

CRACKING OF CONCRETE IN THE TUSCALOOSA LOCK

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SYNOPSIS

THE TUSCALOOSA Lock was constructed on the Warrior River near Tuscaloosa, Alabama, between 1937 and 1939. It was noted in 1947 that cracks had developed in the lock walls. A board of consultants was appointed, and the members of the board examined the structure and recommended that the Concrete Research Division, Waterways Experiment Station, conduct a study to determine the cause of the cracking. The data developed by this study are summarized and discussed in this paper. It was concluded that the cracking resulted from a chemical reaction between the alkalis in the cement and unstable silica in the aggregate. It is believed that this is the first published account of cracking of concrete through cement-aggregate reaction in which chaledonic chert is the major control responsible for the deleterious reaction.

● BETWEEN OCTOBER 1937 and September 1939 the Mobile District of the Corps of Engineers supervised the placement of concrete in the Tuscaloosa Lock and Dam on the Warrior River near Tuscaloosa, Alabama. The cement came from two mills, the aggregates were natural sand and gravel, and the mixing water came from the Tuscaloosa city water supply.

Eight years after the placement of concrete was completed, it was noted that cracks had developed in the lock walls. A board of consultants was appointed to examine the situation and make recommendations. The board met at Tuscaloosa in November 1947, reviewed the available data, examined the structure, and arrived at two conclusions: (1) cracking is more advanced in concrete made with Cement A than in that made with Cement B and (2) additional data on the condition of the structure should be obtained by drilling cores and by making a detailed crack survey.

A series of cores were drilled including a 36-in.-diameter core from monolith No. 5 in the lock wall, a monolith that showed rather extensive cracking at the surface and which was so situated that internal movement might interfere with the proper functioning of the lock gates. The board met again in January 1948, examined the additional data, the cores, especially the 36-in. core hole, and concluded that: (1) the cracking in monolith No. 5 is not as serious as it had appeared from the surface and (2) an investigation should be made by the Waterways Experiment Station to determine the causes of the cracking

LABORATORY INVESTIGATION

It was suspected at the beginning of the laboratory investigation that the cracking in this structure could have been caused by expansion resulting from chemical reaction between the aggregate and the alkalis in the cement. This hypothesis was based on the following considerations:

(1) Several engineers who examined the structure called attention to a similarity in pattern between the cracking manifested here and that in certain structures in other parts of the country where the alkali-aggregate reaction is regarded as the cause of the cracking.

(2) There were fairly clear-cut evidences of internal expansion of the concrete.

(3) The cores and the 36-in. core hole appeared to contain deposits of secondary material, superficially similar to the reaction products of the alkali-aggregate reaction.

(4) The natural gravels of the Atlantic and Gulf Coastal Plains were known to contain chaledonic chert, an aggregate constituent that had been shown to be potentially capable of deleterious chemical reactivity with the alkalis in portland cement.

(5) Certain portland cements produced in the area in which Cement A was made were reported to have been typically of rather high alkali content during the period when cement from this area was being furnished for use in the project.

In opposition to the immediate adoption of this hypothesis as the sole explanation of the cracking were the following considerations:

(1) It was possible that the cracking was at

least in part due to other causes, such as leaching of lime from the concrete by acidic river water or expansion due to reaction between sulfates in the river water and aluminates in the cement.

(2) At the time the study was started, no definite occurrence of concrete cracking due to alkali-aggregate reaction had been described from the South Atlantic or Gulf Coastal region in spite of very widespread use of cements and aggregates generally similar to those used in the Tuscaloosa project.

Cement A. An initial examination of the cores revealed that all of them showed a development of calcium sulfoaluminate and of gel both as exudations on the drilled surfaces and as fillings or partial fillings in cracks and voids; and most of the cores showed cracks visible to the naked eye.

CONDITION OF THE CORES

All of the drilled surfaces of the cores showed white films or mounds of gel on areas of mortar and on particles of chert coarse aggregate



Figure 1. Flecks of gel with included sawdust (A) and mound of gel (B) which grew on core surface after drilling (slightly enlarged). Core 5-1, depth 7.5-9.0.

(3) No instance of concrete cracking due to alkali-aggregate reaction had been described from any locality in which chaledonic chert was the major aggregate constituent involved.

The laboratory investigation was therefore planned to develop as much detailed data as possible that could confirm or disprove the hypothesis that cracking was solely or primarily a result of alkali-aggregate reaction. Two sections of the 36-in. core and sections of 4 $\frac{3}{4}$ -in. core from three other monoliths were sent to the laboratory for study. The 36-in. core sections were 2 ft. and 5 ft. in length and a total of 91 ft. of 4 $\frac{3}{4}$ -in. core was available for study. The 36-in. cores and a majority of the smaller cores came from concrete made with

but not on coarse aggregate particles of other types. Frequently the gel entirely inclosed sawdust¹ particles; mounds of gel rose up as much as $\frac{1}{8}$ in. above the core surface (Fig. 1). These facts make it plain that some of the gel deposition took place after the cores were drilled. All of the drilled surfaces cut air pockets and underside voids containing white or clear exudates with outer surfaces continuous with those of the adjacent paste and mortar and, accordingly, older than the drilling of the core. A number of the drilled surfaces show cracks visible to the naked eye. A few show such cracks filled or partly filled

¹ The core specimens were packed in sawdust when received at the laboratory.

with exudate (Fig. 2). The smoother surfaces produced by sawing with a diamond-edged blade reveal more cracks than appear on the outside of the core. When the concrete was broken open and the surfaces of the largest cracks examined, the surfaces were found to be covered with desiccated gel, which filled the crack and saturated the adjoining mortar. Some of the drilled surfaces intersected empty pebble sockets where poorly bonded aggregate was lost during drilling. Some of the surfaces



Figure 2. Open crack. (A-A). Partially filled with gel (arrows). The crack reaches its greatest width in the chert pebble near the center of the photograph (slightly reduced). Core 60-1, 7 in. from formed surface.

intersected coarse aggregate particles containing cracks visible to the naked eye. Most of the cracked particles were chert; a few were quartzite or sandstone. Many of the cores were fairly dense and free of large voids on the drilled and sawed surfaces. In those cores the concrete near the outside of the structure appeared generally more dense than the concrete in the interior. Other cores were noticeably less dense, and in certain cases were found to contain numerous large irregular voids and, in one case, showed conspicuous honeycomb (Figs. 3 and 4). In all of the con-

crete, macroscopic voids were more common near coarse aggregate particles than away from them. Many of the pebbles had relatively narrow, but extensive, underside voids.

