of 91. It is therefore indicated that, while by some traditional measures of physical quality these aggregates would be regarded as of only fair physical quality, the aggregates are entirely capable of being employed to make concrete having a high degree of frost resistance if the concrete has an adequate air-void system and is otherwise manufactured according to proper practices.

CONCLUSION

It was concluded that deterioration of the sort that developed on some of the curbs and sidewalks in the affected area could have been prevented, and that similar deterioration can be prevented in the future, even in cases where heavy applications of de-icing chemicals may have been used, by the use of air-entrained concrete containing an adequate air-void system.

ACKNOWLEDGMENTS

The study described herein was conducted in 1963. It was made at the Concrete Division, U.S. Army Engineer Waterways Experiment Station, by A.D. Buck, J.H. Hetrick, Jr., W.I. Luke, and Mrs. C.F. Derrington, under the supervision of Mrs. K. Mather, L. Pepper, B. Mather, and T.B. Kennedy.