The concrete containing Cement A showed more signs of reaction than that containing Cement B, but the concrete containing Cement B contained cracks in the upper section and gel throughout the core.



Figure 3. Concrete with numerous large voids, depth about 33 ft, core 5-1. The surface is typical of the core from 14.5 ft to 39.6 ft. Direction of placement towards bottom of photograph. The voids are more frequent adjacent to coarse aggregate particles.

EXUDATES AND DEPOSITS IN THE CONCRETE

Examination of drilled, sawed, and broken surfaces of the concrete showed that several types of deposits were present in voids and cracks and on aggregate particles.

Gel—Gel was the most abundant and conspicuous deposit in and on the concrete. Most of the growth of gel took place before the cores were drilled. The late gel usually looked as if it had been a less viscous material than the gel formed in the structure. It formed flat sheets and low mounds, was usually quite

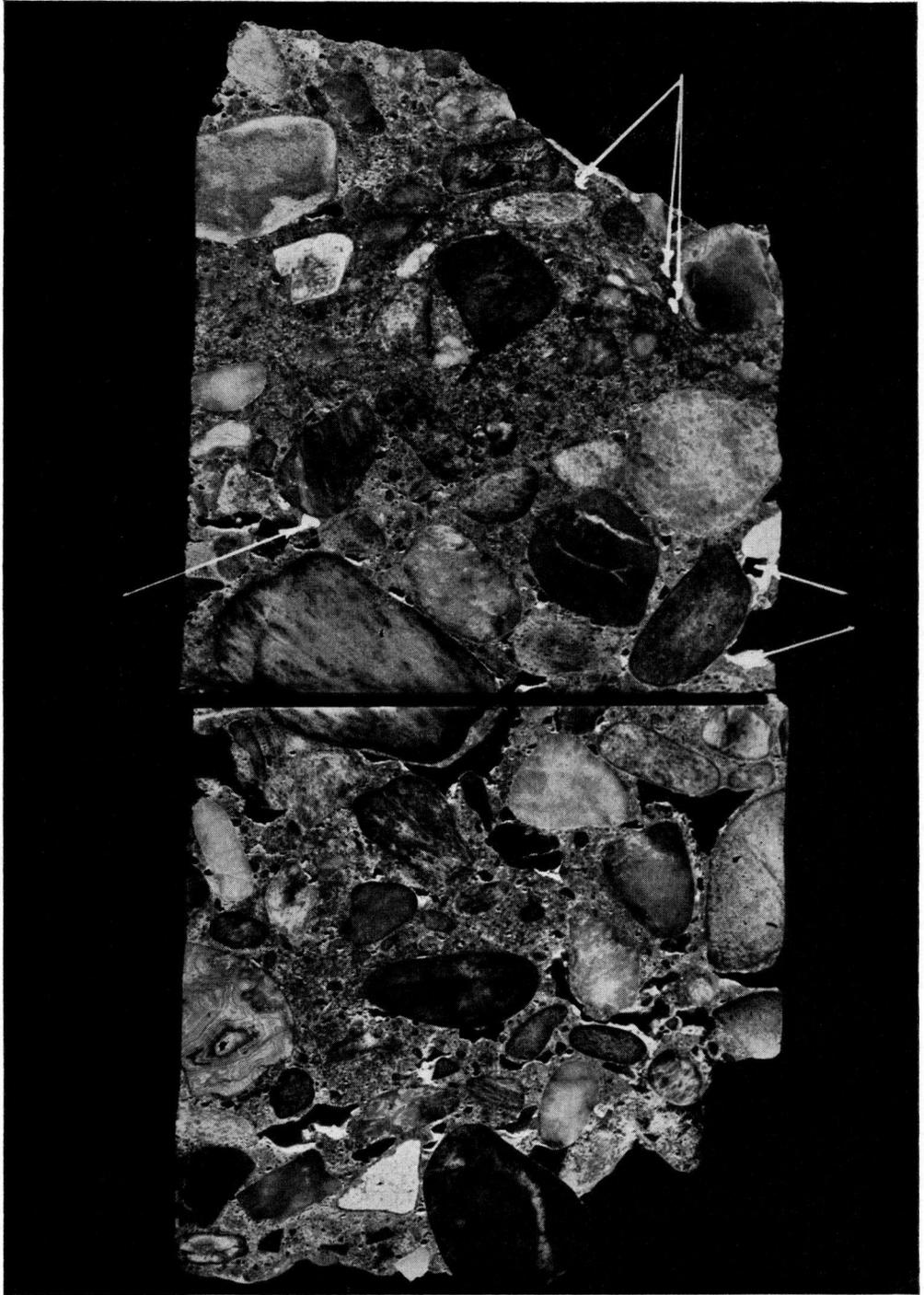


Figure 4. Honeycombed concrete from core 5-1, depth 13-14 ft. Direction of placement towards bottom of photograph. Arrows indicate gel pockets; the large voids in the lower section are gel-lined.

translucent and bluish white, and had developed shrinkage cracks. It is similar in general appearance to the majority of the gel found on expanded mortar bars made for the alkali-reaction test when examined soon after their final removal from storage over water. As the gel dried, it became white and cracked more. The three samples of late gel examined in immersion media were all isotropic with indices of refraction in the range between 1.455 and 1.470. Two varieties of gel, older than the drilling of the cores, formed partial and complete fillings of voids and cracks in mortar, and pores and cracks in coarse aggregate. The less abundant variety was clear to translucent, rubbery to brittle, and usually formed the outer shell of the lining if both varieties were present in one void. The more abundant kind was dull opaque white, rubbery to powdery to brittle, and usually formed the core if both varieties were present. Sometimes concentric shells of the opaque kind differed in color and appearance in reflected light, and in structure and index of refraction in transmitted light. Occasionally, radial or concentric shrinkage cracks in a filling had been filled by later gel of higher index. Two examples were found where translucent gel formed the interior and opaque gel the periphery of the filling. Many voids were entirely filled with gel, or evidently were once entirely filled before shrinkage of the filling. However, most of the void space in the concrete was still empty, even in areas close to gel-filled cracks. Many voids contained no gel, or only a thin partial lining of clear brittle gel. Gel was found in all sections of all the cores, regardless of type of cement or distance from the outer surface of the structure. The most abundant gel, and the greatest amount of gel-permeated and gel-whitened paste, was found near cracks in the upper or outer sections. In the longest core, from monolith No. 5, gel and cracking decreased from top to bottom in the core, but gel was present in the bottom section.

Forty samples of gel, older than the drilling of the cores, and taken from cores representing four monoliths, were examined using the petrographic microscope and their indices of refraction determined. Only 2 of the 40 samples were entirely isotropic. There were two varieties of anisotropic gel. The most common was very finely grained under crossed nicols, and had a low aggregate "pepper and salt"

birefringence resembling chert. Some of it was isotropic on thin edges. The range observed in indices of refraction was from 1.478 to 1.511. It is believed that this variety contained small birefringent crystalline inclusions, but no distinctive shapes or orientations could be made out. Calcium hydroxide inclusions of the size of the birefringent units would have the birefringence found. Some of the gel with pepper-and-salt inclusions also contained irregular or rhombic inclusions with indices of refraction and birefringence agreeing with calcium carbonate. Calcium carbonate was the only inclusion in some of the gel samples.

The second kind of anisotropic gel showed aggregate polarization, low birefringence, and overall wavy extinction with a misshapen black cross. The indices of refraction ranged from 1.480 to 1.502. This variety was regarded as anisotropic due to strain, the strain probably resulting from drying shrinkage in the gel but possibly due to volume changes in the concrete which originally surrounded it. Indices of refraction of all 43 samples are given below:

Index of Refraction	Number of Samples	
	Pre-drilling	Post-drilling
Sodium light between limits shown		
Above 1.520	0	
1.515-1.520	1	
1.510-1.515	0	
1.505-1.510	5	
1.500-1.505	1	
1.495-1.500	2	
1.490-1.495	1	
1.485-1.490	6 (one isotropic)	
1.480-1.485	6	
1.475-1.480	12 (one isotropic)	
1.470-1.475	2	
1.465-1.470	2	
1.460-1.465	1	1
1.455-1.460	1	1
Below 1.455	0	1
	40	3

Parsons and Insley (21) reported a range of indices of refraction of from 1.47 to 1.52 in gel from a specimen where the aggregate was opal. McConnell, Mielenz, Holland, and Greene (17) reported a range from about 1.46 to about 1.49. These values all seem reasonable considering variations in cement, aggregate, and water content at time of examination. Not all of the observations agree with the literature, at least one instance was found where clear isotropic gel was higher in

index than opaque anisotropic gel from the same pocket. It is believed that all the observations can be reconciled if it is assumed that differences in cement, aggregate, mix design, placement, exposure, and timing of the access of unwanted water influenced the amount and composition of reaction products in different field concretes or test specimens which underwent alkali reaction.

Two samples of the gel were subjected to chemical analysis. Sample 1 consisted of material scraped from the wall of the 36-in. core hole in Monolith 5 on 16–19 June 1948. Sample 2 was collected from pockets in 4½-in. cores from Monoliths 20 and 60 after the concrete had dried in laboratory air. The results of these analyses are as follows:

	Sample 1	Sample 2
	percent	percent
Moisture loss at 105 C.	34.6	9.81
Composition calculated on dry basis		
SiO ₂	49.82	61.73
CaO	21.11	12.28
Al ₂ O ₃	1.15	2.17
Fe ₂ O ₃	0.81	0.47
SO ₂	0.16	0.00
Insoluble residue	5.58	8.1
Loss on ignition	—	14.84
Calculated calcium sulfoaluminate	0.47	0.0

McConnell, Mielenz, Holland, and Greene (17) reported that the SiO₂ content of samples of gel ranges from 50 to 85 percent (moisture-free basis).

While cracks and gel were most developed in the upper and outer sections of the core, all sections of all cores contained gel, and gel grew on the core surfaces after they were drilled and stored in a damp condition. The late gel grew more abundantly on the middle and lower sections of the cores. This fact suggests that while growth in the structure had only gone far enough to crack the concrete near the surface, all the necessary ingredients for growth were present in the deeper concrete and that the production of gel in this concrete was accelerated when additional moisture was provided. As an example of the speed with which reaction can develop under favorable conditions, a thin-section blank from a core from monolith 5 was impregnated with resin, ground smooth on one face, and then exposed to warm, humid laboratory air for approximately 36 hr. When the blank was

examined, it was found that three gel pockets and one chalcedony particle on the ground surface had taken up water from the air and swelled up perceptibly above the general level of the ground surface. Figure 5 is a photograph of the specimen at a magnification of about 3×, taken about August 23, 1949. On August 24, 1949, the blank was stored in a closed container over water, and left until October 17, 1949. It was then reexamined and the photograph reproduced as Figure 6 was made at the same magnification.

Certain comments on the rapid and obvious development of the reaction products in this specimen suggest themselves. In the first place, the specimen was heated well above 100 F. (probably to at least 200 F.) in the process of impregnating it with resin. During that heating it was subjected to a more abrupt thermal change than it had ever undergone before. The cement paste lost some water which it would not have lost in laboratory storage at ambient temperatures. Probably the thermal shock and partial dehydration suddenly opened up the general structure and, particularly, the mortar-coarse aggregate boundaries to a degree unusual in concrete undergoing mild weathering. Thus the specimen may have been rendered unusually susceptible to a later addition of moisture. In the second place, while the resin apparently did not thoroughly penetrate the interior, it formed a coating around all the surfaces, including that from which it was later removed by grinding. All the manifestations of activity were probably therefore concentrated on the one ground surface. This specimen is considered in detail because other pieces of Tuscaloosa concrete have been stored in the same closed container since July 1948 without developing any visible changes, except fairly minor increases in gel deposits. Therefore it is not suggested that deterioration of the concrete in Tuscaloosa lock may be expected to proceed at the rapid rate suggested by the two photographs and dates. The photographs do tend to confirm the belief that the reactive potential in the concrete has not been exhausted.

Calcium Carbonate—Carbonation of the cement paste adjoining cracks was found in thin sections of concrete from depths up to 20 ft. from the exterior. A small amount of

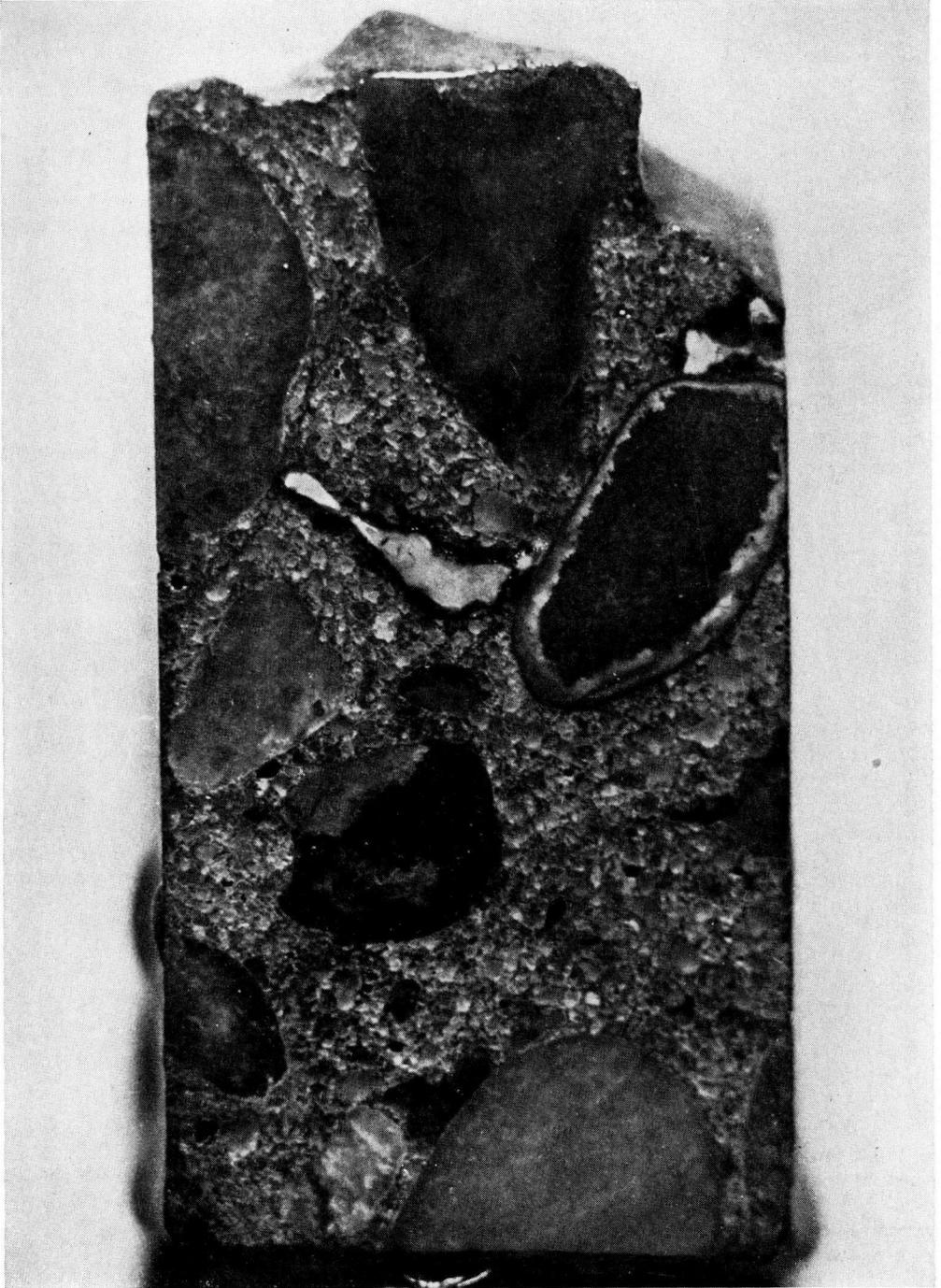


Figure 5. Thin section blank impregnated with resin, ground, exposed to warm humid air for about 35 hr. Magnification about 3X. Photographed August 23, 1949. Two large gel pockets (upper right and upper center) had taken up moisture and swelled. The chalcedonic pebble (lower-left center) had taken up moisture, and there was a wet spot on a sand grain at the lower left.

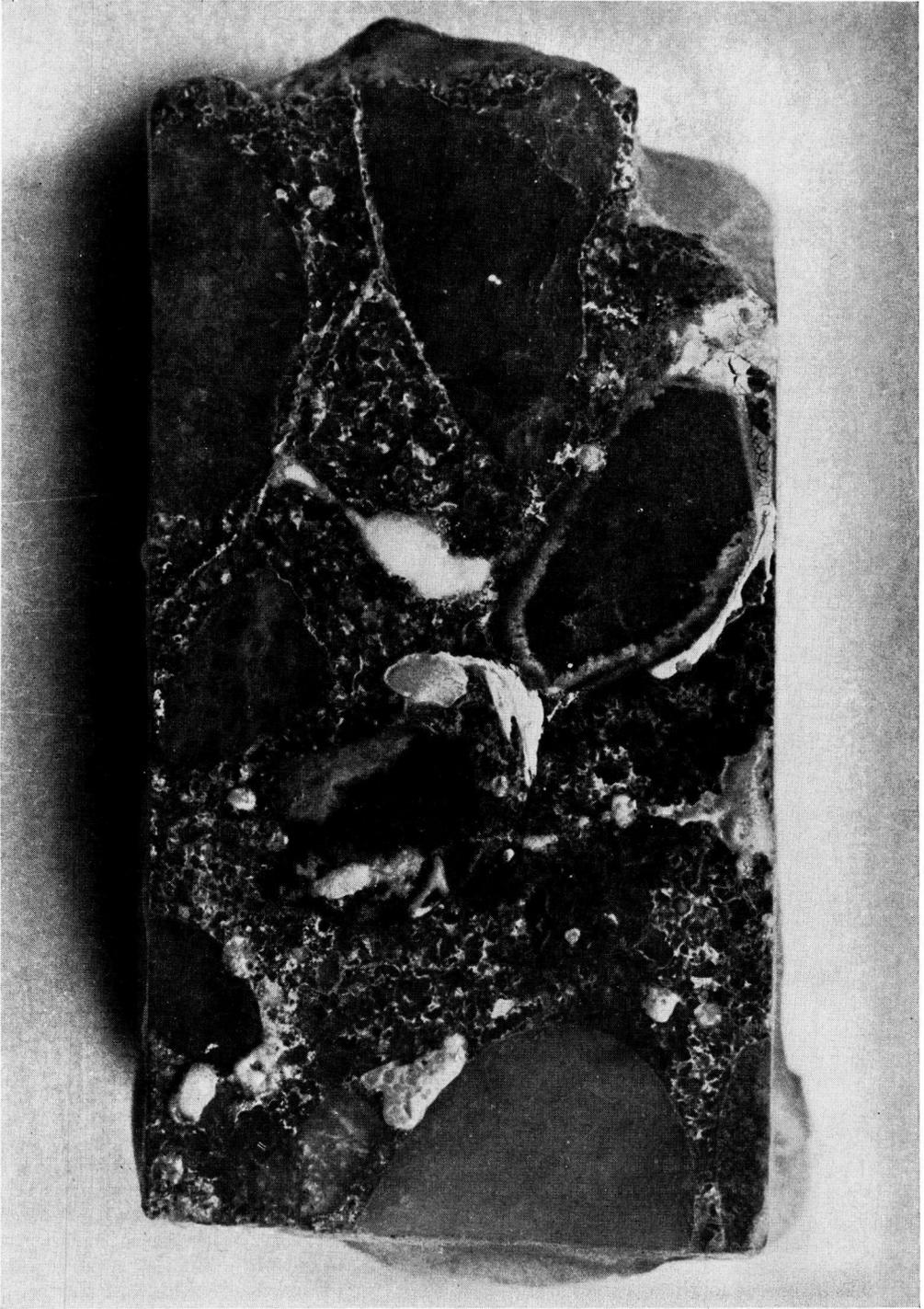


Figure 6. Same specimen after storage over water at room temperature between August 24, 1949, and October 18, 1949. The gel pockets shown in the previous photograph have enlarged; many more have appeared; cracks which were not obvious before are now traced in reaction product.

carbonation was found in one thin section from a core from a depth of about 39 ft. in Monolith 5. It is believed that this carbonation took place after the core was drilled. The amount and extent of carbonation did not appear to be unusual, and are not regarded as significant, except as indicating that concrete as deep as 20 ft. in the structure was accessible to air.

Calcium Sulfoaluminate—Calcium sulfoaluminate was found in voids in every section of every core, regardless of distance from the surface of the structure. It was most abundant in each core near the outer or upper

TABLE 1
COMPOSITION OF COARSE AGGREGATE IN TUSCALOOSA LOCK, AS DETERMINED BY COUNTS OF PARTICLES INTERSECTED ON SAWED SURFACES

Monolith and hole no.	Sawed surfaces counted	Number of coarse aggregate particles, percent ^a	
		Chert ^b	Other ^c
3-1	4	41	59
5-1	33	42	58
20-1	9	42	58
60-1	3	37	63
60-2	3	36	62
60-3	2	32	68
60-4	3	42	58
Average of all cores ^d	—	42	58

^a Calculated as a percentage of the total number of coarse aggregate particles intersected on the sawed surface.

^b Chert determined by macroscopic examination, without any distinction made between chert consisting of quartz and chert consisting of chalcedony.

^c The coarse aggregate constituents other than chert are quartz, quartzite, sandstone, with a few particles of granitic gneiss.

^d Arithmetic averages, based on a total of 5518 coarse aggregate particles.

surface of the structure. In the top section of core from Monolith 3, which was represented by a series of chunks and fragments, sulfoaluminate was very abundant in voids and in pebble sockets. In the cracked outer section of core from Monolith 60, about 8 in. from the surfaces, mats, rosettes, and spherulites of sulfoaluminate filled voids, lined pebblesockets, and coated sand grains. With increasing depths, the sulfoaluminate was found in tufts, rosettes, and linings in the voids but not as linings of pebble sockets.

Calcium Hydroxide—Core from depths 38.4 to 40.2 ft in Monolith 5 contained well-developed tufts and rosettes of sulfoalu-

minate in voids. In some of the voids, clear colorless plates of calcium hydroxide were associated with sulfoaluminate. Calcium hydroxide is less abundant than the sulfoaluminate but is not uncommon. It was the first example of calcium hydroxide in crystals in voids found in field concrete examined by this laboratory. Subsequent observations indicated that the growth of calcium hydroxide crystals in voids is a fairly common occurrence in the interior of structures. The calcium hydroxide in voids was found only in the lower section of the core, where the alkali-aggregate reaction was least advanced. Since accessible calcium hydroxide is fairly easily converted to calcium carbonate by moderately dry air containing carbon dioxide (13), the persistence of the unaltered crystals indicates that this concrete never dried out enough to allow the crystals to be exposed to relatively dry air containing CO₂.

AGGREGATE IN CONCRETE FROM STRUCTURE

Identification of over 5,000 coarse-aggregate particles intersected by sawed surfaces (Table 1) indicated that 42 percent of the coarse aggregate was chert and 58 percent consisted of other types of material, principally vein quartz, quartzite, and sandstone, with very small quantities of granitic gneiss and ochre or limonite. Sixty-eight chert particles which were associated with gel pockets were examined in immersion media; 48 of these particles (71 percent of those examined) contained or consisted of chalcedony. The index of refraction of 40 of the chalcedony particles was determined (Fig. 7); the average of the 40 indices is 1.5365 with an observed range from 1.5240 to 1.5420. Since the chert particles were deliberately selected from those which had adjoining gel pockets, it is believed that the calculated percentage of chalcedonic chert, 71, is a maximum. If it is assumed that from 50 to 70 percent of the chert was chalcedonic, the calculated chalcedony content of the coarse aggregate ranges from 19 to 30 percent. Using the determined average value of the index of refraction of the chalcedony and curves given by Donnay (?), the opal content of the chalcedony can be estimated as between 5.5 and 17.5 percent and, hence, the opal content of the total coarse aggregate as between 1 and 5 percent.

The silica solubility and reduction in alka-

linity were determined on a composite sample taken from particles determined as chalcedony. Duplicate tests gave $S_c = 477$ and $R_c = 46$ ($S_c/R_c = 10.4$).

The fine aggregate was natural sand composed principally of quartz, with some feldspar and a small amount of other minerals, and chert which was particularly conspicuous in the larger sizes. According to information provided by the Mobile District, Corps of Engineers, difficulty was encountered in producing sand with the required amount of fines. The amount of fine sand in the mortar

articles of all the types of coarse aggregate could be found with adjacent gel, gel within coarse aggregate was confined almost entirely to chert particles. The exceptions were some highly fractured quartzite pebbles. The association of gel with chert appeared to be more common than the association of gel with any of the other types of coarse aggregate (Figs. 8 and 9). To test this indication, macroscopic counts were made of sawed surfaces to determine the number of chert particles with and without associated gel, the number of other coarse aggregate particles with and without

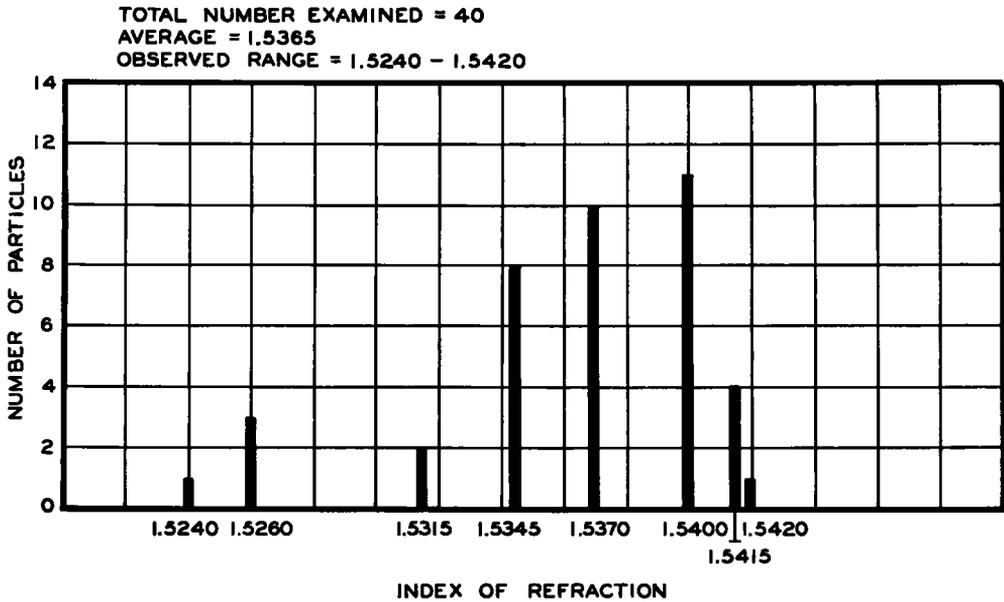


Figure 7. Distribution of chalcedonic chert coarse-aggregate particles selected from concrete from Tuscaloosa Lock, with respect to index of refraction.

was relatively small, and consequently, there are larger areas of cement paste in the mortar than there usually are in the mortar of concrete made with sand graded in accordance with the current Corps of Engineers specifications.

Relation of Chert and Gel Pockets—The gel which grew on the cores after they were stored in sawdust was located on chert particles or on mortar and not on coarse aggregate particles of other types. The gel intersected by the sawed surfaces adjoined coarse aggregate of all the types present or occupied cracks or voids in the mortar. Although par-

associated gel, and the number of gel pockets or linings with no visible association with a coarse aggregate particle (Table 2). Counts were made on 57 sawed surfaces; 580 gel pockets were found, of which 110 were apparently isolated, 281 adjoined chert particles, and 189 adjoined coarse aggregate particles of other types; 5,518 coarse aggregate particles were found, of which 42 percent were chert and 58 percent were not chert. Gel pockets adjoined 12 percent of the chert particles found and only 6 percent of the non-chert particles. These figures leave out of account the possible connections at depth of the apparently isolated pockets. The data in

Table 2 have been used to calculate whether the observed distribution of gel pockets with respect to chalcedony and other types of aggregate is a random one or whether the distribution indicates an association between gel and chert greater than that likely to arise by chance (Fisher (8) pp. 85-99). These calculations were made for the totals of all the

be capable of deleterious reaction with the minor alkalis of portland cement. Such chert was a much more important constituent of the coarse aggregate than of the fine aggregate.

A sample of gravel taken in 1948 from a commercial pit in the area from which the aggregate used in the structure was reported

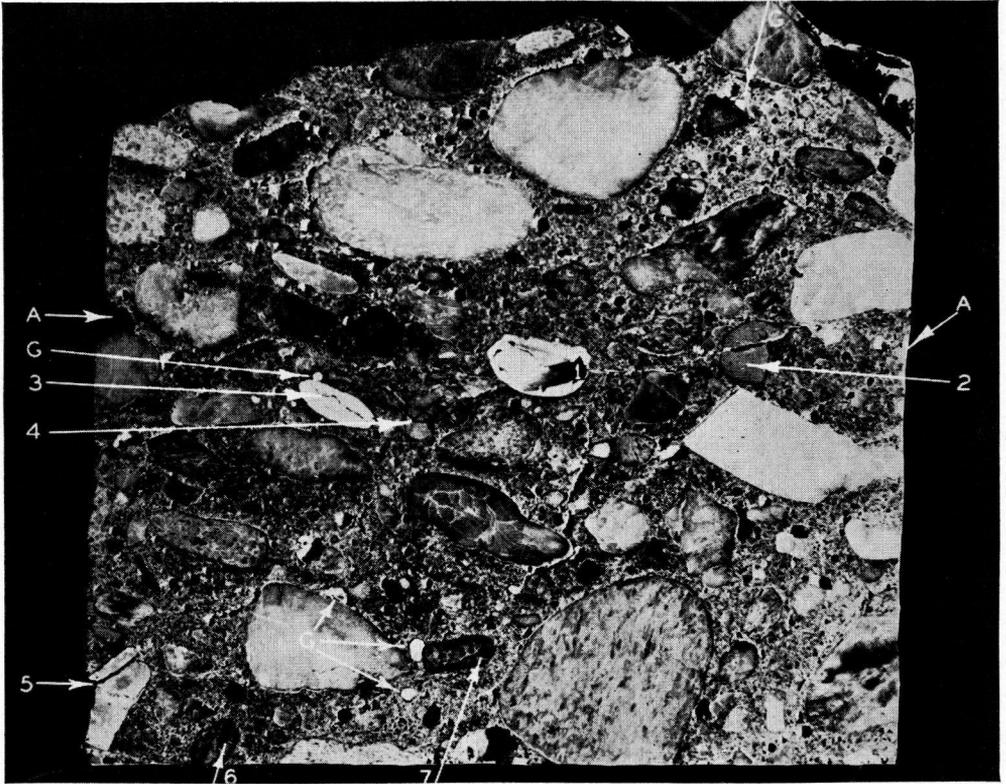


Figure 8. Sawed surface of core cut longitudinally. The direction of placement is toward the top of the photograph. A-A indicates the ends of a crack system which can be traced across the core, passing through two chert pebbles (1 and 2). The white chert pebble (1) has an outer zone very firmly bonded to the matrix and the center of the pebble separated by cracks from the outer zone. The chert pebbles indicated by arrows (2 through 7) show the wide cracks common in chert particles in this concrete. In pebble (2) the gel filling of parts of the crack system can be seen at the left and right. G indicates gel pockets.

surfaces counted. The probability that the association found would occur by chance is less than 1 in 1,000. A study of the detailed data from which Table 2 was prepared also indicated that the percentage of gel pockets in the core containing Cement B, was lower than in any of the cores containing Cement A.

Chalcedonic chert was the only constituent found in the coarse or fine aggregate known to

to have been obtained was examined in the sizes from 1 in. to No. 4 and had more than 50 percent quartz in all sizes smaller than 1 in. and 46 percent quartz in the fraction retained on the 1-in. sieve. Chert was present as follows: 39 percent on the 1-in., 31 percent on $\frac{3}{4}$ -in., 35 percent on $\frac{1}{2}$ -in., 22 percent on $\frac{3}{8}$ -in., and 36 percent on the No. 4 sieves. The remainder of the sample consisted of quartzite, sandstone, and granite. Chalcedony was



Figure 9. Part of area shown in Figure 8 magnified about 3 times. Arrows at margin mark ends of crack. 1, 2, 3 are chert pebbles with well-developed wide cracks; those in 3 are locally gel-filled. 4, 5, are cracked pebbles; the cracks are narrower than those in 1, 2, 3

found in one or two of the chert particles; most of the particles which were powdered and examined were found to contain no material with an index of refraction lower than that of quartz. Physical tests on sand and

deed the quite disturbing prospect is raised by the behavior of the Tuscaloosa concrete that it might possibly have experienced less trouble if the aggregate had been of poorer quality, either more porous or with a larger proportion of reactive constituents.

TABLE 2
DISTRIBUTION OF GEL POCKETS ON SAWED SURFACES OF CONCRETE FROM TUSCALOOSA LOCK

Monolith and hole number	Numbers intersected on sawed surfaces, as percent				Isolated gel pockets
	Coarse aggregate not associated with gel		Coarse aggregate associated with gel		
	Chert	Other	Chert	Other	
3-1	36	56	5	2	1
5-1	36	56	5	2	1
20-1	38	48	5	5	3
60-1	31	57	4	3	2
60-2	32	56	5	5	3
60-3	19	46	9	13	13
60-4	34	48	6	7	4
Average, all 7 cores	36	53	5	4	2
Numerical totals	2032	3016	281	189	110

gravel samples from this deposit are summarized below:

Bulk specific gravity, saturated surface dry: sand = 2.65, gravel = 2.62

Absorption, percent: sand = 0.4, gravel = 0.7

Percentage of particles lighter than 2.40 after 5 hr. boiling: gravel = 2.1

Loss after 5 cycles of magnesium sulfate soundness test, percent: sand = 4.7, gravel = 4.0

Linear coefficient of thermal expansion of sand mortar $\times 10^6$ per deg. F. = 7.4

Durability factor of concrete after 300 cycles of accelerated freezing and thawing = 46

It is therefore suggested that the coarse aggregate used in the construction of the Tuscaloosa Lock contained a materially greater proportion of chalcidonic chert than the sample examined in 1948. The available information on these aggregates, as set forth above, would suggest that by all usual criteria of evaluation they were of as high or higher quality than the majority of the aggregates generally accepted for use and used without serious trouble throughout the coastal portions of the southern United States. In-

RIVER WATER

The presence of calcium sulfoaluminate as an abundant secondary material in the concrete and the nature of the deterioration in general suggested that it was desirable to obtain information on the river water to help to confirm or rule out the probability of sulfate attack on the concrete as a major or primary cause of deterioration. Results of chemical tests on a sample of water from the Warrior River, taken in 1948 at Lock 15 upstream from Tuscaloosa, as reported by the South Atlantic Division Materials Testing Laboratory, Corps of Engineers, are as follows:

pH	6.2
	ppm.
Total solids	35
Calcium as Ca	0.4
Magnesium as Mg	0.5
Iron as Fe	0.3
Silica as SiO ₂	9
Sulfates as SO ₄	0
Free carbon dioxide as CO ₂	4
Total hardness as CaCO ₃	3
Carbonate hardness as CaCO ₃	0

Stewart J. Lloyd, assistant state geologist, Geological Survey of Alabama, states that an analysis of a sample of water from the Warrior River above Tuscaloosa showed 10 parts per million of the SO₄ radical. This is not regarded as an excessive amount, since it is reported that the city water supply of Birmingham, Alabama, on analysis in 1932, showed 61 ppm of SO₄.

The cement used in the Tuscaloosa concrete was required to contain not more than 8 percent of calculated tricalcium aluminate. Cement A was found to have from 6.33 to 7.42 percent and averaged 6.89 percent. Cement B had from 6.50 to 6.96 percent and averaged 6.70 percent.

Acidity of River Water—It has been reported by Steele (23) that the average CaCO₃ content of the water in the Warrior River at the Tuscaloosa Lock is 24 ppm. and the average pH is 5.9. These data were discussed as follows (23):

It would not be surprising if a reader of this article should point to Tuscaloosa Lock and Dam in Alabama and say that the average pH value noted for that dam . . . indicated the possibility of corrosive attacks. . . . Possibly there may be a measure of truth in that statement since the concrete in Tuscaloosa Lock and Dam, after 12 years, shows rather serious deterioration. This deterioration, however, is primarily due to the so-called alkali-aggregate reaction. . . . It is possible that slightly acid waters entering the cracks and crevices in this structure have had a limited effect, but it appears doubtful whether the effect of acid waters would have been noticeable had not the expansive growth and extensive cracking produced by alkali reaction made this possible—in other words, there might have been some effect on the surface produced by the mildly acid waters, but it would have been confined to a thin surface layer of concrete.

These data suggest that any sulfate attack or acid leaching effects on the Tuscaloosa concrete are of very minor and probably insignificant importance.

CHERT AS A CHEMICALLY DELETERIOUS CONSTITUENT

Descriptions of chert and chalcedony have been published by the American Society for Testing Materials (2, 3). Chalcedony is described as follows:

Chalcedony has been considered both as a distinct mineral and as a variety of quartz. It is now generally believed to be composed of a submicroscopic mixture of fibrous quartz with a smaller but variable amount of opal. The properties of chalcedony are intermediate between those of opal and quartz, from which it can be distinguished only by laboratory tests. It frequently occurs as a constituent of the rock chert and is reactive with the alkalies in portland cement.

Chert is described as:

a fine-grained rock which is characterized by hardness, conchoidal fracture in dense varieties, the fracture becoming splintery in porous varieties, and a variety of colors. . . . Chert is composed of silica in the form of chalcedony, cryptocrystalline quartz, or opal, or combinations of any of these three. The determination of which form or forms of silica are present requires careful determination of optical properties, absolute specific gravity, or both. . . .

The writer (14, 15, 16), following Donnay (7) and others, assumes that chalcedony consists of microfibrillar quartz with interstitial opal, that the observed chemical reactivity between certain cherts and the alkalies in

portland cement is actually a reaction involving the opal portion of the chalcedony component in the chert, and that in the absence of opal as such or of chalcedony no reaction should be expected. Attention, however, was called (15) to the indications obtained by Alderman, Gaskin, Jones, and Vivian (1) that cryptocrystalline quartz itself may be reactive. Studies conducted at Pennsylvania State College have been reported recently (9, 10) in which chalcedony has been found to have features suggesting that its properties and those of chalcedonic chert "are adequately explained by the hypothesis that it consists of fine-grained quartz plus a variable quantity of free water in the form of distinct bubbles; there is no evidence of admixed opal" (10).

About all that can be said at this time therefore is that forms of silica consisting of or containing opal, forms having the properties of chalcedony, and possibly certain forms having the properties of microcrystalline quartz are capable of reacting chemically with the alkalies in portland cement. The study reported in this paper serves to document a case in which it is apparently those aggregate particles consisting of or containing silica having the properties of chalcedony that participated in a chemical reaction with the alkalies from the cement with the result that the concrete suffered deterioration. The same caution which was previously suggested (15) is believed still necessary in extrapolating from these data to other concrete containing similar constituents: "The possibility that the expected reaction will not occur or that it may be forestalled . . . should always be borne in mind by the petrographer when called on to predict what will happen if a certain aggregate is used, or by the engineer who evaluates such predictions."

The ability of chalcedony to be a deleteriously chemically reactive constituent in concrete aggregate has been the subject of considerable discussion. Rhoades (22) states: "Typical chalcedony perhaps is no more to be suspected of potential reactivity than quartz. However, authoritative conjecture surrounds the possibility that some chalcedony verges toward an opaline character. . . ." Kelly, Schuman, and Hornibrook (12) state: "the literature has thus far not considered chalcedony a likely source of concrete expansion resulting from alkaline reactivity." On

the other hand, chalcedony has been listed as "deleteriously reactive with high-alkali cement" by Mielenz (19); McConnell, Mielenz, Holland and Greene (17, 18); Blanks (6), and in other papers prepared at the Bureau of Reclamation.

It is believed that the present paper represents the first published description of deterioration of concrete through cement-aggregate reaction in which chalcedony is the major aggregate constituent responsible for the deleterious reaction. McConnell, Mielenz, Holland, and Greene (18) indicated that chalcedony was a minor control in seven previous examples of such deterioration but that in all of these cases glassy volcanic rocks comprised the major control. These seven cases are: Parker Dam, Gene Wash Dam, Copper Basin Dam, Stewart Mountain Dam, American Falls Dam, Owyhee Dam, and street pavements at Kimball, Nebraska. In addition, it may be noted that while phyllite is cited (18) as the only control for the deterioration of the concrete in the structures at Buck Dam, Virginia, petrographic work reported by Kelly, Schuman, and Hornibrook (12) indicates that chalcedony is a major constituent of the phyllite in question.

SUMMARY AND CONCLUSIONS

All of the cores, regardless of brand of cement, contain deposits of gel in voids, cracks, and aggregate particles in all sections, regardless of depth from the upper or outer surface of the structure. The widest fresh cracks are coated with gel and the adjoining paste is soaked with gel. In all of the concrete there is more gel than sulfoaluminate; more voids are filled with gel than with sulfoaluminate. Sulfoaluminate is most developed in the most highly leached and cracked concrete. It is believed that the gel produced by alkali-aggregate reaction is the major cause of the cracking of the upper and outer portions of the cores.

A study of aggregate particles from the concrete revealed that approximately 70 percent of the chert pebbles consisted, at least in part, of chalcedony. Chalcedony is one of the materials capable of participating in a deleterious chemical reaction in concrete. The study of the aggregate did not reveal the presence of any other constituent regarded as capable of participating in such a reaction.

The study of the concrete specimens con-

firmed the indications developed from the examination of the structure that the cracking was largely confined to near-surface zones and was more pronounced in those portions of the structure in which it was reported that Cement A was used. Although specific data on the alkali contents of the cements used in this project are not available, it is regarded as probable that Cement A contained a larger percentage of alkalies than did Cement B.

All of the concrete cores were characterized by the presence of deposits of crystals of calcium sulfoaluminate. Calcium sulfoaluminate is the normal product of the reaction between the tricalcium aluminate in the cement, and the gypsum which is interground with the cement for the purpose of controlling time of set. In normal, nondeteriorated concrete the calcium sulfoaluminate is widely distributed in the cement paste and does not appear as deposits of crystals. Concrete which has suffered deterioration from any cause frequently exhibits crystalline deposits of this material. Unless it can be shown that additional sulfate has been provided from an external source for further reaction with the aluminate portion of the cement, such deposits do not indicate that the concrete containing them has undergone any deterioration due to sulfate attack. In the case of the Tuscaloosa concrete, since the available information does not indicate an additional source of sulfate and since the evidence of deterioration due to alkali-chalcedony reaction is thoroughly established, it is not regarded as likely that there was a significant sulfate-attack factor involved in this occurrence. The possibility of attack on the concrete by the slightly acid river water is regarded as having, at most, an insignificant effect.

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